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A new European plant-specific emission inventory of biogenic volatile organic compounds for use in atmospheric transport models

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Abstract

We present a new European plant-specific emission inventory for isoprene, monoterpenes, sesquiterpenes and other VOC (OVOC), with a spatial resolution of 10 km, for implementation in atmospheric transport models. The inventory incorporates new data on emission factors at standard conditions for tree and crop species that became available in the last years and more accurate data on foliar biomass densities coming from several new litterfall databases. In contrast to previous emission inventories, a bioclimatic correction factor was introduced to correct the foliar biomass densities for the different plant growth conditions that can be found in Pan-Europe. The 2004–2005 averaged annual total biogenic volatile organic compound (BVOC) emissions for the Pan-European domain are estimated to be about 15 Tg with a large contribution from the OVOC class of about 6 Tg and from monoterpenes of about 5 Tg. Annual isoprene emissions are found to be about 3 Tg, insensitive to the chosen emission algorithm. For the first time crop-specific land use information and standard emission factors were employed. Contrary to former European inventories, emissions of monoterpenes and OVOC were found to originate to a large extent from agriculture. However, monoterpene standard emission factors for crops are highly uncertain and probably positively biased by measurement artifacts. Further experiments on crop emissions should be carried out to check the validity of the high emission factors for monoterpenes and OVOC. In view of future intensified use of agricultural crops as biofuels, emissions of OVOC and monoterpenes from agriculture need to be evaluated in the field.

1 Introduction

The composition of plant species that cover the land surface is the primary control on the magnitude of biogenic volatile organic compound (BVOC) flux. On a shorter time scale, variation in atmospheric conditions determines the amount of photosynthetically active photon flux density (PPFD) reaching the leaf surface, the leaf temperature, and soil moisture. All these factors in turn influence variations in BVOC emissions. Temperature and light intensity are key driving variables that regulate emissions of isoprene, monoterpenes and other BVOCs in published emission algorithms (Tingey et al., 1991; Guenther et al., 1993; Guenther et al., 1995; Schuh et al., 1997; Guenther et al., 2006).

Once emitted to the atmosphere, BVOCs react in the presence of nitrogen oxides to increase the concentration of tropospheric ozone (Atkinson and Arey, 2003), which is a respiratory irritant and major component of smog. Emissions of BVOC are significant to ozone production in the European boundary layer (Simpson, 1995; Vogel et al., 1995). The oxidation products of terpenes condense to form secondary organic aerosols (Hoffmann et al., 1997; Kavouras et al., 1998; Griffin et al., 1999) which directly alter Earth's radiative balance and can serve as cloud-condensation nuclei (Andreae and Crutzen, 1997). On the basis of results from smog chamber experiments of Pandis (1991) it has commonly been assumed that the photooxidation of isoprene does not contribute to the production of secondary organic aerosol under ambient conditions (Seinfeld and Pandis, 1998). However, evidence from both field and laboratory experiments has been obtained in the last four years for isoprene contributing to SOA formation (Claeys et al., 2004; Kourtchev et al., 2005; Kroll et al., 2005). Sesquiterpenes are a highly reactive BVOC class with atmospheric lifetimes of only a few minutes. These compounds have a high potential to form secondary organic aerosol (Hoffmann et al., 1997; Jaoui et al., 2003). Bonn and Moortgart (2003) suggest that the reaction of sesquiterpenes with atmospheric ozone could be responsible for the atmospheric new particle formation observed frequently in rural locations.

Recent observations in boreal forests support the role of aerosol production from biogenic hydrocarbon precursors in the activation of cloud droplets (Kerminen et al., 2005; Tunved et al., 2006). In addition, BVOCs released to the atmosphere may represent a relevant source term in the overall carbon budget of an ecosystem (Guenther, 2002; Kesselmeier et al., 2002).

The European landscape is characterised by a great variety of climatic and orographic zones and biomes, ranging from boreal forests in Scandinavia and Russia to

Mediterranean shrub vegetation. For millennia, the European land cover has been intensively modified by man to create an extremely patchy landscape. In addition the orography of Europe is complex, with changes between mountainous and plane landscapes on a small scale. Therefore it is of great importance to use high resolved land cover data of forests, agriculture and other land uses for modelling European BVOC emissions.

The aim of this work is to build up a new plant-specific BVOC emission inventory for Europe with a high spatial resolution. Data on emission factors at standard conditions for tree and crops species and for the landcover classes as compiled in the survey by Lenz et al. (2002) was updated with latest field and laboratory results. From several litterfall databases we derived more accurate data on foliar biomass densities. In contrast to previous BVOC emission inventories, a biomass correction factor was introduced to adjust foliar biomass densities for growing conditions in different climates.

Estimates of European isoprene emission depend on the choice of emission algorithms describing the temperature and light dependence of emissions. Two different representations of the temperature and light dependence, G97 (Guenther, 1997) and MEGAN (Guenther et al., 2006), were used to calculate emission fluxes of isoprene over Europe. Previous European emission estimates for isoprene were about 4 Tg per year, and for total BVOC ranged between 7.5 Tg to 29 Tg per year, (Simpson et al., 1999; Steinbrecher et al., 2008; Lübkert and Schöpp, 1989; Andryukov and Timofeev, 1989), indicating the high uncertainty of BVOC inventories. The reason for this high variability is not always easy to understand, because inventories are not always fully transparent or cannot be compared for various reasons. Therefore, the new inventory presented here aims at full transparency and avoidance of non-needed complexity in order to allow calculations in the frame of a global chemical transport model.

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2 Inventory description

In this work a new inventory of BVOC emission rates for implementation in atmospheric transport models is build up for Europe. For each BVOC class the emissions can be calculated as sum over all grid cells of the European domain:

$$E_c = \sum_i A_i \times \epsilon_{i,c} \times D_i \times \gamma_{CE,i} \quad (1)$$

In Eq. (1), A_i is the vegetated and emitting area in a grid cell i (in m^2), $\epsilon_{i,c}$ is the average emission standard potential (in $\mu g\, g_{DW}^{-1}\, h^{-1}$) of each BVOC class for 30°C leaf temperature and 1000 $\mu mol\, m^{-2}\, s^{-1}$ photosynthetically active photon flux density (PPFD), D_i the foliar biomass density related to dry plant mass (in $g\, m^{-2}$) and $\gamma_{CE,i}$ is the dimensionless canopy emission activity factor, often refered to as environmental correction factor.

The schematic information flow of our BVOC emission model is depicted in Fig. 1. The model contains four main parts: (1) retrieving geo-referenced spatial data from several Geographic Information System (GIS) databases and property data from tabular databases, (2) meteorological input data from the European Centre for Medium Range Weather Forecast (ECMWF) and leaf area index data from MODIS, (3) aggregation of the spatial GIS data for the Pan-European domain, processing of tabular input and writing output to HDF files, (4) calculation of BVOC emissions using a Canopy Environment Model written in Interactive Data Language (IDL). In Sect. 2.1 to 2.4 the procedure of retrieving and aggregating spatial information with plant specific properties is described in detail (part 1 and 3 in Fig. 1). Section 2.5 describes the Canopy Environment Model which was applied to calculate the emission activity factor $\gamma_{CE,i}$ in Eq. (1). Throughout the paper, emission factors and emission rates refer to mass of BVOC compound.

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2.1 Land use aggregation

In this section we derive the vegetated and emitting area A_i in a grid cell. A new land use map covering the European continental domain (–20° W, 20° N to 40° E, 70° N) is compiled by combination of tree species distributions from the *Tree Species Map* (Köble and Seufert, 2002) and crop species distributions from the *Agricultural Land Use Map* (Leip et al., 2008) with the CLC/GLC2000 mosaic (Köble, 2007) land cover data. The *Tree Species Map* distinguishes 115 tree species and is based on the inventory of the ICP (International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) Forest Focus level1 network. The *Agricultural Land Use Map* includes 26 crop species and is based on work of the project CAPRI-DynaSpat (Common Agricultural Policy Regional Impact Analysis – The Dynamic and Spatial Dimension). The CLC/GLC2000 mosaic contains 50 vegetation classes, combining the Corine Land Cover map CLC2000 (see http://terrestrial.eionet.eu.int/) and the global and different regional versions of the GLC2000 (http://www-tem.jrc.it/glc2000/defaultglc2000.htm) for the European continent. All land use data was aggregated to 10 km by 10 km and projected on a regular latitude/longitude grid. Since longitudes are widest at the equator and converge towards the poles, the grid cell area in the new latitude/longitude grid corresponds to about 9.6 km by 9.6 km at the southern border (20° N) and to about 5.5 km by 5.5 km at the northern border (70° N) of the domain.

In the equations below, j is used as an index for tree species, k for crop species, l is an index for the general CLC/GLC 2000 land use classes, and c denotes the BVOC classes.

The CLC/GLC2000 mosaic land use map covers the complete Pan-European domain and the sum of area fractions of CLC/GLC2000 mosaic vegetation classes ($a_{\text{clc},i}$) in a grid cell i is assumed to be the total vegetated area fraction. The vegetation composition of CLC/GLC2000 vegetation classes is described in Sect. 2.4.

Before the plant-specific land use information was merged with the CLC/GLC2000 mosaic land use information, it was assured that $a_{\text{clc},i}$ does not exceed 1 in each grid cell, by relating the cumulated areas of the CLC/GLC2000 mosaic to the total area in each grid cell. Since this was found to be the case for all grid cells, the vegetated areas provided by the CLC/GLC2000 mosaic can be used as a reference for the plant-specific land use data coming from the *Tree Species Map* and from the *Agricultural Land Use Map*. The advantage of using the CLC/GLC2000 mosaic as a reference is that it covers the complete Pan-European region, while both the *Tree Species Map* and the *Agricultural Land Use Map* cover only parts of the European domain. The *Agricultural Land Use Map* contains crop-specific information for EU15 and the *Tree Species Map* contains tree-specific information for 30 European countries.

In the next step, forest and agriculture areas of the CLC/GLC2000 mosaic land cover in a cell were replaced with the areas of the respective tree and crop species coming from the *Tree Species Map* and the *Agricultural Land Use Map*, where this information was available. The forested area in a grid cell covered with the *Tree Species Map* should be the same as the area from forest vegetation classes defined in the CLC/GLC2000 mosaic. But since the maps were created using different methods and data sources, there may be inconsistencies between the CLC/GLC2000 mosaic and the plant-specific land use maps. To avoid these inconsistencies in the new European map, the area fraction $a_{i,j}$ for a single tree species j and the area fraction $a_{i,k}$ for a single crop species k is corrected with the cumulated area fraction of CLC/GLC2000 forest, $a_{\mathrm{clcfor},i}$, or agriculture, $a_{\mathrm{clcagr},i}$, vegetation classes within a grid cell. The corrected area fraction of a tree species, $a'_{i,j}$, is:

$$a'_{i,j} = a_{i,j} \times \frac{a_{\mathrm{clcfor},i}}{\sum_j a_{i,j}} \tag{2}$$

and the corrected area fraction of a crop species, $a'_{i,k}$, is:

$$a'_{i,k} = a_{i,k} \times \frac{a_{\mathrm{clcagr},i}}{\sum_k a_{i,k}} \tag{3}$$

The grid cell area A_i (in m^2) (see Eq. 1), that is covered with vegetation and emits BVOC is:

$$A_i = \left(\sum_{i,j} a'_{i,j} + \sum_{i,k} a'_{i,k} + a_{\mathrm{clc},i} \right) \times A_{\mathrm{cell},i} \qquad (4)$$

where $A_{cell,i}$ is the total area of the grid cell i (in m^2).

2.2 Foliar biomass density

Foliar biomass density distribution for Europe is determined from the land use information and plant-specific values. The foliar biomass density D_i in a grid cell (see Eq. 1) is the sum of the foliar densities of trees, d_j, and of crops, d_k, in the cell, weighted by the area contribution of the plant to the cell area. For the remaining area of a grid cell, covered with vegetation of CLC/GLC2000 classes, the foliar density d_l is added, weighted by the area fraction $a_{i,l}$ of the CLC/GLC2000 class l in that cell:

$$D_i = \sum_j a'_{i,j} d_j f_j + \sum_k a'_{i,k} d_k f_k + \sum_l a_{i,l} d_l f_l \qquad (5)$$

where f_j, f_k and f_l are the dimensionless zonal bioclimatic correction factor for trees, crops and CLC/GLC2000 vegetation classes, respectively. European foliar biomass density distributions calculated from Eq. (5) for agriculture, forest, other land use and total land use are shown in Fig. 2. To reflect different growth conditions for the same tree species within Pan-Europe, e.g. in central Europe compared to the boreal vegetation zone, the foliar biomass densities were harmonised relative to growing conditions in the continental vegetation zone. For this purpose we introduced zonal bioclimatic correction factors for the different plant species and vegetation classes. The determination of these correction factors is described in the following.

The *Indicative Map of European Biogeographical Regions* developed by the European Environment Agency (2007) covering the Pan-European domain was chosen to define the geographic boundaries of European vegetation zones. This biogeographic map is based on the maps of natural vegetation by Noirfalise (1987) for the European Union and by Bohn (1993) for remaining parts of Pan-Europe, as Eastern Europe and Turkey. This map discerns 11 biogeographic (vegetation) zones for Pan-Europe: Arctic, Alpine, Boreal, Atlantic, Continental, Steppic, Pannonian, Anatolian, Mediterranean, Black Sea, and Macaronesia. Northern Africa and Western Arabia which are outside the data coverage of the map are treated as one additional vegetation zone (Africa-Arabia). Macaronesia covers the Canary Islands, Madeira and Azores Islands. Due to the small area covered by this zone, it was added to the Africa-Arabia zone. The bioclimatic correction factors for trees and forests were derived from litterfall and foliar net primary productivity (NPP) data and bioclimatic correction factors for crops and agriculture from crop yield data. The continental vegetation zone is used as a reference zone to define bioclimatic correction factors for trees (f_j), crops (f_k), and CLC/GLC2000 vegetation classes (f_l). Table 1 lists bioclimatic correction factors for main tree species and Table 2 for crop species in each vegetation zone.

According to Köble and Seufert (2002), the main tree species in Europe are *Pinus sylvestris* with a percentage contribution of 31.2% to the forested area in 30 countries, followed by *Picea abies* (21.4%), *Fagus sylvatica* (7.1%), *Betula spp.* (7.0%), *Quercus robur* (2.9%), *Pinus pinaster* (2.5%), *Quercus petraea* (2.3%). Litterfall data and foliar NPP are used as indicators for growth conditions for these tree species. The information on the litterfall and foliar NPP of trees at European sites is extracted from four databases: (1) leaf fall data from the global litterfall database of the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) (Holland et al., 2005), (2) the Forest Focus database for the ICP level2 plots (http://forestfocus-data.jrc.it/FF_PublicActions/_welcome.jsp), (3) the foliage component of NPP from the recent global database on forest carbon fluxes and pools presented by Luyssaert et al. (2007), (4) leaf fall data for birch (*Betula spp.*) from the new AFOLU (Agriculture, Forestry and Other Land Uses) Biomass Compartments database (Teobaldelli, 2008, see http://afoludata.jrc.it/data_fs.cfm). Annual dry foliar biomass in

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$g\,m^{-2}$ was calculated for each data record at European sites from the four databases. NPP data for the foliar compartment from Luyssaert et al. (2007) were converted from carbon to dry biomass using a conversion factor of 2. Depending on the geographic location of the forest site, the resulting foliar biomass for a certain tree species was attributed to the corresponding vegetation zone. By this procedure, altogether 89 litterfall records were compiled for *Pinus sylvestris*, 119 for *Picea abies*, 54 for *Fagus sylvatica*, 439 for *Betula spp.*, and 92 for *Quercus robur* and *Quercus petraea*. The zonal bioclimatic factor for a specific tree species is defined as the fraction of the average foliar biomass in a vegetation zone to its average foliar biomass in the Continental vegetation zone. Bioclimatic correction factors for CLC/GLC forest classes were derived from bioclimatic correction factors of single tree species weighted for their contribution to the tree composition of the respective CLC/GLC forest class (see Sect. 2.4). Zonal bioclimatic correction factors for tree species and forest are given in Table 1.

The average foliar biomass in the Continental vegetation zone has been used to derive the foliar biomass density value d_j for several tree species. This was done with all tree species with more than 10 data records within the Continental vegetation zone. Based on 34 records a value of $350\pm108\,g\,m^{-2}$ was obtained for *Fagus sylvatica* which is at the higher end of the range ($310\pm47\,g\,m^{-2}$) given by Veldt (1991). For European oaks (*Quercus robur* and *Quercus petraea*) a value of $290\pm74\,g\,m^{-2}$ was derived, which is lower than the mean value of $330\pm90\,g\,m^{-2}$) from Veldt (1991) but well within the range of uncertainty. Our values for *Betula spp.*, *Pinus sylv.* and *Picea abies*, $230\pm185\,g\,m^{-2}$, $690\pm240\,g\,m^{-2}$, and $1340\pm700\,g\,m^{-2}$, respectively, are in reasonable agreement with Veldt (1989), but show a large spread. Furthermore, foliar biomass densities could be derived for the Mediterranean oaks *Quercus ilex* and *Quercus coccifera*. They were found to be $510\,g\,m^{-2}$ and $520\,g\,m^{-2}$, respectively, and thus well in agreement with the default value for evergreen broadleaved trees given by Veldt (1989).

Crop yields are used as an indicator for growth conditions of crops. National crop yields per hectare were obtained from the Food and Agriculture Organization of the

United Nations (FAO) (FAOSTAT, 2007), for all countries within the Pan-European domain defined in this work. FAOSTAT is the most widely recognized standard for national level agricultural statistics. Yields are provided in metric tons per harvested hectare, and equal the annual total production in a country divided by the total harvested area. National yields of crop species that corresponded to the crop species given in the *Agricultural Land Use Map* were retrieved from FAOSTAT. The yearly average from 2000–2005 was used to derive the average crop yield in each vegetation zone. European countries were attributed to certain vegetation zones (see explanations in Table 2). The zonal bioclimatic factor for a specific crop species is defined as the fraction of the crop yield in one vegetation zone to its crop yield in the Continental vegetation zone. In the Arctic vegetation zone, the bioclimatic correction factor is 0.55 for all crops and agriculture types. This value is derived from the yield of potatoes grown in Iceland. It should be noted that FAO crop yields not only reflect the influence of climate on agriculture productivity but also depend on agriculture management, farming practices and fertiliser application. Zonal bioclimatic correction factors for crop species and agriculture are compiled in Table 2.

Foliar biomass density values of trees, d_j, and of crops, d_k, for use with Eq. (5) are listed in Tables 3 and 4. Values in Tables 3 and 4 are representative for growing conditions in the temperate and humid part of Europe, which is in our work refered to as the Continental zone. Foliar biomass densities of trees were adopted from the EMEP CORINAIR (1999) manual, which are based on the study of Veldt (1989), and for mediterranean trees from Owen et al. (2001) and completed with values from the GloBEIS database (Geron et al., 1994). For several tree species foliar biomass densities have been derived from litterfall data within the frame of this work. For crop species and for CLC/GLC2000 vegetation classes default values for foliar biomass densities given in the EMEP CORINAIR (1999) manual and from Simpson et al. (1999) were taken.

2.3 BVOC standard emission factors

The procedure to aggregate the foliar densities in a grid cell is followed for the standard emission potential $\epsilon_{i,c}$ of a BVOC class c and is:

$$\epsilon_{i,c} = \sum_j a'_{i,j}\epsilon_{i,j,c} + \sum_k a'_{i,k}\epsilon_{i,k,c} + \sum_l a_{i,l}\epsilon_{i,l,c} \quad (6)$$

where $\epsilon_{i,j,c}$, $\epsilon_{i,k,c}$ and $\epsilon_{i,l,c}$ are the BVOC standard emission potentials of a single tree species, crop species and CLC/GLC2000 vegetation class respectively. European standard emission potential distributions calculated from Eq. (6) for isoprene, monoterpenes (pool), monoterpenes (synthesis), and sesquiterpenes are shown in Fig. 3. In the following part we motivate the choice of BVOC standard emission factors of the most abundant emitters, which were as far as possible derived from original literature values. A complete list of standard emission potentials for all BVOC classes of trees, $\epsilon_{i,j,c}$, and of crops, $\epsilon_{i,k,c}$ is given in Tables 3 and 4. Table 3 also provides values for low vegetation species like shrubs and herbs.

Monoterpenes are known to constitute a main fraction of "essential oils" that are produced and stored in the plant secretory organs (Kesselmeier and Staudt, 1999). It is now well established that stored monoterpenes and other BVOC are released depending on the temperature and this type of emission behaviour is usually refered to as pool emissions. Isoprene is never stored after its production by plants but rapidly lost by volatilisation and isoprene emissions dependent on both temperature and light. Recently, a number of studies revealed that monoterpene (MT) emissions from many plant species exhibit a strong dependence on light and were negligible during the night (e.g. Staudt and Seufert, 1995). This type of emissions is termed newly synthesized emissions.

Conifers are usually associated with emission of monoterpenes and very low or no emissions of isoprene (Geron et al., 2000). For fir trees (genus *Abies*) and pine trees (*Pinus spp.*) we generally adopted the isoprene emission factor of 0.1 $\mu g\, g_{DW}^{-1}\, h^{-1}$ given in the review of Guenther et al. (1994). Among these coniferous trees, only *Abies*

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Borisii-regis was found to be a strong isoprene emitter (Harrison et al., 2001). MT emissions from fir and pine trees are usually pool emissions. However, Moukhtar et al. (2006) found pool emissions and in addition temperature and light dependent (newly synthesized) MT emissions from *Abies alba*. Staudt et al. (1997) also found additional newly synthesized MT emissions from Italian Stone Pine (*Pinus pinea*). For Scots Pine (*Pinus sylvetris*) a value of 2.25 $\mu g\, g_{DW}^{-1}\, h^{-1}$ for pool MT emission is used, taking into account the higher emission factor found by Komenda and Koppmann (2002) in Germany compared to the earlier work of Janson (1993) who had reported 0.8 $\mu g\, g_{DW}^{-1}\, h^{-1}$ for Scots Pine in Sweden.

Norway spruce (*Picea abies*), which dominates the landscape of Scandinavia and large parts of Central Europe, is a low isoprene emitter (Grabmer et al., 2006), while for Sitka spruce (*Picea sitchensis*) an isoprene emission factor of 13 $\mu g\, g_{DW}^{-1}\, h^{-1}$ was found (Hayward et al., 2004). Both spruce species are reported to have both pool and newly synthesized MT emissions.

Birch species (*Betula spp.*) are the main deciduous broadleaf tree species in boreal forests. Both *Betula pendula* and *Betula pubescens* have been reported to be monoterpene and sesquiterpene emitters (Hakola et al., 2001).

Recent investigations of European beech (*Fagus sylvatica*), the dominating deciduous tree species in Europe, revealed the light and temperature dependent character of its monoterpene emissions with standard factors in the range of 4–44 $\mu g\, g_{DW}^{-1}\, h^{-1}$ (Moukhtar et al., 2005; Dindorf et al., 2006). We use 20.3 $\mu g\, g_{DW}^{-1}\, h^{-1}$, which is the mean of the lower and upper limit value taken from Dindorf et al. (2006) and the average value from Moukhtar et al. (2005). In Central Europe, deciduous oaks like *Quercus robur* and *Quercus petraea* are relatively abundant tree species. They are known as strong isoprene emitters and low MT emitters (Steinbrecher et al., 1997; Isidorov et al., 1985).

Within the group of evergreen and semi-evergreen oaks in the Mediterranean most species (*Quercus ilex*, holm oak; *Quercus coccifera*, kermes oak) emit exclusively monoterpenes, while deciduous oaks in the Mediterranean (*Quercus frainetto*, Hun-

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garian oak; *Quercus pyrenaica*, Pyrenean oak) emit exclusively isoprene, others do not emit anything (Csiky and Seufert, 1999). Cork oak (*Quercus suber*) has been found to emit neither isoprene nor monoterpenes (Steinbrecher et al., 1997). However, recently Pio et al. (2005) reported a MT standard emission factor of 25 µg g_{DW}^{-1} h^{-1} which we use in this work. Eucalyptus is one of the world's most important and most widely planted genera, and is used for plantations in the Mediterranean region. It has high emission rates of isoprene (Street et al., 1997) and monoterpenes (He et al., 2000).

Crop plants are considered to be low emitting species. However, grasslands and pastures have been found to emit quite substantial amounts of other VOC (OVOC) compounds (Kesselmeier and Staudt, 1999). Previous estimates of European BVOC emissions from agriculture have been based on generalized crop emission properties (e.g. Simpson et al., 1995; Simpson et al., 1999, Steinbrecher et al., 2008). Simpson et al. (1999) estimate a total of 1440 Gg yr^{-1} BVOC from agriculture crops, consisting mainly of OVOC emissions (1350 Gg yr^{-1}). Isoprene emissions from widespread crops as wheat, oat and rye are generally found to be zero or close to zero (Arey et al., 1991; Winer et al., 1992; König et al.,1995). Most standard emission potentials for crops in this study are adopted from EMEP CORINAIR (1999). We note that recommendations of the CORINAIR (1999) guidelines and values applied in our work rely heavily on the early studies of Arey et al. (1991) and Winer et al. (1992). Reported high MT emission values for tomatoes, potatoes and fruits are probably affected by experimental biases. Some agriculture plant species have been found to be important sesquiterpene emitters, for example sunflower (Schuh et al., 1997) and tomatoes (Winer et al., 1992). Available emission data for OVOC are scarce and only rough estimations on OVOC emissions exist. There are only few studies with chemical speciation of OVOCs. Due to the lack of data, we use a default standard emission potential for OVOC for most plants. The default value is 1.7 µg g_{DW}^{-1} h^{-1} for most tree and crop species as proposed in Guenther et al. (1995).

Plant-specific emission factors for sesquiterpenes in Europe were compiled based on the recent review of Duhl et al. (2007). Studies on sesquiterpene (SQT) emission factors are rare but recently several new investigations on SQT emissions have been published for different tree and crop species (*Picea abies*, Martin et al., 2003; *Pinus halepensis*, Ormeño et al., 2007a; pine trees, Helmig et al., 2007; *Populus hybrides*, Arimura et al., 2004; *Quercus coccifera*, Ormeño et al., 2007b; *Betula pubescens*, Hakola et al., 2001; citrus trees, Hansen and Seufert, 2003, and maize, Gouinguene and Turlings, 2002). Sesquiterpene standard emission factors reported by Vizuete et al. (2004) have been included for some tree and crop species. The inventory of Vizuete et al. (2004) is largely based on early studies of e.g. Helmig et al. (1999). Duhl et al. (2007) state, that values of early SQT studies were very likely positively biased by disturbance-induced emission bursts, elevated enclosure temperatures and disturbances during sample collection. We therefore excluded all SQT standard emission potential values above 5 $\mu g\, g_{DW}^{-1}\, h^{-1}$ reported in Helmig et al. (1999) and Vizuete et al. (2004). If no measurements or no information was available in the literature, we applied a default SQT standard emission potential for all tree and crop species of 0.085 $\mu g\, g_{DW}^{-1}\, h^{-1}$. The default value is derived from the estimate of Griffin et al. (1999), who assumed 5% of the OVOC emissions to be SQT emissions. In the Duhl et al. (2007) review, default values for coniferous trees, broadleaf trees, shrubs and crops are discerned. The respective default values are 0.29±0.41, 1.41±2.20, 7.06±6.83 and 0.19±0.43 $\mu g\, g_{DW}^{-1}\, h^{-1}$. The high standard deviations associated with these numbers allow for the lower default value chosen in this work.

2.4 General land use class emissions

For European regions, where no plant-specific information was available (Eastern Europe, Northern Africa, some European countries), and also for the other land use category (shrubs, wetlands, grassland), general land use classes from the GLC/CLC2000 Mosaic were used. As stated in Sect. 2.1, the CLC/GLC2000 mosaic covers the complete Pan-European domain. The plant composition of each vegetation class was extracted from the GLC/CLC2000 documentation. The plant composition was then applied to derive foliar biomass densities and BVOC standard emission potentials weighted by the contributions of individual crop species from the *Agricultural Land Use Map* and tree species from the *Tree Species Map*. This procedure reduces the bias of BVOC standard emission factors for general land use classes, compared to the application of default values for general land use classes. Except for shrubs and herbs, where plant-specific information was available from the literature (see Table 3), default values for the other land use category were adopted from Guenther et al. (1995) and EMEP CORINAIR (1999). Vegetation classes from the Global Land Cover, GLC2000, were divided into Africa, Northern Eurasia, and Europe parts, if their geographical distribution covers different parts of Pan-Europe. The African region corresponds to the European part of the GLC Africa v5.0 and the GLC Global v1.1, the Northern Eurasia region to the European part of GLC Northern Eurasia v4.0 and the Europe region corresponds to the extent of GLC Europe v1.0. For each of these three regions a different plant composition was derived from the GLC/CLC2000 documentation of the respective GLC region map and used for the weighting of foliar biomass densities and BVOC standard emission potentials. Vegetation composition, foliar biomass densities and BVOC standard emission potentials for GLC/CLC2000 vegetation classes are compiled in Table 5.

2.5 Canopy environment model

In this section a simplified canopy environment model is presented that calculates the emission activity factor $\gamma_{CE,i}$ in Eq. (1) depending on temperature and the light incident on the leaves as well as on the actual emitting leaf surface (part 4 in Fig. 1). The model contains emission algorithms for different BVOC classes. Depending on compound and plant, emissions are either from storage pools of the leaves or are newly synthetisized in the leaves. For pool emissions, the model calculates the pool emission activity factor $\gamma_{CE,i}$(pool). For newly synthesized emissions, i.e. emissions of isoprene and MT_{synt}, $\gamma_{CE,i}$(synt) is calculated.

Monoterpene emissions for most coniferous plants and the emissions of OVOC in general are assumed to be pool emissions depending only on temperature. For this compound group, the emission activity factor is:

$$\gamma_{CE,i}(\text{pool}) = \gamma_{\text{pool}} \times \gamma_{\text{seas}} \tag{7}$$

with γ_{pool} calculated using the approach of Guenther et al. (1993):

$$\gamma_{\text{pool}} = \exp(\beta(T - T_S)) \tag{8}$$

with the empirical coefficient β=0.09 K^{-1}, T the leaf temperature (in K) and T_S the leaf temperature at standard conditions (in K). Emissions of sesquiterpene are assumed to be pool emissions, although there is evidence that emissions of β-caryophyllene, a major SQT emitted by plants, are both light and temperature dependent (e.g. Schuh et al., 1997; Hansen and Seufert, 2003). Hakola et al. (2006) stated that it can be difficult to discern light dependencies from SQT emission data under field conditions since light saturation of the applied emission algorithms is achieved in most cases. Tarvainen et al. (2005) reported measurements of β-caryophyllene emissions from Scots Pine in darkened branch cuvettes that were similarly high as when the cuvette received light. For this study the empirical coefficient β in Eq. (8) was chosen to be 0.17 K^{-1} for SQT emissions. This is the average value for β given by Helmig et al. (2007) for SQT emissions from eight pine tree species.

The seasonality factor γ_{seas} is given by Guenther et al. (2006):

$$\gamma_{\text{seas}} = \frac{0.49LAI}{\sqrt{1 + 0.2LAI^2}} \tag{9}$$

Seasonality of emissions is simulated with the leaf coverage per unit ground area, expressed by the leaf area index (LAI). The seasonality factor ensures that there are no emissions from deciduous trees in wintertime because leaves are not present. It should be noted that this seasonality factor only accounts for the responses to LAI variations. All other seasonal variations (e.g. of temperature and phenology) are not taken into account by this factor.

Isoprene emissions are generally regarded as dependent on light and temperature. Monoterpenes can be released in the same manner as isoprene from many plants (Kesselmeier and Staudt, 1999), a promiment example being European beech (*Fagus sylvatica* L.) (Dindorf et al., 2006). Isoprene emissions depending on temperature and light were calculated based on the recent concept described in Guenther et al. (2006), from now on refered to as MEGAN (Model of Emissions of Gases and Aerosols from Nature). Additional factors controlling isoprene emissions as density of green leaves, soil moisture, and phenology of leaves can be taken into account in the MEGAN version 2 model by Guenther et al. (2006), but were not considered in this work.

For MEGAN the canopy environment emission activity factor is:

$$\gamma_{CE,i}(\text{synt}) = C_{CE} \times \gamma_T \times \gamma_P \times \text{LAI} \tag{10}$$

For the canopy radiation model applied in this work, C_{CE} is set to 1.13 in order to obtain $\gamma_{CE,i}(synt)$=1 at standard conditions. The value for C_{CE} is about 2 times larger than given in Guenther et al. (2006), where C_{CE}=0.57 is used. This is due to the simplified canopy environment model applied in our work (see below).

The temperature dependence of MEGAN is expressed as:

$$\gamma_T = \frac{E_{\text{opt}} \times C_{T2} \cdot \exp(C_{T1} \times x)}{C_{T2} - (C_{T1} \times [1 - \exp(C_{T2} \times x)])} \tag{11}$$

with $x=(\frac{1}{T_{\text{opt}}}-\frac{1}{T})/R$. R is the universal gas constant (R=0.00831 kJ K^{-1} mol^{-1}), C_{T1}, C_{T2} are empirical constants given by Guenther et al. (2006). T is the instantaneous temperature (in K). E_{opt} is the maximum normalized emission capacity, and T_{opt} is the temperature at which E_{opt} occurs. These coefficients are estimated as a function of the average air temperature over the past 24 h (T24) and 240 h (T240):

$$\begin{aligned} E_{\text{opt}} &= 2.034 \times \exp(0.05 \times [\text{T24} - 297]) \\ &\quad \times \exp(0.05 \times [\text{T240} - 297]) \\ T_{\text{opt}} &= 313 + (0.6 \times [\text{T240} - 297]) \end{aligned} \tag{12}$$

In the work of Guenther et al. (2006) all temperatures are considered to be leaf temperatures calculated by a canopy environment model. Since our intention is to provide a BVOC emission model that can be readily implemented in 3-dimensional atmospheric transport models we reduced the complexity of the emission calculation by using air temperature instead of leaf temperature. The light dependence of MEGAN is given by:

$$\gamma_P = \frac{\alpha_m C_p L}{\sqrt{1 + \alpha_m^2 L^2}} \quad (13)$$

The empirical coefficients in Eq. (13), α_m and C_p, depend on the past history of light levels. These parameters are calculated as:

$$\alpha_m = 0.004 - 0.0005 \times \ln(\mathrm{P240})$$

$$C_p = 0.0468 \times \exp(0.0005 \times [\mathrm{P24} - \mathrm{P_0}])(\mathrm{P240})^{0.6}$$

P24 and P240 are the photosynthetically active photon flux density (PPFD) averages over the past 24 and 240 h, respectively. P_0 equals 200 µmol m^{-2} s^{-1} for sunlit leaves and 50 µmol m^{-2} s^{-1} for shaded leaves.

Monoterpene emissions depending on temperature and light were calculated based on Guenther (1997). This approach was also applied to calculate an alternative isoprene emission estimate. The emission activity factor for the direct emissions of these newly synthesized compounds is according to Guenther (1997):

$$\gamma_{CE,i}(\mathrm{synt}) = \gamma_\mathrm{T} \times \gamma_\mathrm{P} \times \gamma_\mathrm{seas} \quad (14)$$

with

$$\gamma_T = \frac{\exp([C_{T1}(T - T_S)]/RT_S T)}{C_{T3} + \exp([C_{T2}(T - T_M)]/RT_S T)} \quad (15)$$

$$\gamma_P = \frac{\alpha C_{L1} L}{\sqrt{1 + \alpha^2 L^2}} \quad (16)$$

Here L is PPFD (in µmol photons m^{-2} s^{-1}), R is the universal gas constant, and C_{L1}, C_{T1}, C_{T2}, C_{T3}, α and T_M are empirical constants given by Guenther (1997). The approach of calculating isoprene and monoterpenes emissions presented with Eqs. (14–16) is termed G97 in the following.

The BVOC emission model applies the radiation code of Weiss and Norman (1985) to calculate the extinction of PPFD as a function of the leaf area index, the distribution of the LAI (leaf area density) inside the canopy, the fraction of leaves and the orientation of these leaves. The canopy is divided into several vertical layers and each layer distinguishes between shaded and sunlit parts of the canopy. The division into shaded and sunlit leaves takes into account the actual solar angle and the foliage density described by the LAI. While PPFD is calculated for each vertical canopy layer, the leaf temperature is simply replaced with air temperature and uniform for the whole canopy in order to reduce the computational demand for calculation of European BVOC emissions.

The canopy environment model was carefully checked to obtain canopy environment emission activity factors ($\gamma_{CE,i}$(synt)) with values close to unity at standard conditions for both the G97 and the MEGAN version. For G97, $\gamma_{CE,i}$(synt) is 0.991 at standard conditions given in Guenther (1997) and for MEGAN $\gamma_{CE,i}$(synt) is 0.997 at the standard conditions mentioned in Guenther et al. (2006).

For each grid cell i of the domain in addition to the emitting area A_i, foliar biomass density D_i, BVOC emission factors $\epsilon_{i,c}$, also LAI maps and meteorological data on temperature and light intensity are required (see Fig. 1). The meteorological data of 2 m air temperature (in K) and solar surface radiation (in W m^{-2}) from ECMWF are the drivers used as input for the BVOC emission model. The meteorological data is used with a horizontal resolution of 1×1 degrees. LAI is taken from MODIS satellite with 0.1 degrees horizontal resolution. Before computation of emissions, meteorological and LAI data is interpolated to the finer resolution of the model domain using linear area averages.

3 Results

Monthly averaged BVOC emission rates for Europe were computed for the two years 2004 and 2005 according to Eq. (1). All calculations were performed with a temporal resolution of 3 h and a spatial resolution of 10 km by 10 km. Two years were selected in order to obtain a more reliable basis for studying seasonal changes, rather than to investigate interannual variability of emissions. The years 2004 and 2005 were both relatively warm years in Europe with mean annual temperatures 0.5–0.6 K higher than in the reference period 1961–1990. The canopy environment model described in Sect. 2.5 was applied to calculate emissions of monoterpenes, sesquiterpenes and OVOC according to the emission algorithms of Guenther (1997). Isoprene emissions were obtained using the temperature and light dependence of the new MEGAN algorithm. In addition, isoprene emissions were computed with G97.

Section 3.1 presents results on BVOC emissions for Europe and the major sources of each compound class. The composition and amount of BVOC emissions from different land use types in the four main vegetation zones of Europe is analysed in Sect. 3.2. The seasonality of emissions is described in Sect. 3.3. In Sect. 3.4 the seasonal behaviour and the major sources of emissions are investigated for small regions, which represent different vegetation zones in Europe. We compare the results from our emission inventory to previous estimates in Sect. 3.5.

3.1 European BVOC emissions

The averaged annual total BVOC emission obtained from the two years 2004 and 2005 for the Pan-European domain is 15 Tg with a large contribution from the OVOC class which represents mainly oxygenated VOC of about 6 Tg and from monoterpenes of about 5 Tg. Annual isoprene emissions are found to be about 3 Tg, independent of the chosen emission algorithm.

Agriculture, forests and other land use areas cover 40.4%, 34.5% and 25.1% of the vegetated surface of Pan-Europe, respectively. Forests and agriculture contribute with about 40% each to the total BVOC emissions, the remaining emissions come from other land use types like shrubs, grassland and wetlands. The large contribution of agriculture is a surprising finding of the presented European emission inventory and is larger than former estimates. For instance, Simpson et al. (1999) have attributed only 20% of the total European BVOC emissions to agriculture.

The European distribution of isoprene emissions for July 2005 calculated with the MEGAN emission algorithm is shown in Fig. 4a. Isoprene emissions calculated with the G97 algorithm for the same month were found to be up to 6% lower than the MEGAN isoprene estimate in Pan-Europe. The largest differences are located in Northern Africa, where the monthly temperature average was above 30°C and mean solar surface radiation was above 240 $W m^{-2}$. We thus assume that the differences are due to the different parameterisation of the temperature and light dependence. Highest isoprene emission rates are found in the Mediterranean region both in summer and winter. In July 2005 up to 2000 $mg m^{-2}$ of isoprene is emitted from the Mediterranean vegetation in certain locations. Forests are the major source of isoprene and contribute 60% to the emitted amount of isoprene. Isoprene emissions constitute 20% of the total emitted BVOC amount in Europe.

Newly synthetisized monoterpene (MT_{synt}) emissions contribute 20% to the annual emitted amount of monoterpenes in Europe. Though the standard emission potential for MT_{synt} is on the average higher than that of MT_{pool}, prevalent solar radiation levels in Europe inhibit a more intense release of MT_{synt}. For example in Sweden and Finland, the monthly averaged MT_{synt} emission rate is below 100 $mg m^{-2}$ in July 2005. Figure 4b shows the distribution of monoterpene emissions for July 2005. Apart from some regions with peak MT emissions (parts of Western France, Nile delta) the emission rates are below 1000 $mg m^{-2}$. Interestingly, monoterpene emission rates over Scandinavia and the Baltic countries which are covered with large boreal coniferous forests are lower than in central Europe. The major fraction of monoterpene emissions in Europe stem from agriculture.

European Maps of BVOC emission rates for July 2005 of OVOC and sesquiterpenes are presented in Fig. 4c and 4d. Half of the emitted amount of the OVOC class originates from agriculture and OVOC emission rates are highest over regions with intensive agriculture as France, the Netherlands and northern Germany (Fig. 4c) with up to 800 mg m^{-2} in July 2005. With the exception of sunflowers and fruit trees the default OVOC standard emission factor of 1.7 µg g_{DW}^{-1} h^{-1} is used for all crop species and agriculture land use classes. Therefore crops with highest foliar biomass density and land coverage will exhibit highest OVOC emissions. Thus it can be deduced that the elevated OVOC emissions in western Europe are from maize, common wheat and other cereals, each covering 10–50% of the area in western France and the Netherlands. Maize is the crop species with the highest foliar biomass density (see Table 4).

Sesquiterpenes contribute only 3% to the total emitted amount. However this class of compounds is of great interest for estimating the formation of secondary organic aerosol. Forests are the largest source of sesquiterpenes and the centre of summertime SQT emissions is in Northeastern Europe, mainly Finland and the European part of Russia (Fig. 4d).

The Contribution of different BVOC classes to the European emissions from forests, agriculture and other land use are presented in Fig. 5a–c. Isoprene, the OVOC class and monoterpenes each contribute about a third to European forest emissions. European Other land use vegetation predominantly emits isoprene. BVOC emissions from agriculture in Europe mainly consist of OVOCs and monoterpenes. For the major vegetation zones of Europe annual amount and composition of BVOC emissions from different land use types are analysed in the next section.

3.2 Emissions from major vegetation zones

The European Union is covered with four major vegetation zones: Atlantic (Western Europe), Continental (Central and Eastern Europe), Boreal (Scandinavia and Northeastern Europe) and Mediterranean. The annual average amounts obtained from the 2004 and 2005 simulations of each BVOC class emitted from agriculture, forest and other land use for these vegetation zones are given in Table 6. BVOC emissions sum

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up to 5.3 Tg from agriculture, 4.8 Tg from forests and 1.7 Tg from other land use.

It is obvious from Table 6 that emissions of monoterpenes from agriculture in the Atlantic zone are very high. Though the geographic extent of this zone is smaller than the Continental zone, agricultural monoterpene emissions are almost a factor of two higher in the Atlantic zone. Elevated MT emission factors have been assigned to fruits, vegetables and root crops (see Table 4), while the more widespread crops like wheat, maize and cereals have very low MT emissions. Fruits cover 10–20% of the agriculture area in the Atlantic zone. There are some hot spot regions for the cultivation of tomatoes and other vegetables in Western France and Netherlands with area fractions of up to 40%. Thus the elevated amount of monoterpene emissions from agriculture in the Atlantic zone is largely due to elevated MT standard emission factors for fruits and vegetables. The high monoterpene emissions from agriculture found here should however be judged with care since the high MT standard emission factors that have been assigned to fruits, vegetables and root crops in our study are probably affected by higher-than-ambient enclosure temperatures. This will be discussed in more detail in Sect. 4.3.

Monoterpene emissions contribute 23% to the BVOC emissions in forests of the Boreal zone. This contribution seems to be small and may be due to lower MT standard emission factors assigned to coniferous trees in this inventory. For instance, only MT pool emissions for *Pinus sylvestris* were considered (see Table 3), while e.g. Steinbrecher et al. (2008) applied a standard emission factor of 2.5 µg g_{DW}^{-1} h^{-1} for both pool and newly synthesized MT emissions. In addition, emissions from *Picea abies* in the Boreal zone are reduced by 40% compared to the Contintental zone due the bioclimatic correction of the foliar biomass density.

For Continental forests it is interesting to note that almost equal fractions of the monoterpene emissions orginate from the pool and the newly synthesized emission routes. Forest BVOC emissions in the Continental zone consist of 38% OVOC, 31% isoprene, 28% monoterpenes and 3% sesquiterpenes. Isoprene emissions from Continental forests amount to 0.4 Tg.

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Monoterpene emissions contribute 25% to the BVOC emissions in forests of the Mediterranean region. These emissions can largely be attributed to the pool MT emissions from *Pinus pinaster* and to newly synthesized MT emissions from *Quercus ilex* (standard emission factor of 25 µg g_{DW}^{-1} h^{-1}). Isoprene emissions constitute 55% of the Mediterranean forest emissions and mainly originate from the Mediterranean oaks. Emissions from other land use vegetation contribute substantially (with 36%) to the BVOC amount emitted in the Mediterranean region. Isoprene emissions from Other land use and from forests in the Mediterranean each amount to about 0.6 Tg.

3.3 Seasonality

The period from May to September is the time with enhanced BVOC emissions (Fig. 6a). During this period ca. 80% of the total annual BVOC amount is released from vegetation. In April deciduous trees start to develop leaves and the increasing density of foliage of deciduous trees leads to a strong increase of BVOC emissions from March to April and from April to May. Between April and May emissions of isoprene, OVOC and monoterpenes more than double and SQT emissions increase by a factor of 3. From June to August emissions from vegetation are highest since light intensities, temperatures and emitting plant biomass are highest during these months. After September emissions decline rapidly with the loss of leaves from deciduous trees. From November to March the monthly emitted amount of OVOC and MT compounds remains essentially constant while isoprene emission amounts show a strong dependence on the available light intensity.

In Fig. 6b the different seasonality of isoprene emissions calculated either using the MEGAN or the G97 algorithm is shown. The seasonal cycle of isoprene emissions calculated with MEGAN and G97 both resemble the shape of a Gaussian distribution with a maximum in July. The seasonal isoprene emission cycle calculated with the G97 emission algorithms is very similar to the MEGAN result. During the summer months, June–August, MEGAN tends to give higher isoprene amounts, while during winter months isoprene emissions from MEGAN are in general lower than those from

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G97. The largest differences are obvious for July and August (up to 15%) and are probably due to the different parameterisation of the light dependence and the different weighting of the foliar biomass influence. MEGAN takes into account the influence of light and temperature conditions during the previous day(s) and when warm and sunny conditions have occured prior to the time of observation, emission rates of isoprene are predicted to be enhanced. A further important difference between the two isoprene emission algorithms is the treatment of foliar biomass seasonality. The canopy emission acitivity is considered to be a linear function of the LAI in the MEGAN parameterisation (Eq. 10), while the seasonality factor used in G97, γ_{seas}, has a weaker dependence on LAI (Eq. 9).

3.4 Regional emission patterns

Four regions within Europe, representative for different vegetation zones, were selected to investigate the seasonal variation of BVOC emissions and the contribution of different land use types on a regional scale. The four regions each cover area squares of 2×2 degrees.

The region in Southern Spain (−7° W, 38° N to −5° W, 40° N) is intended to represent the Mediterranean zone with forests dominated by *Pinus pinaster* or *Quercus ilex*. The region in Western France (−1° W, 46° N to 1° E, 48° N) represents the Atlantic vegetation zone and is largely covered by non-irrigated arable land and agricultural crops like wheat, maize and other cereals are intensively cultivated. The region in Southern Finland (23° E, 61° N to 25° E, 63° N) is located in the Boreal zone. In Finland, boreal coniferous forests cover about 60% of the land area and the dominant tree species are Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). The region in Southern Germany (9° E, 47° N to 11° E, 49° N) is in the Continental zone, which is used in this work as the reference zone to define bioclimatic correction factors. This landscape is characterised by a mosaic of mixed forests with *Fagus sylvatica* and *Pinus sylvestris* as major tree species and agriculture. Total BVOC emissions for the described regions were derived from our European emission inventory. Seasonal averages for the year 2005 are displayed in Table 7 and are given as average BVOC emission rates (in mg m^{-2}) for the whole area of the regions. The yearly averaged BVOC emissions for the year 2005 are highest in Southern Spain and Western France. Emissions from the vegetation in Southern Germany are a factor of 3 and from Southern Finland are a factor of 6 lower than in Southern Spain.

Half of the BVOC emissions in Southern Spain originate from forests and one third from other land use types like Mediterranean shrubland. From spring (March to May, MAM) to summer (June to August, JJA) BVOC emissions from forests and other land use types increase by a factor of 2–3 while emissions from agriculture increase less. The JJA average for forest BVOC emissions is about 500 mg m^{-2}. Isoprene contributes 87% to these summer emissions from forests.

BVOC emissions in Western France are predominantly from agriculture. Emission from forests contribute only one fourth to the total BVOC emissions. Agriculture emissions in summer (JJA) are two times higher than in spring and in autumn (September to November, SON). The JJA average of agricultural emissions is 450 mg m^{-2} and BVOC emissions from agriculture consist mainly of OVOCs (51%) and monoterpenes (44%), with a negligible fraction of isoprene. As stated in Sect. 3.2 the large contribution of monoterpenes to the agriculture emissions is due to high MT standard emission factors that we assigned to fruits, vegetables and root crops and these elevated emission factors are probably affected by measurement artifacts as will be discussed in Sect. 4.3.

In Southern Finland forests clearly are the dominant source. Forest emissions increase by a factor of 5 between MAM and JJA. The JJA average of forest emissions is 100 mg m^{-2}, a factor of 5 lower than the forest emissions in Southern Spain. Isoprene contributes only 14% to the JJA forest emissions in Southern Finland.

BVOC emissions from Southern Germany mainly originate from agriculture and forests with a respective contribution of 60% and 35%. Total BVOC emissions in JJA are a factor of 2–3 higher than in MAM. Isoprene contributes to the JJA BVOC emissions from agriculture and forests with 2% and 8%, respectively. The contribution of isoprene to the yearly averaged BVOC emissions from forests is found to be 6% for

Southern Germany. For comparison, in a study of Smiatek and Steinbrecher (2006) on the temporal and spatial variation of forest VOC emissions in Germany, it is reported that isoprene contributes 9% to the total BVOC emissions from forests in Bavaria and in Baden-Württemberg (Table 3 in Smiatek and Steinbrecher, 2006).

3.5 Comparison with other estimates

The results obtained in our work are compared to other estimates of European BVOC emissions. A list of previous estimates of isoprene and total BVOC emissions for Europe is provided in Table 8. The most recent of the listed estimates is from Steinbrecher et al. (2008), the NatAir (Improving and Applying Methods for the Calculation of Natural and Biogenic Emissions and Assessment of Impacts on Air Quality) project inventory of VOC emission from natural and semi-natural vegetation in Pan-Europe. Steinbrecher et al. (2008) were mainly interested in natural emissions of BVOC and therefore agriculture emissions were estimated using only the general agriculture classes from the CLC/GLC2000 mosaic and applied a default parameterisation for agriculture emission factors and foliar biomass densities. For EU27 they made use of the forest tree species dataset from the *Tree Species Map* (Köble and Seufert, 2002) while for all other parts of the European domain and for all other land use types the general land use classes from CLC/GLC2000 were used. However the NatAir study did not consider the available GIS data on crop species (*Agricultural Land Use Map*) for EU15. The use of general land use classes instead of plant-specific land use data can lead to large inaccuracies and will be discussed in Sect. 4.1.

Their estimate of annual total BVOC emissions is 20 Tg for the NatAir model domain which has almost the same extent as the Pan-European domain of our study. 12 Tg are estimated to originate from forests and 8 Tg from other land uses, including agriculture. The NatAir estimate is about 5–6 Tg higher than our estimate and the earlier estimate given by Simpson et al. (1999). The authors of the NatAir study explain their higher BVOC emission estimate compared to the estimate of Simpson et al. (1999) with the higher temperatures in the selected years and with the use of recent standard emission factors together with plant-specific emission modelling.

Forest emissions of our estimate are 50% lower than the NatAir estimate. Due to the use of the identical forest tree species information, the emissions from forests from our work should be comparable to the NatAir estimate. The observed differences can thus largely be attributed to the use of different standard emission factors for isoprene, terpenes and the OVOC class. The impact of the bioclimatic correction factor on our European emission estimate will be discussed in Sect. 4.4.

The 2 Tg lower annual OVOC emission estimate for Europe of our study can be explained by the lower default value for the OVOC standard emission factor that we applied (1.7 $\mu g\, g_{DW}^{-1}\, h^{-1}$ instead of 2.0 $\mu g\, g_{DW}^{-1}\, h^{-1}$ in NatAir) and the high OVOC emission factor for selected tree species in the NatAir inventory. For instance Steinbrecher et al. (2007) use an OVOC standard emission factor of 10 $\mu g\, g_{DW}^{-1}\, h^{-1}$ for European beech (*Fagus sylvatica*), compared to 1.7 $\mu g\, g_{DW}^{-1}\, h^{-1}$ in our work.

Our isoprene emission estimate of 3 Tg is about 1 Tg lower than previous estimates for Europe that are based on European bottom-up inventories (Simpson et al., 1995; Simpson et al., 1999; Steinbrecher et al., 2008). The lower estimate of our work is likely due to lower standard emission factors for important isoprene-emitters, like Eucalyptus (15 $\mu g\, g_{DW}^{-1}\, h^{-1}$, from Street et al., 1997, for 7 year old trees) and *Quercus robur* (49 $\mu g\, g_{DW}^{-1}\, h^{-1}$, mean value from Isidorov et al., 1985, and Pio et al., 1993).

We compared our estimate for Europe with the estimate from global bottom-up isoprene emission inventories using the canopy environment model as described in Sect. 2.5. Global inventories are known to incorporate a lower degree of detail and are commonly used for global estimates of vegetation emissions. In the frame of this work, simulations with two different global isoprene inventories, the GEIA inventory (Guenther et al., 1995) and the recent MEGAN (Guenther et al., 2006), were performed for the years 2002 and 2003. Meteorological surface data and LAI data were used with the same horizontal resolution as applied for the presented emission estimate. Using the G97 algorithm together with the GEIA isoprene emission inventory gave about 10 Tg isoprene emissions per year in Europe, while using the MEGAN algorithm together with the global MEGAN inventory gave a lower estimate of 4.5 Tg. The difference of the annual amounts of European isoprene emissions between the two global inventories and the presented plant-specific European emission inventory can be attributed to the use of plant-specific foliar biomass density distributions and isoprene standard emission factor distributions for Europe in our inventory. It can be concluded that annual European isoprene emissions calculated with the new global isoprene emission inventory of the MEGAN model (Guenther et al., 2006) are in reasonable agreement with recent European bottom-up estimates (Table 8), while the the former GEIA inventory overestimates isoprene emissions in Europe by more than factor 2 compared to European inventories. It has been recognized that the minimum level of uncertainty in global biogenic emission estimates is a factor of 3 (Guenther et al., 1995) and can be higher for regional estimates.

4 Discussion of uncertainties

In this chapter the uncertainties of biogenic emission due to inaccurate land use information, BVOC standard emission factors, biomass densities and driving variables is discussed.

4.1 General land use and default values

Global inventories of BVOC emissions are built on general land use classes, like ecosystems (e.g. boreal conifers in the GEIA inventory, Guenther et al., 1995) or plant distribution functions (e.g. broadleaf evergreen trees in the MEGAN inventory, Guenther et al., 2006) or vegetation classes (CLC/GLC2000 mosaic). The generalized way to define the geographic distribution of these land use classes and the often insufficient differentiation of vegetation types can lead to a systematic bias in biogenic emission inventories.

In the presented inventory, we relied on plant-specific geo-referenced land use information for all the parts of Europe where this kind of data is available. However, for the

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most Eastern European countries and especially for Russia we had to use the general vegetation classes of CLC/GLC2000. Standard emission factors and foliar biomass densities for agriculture and forest CLC/GLC2000 landcover classes were derived from the predominant plant species in each class. The vegetation class foliar biomass density d_l is thus obtained from the weighted foliar biomass densities of major tree or crop species that contribute to the vegetation composition of the respective class. However, vegetation classes often cover large geographic regions and plant composition of classes may not be representative of the complete geographic extent. For example, the Global Landcover (GLC) vegetation class Needleleaved Evergreen Forest covers large parts of boreal Northern Russia. The GLC Northern Eurasia (v4.0) classifies this forest to consist mainly of Picea, Abies and Pinus trees. This forest type covers large areas by 100%, ignoring that there are actually other land use types like wetlands in these areas. This leads to inconsistencies of the calculated foliar biomass density and becomes clearly visible at the Russian border to Finland (see Fig. 2b). This country border marks the border between plant-specific land use classes and the general land use classes from GLC.

4.2 Standard emission factors

The use of default values for standard emission factors for the OVOC and SQT classes tend to produce inaccurate results. Default values for these compound groups are applied in this inventory to give an European estimate in spite of missing measured data for most plant species. Where possible, SQT emission factors were included in this work, but for most plants these measurements are lacking. There is a clear need for future research on the chemical speciation and emission factors of oxygenated VOC for different crop and tree species. Other VOC are included in our emission inventory using the temperature dependent monoterpene emission algorithm. However, daily cycles of ambient concentrations of methanol, acetone and acetaldehyde, indicate that OVOC emissions are governed by different processes (Rinne et al., 2007), like light, drought or herbivore attack.

Biogenic emissions among plants of the same species or even among parts of the same plant may vary considerable. Funk et al. (2005) found that under normal climate conditions, isoprene emissions from different red oak trees within a single stand differed by a factor of two. Komenda and Koppmann (2002) reported that monoterpenes emission rates measured at two different branches of the same Scots pine tree differed by a factor of two. In the BEMA (Biogenic Emissions in the Mediterranean Area) campaigns, 1993–1994, a high variability of standard emission factors was observed for *Quercus ilex* and *Pinus pinea*, probably due to different stages of leaf development, tree age, habitat and light adaption (Seufert et al., 1997). In all cases we found measurements with different standard emission potentials for the same species in the literature, the mean value was used.

4.3 Emissions from agriculture

Monoterpene emissions from agriculture are highly uncertain since studies on agricultural crops are scarce and the applied standard emission potentials are probably biased by measurements at higher-than-ambient temperatures. To date, the investigation of König et al. (1995) is the only comprehensive work on BVOC emissions from agricultural crops in Europe (see Table 7 in Kesselmeier and Staudt, 1999). In our inventory, the applied high MT emission potentials for *Tomatoes and other vegetables* which is based on the emission potential found for tomatoes in the early screening study of Arey et al. (1991) and the high MT emission potential for *Fruit tree and berry plantations* which is dominated by the high MT_{pool} value from the screening study by Pio et al. (1993) for apples (*Malnus domestica*) are likely associated with sampling artifacts. Tomatoes store large amounts of monoterpenes and sesquiterpenes in trichomes and are sensitive to the experimental bias of the screening studies by e.g. Arey et al. (1991) and Winer et al. (1992). Since these artificially-elevated values have further been used in our inventory to infere standard emission factors of general irrigated agriculture classes, MT emissions in the Mediterranean and in Northern Africa are affected as well.

To quantify the magnitude of this effect for our inventory, we performed a simulation of BVOC emissions for the year 2005 with default monoterpene standard emissions for crops and general agriculture land use classes. For this test, the standard emission factors for MT_{pool} and MT_{synt} were both set to 0.5 $\mu g\, g_{DW}^{-1}\, h^{-1}$ for all crops and agriculture classes from the CLC/GLC2000 land cover. Zero monoterpene emissions were attributed to rice, olive, vineyeards, soya, floriculture, their corresponding CLC/GLC2000 classes, and the tree crops class. The MT standard emission potentials assigned to agriculture in this test are identical to the values that have been applied in the NatAir BVOC inventory (Steinbrecher et al., 2008).

European monoterpene emissions in 2005 decrease from 5 Tg to 3.3 Tg due to the reduced emissions from agriculture. The emitted amount of total BVOC decreases by 11% and the contribution of agriculture emissions to the total BVOC emissions is reduced from 43% to 36%. The distribution of monoterpene emissions between pool and newly synthetized emissions is shifted towards the newly synthetized emissions by applying the same standard emission potential for both emission types. The percentage fraction of MT_{synt} emissions to total MT emissions increases from 20% to 33%. Agriculture as a source of MT becomes less important as its contribution to MT emissions declines from 55% to 33% when default values are applied. Annual monoterpene emissions from agriculture sum up to about 1.1 Tg in the test simulation and are lower than the estimate of about 2 Tg given by Steinbrecher et al. (2008) for other landuse. It should however be considered that the definition of other landuse in the NatAir inventory includes agriculture and other land use types (grassland, wetland, shrubs etc.).

The regional impact on BVOC emissions depends on the area fraction covered with agricultural crops and the dominant type of cultivated crops. In the selected region in Southern Spain (see Sect. 3.4), the yearly averaged rate of BVOC emissions for 2005 is 23% lower when the default values are applied. Similarly, emissions decrease in Western France and Southern Germany by 19% and 17%. The smallest change occurs in Southern Finland, where emissions decrease by only 5% due to the minor role of agriculture in this region.

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In our inventory, OVOC predominantly contributes to agriculture BVOC emissions. Until now it is unclear if the main crops like wheat and other cereals emit OVOC in significant quantities. For example, Winer et al. (1992) detected no oxygenated VOC emissions from wheat. König et al. (1995) have found that total plant BVOC emission of oilseed rape (normalised to 30°C) were increased by a factor of 2 in the blossoming stage compared to the nonblossoming stage, with increases of factor 4–5 for single monoterpenes like α-pinene. Rape cultivations cover 5–10% in large parts of France, England, Germany and Italy and locally cover about 40% in Spain, and rape oil is increasingly used as biofuel. These examples illustrate the clear need for more comprehensive studies on BVOC emissions from European agricultural crops.

4.4 Bioclimatic correction

To adjust foliar biomass densities for main tree species and crops for the different vegetation zones we have introduced a bioclimatic correction factor (see Sect. 2.2). European BVOC emissions were recalculated for the year 2005 with the bioclimatic correction set to unity for all trees, crops and general vegetation classes (f_j=f_k=f_l=1), in order to test the sensitivity of emissions towards this parameter. The total emitted European amount of BVOC from this simulation is only 2% higher than the amount calculated with bioclimatic correction factors according to Tables 1 and 2. For single BVOC classes annual European emissions changed not more than 3%.

However this factor is important when estimating BVOC emissions from different regions within Europe. For the selected region in Southern Spain the yearly averaged rate of BVOC emissions for the year 2005 is 7% higher considering the bioclimate correction of foliar biomass densities. In the region of Western France, which represents the Atlantic vegetation zone, the BVOC emission rate is 26% higher. This can be explained with bioclimate correction factors larger than 1 for main agricultural crops in the Atlantic vegetation zone, leading to elevated foliar biomass densities in Western Europe (see Fig. 2a). The BVOC emission rate in Southern Finland, representative for the Boreal vegetation zone, is 17% lower when taking into account the bioclimatic correction of foliar biomass densities. This change reflects the use of bioclimatic correction factors for main tree species in the Boreal zone that are less than 1. As expected, BVOC emissions of the region in Southern Germany remained unchanged, since this region represents the Continental zone, which is used as a reference zone for defining the bioclimatic correction.

It can thus be concluded, that the introduction of corrected foliar biomass densities has a significant impact on regional BVOC emission estimates, while, on the European scale, the annual and the monthly emitted European amount of BVOC is only marginally influenced by the correction for bioclimatic zones. However, it can not be excluded that a less conservative and more realistic application of bioclimatic corrections which relies on a larger amount of tree specific biomass data may change this picture. For individual bioclimatic zones the bioclimatic correction factors for tree species rely on very few litterfall data records (e.g. *Pinus sylvestris* in the Atlantic and Mediterranean zone). Further exploitation of the biomass compartment databases like the one from AFOLU (see Sect. 2.2) data will help to improve the situation in future.

4.5 Driving variables

Emissions are not only dependent on exogenous driving variables like temperature and light but dependent also on endogenous parameters such as the developmental state of the leaves. While young leaves of deciduous trees begin with photosynthesis short after budbreak, emission of isoprene only starts with a retardation of several days. On the other hand older leaves produce isoprene less efficiently. Reduced emissons in autumn have been found to be correlated with the activity of some terpene synthases (Lehning et al., 1999) and a seasonality for monoterpene synthases acitivity has been observed for *Quercus ilex* (Fischbach et al., 2002). Based on long term laboratory experiments with *Pinus pinea* trees, Staudt et al. (1997) developed an algorithm to adjust for seasonality that was proven to fit very well with observations in the field, where monoterpene emission factors of this species varied between 2.8 and 15 $\mu g\, g_{DW}^{-1}\, h^{-1}$ during the course of the year.

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Soil water availability represents an important environmental constraint under Mediterranean conditions. In the Mediterranean area, summer months are characterized by the highest annual temperatures and radiation levels which occur simultaneously with the most severe drought conditions. Under drought conditions, plants will experience increasing water deficit stress. This affects emissions of different VOC classes in different ways. Pegaro et al. (2004) showed for *Quercus virginiana* Mill. that isoprene emissions remained stable during the first eight days of water withholding and declined thereafter. SQT emissions from orange trees are reported to be strongly reduced under severe water deficit, while not being influenced under mild water stress conditions (Hansen and Seufert, 2003). Results obtained by Ormeño et al. (2007b) indicate that emissions of sesquiterpenes are replaced by monoterpenes when drought is prolonged. They showed that water stress has a positive effect on monoterpene emissions of *Pinus halepensis* and *Cistus albidus*. Monoterpene emissions of water stressed *Rosmarinus officinalis* remained stable (Ormeño et al., 2007b). Contrary to isoprene, the cuticle may be permeable to monoterpenes, allowing monoterpene emissions to be maintained during drought conditions when stomata closure occurs (Pegaro et al., 2004). Since drought limits plant growth, restricted carbon acquisition will reduce emissions in longer drought periods (Bertin and Staudt, 1996).

Sesquiterpenes react rapidly with ozone in the canopy leading to substantial removal of sesquiterpenes within the canopy (Ciccioli et al., 1999). Above canopy fluxes are likely smaller than emissions derived on branch level (using branch enclosure methods) due to losses by deposition and oxidation within the canopy. Within-canopy gas-phase reactions of ozone with monoterpenes, sesquiterpenes and other oxygenated hydrocarbons with short chemical lifetimes will lead to SOA formation inside the canopy. The estimated fluxes of our inventory thus more represent the sum of parent hydrocarbon, its oxidations products and particles released to the atmosphere. Canopy deposition losses should thus be taken into account in future BVOC emission inventories.

Uncertainties of the main driving variables temperature, solar radiation and leaf area index have shown to result in emission estimates that differ more than a factor of three

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for specific times and locations (Guenther et al., 2006). The additional driving factors mentioned above can potentially be addressed in a canopy environment model of the MEGAN type. The plant-specific European inventory of foliar biomass densities and BVOC emission factors developed in this work can be used together with a more sophisticated canopy emission model in future to obtain more accurate BVOC emission for Europe on a high temporal and spatial resolution.

5 Conclusions

Agriculture land use types are identified to be an important source for OVOCs and monoterpenes. Crops cultivated in Western Europe are found to be a significant source of OVOC. However, for the OVOC class large uncertainties remain since chemically speciated measurements are lacking for most plant species. Monoterpene emissions from agriculture are highly uncertain because the estimate relies on scarce literature data available for crops in Europe and on early screening studies. The small number of available studies on agriculture emissions is a serious limitation of current BVOC emission inventories for Europe. In our European inventory for the first time crop-specific land use information was employed together with crop-specific standard emission factors wherever applicable. Further work on agriculture emissions should be carried out to check the validity of the high standard emission factors for monoterpenes and OVOC. In view of the discussion on the increased use of biofuels in Europe it will be of great importance to give a more accurate estimate of BVOC emissions from agriculture crops cultivated for biofuel production.

The presented emission inventory serves as an improved basis – especially with regard to the plant-specific land use data and up-to-date standard emission factors – for estimating BVOC emissions in Europe. In contrast to previous BVOC emission inventories, a bioclimatic correction factor was introduced to correct the foliar biomass densities for the different plant growth conditions that can be found in Pan-Europe. This leads to reduced BVOC emissions from boreal forests while emissions from agriculture

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in Western Europe are increased compared to an estimate that does not consider the influence of different growth conditions on the foliar biomass density. Forests are found to be the largest source for isoprene released to the atmosphere in Europe and therefore an accurate estimate of the foliar biomass density for the main tree species is essential for the correct prediction of isoprene emissions.

To improve predictions of European air quality it is important to use BVOC emissions that are as accurate as possible since the importance of anthropogenic VOC as precursors of photochemically produced ozone will decline due to pollution abatement strategies.

The databases of foliar biomass densities, standard emission potentials, and resulting emissions are created in HDF format to facilitate the implementation into atmospheric transport models. The databases can be obtained upon request from the authors and are made available on the AFOLU web portal (http://afoludata.jrc.it/data_fs.cfm). Resulting European emission fields can be used in future to investigate secondary particle formation from isoprene, monoterpenes and sesquiterpenes with regional or global chemistry transport models.

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Table 1. Bioclimatic correction for main tree species and forest vegetation classes in European vegetation zones. The Continental vegetation zone is used as the reference zone[a,b].

	Tree species	Alpine	Arctic	Atlantic	Boreal	Contin.	Mediterr.	Steppic
	Betula spp.	0.81	0.51	0.73	1.36	1.00	1.00	1.11
	Fagus sylvatica	0.73	0.73	0.74	0.73	1.00	1.00	1.00
	Picea abies	0.86	0.60	0.58	0.60	1.00	1.00	1.00
	Pinus sylvestris	0.96	0.96	1.83	0.96	1.00	1.69	2.09
	Quercus robur/petraea	0.89	0.89	0.89	0.89	1.00	1.00	1.00
ID[c]	Vegetation class							
23	Broad-Leaved Forest	0.92	0.89	0.91	0.97	1.00	1.00	1.01
24	Coniferous Forest	0.93	0.82	1.16	0.82	1.00	1.27	1.43
25	Mixed Forest	0.92	0.86	1.04	0.90	1.00	1.14	1.22
100	Broadl. Everg. Forest	0.92	0.89	0.91	0.97	1.00	1.00	1.01
101a	Broadl. Dec. Forest	0.90	0.75	0.86	1.18	1.00	1.00	1.05
101b	Broadl. Dec. Forest	0.86	0.80	0.85	0.97	1.00	1.00	1.02
101c	Broadl. Dec. Forest	0.92	0.89	0.91	0.97	1.00	1.00	1.01
102a	Needl. Everg. Forest	0.89	0.72	1.04	0.98	1.00	1.21	1.36
102b	Needl. Everg. Forest	0.93	0.82	1.16	0.82	1.00	1.27	1.43
102c	Needl. Everg. Forest	1.00	1.00	1.00	1.00	1.00	1.00	1.00
103	Needl. Decid. Forest	1.00	1.00	1.00	1.00	1.00	1.00	1.00
104a	Mixed Forest	0.89	0.73	0.95	1.08	1.00	1.10	1.21
104b	Mixed Forest	0.92	0.86	1.04	0.90	1.00	1.14	1.22
104c	Mixed Forest	0.92	0.86	1.04	0.90	1.00	1.14	1.22

[a] Bioclimatic factors are derived from litterfall fluxes of major tree species from different databases as described in the text. Litterfall flux measurements were attributed to the respective vegetation zone where the forest site is located in. A bioclimatic correction factor of 1 was used for the following vegetation zones: Anatolian, Black Sea, Pannonian, and Africa-Arabia. No data on the selected European tree species were found for these zones. The following forest types from the CLC/GLC2000 land use database are assigned a bioclimatic correction factor of 1 in all vegetation zones: forest and shrub/grassland mosaic, regularly flooded saline tree area. All tree species not listed here are assigned a bioclimatic correction factor of 1 in all vegetation zones.

[b] Forest sample sites with elevation >900 m south of 60° N and >500 m north of 60° N are defined as Alpine. In case no data for one of the listed tree species was found in the Mediterranean or Steppic vegetation zone, the reference value of 1.00 is used. In case no data was found for the Boreal zone, the value from the Alpine zone is used. In case no data was found for Arctic or Alpine zones, the value from the Boreal zone is used instead.

[c] Vegetation class ID of CLC/GLC2000 landcover mosaic as indicated in Köble (2007). Letter a refers to GLC Northern Eurasia v4.0, letter b refers to GLC Europe v1.0 and letter c refers to GLC Africa v5.0 + GLC Global v1.1.

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Table 2. Bioclimatic correction for crops and agriculture vegetation classes in European vegetation zones. The Continental vegetation zone is used as the reference zone[a].

Crop species or Vegetation class	Alpine	Anatol.	Atlantic	Black Sea	Boreal	Contin.	Mediterr.	Pannon.	Steppic	Africa-Arabia
Barley	0.90	0.59	1.51	0.43	0.67	1.00	0.66	0.82	0.51	0.36
Durum Wheat[b]	0.87	0.47	1.72	0.40	0.74	1.00	0.59	0.86	0.55	0.49
Fruit trees and berry plantations[c]	0.98	1.00	1.39	0.13	0.27	1.00	0.72	0.68	0.19	0.66
Maize	0.88	0.74	1.68	0.32	0.46	1.00	1.25	0.86	0.49	1.15
Olive groves	1.70	1.45	0.74	1.42[d]	1.00[d]	1.00	1.42	1.00[d]	1.00[d]	1.40
Rape and turnip rape	1.02	0.22	1.46	0.66[d]	0.72	1.00	0.66	0.83	0.46	0.62
Fibre and oleaginous crops[e]	1.02	0.22	1.46	0.66[d]	0.72	1.00	0.66	0.83	0.46	0.62
Vineyards	1.00	0.96	0.71	0.42	0.72	1.00	1.13	1.05	0.65	1.28
Oats	0.92	0.62	1.78	0.37	0.77	1.00	0.52	0.72	0.49	0.23
Other cereals[f]	0.92	0.34	1.29	0.14	0.58	1.00	0.41	0.73	0.16	0.40
Other crops[f]	0.92	0.34	1.29	0.14	0.58	1.00	0.41	0.73	0.16	0.40
Fodder other on arable land	0.58	1.09	0.77	1.17[d]	0.31	1.00	1.17	1.00[d]	1.00[d]	1.34
Other non permanent industrial crops[e]	0.92	0.34	1.29	0.14	0.58	1.00	0.41	0.73	0.16	0.40
Tomatoes and Fresh Vegetables[g]	0.82	0.72	0.59	0.56	0.62	1.00	0.78	0.75	0.51	0.70
Rice	1.15	1.48	1.32	0.00	0.85	1.00	1.39	0.89	0.90	1.23
Potatoes	0.86	1.12	1.76	0.47	0.75	1.00	0.88	0.93	0.41	0.97
Dry pulses	1.31	0.27	1.67	0.58[d]	0.76	1.00	0.58	0.45	0.65	0.43
Other root crops	0.86	1.12	1.76	0.47	0.75	1.00	0.88	0.93	0.41	0.97
Rye	0.96	0.50	1.27	0.26	0.76	1.00	0.54	0.63	0.50	0.43
Soya	1.38	2.24	1.75	1.87	0.75	1.00	1.68	1.42	0.88	1.03
Sugar beet	1.02	0.96	1.39	0.38	1.22	1.00	1.36	1.02	0.48	1.10
Sunflower	0.68	0.78	1.20	0.32	0.45	1.00	0.62	1.03	0.61	0.75
Common wheat[b]	0.87	0.47	1.72	0.40	0.74	1.00	0.59	0.86	0.55	0.49
Non-Irrigated Arable Land[b]	0.87	0.47	1.72	0.40	0.74	1.00	0.59	0.86	0.55	0.49
Permanently Irrigated Land[g]	0.82	0.72	0.59	0.56	0.62	1.00	0.78	0.75	0.51	0.70
Rice Fields	1.15	1.48	1.32	1.39[d]	0.85	1.00	1.39	0.89	0.90	1.23
Vineyards	1.00	0.96	0.71	0.42	0.72	1.00	1.13	1.05	0.65	1.28

Table 2. Continued.

Crop species or Vegetation class	Alpine	Anatol.	Atlantic	Black Sea	Boreal	Contin.	Mediterr.	Pannon.	Steppic	Africa-Arabia
Olive Groves	1.70	1.45	0.74	1.42[d]	1.00[d]	1.00	1.42	1.00[d]	1.00[d]	1.40
Pastures	0.58	1.09	0.77	1.17[d]	0.31	1.00	1.17	1.00[d]	1.00[d]	1.34
Annual Crops assoc. w. Permanent Crops[e]	0.92	0.34	1.29	0.14	0.58	1.00	0.41	0.73	0.16	0.40
Complex Cultivation Patterns	1.14	0.38	1.47	0.13	0.76	1.00	0.56	0.54	0.58	0.43
Agriculture w. significant Areas of Natural Veg.	0.94	0.42	1.28	0.20	0.67	1.00	0.48	0.68	0.33	0.42
Agro-Forestry Areas	1.54	1.84	1.24	0.94	0.37	1.00	1.55	0.71	0.44	1.21
Non Irrigated Cropland[b]	0.87	0.47	1.72	0.40	0.74	1.00	0.59	0.86	0.55	0.49
Irrigated Cropland[g]	0.82	0.72	0.59	0.56	0.62	1.00	0.78	0.75	0.51	0.70
Cropland unspecified	1.04	0.91	1.31	0.90[d]	0.71	1.00	0.90	0.81	0.53	0.81

[a] Bioclimatic factors are derived from FAO crop yields reported by the respective nations that were chosen to represent a specific vegetation zone. The Anatolian zone is represented by Turkey, the Alpine zone by Bosnia and Herzegovina, Macedonia, Slovakia, Slovenia, Switzerland, the Atlantic zone by Belgium, Denmark, France, Ireland, the Netherlands, United Kingdom, the Black Sea zone by Georgia, the Boreal zone by Estonia, Finland, Latvia, Lithuania, the Russian Federation, Sweden, the Continental zone by Austria, Belarus, Bulgaria, Croatia, France, Germany, Luxembourg, Poland, Romania, the Mediterranean zone by Albania, Greece, Italy, Malta, Portugal, Spain, Cyprus, the Pannonian zone by Hungary, the Steppic zone by Moldavia, Ukraine, the Africa-Arabia zone by Israel, Jordan, Lebanon, Syrian Arab Republic, Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, Tunisia.
The following crops and agriculture types are assigned a bioclimatic factor of 1 in all vegetation zones except for the Arctic: citrus fruits, nurseries, floriculture, fallow land, permanent gras and grazing, and tobacco from the *Agricultural Land Use Map*, and the vegetation classes tree crops and cropland/forest/shrubland/grassland mosaic from CLC/GLC2000. In the Arctic vegetation zone, the bioclimatic factor is 0.55 for all crops and agriculture types.
[b] From FAO crop yields of wheat.
[c] From FAO crop yields of apple.
[d] No yields reported to FAO, the bioclimatic factor from Mediterranean is used for Black Sea and the bioclimatic factor from Continental is used for other zones.
[e] From FAO crop yields of rape seed.
[f] From FAO crop yields of cereals.
[g] From FAO crop yields of vegetables.

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Table 3. Foliar biomass densities in g dry mass m^{-2} and standard emission potentials (in $\mu g\ g_{DW}^{-1}\ h^{-1}$) of isoprene, monoterpenes, ORVOC and sesquiterpenes for tree species and low vegetation species (shrubs and herbs). MT synt are monoterpenes emitted with temperature and light dependence and MT pool are only temperature dependent. MT emissions observed for tree species without MT reservoirs in their secretory organs have been assigned to newly sythesized emissions (MT synt) even if reported as being only temperature dependent in the cited literature. NE: compound not emitted. The default standard emission potential for OVOC is 1.7 $\mu g\ g_{DW}^{-1}\ h^{-1}$ for all species as proposed in Guenther et al. (1995), unless measured values from Owen et al. (1997) are available. For sesquiterpenes the default standard emission potential for all species is 0.085 $\mu g\ g_{DW}^{-1}\ h^{-1}$. A. f. is the percentage area of each tree species to the total forest area of the *Tree Species Map*, from Lenz et al. (2002).

Species	*d*	Stand. emission potential ($\mu g\ g_{DW}^{-1}\ h^{-1}$)					A. f.	Ref. *d*	Ref.	Ref.	Ref.	Ref.
	($g\ m^{-2}$)	ISOP	MT_{synt}	MT_{pool}	OVOC	SQT	(%)		ϵ_{ISOP}	ϵ_{MTsynt}	ϵ_{MTpool}	ϵ_{SQT}
Abies alba	1260	0.1	0.26	0.63	1.7	0.904	1.505	AAK95	MO06	MO06	MO06	HE99
Abies borisii-regis	1260	18.4	0	2.7	1.7	0.904	0.149	*Abies alba*	HR01	NE	HR01	HE99
Abies cephalonica	1260	0.1	0	3	1.7	0.904	0.223	*Abies alba*	GU94	NE	GU94	HE99
Abies grandis	1260	0.1	0	3	1.7	0.904	0.003	*Abies alba*	GU94	NE	GU94	HE99
Acer campestre	320	0.1	1.5	0	1.7	0.000	0.046	CO99,[1]	GU94	GU94	NE	VI04
Acer monspessulanum	320	0.1	1.5	0	1.7	0.000	0.020	CO99,[1]	GU94	GU94	NE	VI04
Acer opalus	320	0.1	1.5	0	1.7	0.000	0.044	CO99,[1]	GU94	GU94	NE	VI04
Acer platanoides	320	0.1	1.5	0	1.7	0.000	0.337	CO99,[1]	GU94	GU94	NE	VI04
Acer sp.	320	0.1	1.5	0	1.7	0.000	0.122	CO99,[1]	GU94	GU94	NE	VI04
Alnus cordata	320	0.1	5	0	1.7	0.339	0.072	CO99,[2]	DR89	PIO93	NE	HE99
Alnus glutinosa	320	0.1	5	0	1.7	0.339	0.346	CO99,[2]	DR89	PIO93	NE	HE99
Alnus incana	320	0.1	5	0	1.7	0.339	0.188	CO99,[2]	DR89	PIO93	NE	HE99
Alnus viridis	320	0.1	5	0	1.7	0.339	0.004	CO99,[2]	DR89	PIO93	NE	HE99
Arbutus andrachne	300	0	0.12	0	0.12	0.085	0.009	VE89,[1]	From *Arbutus unedo*			
Arbutus unedo	300	0	0.12	0	0.12	0.085	0.042	VE89,[1]	NE	OW97	NE	
Betula pendula	240	0	2.82	0	1.7	0.061	2.321	This work	NE	[a]	NE	KO95
Betula pubescens	240	0	1.45	0.2	1.7	2.687[b]	4.661	This work	NE	HK01	NE	HK01
Buxus sempervirens	980	11.5[b]	0	0	1.7	0.085	0.025	OW01	OW01	OW01	OW01	
Carpinus betulus	320	0.1	1.6	0	1.7	0.020	0.970	CO99,[3]	GU94	GU94	NE	KO95
Carpinus orientalis	320	0.1	1.6	0	1.7	0.020	0.012	CO99,[3]	GU94	GU94	NE	KO95
Castanea sativa	380	0	14.9	0	1.7	0.085	1.077	VE89	NE	[c]	NE	
Cedrus atlantica	700	0	0	1.5	1.7	0.622	0.024	CO99,[4]	NE	NE	GU94	VI04
Cedrus deodara	700	0	0	1.5	1.7	0.622	0.003	CO99,[4]	NE	NE	GU94	VI04
Cercis siliquastrum	300	0.1	0.1	0	1.7	0.085	0.011	VE89,[1]	GU94	GU94	NE	
Ceratonia siliqua	300	0	0	1	1.7	0.085	0.003	VE89,[1]	NE	NE	OW00	
Corylus avellana	300	0	0	1.5	1.7	0.085	0.010	VE89,[1]	NE	NE	GU94	
Cupressus sempervirens	700	0	0	0.65	1.7	0.085	0.030	CO99	CO99	CO99	CO99	

Table 3. Continued.

Species	*d* ($g\,m^{-2}$)	Stand. emission potential ($\mu g\,g_{DW}^{-1}\,h^{-1}$) ISOP	MT_{synt}	MT_{pool}	OVOC	SQT	A. f. (%)	Ref. *d*	Ref. ϵ_{ISOP}	Ref. ϵ_{MTsynt}	Ref. ϵ_{MTpool}	Ref. ϵ_{SQT}
Erica arborea	96	20.3	0	0	0	0.085	0.011	OW01	OW97	OW97	OW97	
Erica multiflora	150	2	0.03	0	0	0.085	<0.001	OW01	OW97	OW97	OW97	
Erica scoparia	150	2	0.03	0	0	0.085	<0.001	OW01	From *Erica multiflora*			
Eucalyptus sp.	400	15	0	5.4	1.7	3.605	0.847	CO99	STR97	NE	H00	VI04
Fagus moesiaca	320	0.1	0.6	0	1.7	0.085	0.148	CO99,[5]	GU94	GU94	NE	
Fagus orientalis	320	0.1	0.6	0	1.7	0.085	0.015	CO99,[5]	GU94	GU94	NE	
Fagus sylvatica	350	0	20.3	0	1.7	0.085	7.107	This work	NE	[d]	NE	
Fraxinus angustifolia	320	0.1	0.1	0	1.7	0.061	0.049	CO99,[6]	GU94	GU94	NE	VI04
Fraxinus excelsior	320	0.1	0.1	0	1.7	0.061	0.596	CO99,[6]	GU94	GU94	NE	VI04
Fraxinus ornus	320	0.1	0.1	0	1.7	0.061	0.091	CO99,[6]	GU94	GU94	NE	VI04
Ilex aquifolium	375	0.1	0.2	0	1.7	0.000	0.006	GE94	GU94	GU94	NE	VI04
Juglans nigra	320	0.1	0	3	1.7	0.170	0.001	CO99	GU94	NE	GU94	WI92
Juglans regia	300	0.1	0	9.4	1.7	0.170	0.003	VE89	PIO93	NE	PIO93	WI92
Juniperus communis	700	0.1	0	0.77	0.76	0.000	0.025	CO99,[7]	From *Juniperus phoenicea*			
Juniperus oxycedrus	700	0.08	0	0.96	0.96	0.000	0.038	CO99,[7]	OW97	OW97	OW97	VI04
Juniperus phoenicea	700	0.1	0	0.77	0.76	0.000	0.015	CO99,[7]	OW97	OW97	OW97	VI04
Juniperus thurifera	700	0.1	0	0.77	0.76	0.000	0.147	CO99,[7]	From *Juniperus phoenicea*			
Larix decidua	300	0	0	8.2	1.7	0.633	0.808	VE89,[2]	NE	NE	IS85	VI04
Larix kaempferi	300	0	0	8.2	1.7	0.633	0.065	VE89,[2]	NE	NE	IS85	VI04
Laurus nobilis	500	0	0	0.93	1.7	0.085	<0.001	VE89,[3]	NE	NE	PIO93	
Malus domestica	375	0.8	0	14	1.7	0.085	0.002	GE94	PIO93	NE	PIO93	
Olea europaea	200	0	0	0.3	1.7	0.060	0.041	CO99	NE	NE	AR91	AR91
Ostrya carpinifolia	320	0.1	1.6	0	1.7	0.000	0.288	CO99,[3]	GU94	GU94	NE	VI04
Phillyrea latifolia	300	0	0	0.47	1.7	0.085	0.028	VE89,[1]	NE	NE	OW97	
Picea abies	1340	0.345	1.8[e]	1.15[e]	1.7	0.119	21.36	This work	[f]	KE96	[f]	MA03
Picea sitchensis	1400	13	1.49	1.49	1.7	0.904	0.776	VE89	HY04	HY04	HY04	VI04
Pinus brutia	700	0.1	0	1.6[b]	1.7	0.350	0.040	VE89,[4]	GU94	NE	CR92	OR07a
Pinus canariensis	700	0.1	0	2.15[b]	1.7	0.339	0.062	VE89,[4]	GU94	NE	CR92	HE99
Pinus cembra	700	0.1	0	3	1.7	0.339	0.020	VE89,[4]	GU94	NE	GU94	HE99
Pinus contorta	700	0.1	0	3	1.7	0.100	0.198	VE89,[4]	GU94	NE	GU94	HE07
Pinus halepensis	700	0.1	0	1.6[b]	1.7	0.350	1.296	VE89,[4]	GU94	NE	CR92	OR07a
Pinus leucodermis	700	0.1	0	1.6[b]	1.7	0.350	0.008	VE89,[4]	GU94	NE	CR92	OR07a
Pinus mugo	700	0.1	0	3	1.7	0.339	0.002	VE89,[4]	GU94	NE	GU94	HE99
Pinus nigra	700	0.1	0	3	1.7	0.339	1.735	VE89,[4]	GU94	NE	GU94	HE99
Pinus pinaster	700	0.1	0	3	1.7	0.339	2.532	VE89,[4]	GU94	NE	GU94	HE99
Pinus pinea	700	0.1	5.5[b]	5.5[b]	1.7	0.339	0.233	VE89,[4]	GU94	STA97	STA97	HE99
Pinus radiata	700	0.1	0	3	1.7	0.339	0.136	VE89,[4]	GU94	NE	GU94	HE99
Pinus strobus	700	0.1	0	3	1.7	0.100	0.031	VE89,[4]	GU94	NE	GU94	HE07
Pinus sylvestris	690	0.1	0	2.25	1.7	0.209	31.15	This work	GU94	NE	[g]	[h]
Pinus uncinata	700	0.1	0	3	1.7	0.339	0.056	VE89,[4]	GU94	NE	GU94	HE99

Table 3. Continued.

Species	*d* ($g\,m^{-2}$)	Stand. emission potential ($\mu g\,g_{DW}^{-1}\,h^{-1}$) ISOP	MT_{synt}	MT_{pool}	OVOC	SQT	A. f. (%)	Ref. *d*	Ref. ϵ_{ISOP}	Ref. ϵ_{MTsynt}	Ref. ϵ_{MTpool}	Ref. ϵ_{SQT}
Pistacia lentiscus	1014	0	0	0.4	1.7	0.085	0.001	OW01	NE	NE	HA97	
Pistacia terebinthus	230	0	0	0.4	1.7	0.085	0.014	OW01	From *Pistacia lentiscus*			
Platanus orientalis	320	35	0	0	1.7	0.000	0.068	CO99	GU94	NE	NE	VI04
Populus alba	320	60	1.3	0	1.7	0.339	0.031	CO99,[8]	PIO93	PIO93	NE	HE99
Populus canescens	320	60	1.3	0	1.7	0.339	0.060	CO99,[8]	PIO93	PIO93	NE	HE99
Populus hybrides	320	70	0	0	1.7	0.090[b]	0.179	CO99,[8]	From *Populus nigra*			AM04
Populus nigra	320	70	0	0	1.7	0.339	0.044	CO99,[8]	OW00	NE	NE	HE99
Populus tremula	320	51	4.6	0	1.7	0.339	0.598	CO99,[8]	HK98	HK98	NE	HE99
Prunus avium	300	0	0.3	0	1.7	0.100	0.151	CO99,[9]	WI92	WI92	NE	AR91
Prunus padus	300	0	0.3	0	1.7	0.100	0.001	CO99,[9]	From *Prunus avium*			AR91
Prunus serotina	300	0	0.3	0	1.7	1.950	0.005	CO99,[9]	From *Prunus avium*			[i]
Pseudotsuga menziesii	1000	1.5	0	2.3	1.7	0.113	0.420	CO99	DR89	NE	DR89	VI04
Pyrus communis	300	0	0.6	0	1.7	0.085	0.005	VE89,[1]	NE	PIO93	NE	
Quercus cerris	320	0.2	3.1	0	1.7	0.085	1.037	VE89,[5]	CS99	OW97	NE	
Quercus coccifera	520	0.1	17.5	0	1.7	0.500	0.225	This work	HA96	HA96	HA96	OR07b
Quercus faginea	320	111	0.5	0	1.7	0.085	0.228	VE89,[5]	CS99	CS99	CS99	
Quercus frainetto	320	85	0	0	1.7	0.085	0.517	VE89,[5]	[j]	NE	NE	
Quercus fructosa	320	59	0.3	0	1.7	0.085	0.048	VE89,[5]	CS99	CS99	NE	
Quercus ilex	510	0.1	25	0	1.7	0.085	2.177	This work	BE97	BE97	NE	
Quercus macrolepsis	320	0.2	0.7	0	1.7	0.085	0.019	VE89,[5]	CS99	CS99	NE	
Quercus petraea	290	45	0.2	0	1.7	0.000	2.309	This work	STB97	STB97	NE	KO95
Quercus pubescens	320	91	0.2	0	1.7	0.085	1.488	VE89,[5]	STB97	STB97	NE	
Quercus pyrenaica	320	59	1.1	0	1.7	0.085	0.618	VE89,[5]	CS99	[k]	NE	
Quercus robur	290	49	1.1	0	1.7	0.085	2.930	This work	[l]	IS85	NE	
Quercus rotundifolia	500	0.2	14.6	0	1.7	0.085	0.201	VE89,[3]	CS99	CS99	NE	
Quercus rubra	320	53[b]	0.1	0	1.7	0.085	0.132	VE89,[5]	PI95	PI95	NE	
Quercus suber	500	0.1	25	0	1.7	0.085	0.835	VE89,[3]	STB97	PIO05	NE	
Quercus trojana	320	0.2	0.2	0	1.7	0.085	0.041	VE89,[5]	CS99	CS99	NE	
Robinia pseudoacacia	320	12	4.7	0	1.7	0.085	0.464	CO99	WI83	WI83	NE	
Salix alba	150	37	1.1	0	1.7	0.000	0.003	CO99,[10]	PIO93	PIO93	NE	VI04
Salix caprea	150	34	0.2	0	1.7	0.000	0.037	CO99,[10]	OW97	STB93	NE	VI04
Salix cinerea	150	28	0.8	0	1.7	0.000	0.001	CO99,[10]	From *Salix spp.*			
Salix eleagnos	150	28	0.8	0	1.7	0.000	0.001	CO99,[10]	From *Salix spp.*			
Salix sp.	150	28	0.8	0	1.7	0.000	0.024	CO99,[10]	OW00	OW00	OW00	VI04
Sorbus aria	300	0	1.5	0	1.7	0.085	0.036	VE89,[1]	NE	GU94	NE	
Sorbus aucuparia	300	0	1.5	0	1.7	0.085	0.046	VE89,[1]	NE	GU94	NE	
Sorbus domestica	300	0	1.5	0	1.7	0.085	0.010	VE89,[1]	NE	GU94	NE	
Sorbus torminalis	300	0	1.5	0	1.7	0.085	0.016	VE89,[1]	NE	GU94	NE	
Thuya sp.	1500	0.1	0	0.6	1.7	0.000	0.003	GE94	DR89	NE	DR89	VI04
Tilia cordata	320	0	0	0	1.7	0.000	0.211	CO99,[11]	CO99	CO99	CO99	VI04

Table 3. Continued.

Species	*d* ($g\,m^{-2}$)	Stand. emission potential ($\mu g\, g_{DW}^{-1}\, h^{-1}$) ISOP	MT_{synt}	MT_{pool}	OVOC	SQT	A. f. (%)	Ref. *d*	Ref. ϵ_{ISOP}	Ref. ϵ_{MTsynt}	Ref. ϵ_{MTpool}	Ref. ϵ_{SQT}
Tilia platyphyllos	320	0	0	0	1.7	0.000	0.044	CO99,[11]	CO99	CO99	CO99	VI04
Tsuga sp.	700	0	0	0.4	1.7	0.113	0.020	GE94	NE	NE	DR89	HE99
Ulmus glabra	320	0.1	0.2	0	1.7	0.000	0.030	CO99,[12]	GU94	GU94	NE	VI04
Ulmus laevis	320	0.1	0.2	0	1.7	0.000	0.006	CO99,[12]	GU94	GU94	NE	VI04
Ulmus minor	320	0.1	0.2	0	1.7	0.000	0.012	CO99,[12]	GU94	GU94	NE	VI04
Shrubs and Herbs												
Ulex parviflorus	574	15	0.2	0	1.7	0.085		OW00	OW00	OW00	NE	
Myrtus communis	47	81.1	0.3	0	1.7	0.085		OW00	[m]	OW97	NE	
Lavandula sp	100	0	8.0	0	1.7	0.085		OW00	OW00	OW00	NE	
Rosmarinus officinalis	116	0	2.2	0	1.7	0.700		OW00	NE	HA97	NE	OR07b
Nerium oleander	473	0	0.01	0	1.7	0.085		OW00	NE	OW00	NE	
Erica sp	96	2	0.03	0	1.7	0.085		OW00	OW97	OW97	NE	
Vaccinium sp.	30	0.1	0	0	1.7	13.9		CO99	CO99	CO99	NE	VI04

[a] Mean value of König et al. (1995) and Hakola et al. (2001).
[b] Mean value.
[c] Mean value of Pio et al. (1993) and Seufert (1997).
[d] Mean value of Dindorf et al. (2006) and Moukhtar et al. (2005).
[e] Half of the monoterpene standard emission potential given in Kempf et al. (1996) attributed to newly synthesized emissions.
[f] Mean value of Kempf et al. (1996) and Grabmer et al. (2006).
[g] Mean value of Janson (1993) and Komenda and Koppmann (2002).
[h] Mean value of Tarvainen et al. (2005) and Hakola et al. (2006).
[i] Mean value of Arey et al. (1991) and Helmig et al. (1999).
[j] Mean value of Steinbrecher et al. (1997) and Csiky and Seufert (1999).
[k] Mean value of Csiky and Seufert (1999) and Pio et al. (1993).
[l] Mean value of Isidorov et al. (1985) and Pio et al. (1993).
[m] Mean value of Hansen et al. (1997) and Owen et al. (1997).
References: AAK95 Andreani-Aksoyoglu and Keller (1995); MO06 Moukhtar et al. (2006); HE99 Helmig et al. (1999) HR01 Harrison et al. (2001); GU94 Guenther et al. (1994); CO99 CORINAIR (1999); VI04 Vizuete et al. (2004); DR98 Drewitt et al. (1998); PIO93 Pio et al. (1993), screening study, reported values may be affected by artificially-enhanced MT emissions; VE89 Veldt (1989), value for: [1] default deciduous broadleaved, [2] *Larix* default, [3] default evergreen broadleaved, [4] other *Pinus spp.*, [5] deciduous oaks; OW97 Owen et al. (1997); OW00 Owen and Hewitt (2000); CO99 CORINAIR (1999), value for [1] *Acer sp.*, [2] *Alnus sp.*, [3] *Carpinus*, [4] *Cedrus*, [5] *Fagus sp.*, [6] *Fraxinus*, [7] *Juniperus*, [8] *Populus*, [9] *Prunus*, [10] *Salix*, [11] *Tilia*, [12] *Ulmus* ; KO95 König et al. (1995); HK01 Hakola et al. (2001); OW01 Owen et al. (2001); STR97 Street et al. (1997); H00 He et al. (2000); GE94 Geron et al. (1994); WI92 Winer et al. (1992);IS85 Isidorov et al. (1985); AR91 Arey et al. (1991), screening study, reported values may be affected by artificially-enhanced MT and SQT emissions; KE96 Kempf et al. (1996); MA03 Martin et al. (2003); HY04 Hayward et al. (2004); CR92 Corchnoy et al. (1992); OR07a Ormeño et al. (2007a); HE97 Helmig et al. (2007); STA97 Staudt et al. (1997); HA97 Hansen et al. (1997); AM04 Arimura et al. (2004); HK98 Hakola et al. (1998); CS99 Csiky and Seufert (1999); HA96 **?**; OR07b Ormeño et al. (2007b); BE97 Bertin et al. (1997); STB97 Steinbrecher et al. (1997); PI95 Pier (1995); PIO05 Pio et al. (2005); WI83 Winer et al. (1983); STB93 Steinbrecher et al. (1993).

Table 4. Foliar biomass densities in g dry mass m^{-2} and standard emission potentials (in $\mu g\, g_{DW}^{-1}\, h^{-1}$) of isoprene, monoterpenes, ORVOC and sesquiterpenes for crop species. MT synt are monoterpenes emitted with temperature and light dependence and MT pool are only temperature dependent. NE: compound not emitted.

Species	d	Stand. emission potential ($\mu g\, g_{DW}^{-1}\, h^{-1}$)					Ref. d	Ref. ϵ_{ISOP}	Ref. ϵ_{MT}	Ref. ϵ_{SQT}
	($g\, m^{-2}$)	ISOP	MT_{synt}	MT_{pool}	OVOC	SQT				
Barley	1290	0.006	0.00	0.02	1.70	0.000	CO99	CO99	CO99	VI04
Citrus fruits	500	0.00	0.00	1.35	1.70	0.041	CO99[a]	CO99	AR91[b]	HA03[c]
Durum Wheat	800	1.00	0.00	0.08	1.70	0.000	CO99	LA93	LA93	[d]
Floriculture	1000	0.00	0.00	0.00	1.70	0.085	SI99[e]	WI89[f]	WI89[f]	
Permanent gras and grazing	400	0.00	0.00	0.10	1.70	0.000	CO99[g]	CO99	CO99	VI04
Fallow land	400	0.00	0.00	0.10	1.70	0.085	CO99[g]	CO99	CO99	
Fruit tree and berry plantations	251.25	0.23	0.18	3.50	1.31	3.539	[h]	[h]	[h]	[h]
Maize	1610	0.00	0.00	0.00	1.70	0.010	CO99	CO99	CO99	GO02
Olive groves	200	0.00	0.00	0.11	1.70	0.060	CO99	AR91	AR91	AR91
Rape and turnip rape	400	0.00	0.00	0.12	1.70	0.085	CO99	CO99	CO99	
Fibre and oleaginous crops	400	0.00	0.00	0.12	1.70	0.085	CO99	CO99	CO99	
Vineyards	410	0.002	0.00	0.002	1.70	0.160	CO99	CO99	CO99	AR91
Nurseries	675.5	17.76	5.18	2.34	1.70	0.495	[i]	[i]	[i]	[i]
Oats	750	0.01	0.00	0.03	1.70	0.000	CO99	CO99	CO99	VI04
Other cereals	1335	0.09	0.00	0.13	1.70	0.000	CO99[j]	CO99	CO99	VI04
Other crops	1335	0.09	0.00	0.13	1.70	0.150	CO99[j]	CO99	CO99	AR91
Fodder other on arable land	400	0.00	0.00	0.10	1.70	0.000	CO99[g]	CO99	CO99	VI04
Non permanent industrial crops	1335	0.09	0.00	0.13	1.70	0.150	CO99[j]	CO99	CO99	AR91
Tomatoes and other vegetables	1000	0.00	0.00	30.3	1.70	0.400	SI99[e]	CO99	AR91[k]	WI92
Rice	1050	0.10	0.00	0.24	1.70	0.000	CO99	CO99	CO99	WI92
Potatoes	1000	0.00	0.00	1.40	1.70	0.497	SI99[e]	AR91[l]	AR91[l]	VI04[m]
Dry pulses	1000	0.00	0.00	0.00	1.70	0.497	SI99[e]	WI92[n]	WI92[n]	VI04[m]
Other root crops	1000	0.00	0.00	1.40	1.70	0.497	SI99[e]	AR91[l]	AR91[l]	VI04[m]
Rye	400	0.00	0.00	0.10	1.70	0.000	CO99	CO99	CO99	VI04
Soya	740	0.03	0.00	0.00	1.70	0.063	CO99	CO99	CO99	VI04
Sugar beet	1000	0.00	0.00	1.40	1.70	0.497	SI99[e]	AR91[l]	AR91[l]	VI04[m]
Sunflower	1000	0.03	0.00	0.28	0.23	0.210	SI99[e]	SC97	SC97	SC97
Common wheat	800	0.00	0.00	0.00	1.70	0.000	CO99	CO99	CO99	[d]
Tobacco	490	0.00	0.00	0.12	1.70	0.085	CO99	CO99	CO99	

[a] Evergreen trees default. [b] Mean value Navel and Valencia orange. [c] From citrus trees. [d] Mean value of Winer et al. (1992) and König et al. (1995). [e] Crops default. [f] From irrigated pastures. [g] Grassland default. [h] Mean of *Arbutus unedo*, *Vaccinum*, *Malus domestica*, *Pyrus communis*. [i] same as Mixed Forest class of CLC2000. [j] Miscellaneous crops default. [k] From tomatoes. [l] From carrots. [m] From potatoes. [n] From beans. References: CO99 CORINAIR (1999); VI04 Vizuete et al. (2004); AR91 Arey et al. (1991), screening study, reported values may be affected by artificially-enhanced MT and SQT emissions (see text, Sect. 4.3); HA03 Hansen and Seufert (2003); LA93 Lamb et al. (1993); SI99 Simpson et al. (1999); WI89 Winer et al. (1989);GO02 Gouinguene and Turlings (2002); WI92 Winer et al. (1992), screening study, reported values may be affected by artificially-enhanced MT and SQT emissions (see text, Sect. 4.3); SC97 Schuh et al. (1997).

Table 5. Vegetation composition, Standard emission potential and foliar biomass densities for each CLC and GLC vegetation class[a]. Values for agriculture CLC classes are derived from individual crop species as specified in the plant composition list, and taken from Table 4.

ID	CLC/GLC2000 Vegetation class	*d* ($g\,m^{-2}$)	Stand. emission potential ($\mu g\, g_{DW}^{-1}\, h^{-1}$) ISOP	MT_{synt}	MT_{pool}	OVOC	SQT	Plant Composition[b]
10	Green Urban Areas	400	0.00	0.00	0.10	1.70	0.085	CO99, grassland default
12	Non-Irrigated Arable Land	800	1.00	0.00	0.08	1.70	0.000	Durum Wheat
13	Permanently Irrigated Land	1000	0.00	0.00	15.8	1.70	0.449	50% Tomatoes, 50% Sugar beet
14	Rice fields	1050	0.10	0.00	0.24	1.70	0.000	Rice
15	Vineyards	410	0.00	0.00	0.00	1.70	0.160	Vineyards
16	Fruit trees and berry plantations	250	0.23	0.18	3.50	1.31	3.539	Fruit tree and berry plantations
17	Olive groves	200	0.00	0.00	0.11	1.70	0.060	Olive groves
18	Pastures	400	0.00	0.00	0.10	1.70	0.000	Fodder other on arable land
19	Annual Crops ass. w. perm. crops	1340	0.09	0.00	0.13	1.70	0.150	Non permanent industrial crops
20	Complex Cultivation Patterns	330	0.11	0.09	1.80	1.50	1.769	50% Dry Pulses, 50% Rye
21	Agriculture, with natural Veg.	600	0.50	0.00	0.09	1.70	0.000	50% Non perm. ind. crops, 50% Rye
22	Agro-Forestry Areas	840	0.05	0.00	0.43	1.70	0.100	25% Citrus, 25% Olive, 50% LC 19
23	Broad-Leaved Forest	360	21.6	8.49	1.55	1.70	0.782	[c]
24	Coniferous Forest	950	0.20	1.82	2.46	1.70	0.199	[d]
25	Mixed Forest	660	10.9	5.15	2.01	1.70	0.491	50% LC 23, 50% LC 24
26	Natural Grassland	420	0.00	0.00	0.10	1.70	0.085	CO99, grassland A3
27	Moors and Heathland	350	8.00	0.00	0.65	1.70	0.085	CO99, moorland/heathland
28	Sclerophyllous Vegetation	340	20.3	10.7	0.00	1.31	0.189	[e]
29	Transitional Woodland-Shrub	400	8.17	12.8	0.00	1.23	0.209	[f]
32	Sparsely Vegetated Areas	140	0.40	0.01	0.03	1.70	0.085	30% LC 10, 20% *Erica sp.*, 50% no veg.
35	Inland Marshes	200	8.00	0.40	0.40	1.70	0.085	G95, marshes
36	Peatbogs	330	21.1	3.92	0.04	1.56	1.495	[g], 50% cover
37	Salt-Marshes	200	8.00	0.40	0.40	1.70	0.085	G95, marshes
100	Broadleaved Evergreen Forest	360	21.6	8.49	1.55	1.70	0.782	as LC 23
101a	Broadleaved Deciduous Forest	280	17.6	2.62	0.10	1.70	1.479	[h]
101b	Broadleaved Deciduous Forest	340	18.6	11.8	0.00	1.70	0.072	[i]
101c	Broadleaved Deciduous Forest	250	21.6	8.49	1.55	1.70	0.782	as LC 23, 70% cover
102a	Needleleaved Evergreen Forest	650	0.14	1.00	1.14	1.70	0.995	[j], 80% cover
102b	Needleleaved Evergreen Forest	950	0.20	1.82	2.46	1.70	0.199	as LC 24
102c	Needleleaved Evergreen Forest	700	0.10	2.75	4.25	1.70	0.339	[k]
103	Needleleaved Deciduous Forest	300	0.00	0.00	8.20	1.70	0.633	*Larix decidua*
104a	Mixed Forest	460	8.85	1.81	0.62	1.70	1.237	50% LC 101a, 50% LC 102a
104b	Mixed Forest	660	10.9	5.15	2.01	1.70	0.491	as LC 25
104c	Mixed Forest	530	10.9	5.15	2.01	1.70	0.491	as LC 25, 80% cover
105a	Forest and Shrub/Grassland Mos.	100	8.00	0.00	0.65	1.70	0.085	as LC 27, 30% cover

Table 5. Continued.

ID	CLC/GLC2000 Vegetation class	d ($g\,m^{-2}$)	Stand. emission potential ($\mu g\, g_{DW}^{-1}\, h^{-1}$) ISOP	MT_{synt}	MT_{pool}	OVOC	SQT	Plant Composition[b]
105b	Forest and Shrub/Grassland Mos.	410	5.72	8.97	0.03	1.37	0.172	70% LC 29, 30% LC 26
105c	Forest and Shrub/Grassland Mos.	410	5.72	8.97	0.03	1.37	0.172	70% LC 29, 30% LC 26
107	Evergreen Shrubland	370	14.3	11.8	0.00	1.27	0.199	50% LC 28, 50% LC 29
108a	Deciduous Shrubland	330	15.9	7.19	0.05	1.48	0.839	50% LC 101b, 50% LC 107
108b	Deciduous Shrubland	230	13.7	2.23	0.05	1.66	3.138	[l]
108c	Deciduous Shrubland	260	20.4	5.31	0.78	1.70	0.495	[m]
109	Grassland	210	14.5	1.96	0.35	1.63	0.790	50% LC 26 + 50% LC 36
110a	Sparse Grassland	100	14.5	1.96	0.35	1.63	0.790	LC 109, 50% cover
110b	Sparse Grassland	210	14.5	1.96	0.35	1.63	0.790	LC 109
110c	Sparse Grassland	10	0.73	0.10	0.02	0.08	0.040	LC 109, 5% cover
111a	Wetland unspecified	330	21.1	3.92	0.04	1.56	1.495	LC 36
111b	Wetland unspecified	330	21.1	3.92	0.04	1.56	1.495	LC 36
111c	Wetland unspecified	380	10.5	1.96	0.07	1.63	0.790	50% LC 36, 50% LC 26
112a	Non Irrigated Cropland	800	1.00	0.00	0.08	1.70	0.085	LC 12
112b	Non Irrigated Cropland	600	0.50	0.00	0.09	1.70	0.085	50% LC 12, 50% LC 18
112c	Non Irrigated Cropland	520	0.30	0.00	0.09	1.70	0.00	30% LC 12, 70% LC 18
113	Irrigated Cropland	1000	0.00	0.00	15.8	1.70	0.449	LC 13
114	Tree Crops	200	20.0	0.00	0.00	1.70	0.085	CO99, Date Palm
117a	Cropland/Forest/Shrubland/Grass Mosaic	550	0.32	0.29	0.54	1.70	0.579	[n]
117b	Cropland/Forest/Shrubland/Grass Mosaic	600	0.34	6.10	1.15	1.70	0.085	[o]
117c	Cropland/Forest/Shrubland/Grass Mosaic	370	16.5	4.25	0.64	1.70	0.396	20% LC 12, 80% LC 108
125	Cropland unspecified	600	0.10	0.00	0.24	1.70	0.000	30% LC 14, 70% LC 18
127	Wetland - Bogs and Marshes	330	21.1	3.92	0.04	1.56	1.495	LC 36
128	Wetland - Palsa Bogs	170	21.1	3.92	0.04	1.56	1.495	LC 36, 50% cover
129	Wetland - Riparian Vegetation	300	19.4	3.46	0.02	1.63	0.855	[p]
131	Tree Cover, regularly flooded, saline	250	5.0	0.10	0.10	1.70	0.075	G95, African Swamp

[a] Vegetation class ID of CLC/GLC2000 landcover mosaic as indicated in Köble (2007). Letter a refers to GLC Northern Eurasia v4.0, letter b refers to GLC Europe v1.0 and letter c refers to GLC Africa v5.0 + GLC Global v1.1. [b] LC is an abbreviation for CLC/GLC2000 land use class. [c] 15% *Fagus sylvatica*, 10% *Q. ilex*, 10% *Betula pubescens*, 10% *Q. robur*, 10% *Q. pubescens*, 10% *Q. petraea*, 20% Eucalyptus, 5% *Juglans regia*. [d] 40% *Pinus silvestris*, 40% *Picea abies*, 20% *Pinus pinea*. [e] 25% *Q.ilex*, 25% *Q. coccifera*, 25% *Arbutus unedo*, 25% *Myrtus communis*. [f] 30% *Q.ilex*, 30% *Q. coccifera*, 30% *Arbutus unedo*, 10% *Myrtus communis*. [g] 10% *Arunda donax*, 10% *Vaccinum sp.*, 10% *Salix sp.*, 40% *Betula pendula*, 30% *Fraxinus angustifolia*. [h] 50% *Betula pubescens*, 30% *Populus tremula*, 10% *Alnus glutinosa*, 5% *Q. petrea*, 5% *Tilia cordata*. [i] 30% *Fagus sylvatica*, 20% *Betula pendula*, 10% *Q. robur*, 10% *Q. pubescens*, 10% *Q. petraea*, 10% *Q. suber*, 10% *Q. ilex*. [j] 30% *Picea abies*, 30% *Pinus sylvestris*, 10% *Abies alba*, 30% *Betula pubescens*. [k] 50% *Pinus pinea*, 50% *Pinus pinaster*. [l] 15% *Erica sp.*, 15% *Vaccinum sp.*, 40% LC 101b, 30% LC 36. [m] 50% LC 101c, 10% *Ulex parviflorus*, 10% *Myrtus communis*, 10% *Lavandula sp*, 10% *Rosmarinus officinalis*, 10% *Nerium oleander*. [n] 30% LC 12, 30% LC 18, 20% *Pinus sylvestris*, 20% *Betula pubescens*. [o] 30% LC 12, 30% LC 18, 20% *Q. ilex*, 20% *Pinus pinea*. [p] 50% LC 36, 20% *Salix spp.*, 10% *Alnus cordata*, 10% *Betula pendula*, 10% *Populus alba*. References: CO99 CORINAIR (1999); G95 Guenther et al. (1995).

Table 6. 2004–2005 annual averaged BVOC emissions for the four major vegetation zones in Europe from the presented inventory. For the main land use types agriculture, forests and Other land use, annual emissions (in Gg) are shown for each BVOC class in the four vegetation zones Atlantic, Boreal, Continental, and Mediterranean.

Land Use type	BVOC class	Atlantic	Boreal	Continental	Mediterranean
Agriculture	ISOP	33	6	61	28
	MT_{synt}	12	3	21	5
	MT_{pool}	1121	125	586	404
	OVOC	883	245	1248	332
	SQT	44	16	58	22
	Total	2093	395	1974	792
Forest	ISOP	251	262	414	582
	MT_{synt}	47	70	156	64
	MT_{pool}	99	346	207	205
	OVOC	186	987	505	196
	SQT	12	152	41	20
	Total	595	1816	1323	1067
Other Land Use	ISOP	42	87	76	573
	MT_{synt}	24	47	35	233
	MT_{pool}	15	9	13	38
	OVOC	102	160	82	184
	SQT	6	24	10	14
	Total	189	328	216	1041

Table 7. Regional BVOC emission estimates from the presented inventory for 2005. Four regions have been selected. BVOC emission rates are given as seasonal averages (three month averages) in mg m^{-2} for the main land use types agriculture, forests and other land uses and for the total land use of each region (DJF: December to February, MAM: March to May, JJA: June to August, SON: September to November).

Region	Land Use	DJF	MAM	JJA	SON
Southern Spain	Agriculture	34	82	129	51
	Forest	31	184	492	114
	Other Land Use	19	101	272	64
	Total	84	366	894	230
Western France	Agriculture	95	222	446	203
	Forest	13	59	171	56
	Other Land Use	0	1	3	1
	Total	109	282	620	261
Southern Finland	Agriculture	4	8	31	12
	Forest	8	22	99	33
	Other Land Use	1	3	17	4
	Total	13	33	147	49
Southern Germany	Agriculture	22	65	155	69
	Forest	10	37	99	39
	Other Land Use	1	6	18	6
	Total	33	108	272	114

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Table 8. Comparison with other European BVOC emission estimates from bottom-up inventories. Estimates from global emission inventories are included for the sake of completeness.

Total BVOC[a] $Gg\,yr^{-1}$	Forest BVOC[b] $Gg\,yr^{-1}$	ISOP $Gg\,yr^{-1}$	Reference	Inventory	Extent to East
15	6	3.1	This Work, G97	This Work	40° E
		3.3	This Work, MEGAN	This Work	40° E
		10.3	This Work, G97	GEIA [c,d]	36° E
		4.5	This Work, MEGAN	MEGAN [c,e]	36° E
20	12	4	Steinbrecher et al. (2008)	NatAir	40° E
34		17	Lathière et al. (2006)	ORCHIDEE[c]	50° E
13.5	11	4.6	Simpson et al. (1999)	EMEP	[f]
10	9	4.5	Simpson et al. (1995)	EMEP	[f]
7.5	7.5		Lübkert and Schöpp (1989)	Forest VOC Inv.	42° E
29			Andryukov and Timofeev (1989)	Total VOC Inv.	42° E

[a] Total amount of BVOC emissions from all land use types.
[b] BVOC emissions from forests only.
[c] Global BVOC inventory. The estimates are from model simulations using the global inventory.
[d] Guenther et al. (1995)
[e] Guenther et al. (2006)
[f] Includes the European part of the former USSR.

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European BVOC emissions

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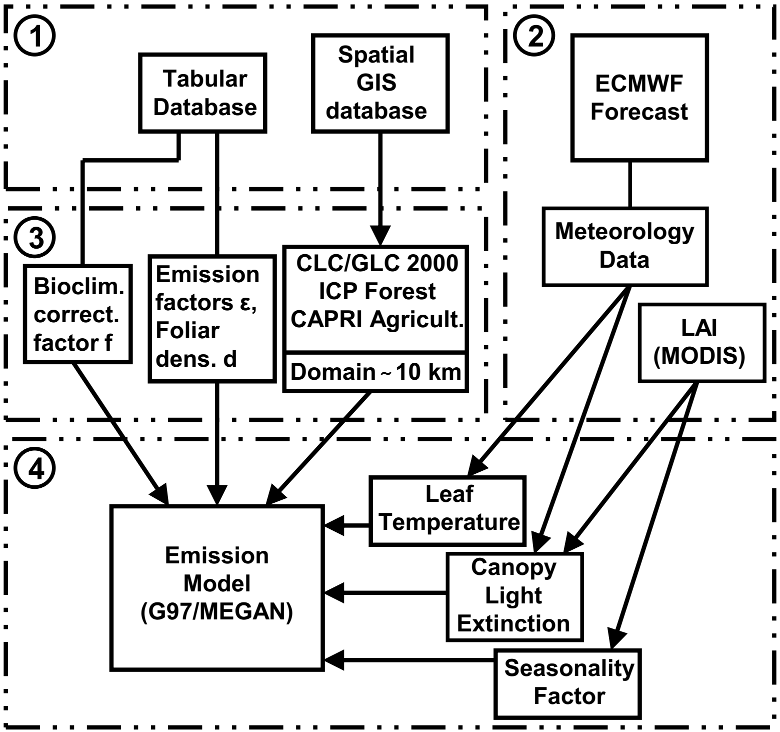

Fig. 1. BVOC emission model, schematic overview.

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European BVOC emissions

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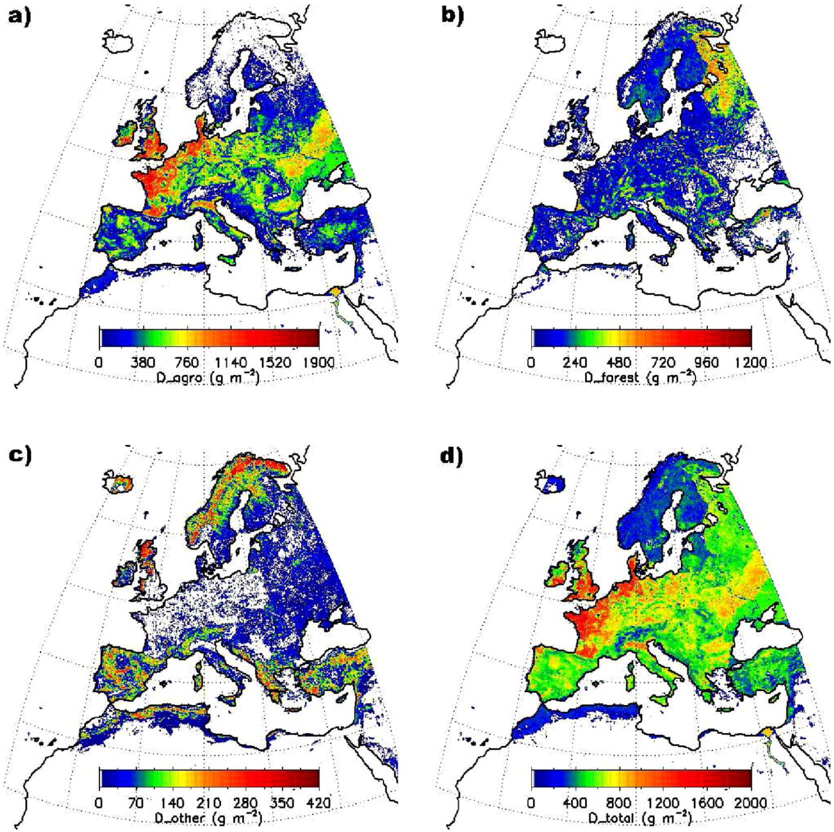

Fig. 2. European foliar biomass density (in g m^{-2}) distributions. **(a)** Agriculture land use (crop species from *Agricultural Land Use Map*) and agriculture vegetation classes from CLC/GLC2000), **(b)** Forest land use (tree species from the *Tree Species Map* and forest vegetation classes from CLC/GLC2000), **(c)** Other land use (vegetation classes from CLC/GLC2000), **(d)** Total land use.

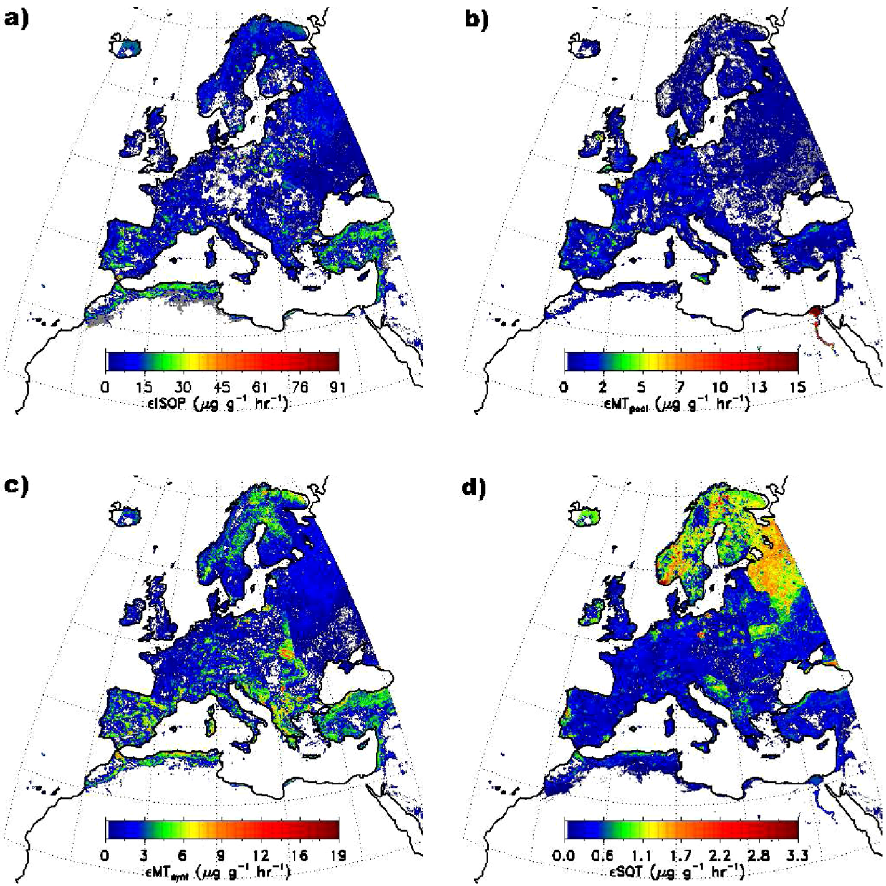

Fig. 3. European BVOC standard emission potential (in $\mu g\, g_{DW}^{-1}\, h^{-1}$) distributions: **(a)** isoprene **(b)** monoterpenes (pool) **(c)** monoterpenes (synthesis) **(d)** sesquiterpenes.

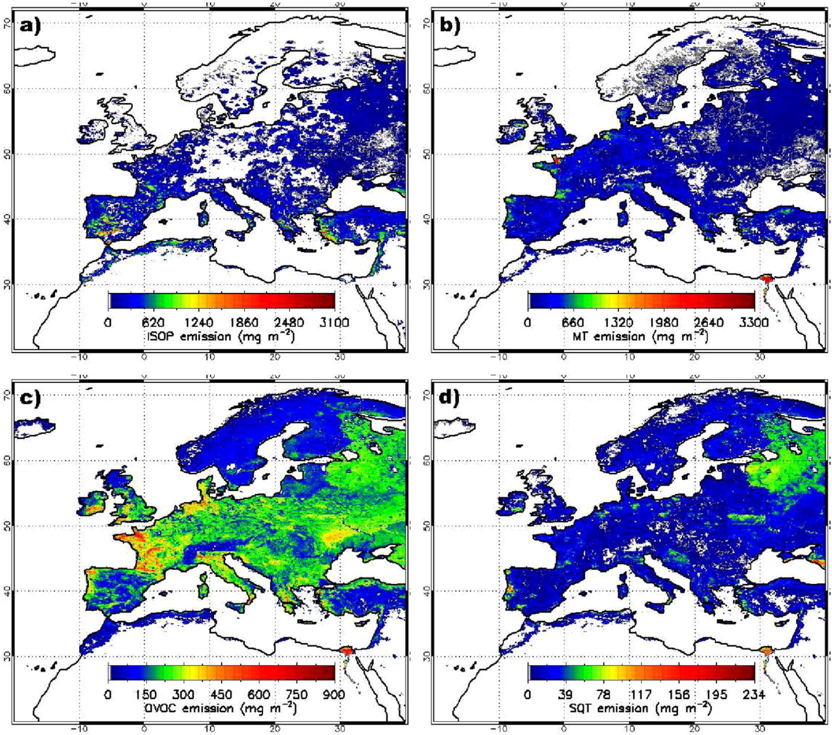

Fig. 4. European emission (in mg m^{-2}) distribution for July 2005 of: **(a)** isoprene, **(b)** monoterpenes, **(c)** OVOC, **(d)** sesquiterpenes. Isoprene emissions are calculated with MEGAN. The maximum differences for July 2005 between the isoprene emission distribution calculated with MEGAN and G97 is only 6%. Emissions shown here are assessed with the assumption that terpenes and other VOC emitted by plants are directly emitted into the atmosphere, ignoring eventual oxidation and losses within the canopy.

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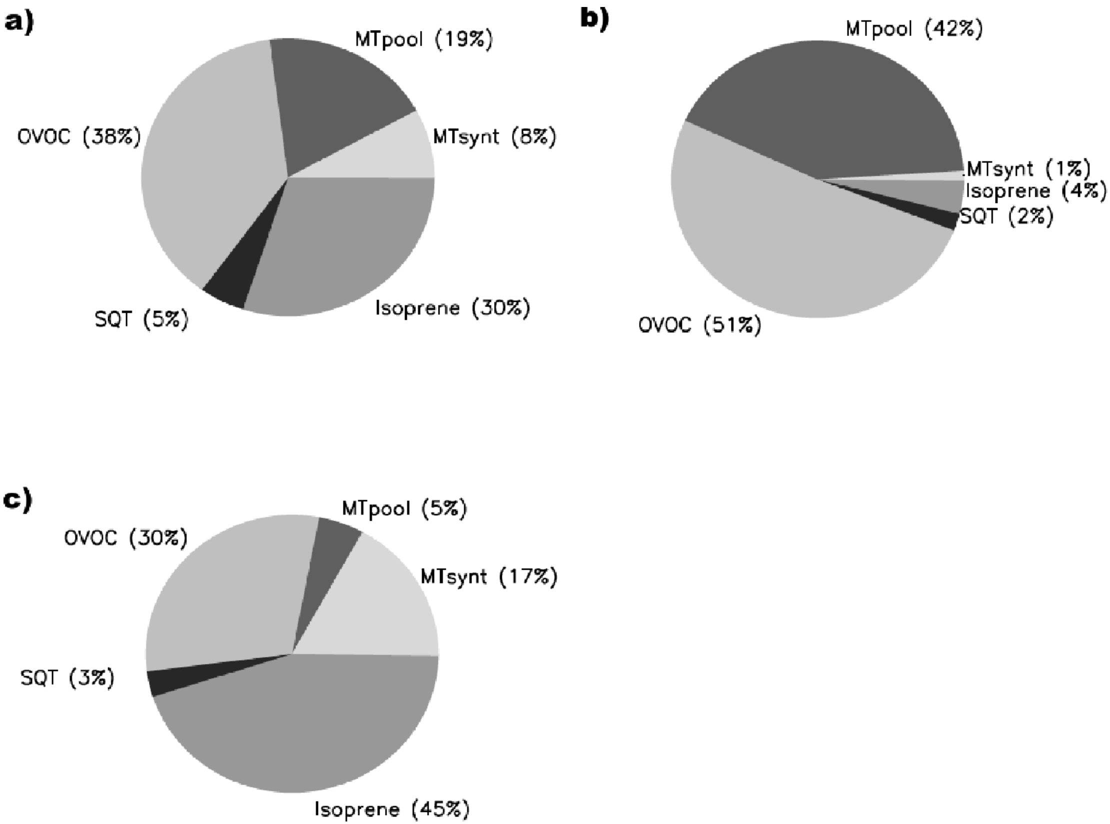

Fig. 5. European BVOC class emission contributions to each land use type: **(a)** forest, **(b)** agriculture, **(c)** other land use.

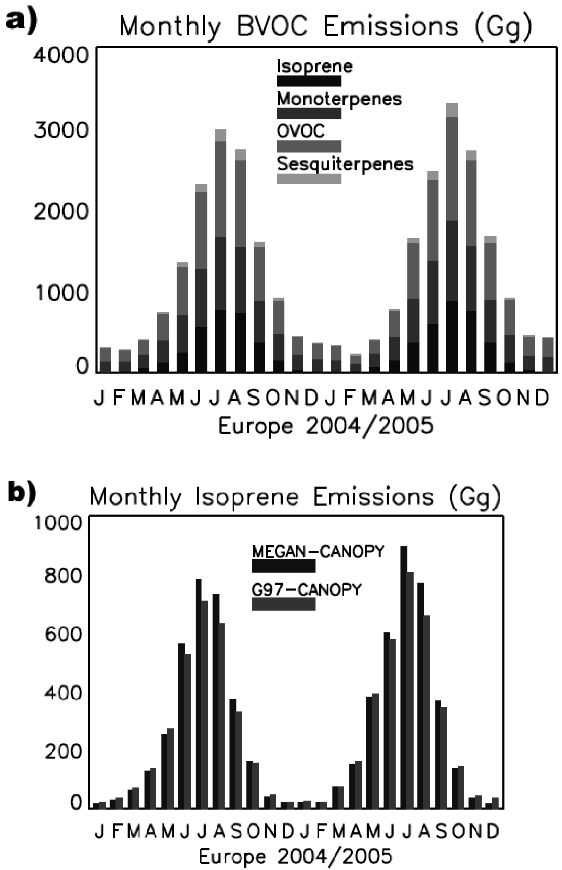

Fig. 6. Seasonal variation of European emissions: **(a)** BVOC, **(b)** isoprene.