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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 oxygenated VOC (OVOC), on a spatial resolution of 0.089×0.089 degrees, for implementation in atmospheric transport models. The inventory incorporates more accurate data on foliar biomass densities from several litterfall databases that became available in the last years for the main tree species in Europe. A bioclimatic correction factor was introduced to correct the foliar biomass densities of trees and crops for the different plant growth conditions that can be found in Pan-Europe. Long-term seasonal variability of agriculture and forest emissions was taken into account by implementing a new growing season concept. The 2004–2005 averaged annual total biogenic volatile organic compound (BVOC) emissions for the Pan-European domain are estimated to be about 12 Tg with a large contribution from the OVOC class of about 4.5 Tg and from monoterpenes of about 4 Tg. Annual isoprene emissions are found to be about 3.5 Tg, insensitive to the chosen emission algorithm. Emissions of OVOC were found to originate to a large extent from agriculture. Further experiments on crop emissions should be carried out to check the validity of the applied standard emission factors. The new inventory aims at a fully transparent and verifiable aggregation of detailed land use information and at the inclusion of plant-specific emission data. Though plant-specific land use data is available with relatively high accuracy, a lack of experimental biomass densities and emission data on terpenes, sesquiterpenes and oxygenated VOC, in particular for agricultural plants, currently limits the setup of a highly accurate plant-specific emission inventory.

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1 Introduction

The amount and composition of plant species that cover the land surface is the primary control on the type and 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, 1995, 2006; Schuh et al., 1997; Staudt et al., 2000).

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
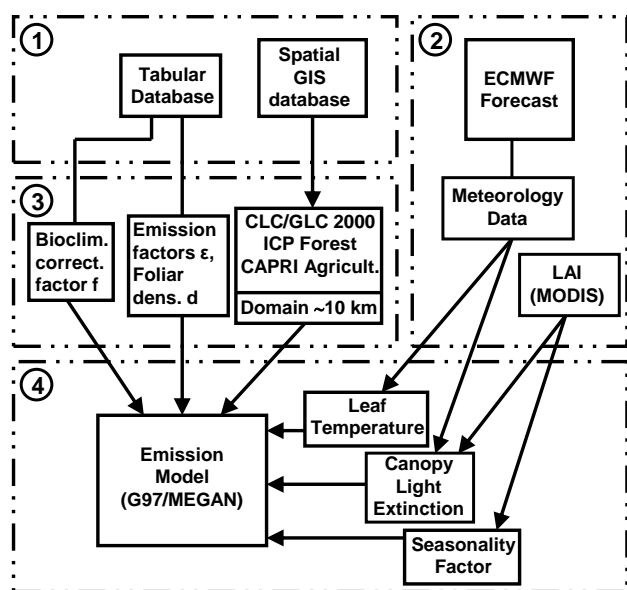
Fig. 1. BVOC emission model, schematic overview.

secondary organic aerosol (Hoffmann et al., 1997; Jaoui et al., 2003). Bonn and Moortgat (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 plain landscapes on a small scale. Type and amount of BVOC emissions is highly variable; even within a plant taxonomic group like the important *Quercus* (oak) *genus* one can observe several species emitting huge amount of isoprene, other species emitting monoterpenes, others are close to zero emitters (Csiky and Seufert, 1999). Therefore it is of great importance to use highly resolved land cover data of forests, agriculture and other land use for modelling European BVOC emissions.

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 (Guen-

ther, 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 (Lübkert and Schöpp, 1989; Andryukov and Timofeev, 1989; Simpson et al., 1999; Steinbrecher et al., 2009), 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 unnecessary complexity in order to allow calculations in the frame of a global chemical transport model.

2 Inventory description

In this work a new plant-specific BVOC emission inventory with high spatial resolution for implementation in atmospheric transport models is developed for Europe. Data on emission potentials at standard conditions for tree and crop species and for landcover classes was adopted from the work of Steinbrecher et al. (2009), 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. Throughout this work, emission potentials are given for standard conditions, i.e. 30°C leaf temperature and $1000\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ photosynthetic photon flux density (PPFD). From several litterfall databases we derived more accurate data on foliar biomass densities for the most abundant tree species. A biomass correction factor was introduced for forest and agriculture land use classes to adjust foliar biomass densities for growing conditions in different climates. To account for the long-term seasonal variability of emissions, a new growing season concept was introduced based on detailed phenology data for major agricultural crops and on a seasonal algorithm for deciduous and evergreen vegetation by Staudt et al. (2000).

For each BVOC class the emissions can be calculated as sum over all grid cells of the European domain:

$$E_b = \sum_i A_i \cdot \epsilon_{b,i} \cdot D_i \cdot \gamma_{\mathrm{CE},i} \qquad (1)$$

In Eq. (1), A_i is the vegetated and emitting area in a grid cell i (in $\mathrm{m^2}$), $\epsilon_{b,i}$ is the average emission standard potential (in $\mu\mathrm{g\,g_{DW}^{-1}\,h^{-1}}$) of each BVOC class, D_i the foliar biomass density related to dry mass (in $\mathrm{g\,m^{-2}}$) and $\gamma_{\mathrm{CE},i}$ is the dimensionless canopy emission activity factor, often referred to as the 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 Sects. 2.1 to 2.3 the procedure of retrieving and aggregating spatial information with plant specific properties is described in detail (part 1 and 3 in Fig. 1). Section 2.4 describes the Canopy Environment Model which was applied to calculate the emission activity factor $\gamma_{\text{CE},i}$ in Eq. (1). Throughout the paper, emission factors and emission rates refer to mass of BVOC compound. We note that isoprene emission estimates by Guenther et al. (2006) are given in mass carbon and that these were converted to mass of isoprene for the comparison with the estimates of this work (Sect. 3.5).

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, $72°$ 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 level 1 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 *Agricultural Land Use Map* contains crop-specific information for EU15 and the *Tree Species Map* contains tree-specific information for 30 European countries. 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%).

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://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php) for the European continent. 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.

All land use data was aggregated and then projected on a regular latitude/longitude grid. The data is available in WGS84 projection with a horizontal resolution of 0.089×0.089 degrees for continental Pan-Europe. 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 9.6 km by 3.2 km at the northern border ($72°$ N) of the domain.

In the equations below, t is used as an index for tree species, c for crop species, g is an index for the general CLC/GLC 2000 land use classes, and b 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. General land use classes from the CLC/GLC2000 mosaic belong to one of the three main land use categories: agriculture, forest and other land use category (i.e. shrubland, wetland, and grassland). The CLC/GLC2000 area fraction in a grid cell is the sum of the cumulated area fractions of agriculture, $a_{\text{clcagr},i}$, forest, $a_{\text{clcfor},i}$, and other land use, $a_{\text{clcoth},i}$, vegetation classes:

$$a_{\text{clc},i} = a_{\text{clcagr},i} + a_{\text{clcfor},i} + a_{\text{clcoth},i} \tag{2}$$

By relating the cumulated areas of the CLC/GLC2000 mosaic to the total area in each grid cell, it was assured that $a_{\text{clc},i}$ does not exceed 1 in each grid cell. Thus the vegetated areas provided by the CLC/GLC2000 mosaic can be used as a reference for the plant-specific land use data 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.

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 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 $a_{t,i}$ for a single tree species t and the area fraction $a_{c,i}$ for a single crop species c is corrected with the cumulated area fraction of CLC/GLC2000 forest or agriculture vegetation

classes within a grid cell. The corrected area fraction of a tree species, $a'_{t,i}$, is:

$$a'_{t,i} = a_{t,i} \cdot \frac{a_{\text{clcfor},i}}{\sum_t a_{t,i}} \qquad (3)$$

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

$$a'_{c,i} = a_{c,i} \cdot \frac{a_{\text{clcagr},i}}{\sum_c a_{c,i}} \qquad (4)$$

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

$$A_i = (\sum_{t,i} a'_{t,i} + \sum_{c,i} a'_{c,i} + a_{\text{clcoth},i}) \cdot A_{\text{cell},i} \qquad (5)$$

where $A_{\text{cell},i}$ 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_t, and of crops, d_c, 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_g is added, weighted by the area fraction $a_{g,i}$ of the CLC/GLC2000 class g in that cell:

$$D_i = \sum_t a'_{t,i} d_t f_t + \sum_c a'_{c,i} d_c f_c + \sum_g a_{g,i} d_g f_g \qquad (6)$$

where f_t, f_c and f_g are the dimensionless zonal bioclimatic correction factors for trees, crops and CLC/GLC2000 vegetation classes, respectively. European foliar biomass density distributions calculated from Eq. (6) for agriculture, forest, other land use and total land use are shown in Fig. A1 in the Electronic Supplement (see http://www.biogeosciences.net/6/1059/2009/bg-6-1059-2009-supplement.pdf).

To consider different growth conditions for the same tree species within Pan-Europe, e.g. in the Boreal zone compared to growth conditions in Central Europe, the foliar biomass densities were scaled 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. Zonal bioclimatic correction factors were defined for 10 European vegetation zones using the *Indicative Map of European Biogeographical Regions* developed by the European Environment Agency (2007): Alpine, Boreal, Atlantic, Continental, Steppic, Pannonian, Anatolian, Mediterranean, Black Sea and Africa-Arabia. The Africa-Arabia zone extends over Northern Africa, Western Arabia and the biogeographic region Macaronesia (Canary Islands, Madeira and Azores Islands).

The Continental vegetation zone is used as a reference zone to define bioclimatic correction factors for trees (f_t), crops (f_c), and CLC/GLC2000 vegetation classes (f_g). Table 1 lists bioclimatic correction factors for main tree species and Table 2 for crop species in each vegetation zone.

To derive the biomass correction of a vegetation zone of interest, tree foliar biomass data and agricultural biomass data for both the selected vegetation zone and the Continental vegetation zone is needed. Tree and forest foliar biomass data was derived from litterfall and foliar net primary productivity (NPP) data and crop and agriculture biomass data was derived from national crop yield information. The zonal bioclimatic factor for a tree species is defined as the ratio of the average foliar biomass of this tree species in the selected vegetation zone to its average foliar biomass in the Continental zone. The zonal bioclimatic factor for a crop species is defined as the ratio of the harvested yield of this crop in the selected vegetation zone to its crop yield in the Continental zone. The extraction of the necessary tree foliar biomass data and crop yield data from available databases is described in the following.

Litterfall data and foliar NPP are used as indicators for growth conditions for the main 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://forest.jrc.ec.europa.eu/; http://www.icp-forests.org/), (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.ec.europa.eu/index.php/login). Annual dry foliar biomass in 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. We note that the conversion factor from dry biomass to carbon may vary depending on the actual C/N ratio (Holland et al., 2005) but due to incomplete datasets a factor of 2 was generally used for the conversion. 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*. Zonal bioclimatic correction factors for tree species and forests are given in Table 1.

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

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.

the Pan-European domain defined in this work. FAOSTAT is the most widely recognized standard for national level agricultural statistics. National yields (yearly average of 2000–2005) of crop species given in the *Agricultural Land Use Map* were retrieved from FAOSTAT. The national crop yields were allocated to the vegetation zone to which main parts of the respective country belong geographically (see explanations in Table 2). 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.

The Foliar biomass density d_t for several tree species was derived from the four forest biomass databases (DAAC, ICP, global database by Luyssaert et al. (2007), and AFOLU). This was done for tree species with more than 10 data records within the Continental vegetation zone. Based on 34 records a value of $350 \pm 108 \, \text{g m}^{-2}$ was obtained for *Fagus sylvatica* which is at the higher end of the range ($310 \pm 47 \, \text{g m}^{-2}$) given by Veldt (1991). For European oaks (*Quercus robur* and *Quercus petraea*) a value of $290 \pm 74 \, \text{g m}^{-2}$ was derived, which is lower than the mean value of $330 \pm 90 \, \text{g m}^{-2}$) from Veldt (1991) but well within the range of uncertainty. Our values for *Betula spp.*, *Pinus sylv.* and *Picea abies*, $230 \pm 185 \, \text{g m}^{-2}$, $690 \pm 240 \, \text{g m}^{-2}$, and $1340 \pm 700 \, \text{g m}^{-2}$, 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*

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 [h]	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 perman. 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
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 perm. 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. 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 allocated to 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.
[h] We note that high values ($f_c > 1$) for olive groves, rice, soya and dry pulses in the Alpine zone are a result of defining certain countries as alpine though only parts of the country belong to the Alpine zone. The high values have no effect on the calculation of the emissions since the mentioned crops are not cultivated in the Alpine zone.

and *Quercus coccifera*. They were found to be $510\,\mathrm{g\,m^{-2}}$ and $520\,\mathrm{g\,m^{-2}}$, respectively, and thus well in agreement with the default value for evergreen broadleaved trees given by Veldt (1989).

Foliar biomass density values of trees, d_t, and of crops, d_c, for use with Eq. (6) are listed in Table 3 and 4. Most values in Table 3 and 4 are representative for growing conditions in the temperate and humid part of Europe, which is in our work referred to as the Continental zone. To determine D_i, foliar biomass densities of main tree and all crop species and classes were corrected with the bioclimatic factor for different climatic regions. 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 Geron et al. (1994) taken from the GloBEIS database. For several tree species, foliar biomass densities have been derived from litterfall data within the frame of this work. For crop species, default values for foliar biomass densities given in the EMEP/CORINAIR (1999) manual and from Simpson et al. (1999) were taken. The plant composition of CLC/GLC2000 vegetation classes was extracted from the CLC/GLC2000 documentation. The plant composition (see Table 5) was used to derive foliar biomass densities for the respective CLC/GLC2000 class by weighting 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 foliar biomass densities for general land use classes, compared to the application of default values for general land use classes.

2.3 BVOC standard emission factors

The aggregation of the standard emission potential $\epsilon_{b,i}$ of a BVOC class b in a grid cell follows the procedure for the foliar densities; it is:

$$\epsilon_{b,i} = \sum_t a'_{t,i}\epsilon_{b,t,i} + \sum_c a'_{c,i}\epsilon_{b,c,i} + \sum_g a_{g,i}\epsilon_{b,g,i} \qquad (7)$$

where $\epsilon_{b,t,i}$, $\epsilon_{b,c,i}$ and $\epsilon_{b,g,i}$ are the BVOC standard emission potentials of a single tree species, crop species and CLC/GLC2000 vegetation class respectively. Data on emission potentials at standard conditions for tree and crops species and for the CLC/GLC2000 classes was adopted from the work of Steinbrecher et al. (2009), the NatAir project inventory. European standard emission potential distributions calculated from Eq. (7) for isoprene, monoterpenes (pool), monoterpenes (synthesis), and sesquiterpenes are shown in Fig. A2 (in the Electronic Supplement: http://www.biogeosciences.net/6/1059/2009/bg-6-1059-2009-supplement.pdf). A complete list of standard emission potentials for all BVOC classes of trees, $\epsilon_{b,t,i}$, and of crops, $\epsilon_{b,c,i}$ is given in Tables 3 and 4. Vegetation composition, foliar biomass densities and BVOC standard emission potentials for CLC/GLC2000 vegetation classes are compiled in Table 5.

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 referred to as pool emissions. Isoprene is never stored after its production by plants but rapidly lost by volatilisation and isoprene emissions are dependent on both temperature and light. 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 (Staudt and Seufert, 1995; Bertin et al., 1997; Moukhtar et al., 2005; Dindorf et al., 2006). This type of emissions is termed newly synthesized emissions.

Crop plants are considered to be low emitting species. However, grasslands and pastures have been found to emit quite substantial amounts of oxygenated VOC (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, 1999; Steinbrecher et al., 2009). Simpson et al. (1999) estimate a total of $1440\,\mathrm{Gg\,yr^{-1}}$ BVOC from agriculture crops, consisting mainly of oxygenated VOC emissions ($1350\,\mathrm{Gg\,yr^{-1}}$). 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). Available emission data for oxygenated VOC (OVOC) are scarce and only rough estimations on oxygenated VOC emissions exist (e.g. Seco et al., 2007, and references therein) and there are only a few studies with chemical speciation of OVOCs. The OVOC class includes all oxygenated compounds with C1–C12, like alcohols, ketones, aldehydes, etc., which are volatile. A large fraction of oxygenated VOC (often abbreviated as oxyVOC) is composed of short-chained VOC, like methanol, ethanol, formaldehyde, acetaldehyde, acetone, formic acid, and acetic acid. In this work, the standard emission potentials for OVOC were adopted from the NatAir study (Steinbrecher et al., 2009). For most plant species and land use classes a default value of $2.0\,\mu\mathrm{g\,g_{DW}^{-1}\,h^{-1}}$ is applied.

Information on plant-specific emission factors for sesquiterpenes in Europe has been compiled in the recent review of Duhl et al. (2007). Duhl et al. (2007) state that values of early sesquiterpene (SQT) emission studies were very likely positively biased by disturbance-induced emission bursts, elevated enclosure temperatures and disturbances during sample collection. In the Duhl et al. (2007) review, average values of SQT standard emission potentials for coniferous trees, broadleaf trees, shrubs and crops are presented but these authors note that the high standard deviations associated with each class preclude using these data to assign emission factors to individual plant functional types since there is no significant difference between these average values. The respective average and standard

Table 3. Foliar biomass densities in g dry mass m^{-2} and standard emission potentials (in μg g$_{DW}^{-1}$ hr^{-1} at 30°C leaf temperature and 1000 μmol m^{-2} s^{-1} PPFD) of isoprene, monoterpenes, oxygenated VOC (OVOC) and sesquiterpenes for tree species. MT$_{synt}$ are monoterpenes emitted with temperature and light dependence and MT$_{pool}$ are only temperature dependent. Standard emission potentials are adopted from the NatAir inventory (Steinbrecher et al., 2009). The default standard emission potential for OVOC is 2.0 μg g$_{DW}^{-1}$ hr^{-1} and the default standard emission potential for sesquiterpenes is 0.1 μg g$_{DW}^{-1}$ hr^{-1}. A. f. is the percentage area of each tree species to the total forest area of the *Tree Species Map*, taken from Lenz et al. (2002). Seasonality type: eve=broadleaf/coniferous evergreen, dec=broadleaf/coniferous deciduous.

Species	*d* (gm^{-2})	Stand. emission potential (μg g$_{DW}^{-1}$ hr^{-1})					Seas. type	A. f. (%)	Ref. *d*
		ISOP	MT$_{synt}$	MT$_{pool}$	OVOC	SQT			
Abies alba	1260	1.0	0.5	1.0	2.0	0.1	eve	1.505	AAK95
Abies borisii-regis	1260	18.4	2.5	0.2	2.0	0.1	eve	0.149	*Abies alba*
Abies cephalonica	1260	0.0	0.3	0.6	2.0	0.1	eve	0.223	*Abies alba*
Abies grandis	1260	0.0	0.3	0.6	2.0	0.1	eve	0.003	*Abies alba*
Acer campestre	320	0.0	1.5	0.0	2.0	0.1	dec	0.046	CO99,[1]
Acer monspessulanum	320	0.0	1.5	0.0	2.0	0.1	dec	0.020	CO99,[1]
Acer opalus	320	0.1	1.5	0.0	2.0	0.1	dec	0.044	CO99,[1]
Acer platanoides	320	0.1	1.5	0.0	2.0	0.1	dec	0.337	CO99,[1]
Acer sp.	320	0.1	1.5	0.0	2.0	0.1	dec	0.122	CO99,[1]
Alnus cordata	320	0.0	1.5	0.0	2.0	0.1	dec	0.072	CO99,[2]
Alnus glutinosa	320	0.0	1.5	0.0	2.0	0.1	dec	0.346	CO99,[2]
Alnus incana	320	0.0	1.5	0.0	2.0	0.1	dec	0.188	CO99,[2]
Alnus viridis	320	0.0	1.5	0.0	2.0	0.1	dec	0.004	CO99,[2]
Arbutus andrachne	300	0.0	0.0	0.0	2.0	0.1	dec	0.009	VE89,[1]
Arbutus unedo	300	0.1	0.0	0.1	2.0	0.1	dec	0.042	VE89,[1]
Betula pendula	240	0.0	0.0	3.0	2.0	2.0	dec	2.321	This work
Betula pubescens	240	0.0	0.0	3.0	2.0	2.0	dec	4.661	This work
Buxus sempervirens	980	10.0	0.0	0.2	2.0	0.1	eve	0.025	OW01
Carpinus betulus	320	0.0	0.0	0.1	2.0	0.1	dec	0.970	CO99,[3]
Carpinus orientalis	320	0.0	0.0	0.0	2.0	0.1	dec	0.012	CO99,[3]
Castanea sativa	380	0.0	10.0	0.0	2.0	0.1	dec	1.077	VE89
Cedrus atlantica	700	0.0	0.0	1.0	2.0	0.1	eve	0.024	CO99,[4]
Cedrus deodara	700	0.0	0.0	1.0	2.0	0.1	eve	0.003	CO99,[4]
Cercis siliquastrum	300	0.0	0.0	0.0	2.0	0.1	dec	0.011	VE89,[1]
Ceratonia siliqua	300	0.0	0.0	0.0	2.0	0.1	eve	0.003	VE89,[1]
Corylus avellana	300	0.0	0.0	0.0	2.0	0.1	dec	0.010	VE89,[1]
Cupressus sempervirens	700	0.0	0.0	0.7	2.0	0.1	eve	0.030	CO99
Erica arborea	96	13.0	0.0	0.0	2.0	0.1	eve	0.011	OW01
Erica multiflora	150	0.0	0.0	0.0	2.0	0.1	eve	<0.001	OW01
Erica scoparia	150	0.0	0.0	0.0	2.0	0.1	eve	<0.001	OW01
Eucalyptus sp.	400	50.0	0.0	5.4	2.0	0.1	eve	0.847	CO99
Fagus moesiaca	320	0.0	0.0	0.0	2.0	0.1	dec	0.148	CO99,[5]
Fagus orientalis	320	0.0	0.0	0.0	2.0	0.1	dec	0.015	CO99,[5]
Fagus sylvatica	350	0.0	21.1	0.0	2.0	0.1	dec	7.107	This work
Fraxinus angustifolia	320	0.0	0.0	0.0	2.0	0.1	dec	0.049	CO99,[6]
Fraxinus excelsior	320	0.0	0.0	0.0	2.0	0.1	dec	0.596	CO99,[6]
Fraxinus ornus	320	0.0	0.0	0.0	2.0	0.1	dec	0.091	CO99,[6]
Ilex aquifolium	375	0.0	0.0	0.0	2.0	0.1	eve	0.006	GE94
Juglans nigra	320	0.0	0.0	1.0	2.0	0.1	dec	0.001	CO99
Juglans regia	300	0.0	0.0	1.0	2.0	0.1	dec	0.003	VE89
Juniperus communis	700	0.0	0.3	0.6	2.0	0.1	eve	0.025	CO99,[7]
Juniperus oxycedrus	700	0.0	0.0	1.5	2.0	0.1	eve	0.038	CO99,[7]
Juniperus phoenicea	700	0.0	0.0	1.5	2.0	0.1	eve	0.015	CO99,[7]
Juniperus thurifera	700	0.0	0.0	0.0	2.0	0.1	eve	0.147	CO99,[7]
Larix decidua	300	0.0	0.0	5.0	2.0	0.1	dec	0.808	VE89,[2]

Table 3. Continued.

Species	d (gm^{-2})	Stand. emission potential (μg g$_{DW}^{-1}$ hr^{-1}) ISOP	MT$_{synt}$	MT$_{pool}$	OVOC	SQT	Seas. type	A. f. (%)	Ref. d
Larix kaempferi	300	0.0	0.0	5.0	2.0	0.1	dec	0.065	VE89,[2]
Laurus nobilis	500	0.0	0.0	0.0	2.0	0.1	eve	<0.001	VE89,[3]
Malus domestica	375	0.0	0.0	0.0	2.0	0.1	dec	0.002	GE94
Olea europaea	200	0.0	0.0	0.1	2.0	0.1	eve	0.041	CO99
Ostrya carpinifolia	320	0.0	0.0	0.0	2.0	0.1	dec	0.288	CO99,[3]
Phillyrea latifolia	300	0.0	0.0	0.5	2.0	0.1	eve	0.028	VE89,[1]
Picea abies	1340	1.0	2.1	0.4	2.0	0.1	eve	21.36	This work
Picea sitchensis	1400	4.8	0.0	6.5	2.0	0.1	eve	0.776	VE89
Pinus brutia	700	0.0	0.0	2.0	2.0	0.1	eve	0.040	VE89,[4]
Pinus canariensis	700	0.0	0.0	6.0	2.0	0.1	eve	0.062	VE89,[4]
Pinus cembra	700	0.0	0.0	2.5	2.0	0.1	eve	0.020	VE89,[4]
Pinus contorta	700	0.0	0.0	6.0	2.0	0.1	eve	0.198	VE89,[4]
Pinus halepensis	700	0.0	0.0	2.7	2.0	0.1	eve	1.296	VE89,[4]
Pinus leucodermis	700	0.0	0.0	6.0	2.0	0.1	eve	0.008	VE89,[4]
Pinus mugo	700	0.0	0.0	6.0	2.0	0.1	eve	0.002	VE89,[4]
Pinus nigra	700	0.0	3.0	3.0	2.0	0.1	eve	1.735	VE89,[4]
Pinus pinaster	700	0.0	0.0	2.0	2.0	0.1	eve	2.532	VE89,[4]
Pinus pinea	700	0.0	3.0	3.0	1.8	0.1	eve	0.233	VE89,[4]
Pinus radiata	700	0.0	3.0	3.0	2.0	0.1	eve	0.136	VE89,[4]
Pinus strobus	700	0.0	2.5	2.5	2.0	0.1	eve	0.031	VE89,[4]
Pinus sylvestris	690	0.1	2.5	2.5	2.0	0.1	eve	31.15	This work
Pinus uncinata	700	0.1	2.5	2.5	2.0	0.1	eve	0.056	VE89,[4]
Pistacia lentiscus	1014	0.0	0.0	0.6	2.0	0.1	eve	0.001	OW01
Pistacia terebinthus	230	0.0	0.0	0.1	2.0	0.1	eve	0.014	OW01
Platanus orientalis	320	18.5	0.0	0.1	2.0	0.1	dec	0.068	CO99
Populus alba	320	60.0	0.0	0.0	2.0	0.1	dec	0.031	CO99,[8]
Populus canescens	320	70.0	0.0	0.0	3.5	0.1	dec	0.060	CO99,[8]
Populus hybrides	320	70.0	0.0	0.0	2.0	0.1	dec	0.179	CO99,[8]
Populus nigra	320	70.0	0.0	0.0	2.0	0.1	dec	0.044	CO99,[8]
Populus tremula	320	60.0	0.0	0.0	2.0	0.1	dec	0.598	CO99,[8]
Prunus avium	300	0.0	0.0	0.1	2.0	0.1	dec	0.151	CO99,[9]
Prunus padus	300	0.0	0.0	0.1	2.0	0.1	dec	0.001	CO99,[9]
Prunus serotina	300	0.0	0.0	0.1	2.0	0.1	dec	0.005	CO99,[9]
Pseudotsuga menziesii	1000	1.0	0.0	2.0	2.0	0.1	eve	0.420	CO99
Pyrus communis	300	0.0	0.0	0.0	2.0	0.1	dec	0.005	VE89,[1]
Quercus cerris	320	0.1	0.0	0.6	2.0	0.1	dec	1.037	VE89,[5]
Quercus coccifera	520	0.1	25.0	0.0	2.0	0.1	eve	0.225	This work
Quercus faginea	320	111.0	0.0	0.0	2.0	0.1	dec	0.228	VE89,[5]
Quercus frainetto	320	85.0	0.0	0.0	2.0	0.1	dec	0.517	VE89,[5]
Quercus fructosa	320	0.1	20.0	0.0	2.0	0.1	eve	0.048	VE89,[5]
Quercus ilex	510	0.1	43.0	0.0	2.0	0.1	eve	2.177	This work
Quercus macrolepsis	320	0.2	0.0	0.7	2.0	0.1	dec	0.019	VE89,[5]
Quercus petraea	290	45.0	0.0	0.3	2.0	0.1	dec	2.309	This work
Quercus pubescens	320	70.0	0.0	0.3	2.0	0.1	dec	1.488	VE89,[5]
Quercus pyrenaica	320	59.0	0.0	0.3	2.0	0.1	dec	0.618	VE89,[5]
Quercus robur	290	70.0	0.0	1.0	2.0	0.1	dec	2.930	This work
Quercus rotundifolia	500	0.2	14.6	0.0	2.0	0.1	eve	0.201	VE89,[3]
Quercus rubra	320	35.0	0.0	0.1	2.0	0.1	dec	0.132	VE89,[5]
Quercus suber	500	0.2	20.0	0.0	2.0	0.1	eve	0.835	VE89,[3]
Quercus trojana	320	0.2	0.0	0.2	2.0	0.1	eve	0.041	VE89,[5]

Table 3. Continued.

Species	d (gm^{-2})	Stand. emission potential (μg g$_{DW}^{-1}$ hr^{-1})					Seas. type	A. f. (%)	Ref. d
		ISOP	MT$_{synt}$	MT$_{pool}$	OVOC	SQT			
Robinia pseudoacacia	320	12.0	0.0	0.1	2.0	0.1	dec	0.464	CO99
Salix alba	150	37.2	0.0	1.1	2.0	0.1	dec	0.003	CO99,[10]
Salix caprea	150	18.9	0.0	0.1	2.0	0.1	dec	0.037	CO99,[10]
Salix cinerea	150	28.0	0.0	0.8	2.0	0.1	dec	0.001	CO99,[10]
Salix eleagnos	150	28.0	0.0	0.8	2.0	0.1	dec	0.001	CO99,[10]
Salix sp.	150	28.0	0.0	0.8	2.0	0.1	dec	0.024	CO99,[10]
Sorbus aria	300	0.0	0.0	0.0	2.0	0.1	dec	0.036	VE89,[1]
Sorbus aucuparia	300	0.0	0.0	0.0	2.0	0.1	dec	0.046	VE89,[1]
Sorbus domestica	300	0.0	0.0	0.0	2.0	0.1	dec	0.010	VE89,[1]
Sorbus torminalis	300	0.0	0.0	0.0	2.0	0.1	dec	0.016	VE89,[1]
Thuya sp.	1500	0.0	0.0	0.6	2.0	0.1	eve	0.003	GE94
Tilia cordata	320	0.0	0.0	0.0	2.0	0.1	dec	0.211	CO99,[11]
Tilia platyphyllos	320	0.0	0.0	0.0	2.0	0.1	dec	0.044	CO99,[11]
Tsuga sp.	700	0.1	0.0	0.2	2.0	0.1	eve	0.020	GE94
Ulmus glabra	320	0.1	0.0	0.1	2.0	0.1	dec	0.030	CO99,[12]
Ulmus laevis	320	0.1	0.0	0.1	2.0	0.1	dec	0.006	CO99,[12]
Ulmus minor	320	0.1	0.0	0.1	2.0	0.1	dec	0.012	CO99,[12]

References: AAK95 Andreani-Aksoyoglu and Keller (1995); VE89 Veldt (1989), value for: [1] default deciduous broadleaved, [2] *Larix* default, [3] default evergreen broadleaved, [4] other *Pinus spp.*, [5] deciduous oaks; CO99 EMEP/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* ; OW01 Owen et al. (2001); GE94 Geron et al. (1994).

deviation values are 0.29 ± 0.41, 1.41 ± 2.20, 7.06 ± 6.83 and 0.19 ± 0.43 μg g$_{DW}^{-1}$ h^{-1}. The high standard deviations associated with these numbers allow for the lower default value of 0.1 μg g$_{DW}^{-1}$ h^{-1} that was chosen in this work. We applied the default standard emission potential for all tree species, with the exception of birch. For *Betula pendula* and *Betula pubescens* experimental data showed elevated emission potentials (König et al., 1995; Hakola et al., 2001; Vuorinen et al., 2005).

2.4 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 originate from the storage pools of the leaves and/or are newly synthesized 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.

2.4.1 Temperature-dependent emissions

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:

$$\gamma_{CE,i}(\text{pool}) = \gamma_{\text{pool}} \cdot \gamma_{\text{seas}} \tag{8}$$

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

$$\gamma_{\text{pool}} = \exp(\beta(T - T_S)) \tag{9}$$

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). The calculation of γ_{seas} is explained in Sect. 2.4.3.

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

Table 4. Foliar biomass densities in g dry mass m^{-2} and standard emission potentials (in μg g$_{DW}^{-1}$ hr^{-1} at 30°C leaf temperature and 1000 μmol m^{-2} s^{-1} PPFD) of isoprene, monoterpenes, OVOC and sesquiterpenes for crop species. MT synt are monoterpenes emitted with temperature and light dependence and MT pool are only temperature dependent. Standard emission potentials are adopted from the NatAir inventory (Steinbrecher et al., 2009). The default standard emission potential for OVOC is 2.0 μg g$_{DW}^{-1}$ hr^{-1} and the default standard emission potential for sesquiterpenes is 0.1 μg g$_{DW}^{-1}$ hr^{-1}.

| Species | d (g m^{-2}) | Stand. emission potential (μg g$_{DW}^{-1}$ hr^{-1}) | | | | | Seas. [a] type | Ref. d |
		ISOP	MT$_{synt}$	MT$_{pool}$	OVOC	SQT		
Barley	1290	0.0	0.5	0.5	2.0	0.1	barl	CO99
Citrus fruits	500	0.0	0.5	0.5	2.0	0.1	eve	CO99b
Durum Wheat	800	0.5	0.5	0.5	2.0	0.1	swhe	CO99
Floriculture	1000	0.0	0.5	0.5	2.0	0.1	non	SI99[c]
Permanent gras and grazing	400	0.5	0.5	0.5	2.0	0.1	eve	CO99[d]
Fallow land	400	0.5	0.5	0.5	2.0	0.1	eve	CO99[d]
Fruit tree and berry plantations	251	0.5	0.5	0.5	2.0	0.1	dec	[e]
Maize	1610	0.0	0.5	0.5	2.0	0.1	maiz	CO99
Olive groves	200	0.0	0.5	0.5	2.0	0.1	eve	CO99
Rape and turnip rape	400	0.0	0.5	0.5	2.0	0.1	rape	CO99
Fibre and oleaginous crops	400	0.0	0.5	0.5	2.0	0.1	sunf	CO99
Vineyards	410	0.0	0.5	0.5	2.0	0.1	maiz	CO99
Nurseries	660	0.5	0.5	0.5	2.0	0.1	non	[f]
Oats	750	0.5	0.5	0.5	2.0	0.1	barl	CO99
Other cereals	1335	0.5	0.5	0.5	2.0	0.1	swhe	CO99[g]
Other crops	1335	0.5	0.5	0.5	2.0	0.1	swhe	CO99[g]
Fodder other on arable land	400	0.5	0.5	0.5	2.0	0.1	maiz	CO99[d]
Non permanent industrial crops	1335	0.5	0.5	0.5	2.0	0.1	sunf	CO99[g]
Tomatoes and other vegetables	1000	0.0	0.5	0.5	2.0	0.1	non	SI99[c]
Rice	1050	0.0	0.5	0.5	2.0	0.1	maiz	CO99
Potatoes	1000	0.0	0.5	0.5	2.0	0.1	pota	SI99[c]
Dry pulses	1000	0.0	0.5	0.5	2.0	0.1	rape	SI99[c]
Other root crops	1000	0.0	0.5	0.5	2.0	0.1	roof	SI99[c]
Rye	400	0.0	0.5	0.5	2.0	0.1	swhe	CO99
Soya	740	0.0	0.5	0.5	2.0	0.1	sunf	CO99
Sugar beet	1000	0.0	0.5	0.5	2.0	0.1	roof	SI99[c]
Sunflower	1000	0.0	0.5	0.5	2.0	0.1	sunf	SI99[c]
Common wheat	800	0.5	0.5	0.5	2.0	0.1	swhe	CO99
Tobacco	490	0.0	0.5	0.5	2.0	0.1	sunf	CO99

[a] Seasonality types: eve=broadleaf/coniferous evergreen, dec=broadleaf/coniferous deciduous, non=no seasonality, barl=spring and winter barley, maiz=fodder and grain maize, swhe=spring and winter wheat, pota=potato, roof=sugar beet, sunf=sunflower, rape=spring and winter rape.
[b] Evergreen trees default.
[c] Crops default.
[d] Grassland default.
[e] Mean of *Arbutus unedo*, *Vaccinum*, *Malus domestica*, *Pyrus communis*.
[f] same as Mixed Forest class of CLC2000.
[g] Miscellaneous crops default.
References: CO99 EMEP/CORINAIR (1999); SI99 Simpson et al. (1999).

cuvettes that were similarly high as when the cuvette received light. For this study the empirical coefficient β in Eq. (9) 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.

2.4.2 Temperature- and light-dependent emissions

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 prominent example being European beech

Table 5. Vegetation composition, Standard emission potential and foliar biomass densities for each CLC and GLC vegetation class[a]. Foliar biomass density values for agriculture CLC classes are derived from individual crop species as specified in the plant composition list, and taken from Table 4. Standard emission potentials are adopted from the NatAir inventory (Steinbrecher et al., 2009). The plant composition of most GLC vegetation class was extracted from the CLC/GLC2000 documentation or adopted from the corresponding CLC vegetation class. For some GLC classes (e.g. *Broadleaved Deciduous Forest* in Northern Europe) the plant composition is derived from regions where more details on the vegetation composition were available.

ID	CLC/GLC2000 Vegetation class	d (g m^{-2})	ISOP	MT$_{synt}$	MT$_{pool}$	OVOC	SQT	Seas.[b] type	Plant Composition[c]
10	Green Urban Areas	400	2.0	1.0	1.0	2.0	0.1	dec	grassland
12	Non-Irrigated Arable Land	800	0.5	0.5	0.5	2.0	0.1	barl	Durum Wheat
13	Permanently Irrigated Land	1000	0.5	0.5	0.5	2.0	0.1	maiz	50% Tomatoes, 50% Sugar beet
14	Rice fields	1050	0.0	0.5	0.1	2.0	0.1	maiz	Rice
15	Vineyards	410	0.0	0.5	0.1	2.0	0.1	maiz	Vineyards
16	Fruit trees and berry plantations	250	0.5	0.5	0.5	2.0	0.1	dec	Fruit tree and berry plantations
17	Olive groves	200	0.0	0.5	0.5	2.0	0.1	eve	Olive groves
18	Pastures	400	0.5	0.5	0.5	2.0	0.1	dec	Fodder other on arable land
19	Annual Crops w. perm. crops	1340	0.5	0.5	0.5	2.0	0.1	dec	Non permanent industrial crops
20	Complex Cultivation Patterns	330	0.5	0.5	0.5	2.0	0.1	dec	50% Dry Pulses, 50% Rye
21	Agriculture, with natural Veg.	600	0.5	0.5	0.5	2.0	0.1	dec	50% Non perm. ind. crops, 50% Rye
22	Agro-Forestry Areas	840	1.0	1.0	1.0	2.0	0.1	dec	25% Citrus, 25% Olive, 50% LC 19
23	Broad-Leaved Forest	360	15.0	5.0	0.5	2.0	0.1	dec	[d]
24	Coniferous Forest	950	3.0	2.5	2.5	2.0	0.1	eve	[e]
25	Mixed Forest	660	10.0	2.0	2.0	2.0	0.1	mix	50% LC 23, 50% LC 24
26	Natural Grassland	420	0.5	0.5	0.5	2.0	0.1	eve	grassland
27	Moors and Heathland	350	10.0	1.0	1.0	2.0	0.1	eve	moorland/heathland
28	Sclerophyllous Vegetation	340	5.0	15.0	15.0	2.0	0.1	eve	[f]
29	Transitional Woodland-Shrub	400	5.0	5.0	5.0	2.0	0.1	eve	[g]
32	Sparsely Vegetated Areas	140	0.5	0.5	0.5	2.0	0.1	eve	30% LC 10, 50% no veg.
35	Inland Marshes	200	10.0	1.0	1.0	2.0	0.1	eve	marshes
36	Peatbogs	330	10.0	1.0	1.0	2.0	0.1	eve	[h], 50% cover
37	Salt-Marshes	200	10.0	1.0	1.0	2.0	0.1	eve	marshes
100	Broadleaved Evergreen Forest	360	10.0	10.0	0.5	2.0	0.1	eve	as LC 23
101a	Broadleaved Deciduous Forest	280	30.0	0.5	0.5	2.0	0.1	dec	[i]
101b	Broadleaved Deciduous Forest	340	30.0	0.5	0.5	2.0	0.5	dec	[j]
101c	Broadleaved Deciduous Forest	250	30.0	0.5	0.5	2.0	0.1	dec	as LC 23, 70% cover
102a	Needleleaved Evergreen Forest	650	3.0	2.5	2.5	2.0	0.1	eve	[k], 80% cover
102b	Needleleaved Evergreen Forest	950	1.0	2.5	2.5	2.0	0.1	eve	as LC 24
102c	Needleleaved Evergreen Forest	700	1.0	2.5	2.5	2.0	0.1	eve	[l]
103	Needleleaved Deciduous Forest	300	0.5	0.0	8.0	2.0	0.1	dec	*Larix decidua*
104a	Mixed Forest	460	10.0	3.0	3.0	2.0	0.1	mix	50% LC 101a, 50% LC 102a
104b	Mixed Forest	660	7.0	5.0	3.0	2.0	0.1	mix	as LC 25
104c	Mixed Forest	530	7.0	5.0	3.0	2.0	0.1	mix	as LC 25, 80% cover
105a	Forest, Shrub/Grassland Mos.	100	10.0	1.0	1.0	2.0	0.1	mix	as LC 27, 30% cover
105b	Forest, Shrub/Grassland Mos.	410	5.0	1.0	1.0	2.0	0.1	mix	70% LC 29, 30% LC 26
105c	Forest, Shrub/Grassland Mos.	410	5.0	1.0	1.0	2.0	0.1	mix	70% LC 29, 30% LC 26
107	Evergreen Shrubland	370	3.0	2.5	2.5	2.0	0.1	eve	50% LC 28, 50% LC 29
108a	Deciduous Shrubland	330	3.0	2.5	2.5	2.0	0.1	dec	50% LC 101b, 50% LC 107
108b	Deciduous Shrubland	230	5.0	1.0	1.0	2.0	0.1	dec	[m]
108c	Deciduous Shrubland	260	5.0	1.0	1.0	2.0	0.1	dec	[n]
109	Grassland	210	0.5	0.5	0.5	2.0	0.1	eve	50% LC 26+50% LC 36
110a	Sparse Grassland	100	0.5	0.5	0.5	2.0	0.1	eve	LC 109, 50% cover
110b	Sparse Grassland	210	0.5	0.5	0.5	2.0	0.1	eve	LC 109
110c	Sparse Grassland	10	0.5	0.5	0.5	2.0	0.1	eve	LC 109, 5% cover
111a	Wetland unspecified	330	10.0	1.0	1.0	2.0	0.1	eve	LC 36
111b	Wetland unspecified	330	10.0	0.5	0.5	2.0	0.1	eve	LC 36
111c	Wetland unspecified	380	10.0	0.5	0.5	2.0	0.1	eve	50% LC 36, 50% LC 26
112a	Non Irrigated Cropland	800	0.5	0.5	0.5	2.0	0.1	dec	LC 12
112b	Non Irrigated Cropland	600	0.5	0.5	0.5	2.0	0.1	dec	50% LC 12, 50% LC 18
112c	Non Irrigated Cropland	520	0.5	0.5	0.5	2.0	0.1	dec	30% LC 12, 70% LC 18
113	Irrigated Cropland	1000	0.5	0.5	0.5	1.0	0.1	dec	LC 13
114	Tree Crops	200	0.0	0.0	0.0	2.0	0.1	eve	Date Palm

Table 5. Continued.

ID	CLC/GLC2000 Vegetation class	d ($\mathrm{g\,m^{-2}}$)	\multicolumn{5}{c}{Stand. emission potential ($\mu\mathrm{g\,g_{DW}^{-1}\,hr^{-1}}$)}	Seas.[b] type	Plant Composition[c]
			ISOP	MT$_{\mathrm{synt}}$	MT$_{\mathrm{pool}}$	OVOC	SQT		
117a	Cropland/Forest/Shrubland/Grass Mos.	550	1.0	1.0	1.0	2.0	0.1	eve	o
117b	Cropland/Forest/Shrubland/Grass Mos.	600	5.0	0.5	0.5	2.0	0.1	eve	p
117c	Cropland/Forest/Shrubland/Grass Mos.	370	5.0	0.5	0.5	2.0	0.1	eve	20% LC 12, 80% LC 108
125	Cropland unspecified	600	0.5	0.5	0.5	2.0	0.1	dec	30% LC 14, 70% LC 18
127	Wetland - Bogs and Marshes	330	10.0	1.0	1.0	2.0	0.1	eve	LC 36
128	Wetland - Palsa Bogs	170	10.0	1.0	1.0	2.0	0.1	eve	LC 36, 50% cover
129	Wetland - Riparian Vegetation	300	10.0	1.0	1.0	2.0	0.1	eve	q
131	Tree Cover, regularly flooded	250	5.0	0.1	0.1	2.0	0.1	eve	African Swamp

[a] Vegetation class ID of CLC/GLC2000 landcover mosaic as indicated in Köble (2007). [b] Seasonality types: eve=broadleaf/coniferous evergreen, dec=broadleaf/coniferous deciduous, mix=50% evergreen, 50% deciduous, barl=spring and winter barley, maiz=fodder and grain maize. [c] LC is an abbreviation for CLC/GLC2000 land use class. [d] 15% *Fagus sylvatica*, 10% *Q. ilex*, 10% *Betula pubescens*, 10% *Q. robur*, 10% *Q. pubescens*, 10% *Q. petraea*, 20% Eucalyptus, 5% *Juglans regia*. [e] 40% *Pinus sylvestris*, 40% *Picea abies*, 20% *Pinus pinea*. [f] 25% *Q.ilex*, 25% *Q. coccifera*, 25% *Arbutus unedo*, 25% *Myrtus communis*. [g] 30% *Q.ilex*, 30% *Q. coccifera*, 30% *Arbutus unedo*, 10% *Myrtus communis*. [h] 10% *Arunda donax*, 10% *Vaccinum sp.*, 10% *Salix sp.*, 40% *Betula pendula*, 30% *Fraxinus angustifolia*. [i] 50% *Betula pubescens*, 30% *Populus tremula*, 10% *Alnus glutinosa*, 5% *Q. petrea*, 5% *Tilia cordata*. [j] 30% *Fagus sylvatica*, 20% *Betula pendula*, 10% *Q. robur*, 10% *Q. pubescens*, 10% *Q. petraea*, 10% *Q. suber*, 10% *Q. ilex*. [k] 30% *Picea abies*, 30% *Pinus sylvestris*, 10% *Abies alba*, 30% *Betula pubescens*. [l] 50% *Pinus pinea*, 50% *Pinus pinaster*. [m] 15% *Erica sp.*, 15% *Vaccinum sp.*, 40%. [n] 50% LC 101c, 10% *Ulex parviflorus*, 10% *Myrtus communis*, 10% *Lavandula sp*, 10% *Rosmarinus officinalis*, 10% *Nerium oleander*. LC 101b, 30% LC 36. [o] 30% LC 12, 30% LC 18, 20% *Pinus sylvestris*, 20% *Betula pubescens*. [p] 30% LC 12, 30% LC 18, 20% *Q. ilex*, 20% *Pinus pinea*. [q] 50% LC 36, 20% *Salix spp.*, 10% *Alnus cordata*, 10% *Betula pendula*, 10% *Populus alba*.

(*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 referred 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. The main reason for choosing a simplified setup of the MEGAN model is to be comparable with the previous algorithm by Guenther (1997) that describes only temperature and light-dependence of emissions. The use of temperature and light dependent isoprene emission algorithms is supported by a recent study of Boissard et al. (2008) who demonstrated that, based on 25 emitter species and using varying environmental conditions ($10°$ S to $60°$ N), isoprene emissions are mainly sensitive (76% of the overall variability) to instantaneous temperature and photosynthetic photon flux density and to the cumulated 3 weeks air temperature.

The MEGAN canopy environment emission activity factor is:

$$\gamma_{\mathrm{CE},i}(\mathrm{synt}) = C_{\mathrm{CE}} \cdot \gamma_{\mathrm{T}} \cdot \gamma_{\mathrm{P}} \cdot \mathrm{LAI} \tag{10}$$

For the canopy radiation model applied in this work, C_{CE} is set to 1.13 in order to obtain $\gamma_{\mathrm{CE},i}(\mathrm{synt})=1$ at standard conditions. The value for C_{CE} is about 2 times larger than given in Guenther et al. (2006), where $C_{\mathrm{CE}}=0.57$ is used. This is due to the simplified canopy environment model applied in our work (see Sect. 2.4.4).

The temperature dependence of MEGAN is expressed as:

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

with $x = (\frac{1}{T_{\mathrm{opt}}} - \frac{1}{T})/R$. R is the universal gas constant ($R=0.00831\,\mathrm{kJ\,K^{-1}\,mol^{-1}}$), 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 Eopt occurs. These coefficients are estimated as a function of the average air temperature over the past 24 h (T24) and 240 h (T240):

$$E_{\mathrm{opt}} = 2.034 \cdot \exp(0.05 \cdot [\mathrm{T24} - 297])$$
$$\cdot \exp(0.05 \cdot [\mathrm{T240} - 297])$$
$$T_{\mathrm{opt}} = 313 + (0.6 \cdot [\mathrm{T240} - 297]) \tag{12}$$

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:

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

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

$$\alpha_m = 0.004 - 0.0005 \cdot \ln(\text{P240})$$
$$C_p = 0.0468 \cdot \exp(0.0005 \cdot [\text{P24} - \text{P}_0])(\text{P240})^{0.6} \quad (14)$$

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

$$\gamma_{\text{CE},i}(\text{synt}) = \gamma_T \cdot \gamma_P \cdot \gamma_{\text{seas}} \quad (15)$$

with

$$\gamma_T = \frac{\exp([C_{\text{T1}}(T - T_S)]/RT_ST)}{C_{\text{T3}} + \exp([C_{\text{T2}}(T - T_M)]/RT_ST)} \quad (16)$$

$$\gamma_P = \frac{\alpha C_{\text{L1}} L}{\sqrt{1 + \alpha^2 L^2}} \quad (17)$$

Here L is PPFD (in μmol photons $\text{m}^{-2}\,\text{s}^{-1}$), 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 monoterpene emissions presented with Eqs. (15–17) is termed G97 in the following.

2.4.3 Seasonal variability of emissions

Seasonality of emissions (non-temperature and non-light) accounts for several characteristic observations:

1. Development stage of leaves on deciduous trees has an impact on their emission capacity. Emissions from deciduous vegetation are reduced or become negligible during winter dormancy and due to loss of leaves.

2. Emissions from agriculture are limited to the growing season. Exceptions are tomatoes and other fruits and vegetables that are cultivated in greenhouses.

3. Emissions from evergreen vegetation occur during the whole year and have a seasonal variation.

4. Snow coverage prevents emissions from all vegetation types. Though there might be emission from non-covered parts of a coniferous tree, it is assumed that these are close to zero and negligible.

Several vegetation types with different seasonality of emissions due to leaf phenology and growing season were defined: seven agriculture crop types with different growing seasons, deciduous vegetation type (broadleaf and coniferous trees, wetlands and other deciduous vegetation) and evergreen vegetation type (broadleaf and coniferous trees, grassland, pastures and other evergreen vegetation).

Seasonality of emissions is derived from the leaf coverage per unit ground area, expressed by the leaf area index (LAI), in combination with data on growing season for crops and leaf-on season for deciduous trees. MODIS-based LAI data provides information regarding the evolution and structure of seasonal vegetation characteristics (Zhang et al., 2004). MODIS LAI data with 1 km horizontal resolution is retrieved for the years 2004/2005 from Boston University (ftp://primavera.bu.edu/pub/datasets/MODIS/MOD15_BU/) and averaged over the model grid, i.e. the total LAI of a model grid cell corresponds to one MODIS derived LAI value. This LAI value is used to calculate the actual LAI of each vegetation type v (see below) and by scaling emissions with the vegetation type LAI the seasonal variability of emissions with respect to growing season length and development stages of leaves is simulated. A phenology correction factor p is introduced into the model with values between 0 and 1, with $p=0$ during no emission months and $p=1$ during full emission months.

Growing season dates (emergence, subsequent growth stages, harvest) for seven different crops, i.e. maize (fodder and grain maize), potato, rape seed (spring and winter), wheat, (spring and winter), sugar beet, sunflower and barley (spring and winter), have been obatined from Bouraoui and Aloe (2007). All other agriculture crops have been attributed to one of these seven crop phenology types (see Table 4). The crop growing season is defined by the time period between emergence and harvest. The harvest month was chosen as end date for emissions. Starting from the date of emergence, p is linearly increasing from 0 to 1, i.e. from growing seedlings to fully developed plants. The p of fully developed plants is set to 1, while after harvest p is 0. Monthly crop phenology data with a horizontal resolution of 50 km was used to derive an average p value for the seven crop types in each bioclimatic zone. Greenhouse tomatoes and plantation crops are treated as non-seasonal crops ($p=1$ all year).

Deciduous trees lose their leaves in winter. With the development of new leaves in spring, emissions are retarded. For deciduous and evergreen vegetation types, the seasonal variation of the phenology correction factor has the form of a bell shape with maximum in July, and can be calculated following Staudt et al. (2000):

$$p = 1 - \rho(1 - \exp[(M - M_0)/\tau]) \quad (18)$$

With M being the month of the calendar year, $M_0=7$ (July), ρ determines the relative amplitude, and τ is the length of the active emission period in months. For deciduous vegetation, ρ is set to 1, considering that emissions are zero during a dormancy period. The latitudinal separation of the growing season length is the same as in the NatAir inventory (Steinbrecher et al., 2009):

>65° N and in the arctic zone: τ=3; from 50–65° N: τ=5; between 40–50° N: τ=6; and in Southern Europe at latitude <40° N: τ=8.

For evergreen coniferous trees, evergreen broadleaf trees, other evergreen vegetation, and grassland (see Table 5), Eq. (18) is used with the parameters ρ=0.8 and τ=12 in all geographic zones.

The total LAI in a grid cell ($\text{LAI}_{\text{tot},i}$) is the sum of the LAI contributions of each vegetation type v (seven agriculture types, deciduous and evergreen), $\text{LAI}_{v,i}$. Total LAI by definition equals the MODIS LAI ($\text{LAI}_{\text{modis},i}$) in that cell:

$$\text{LAI}_{\text{tot},i} = \text{LAI}_{\text{modis},i} = \sum_v \text{LAI}_{v,i} \qquad (19)$$

LAI values for each vegetation phenology type LAI_v in a grid cell are calculated from the MODIS LAI of the cell considering the respective phenology correction p_v and area fraction a_v. For a grid cell that contains wheat (index crop), deciduous (index dec) and evergreen coniferous (index eve) trees, the respective LAI_{crop} of wheat would be:

$$\text{LAI}_{\text{crop}} = \frac{a_{\text{crop}} \cdot p_{\text{crop}} \cdot \text{LAI}_{\text{modis}}}{a_{\text{crop}} \cdot p_{\text{crop}} + a_{\text{dec}} \cdot p_{\text{dec}} + a_{\text{eve}} \cdot p_{\text{eve}}} \qquad (20)$$

LAI for all other vegetation types are calculated in analogy to Eq. (20). To illustrate the effectiveness of this approach, we consider a grid cell containing area fractions of 40% wheat, 40% deciduous trees, and 20% evergreen coniferous trees at 45° N. January: MODIS LAI is 0 indicating snow coverage; phenology correction is p_{crop}=0 and p_{dec}=0.37, and p_{eve}=0.69; then all vegetation type LAI are 0. March: MODIS LAI is 2; phenology correction is p_{crop} is 0.25 (emerging seedlings) and p_{dec} is 0.51, and p_{eve} is 0.77. Thus emissions from crop and deciduous trees are about to evolve while evergreen trees almost emit fully; then the calculated respective LAI are: LAI_{crop}=0.43, LAI_{dec}=0.89, and LAI_{eve}=0.67. July: MODIS LAI is 6, all vegetation types are emitting; all p values are 1 and the respective vegetation type LAI are LAI_{crop}=2.4, LAI_{dec}=2.4, and LAI_{eve}=1.2.

To calculate seasonal canopy emission activities $\gamma_{\text{CE},i}(\text{synt})$ for different vegetation types in the MEGAN model, the specific vegetation type LAI of the grid cell obtained from Eq. (20) are inserted into Eq. (10). In the G97 model the seasonality of emissions from each vegetation type is taken into account by using the seasonality factor γ_{seas} (see Eqs. 8 and 15) together with the specific vegetation type LAI:

$$\gamma_{\text{seas}} = \frac{0.49\text{LAI}_v}{\sqrt{1 + 0.2\text{LAI}_v^2}} \qquad (21)$$

This approach consequently leads to a scaling of the emission from a certain vegetation type during the months when the emissions are not at the full extent due to phenology of leaves. The seasonality factor ensures that there are zero emissions from deciduous trees in wintertime when leaves are not present. Emissions from agriculture occur only during the growing season. This approach also ensures that in case of a completely snow covered surface in a grid cell (i.e. monthly average $\text{LAI}_{\text{tot},i}$=0), emissions from all vegetation types are set to zero.

2.4.4 Setup of the canopy environment model

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 is 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 ($\gamma_{\text{CE},i}(\text{synt})$) with values close to unity at standard conditions for both the G97 and the MEGAN version. For G97, $\gamma_{\text{CE},i}(\text{synt})$ is 0.991 at standard conditions given in Guenther (1997) and for MEGAN $\gamma_{\text{CE},i}(\text{synt})$ 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 $\epsilon_{i,b}$, meteorological maps of 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.

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 0.089×0.089 degrees. Two years were selected in order to obtain a more reliable basis for studying seasonal changes, rather than to investigate inter-annual 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. 2.4 was applied to calculate emissions of monoterpenes, sesquiterpenes and OVOC according to the emission algorithms of Guenther (1997). Isoprene emissions
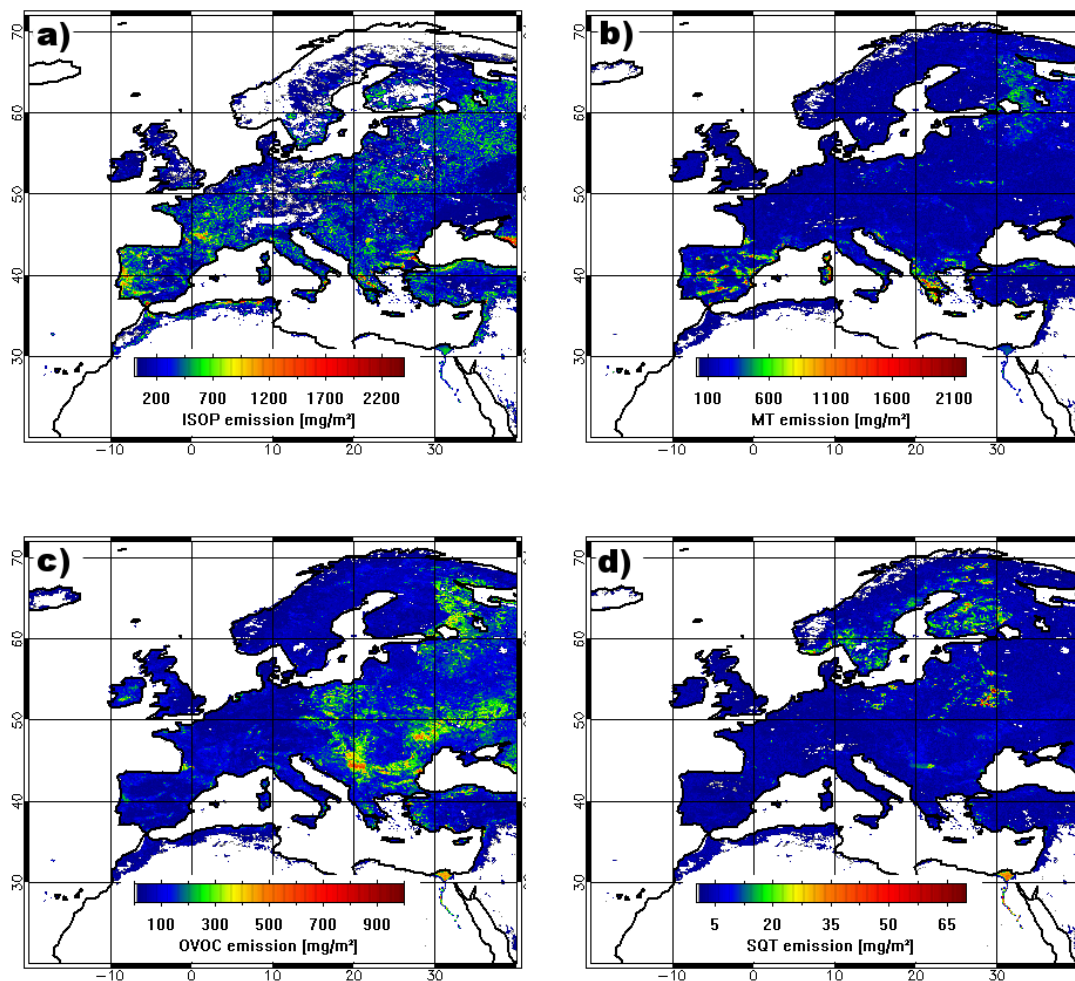
Fig. 2. European emission (in mg m^{-2}) distribution for July 2005 of: **(a)** isoprene, **(b)** monoterpenes, **(c)** OVOC, **(d)** sesquiterpenes. Isoprene emissions are calculated with MEGAN. The maximum differences for July 2005 between the isoprene emission distribution calculated with MEGAN and 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.

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 contributions to the emissions are investigated for four European countries. Results for these countries are compared with previous national inventories. Finally, we compare the total BVOC emission amounts obtained in our emission inventory to previous European emission estimates in Sect. 3.5.

3.1 European BVOC emissions

The average annual total BVOC emission obtained from the two years 2004 and 2005 for the Pan-European domain is 12 Tg. Calculated annual emissions from both years are very similar: 11.6 Tg in 2004 and 12.3 Tg in 2005. The OVOC class which represents mainly oxygenated VOC contributes about 4.5 Tg and monoterpenes about 4 Tg to the total BVOC emissions. Annual isoprene emissions are found to be about 3.5 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 contribute with 55% and agriculture contributes with 27% to the total BVOC emissions, the remaining emissions come from other land use types like shrubs, grassland and wetlands. The contribution of agriculture
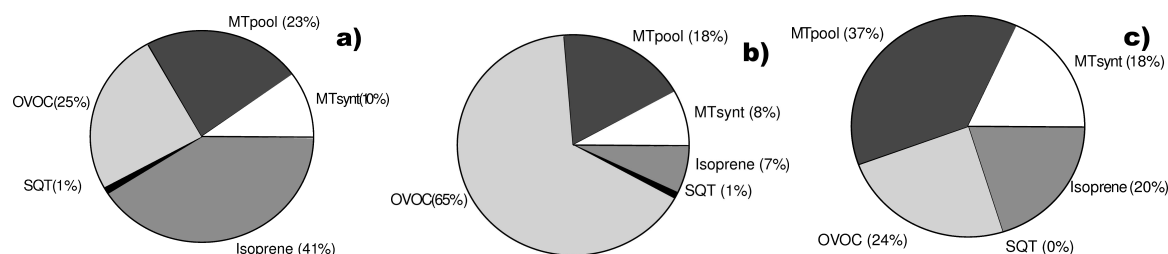
Fig. 3. European BVOC class emission contributions to each land use type: **(a)** forest **(b)** agriculture **(c)** other land use.

in the presented European emission inventory is somewhat higher than in the European inventory of Simpson et al. (1999) who have attributed 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. 2a. Isoprene emissions calculated with the G97 algorithm for the same summer month were found to be up to 10% 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 parameterization 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 80% to the emitted amount of isoprene. Isoprene emissions constitute 28% of the total emitted BVOC amount in Europe.

Newly synthesized monoterpene (MT_{synt}) emissions contribute 31% to the annual emitted amount of monoterpenes in Europe. Though the emission rate of MT_{synt} can regionally be higher than that of MT_{pool} (see Fig. A3, Electronic Supplement: http://www.biogeosciences.net/6/1059/2009/ bg-6-1059-2009-supplement.pdf), prevalent solar radiation levels in Europe inhibit a more intense release of MT_{synt}. The monthly averaged MT_{synt} emission rate in July 2005 is below $100 \, mg \, m^{-2}$ in Sweden and Finland, while it is much higher, 800–$1200 \, mg \, m^{-2}$, in Spain, Italy and Greece (Fig. A3b, Electronic Supplement: http://www.biogeosciences.net/6/ 1059/2009/bg-6-1059-2009-supplement.pdf). Figure 2b shows the distribution of monoterpene emissions for July 2005. Apart from some regions with elevated monoterpene emissions, like Spain, Corsica and Greece, the emission rates are below $1000 \, mg \, m^{-2}$. Relatively high monoterpene emission rates can be found over Scandinavia and the Baltic countries which are covered with large boreal coniferous forests. In the boreal region, monoterpene emissions constitute about 50% of the forest emissions. The major fraction of monoterpene emissions in Europe stem from forests.

European Maps of BVOC emission rates for July 2005 of OVOC and sesquiterpenes are presented in Fig. 2c and 2d. Half of the emitted amount of the OVOC class originates from agriculture and OVOC emission rates are highest over regions with intensive agriculture in Eastern Europe (Fig. 2c) with up to $800 \, mg \, m^{-2}$ in July 2005. Crops with highest foliar biomass density and land coverage will exhibit highest OVOC emissions. It can be deduced that 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 1% 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 Sweden, Finland and the European part of Russia (Fig. 2d). The Nile Delta is a region with relatively high sesquiterpene ($35 \, mg \, m^{-2}$), OVOC ($500 \, mg \, m^{-2}$) and newly synthesized monoterpene ($900 \, mg \, m^{-2}$) emissions in July 2005. This region is covered by 100% with the GLC vegetation class of irrigated cropland. The Nile Delta is thus one example how inaccurate, not crop-specific, land use information can affect emission rates calculated in this inventory.

The contribution of different BVOC classes to the European emissions from forests, agriculture and other land use are presented in Fig. 3a–c. Isoprene dominates European forest emissions, while the OVOC class contributes a fourth and the monoterpenes about a third to the forest emissions. European other land use vegetation predominantly emits monoterpenes. BVOC emissions from agriculture in Europe mainly consist of OVOCs. 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

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 and for the total land use, annual emissions (in Gg) are shown for each BVOC class in the four vegetation zones Atlantic, Boreal, Continental, and Mediterranean and for the total of these four zones.

Land Use type	BVOC class	Atlantic	Boreal	Continental	Mediterranean	Total
Agriculture	ISOP	15	8	51	12	86
	MT_{synt}	28	14	128	19	189
	MT_{pool}	35	29	151	18	233
	OVOC	141	76	538	69	824
	SQT	2	1	9	2	14
	Total	221	128	877	119	1346
Forest	ISOP	186	350	382	235	1154
	MT_{synt}	41	354	141	88	625
	MT_{pool}	23	494	89	63	668
	OVOC	31	461	140	64	695
	SQT	1	21	6	1	29
	Total	282	1680	759	451	3172
Other Land Use	ISOP	27	20	14	95	155
	MT_{synt}	10	12	11	130	163
	MT_{pool}	23	69	10	210	311
	OVOC	32	44	11	70	157
	SQT	0.4	1	0.2	2	3
	Total	92	145	46	507	789
Total Land Use	Total	**595**	**1953**	**1682**	**1077**	**5307**

class emitted from agriculture, forest and other land use for these vegetation zones are given in Table 6. BVOC emissions sum up to 1.3 Tg from agriculture, 3.2 Tg from forests and 0.8 Tg from other land use.

Emissions in the Atlantic zone are mainly from forests and agriculture (Table 6). Agriculture emissions mainly consist of OVOCs, while the forest emissions mainly consist of isoprene. 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%. Widespread crops like wheat, maize, rape, and cereals have been assigned MT standard emission factors of $0.5 \, \mu g \, g_{DW}^{-1} \, h^{-1}$ each for pool and newly synthesized MT emissions. The uncertainties associated with agriculture emissions are further discussed in Sect. 4.3.

About 90% of the emissions of the Boreal zone are from forests. Monoterpene emissions contribute 50% and isoprene emissions contribute 20% to the BVOC emissions in forests of the Boreal zone. It should be noted that emissions from *Picea abies* in the Boreal zone are reduced by 40% compared to the Contintental zone due to the bioclimatic correction of the foliar biomass density. Despite this reduction total BVOC emissions from boreal forest are about two times the continental forest emissions.

Forest and agriculture contribute almost equally to BVOC emissions from the Continental zone. For continental forests it is interesting to note that a higher fraction of the monoterpene emissions originate from the newly synthesized emis-

sion route. This is certainly due to the dominance of European beech (*Fagus sylvatica*). Forest BVOC emissions in the Continental zone consist of 18% OVOC, 50% isoprene, 30% monoterpenes and 1% sesquiterpenes. Isoprene emissions from continental forests amount to 0.4 Tg.

Monoterpene emissions contribute 33% 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 $43 \, \mu g \, g_{DW}^{-1} \, h^{-1}$). Isoprene emissions constitute 52% of the Mediterranean forest emissions and mainly originate from the Mediterranean oaks. Emissions from other land use vegetation contribute substantially (with 47%) to the BVOC amount emitted in the Mediterranean region. BVOC emissions from other land use and from forests in the Mediterranean each amount to about 0.5 Tg.

3.3 Seasonality

The period from May to September is the time with enhanced BVOC emissions (Fig. 4). 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
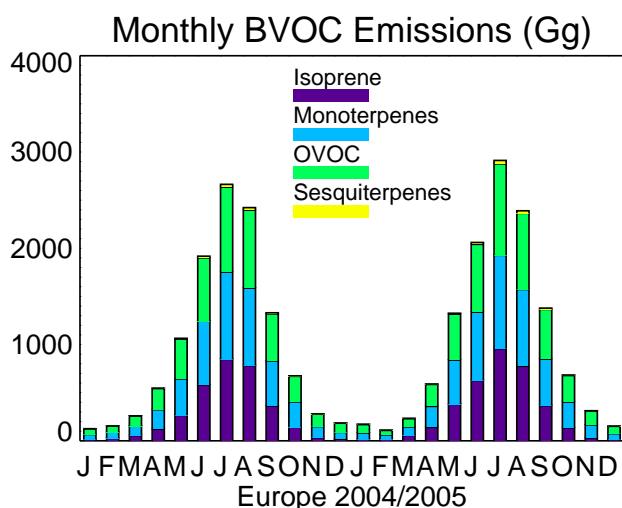
Fig. 4. Seasonal variation of European BVOC emissions.

Fig. 5. Seasonal variation of the land use contributions to European total BVOC emissions.

emissions from vegetation are highest since light intensities, temperatures and emitting plant biomass are highest during these months. After September emissions decline rapidly due to the loss of leaves from deciduous trees and due to the end of the growing season for most agriculture crops. 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.

The seasonal variation of contributions from the main land use types (agriculture, forests, other land use) to the emission of BVOC is shown in Fig. 5. In summer, forests are the main source of biogenic VOC, due to their high density of available foliar biomass for emitting these compounds. As shown in Fig. 3a, isoprene is the most abundant compound in European forest emissions. The contribution from the three main land use types becomes almost equal during the winter months (November to March).

In Fig. 6 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 G97. The relative difference between the two algorithms is not larger than 35% for the studied months, and most likely caused by 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
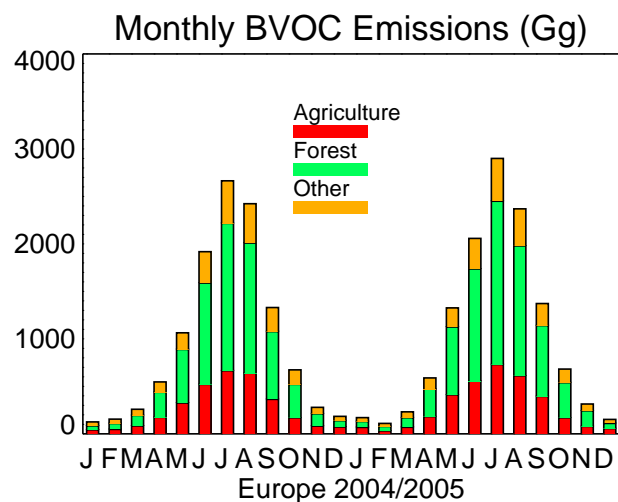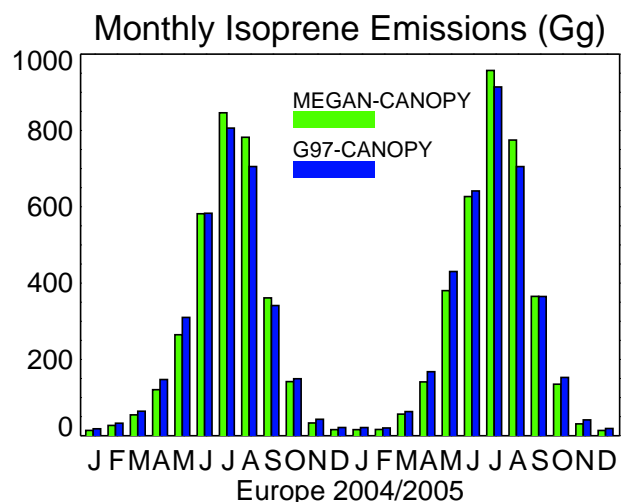
Fig. 6. Seasonal variation of European isoprene emissions.

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. 21). It is noted that the canopy average γ_P in Eq. (10) (for MEGAN) and in Eq. (15) (for G97) also varies with LAI and thus the overall response to LAI in both models is less than linear.

Table 7. Country-specific BVOC emissions from the presented inventory for Spain, Great Britain, Finland and Germany, calculated for the year 2005. Seasonal emissions are given as 3-monthly emission sum (in Gg) for the main land use types agriculture, forests and other land uses and for the total land use. The annual emission amount (in Gg) is compared to the country-specific emission estimate given by Simpson et al. (1999) for each land use. (DJF: December to February, MAM: March to May, JJA: June to August, SON: September to November).

Region	Land Use	DJF	MAM	JJA	SON	Total	Simpson et al. (1999)
Spain							
	Agriculture	5	19	45	17	**87**	87
	Forest	19	77	265	82	**444**	511
	Other Land Use	32	104	278	97	**511**	222
	Total	57	200	588	196	**1042**	820
Great Britain							
	Agriculture	15	22	50	26	**113**	76
	Forest	4	7	21	9	**40**	77
	Other Land Use	8	11	31	16	**65**	25
	Total	27	40	102	51	**219**	178
Finland							
	Agriculture	0	1	5	2	**8**	9
	Forest	5	44	266	88	**404**	341
	Other Land Use	1	18	112	35	**166**	5
	Total	6	63	383	125	**577**	355
Germany							
	Agriculture	7	24	64	28	**123**	66
	Forest	10	40	123	45	**217**	377
	Other Land Use	0	2	5	2	**9**	31
	Total	17	66	191	75	**349**	474

3.4 Country-specific emission patterns

Four countries within Europe, each representing a different vegetation zone, were selected to investigate the seasonal variation of BVOC emissions and the contribution of different land use types on a regional scale. Emitted BVOC amounts from different land use types are compared to other country-specific estimates from earlier inventories.

Spain is intended to represent the Mediterranean zone with forests dominated by *Pinus pinaster* or *Quercus ilex*. Great Britain was chosen to represent the Atlantic vegetation zone and is covered by non-irrigated arable land, agricultural crops, deciduous and evergreen forests. In Scotland a high fraction of other land use, moors and heathland, can be found. Finland represents the Boreal zone and 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*). Germany is in the Continental zone, which is used in this work as the reference zone to define bioclimatic correction factors. Northern Germany is dominated by agriculture, while the landscape in Southern Germany is characterised by a mosaic of mixed forests with *Fagus sylvatica* and *Picea abies* as major tree species and agriculture.

Seasonal BVOC emissions for the year 2005 are displayed in Table 7 and country-specific BVOC emissions are given in Gg for each country. BVOC emissions for the year 2005 are highest in Spain and sum up to about 1 Tg. Emissions from the vegetation in Germany are a factor of 3 lower than in Spain. The emitted amounts for Spain, Germany and Great Britain are within 30% of the national estimates given in the European inventory by Simpson et al. (1999). Our emission amount for Finland is roughly 60% higher than the estimate of Simpson et al. (1999) due to higher emissions from other land use types in our inventory (see Table 7).

Half of the BVOC emissions in Spain originate from other land use types like Mediterranean shrubland. Forests are also a very important source, while emissions from agriculture play a minor role in Spain. 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 3, while emissions from agriculture increase less. Isoprene contributes 65% to the summer emissions from forests. Isoprene emission from forests sum up to 267 Gg per year, which is 50% higher than the previous estimate given by Simpson et al. (1999). The BVOC emission amount for forests and agriculture is in good agreement with Simpson et al. (1999) while the other land use emission amount is a factor of 2 higher than the estimate given by Simpson et al. (1999).

One half of the BVOC emissions in Great Britain are from agriculture, the other half is from forests and other land use. Emission from forests contribute only one fifth to the total BVOC emissions. Agriculture emissions in summer (JJA) are two times higher than in spring and in autumn (September

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
12	6.5	3.4	This Work, G97	This Work	40° E
		3.4	This Work, MEGAN	This Work	40° E
		10.3	This Work, G97	GEIA (Guenther et al., 1995)[c]	36° E
		4.5	This Work, MEGAN	MEGAN (Guenther et al., 2006)[c]	36° E
15–25	9–15	4–5	Steinbrecher et al. (2009)	NatAir	40° E
34		17	Lathière et al. (2006)	ORCHIDEE[c]	50° E
13.5	11	4.6	Simpson et al. (1999)	EMEP	[d]
10	9	4.5	Simpson et al. (1995)	EMEP	[d]
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] Includes the European part of the former USSR.

to November, SON). Agriculture BVOC emissions sum up to 113 Gg per year and this is 50% higher than the estimate of Simpson et al. (1999) for pastures and crops in the United Kingdom (i.e. Great Britain excluding Northern Ireland). This discrepancy may be an indication for the importance of using crop-specific land use information together with crop-specific growing seasons. In the highly spatially and temporally resolved inventory for Great Britain from Stewart et al. (2003) annual emissions of isoprene and terpenes based on the year 1998, were found to be 8 Gg and 83 Gg, respectively. Their estimate of 8 Gg yr^{-1} isoprene emissions is seven times less than the isoprene emission given in Simpson et al. (1999) for the United Kingdom and four times less than our estimate of 32 Gg yr^{-1}. Stewart et al. (2003) concluded that the standard emission potential attributed to the isoprene emissions from Sitka spruce (*Picea sitchensis*) is crucial in determining isoprene emissions from Great Britain.

In Finland forests clearly are the dominant BVOC source. Forest emissions increase by a factor of 5 between MAM and JJA. Isoprene contributes only 12% to the JJA forest emissions in Finland. BVOC emissions in Finland are 8 Gg yr^{-1} from agriculture crops and 404 Gg yr^{-1} from forest, and thus close to the estimate given by Simpson et al. (1999). Other land use BVOC emissions are much higher than in the inventory from Simpson et al. (1999), indicating that wetlands, moors and heathlands are probably more important emitters than thought previously. The important role of wetlands for isoprene emissions in Finland was confirmed in the recent inventory study by Tarvainen et al. (2007). Our annual forest BVOC and isoprene emission amounts are more than two times higher than the respective estimates of 146 Gg BVOC and 15 Gg isoprene for boreal forests in Finland given by Tarvainen et al. (2007) for the year 1997. One reason for

the lower forest emissions in this inventory may be the use of lower isoprene and monoterpene standard emission potentials for Norway spruce (*Picea abies*).

BVOC emissions from Germany mainly originate from agriculture and forests with a respective contribution of 35% and 62%. Total BVOC emissions in JJA are a factor of 3 higher than in MAM. Isoprene contributes to the JJA BVOC emissions from agriculture and forests with 9% and 33%, respectively. The contribution of isoprene to the yearly averaged BVOC emissions from forests is found to be 28% for Germany. Isoprene emissions from forests sum up to 62 Gg per year, and are 45% lower than German isoprene forest emissions given by Simpson et al. (1999). Our forest isoprene emissions for Germany are in good agreement with the average isoprene forest emissions of 40 Gg yr^{-1} for the decade 1994–2003 found in the German forest BVOC inventory by Smiatek and Steinbrecher (2006). Our forest BVOC emission estimate of 217 Gg yr^{-1} is lower than the estimate of 377 Gg yr^{-1} by Simpson et al. (1999) and the estimate of 366 Gg yr^{-1} by Smiatek and Steinbrecher (2006). In our inventory, agriculture is found to be an important source, emitting 123 Gg yr^{-1} BVOC. This amount exceeds the emission estimate from Simpson et al. (1999) for crops in Germany by a factor of two.

3.5 Comparison with other European 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. (2009), the NatAir project inventory of VOC emission from natural and semi-natural vegetation.

The NatAir model domain has almost the same extent as the Pan-European domain of our study. Steinbrecher et al. (2009) were mainly interested in natural emissions of BVOC and therefore agriculture emissions were estimated using the general agriculture classes from the CLC/GLC2000 mosaic and they 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. 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. The NatAir study calculates European emissions based on the years 1997, 2000, 2001 and 2003 to address inter-annual variability of emissions. The years 1997 and 2002 were fairly cold years while 2001 and in particular 2003 were relatively warm years. Their estimate of annual total BVOC emissions amounts to 20 Tg for the average of the four years, with a variation from 15–25 Tg for the particular years. The lowest NatAir estimate of 15 Tg is about 2–3 Tg higher than our estimate and the earlier estimate given by Simpson et al. (1999). From the average total NatAir amount of 20 Tg BVOC emissions, 12 Tg are estimated to originate from forests and 8 Tg from other land uses, including agriculture. Non-forest emissions obtained in our work sum up to 5 Tg and are lower than the average NatAir non-forest emissions.

Forest emissions of our estimate are 45% lower than the NatAir estimate. Due to the use of the identical forest tree species information (forest cover database and standard emission factors), the emissions from forests should be comparable. A possible reason for the deviation may be the higher temperatures in the selected years of the NatAir study. Forest emissions obtained in our work are very similar to the early estimate of Lübkert and Schöpp (1989). These authors used a very simple model for calculating forest emission based on altitude-resolved forest cover data and spatially and temporally interpolated temperature data. They used only one temperature-dependent emission factor for each deciduous and coniferous trees. These emission factors were different for day and for night. The good agreement with our work indicates that the use of accurate forest data is probably more important for the prediction of forest emissions than the application of a great amount of detail to describe the short-term variation of emissions.

The 4 Tg lower annual OVOC emission estimate for Europe of our study compared to the NatAir estimate can be explained by the different aggregation procedure applied in this work and the applied growing season concept which includes detailed growing season lengths for seven different agricultural crops. The same default standard emission factor for OVOC as in the NatAir inventory was applied in this work and also the land use information is based on the same database. In contrast to the NatAir inventory plant-specific agriculture land use data was employed in the presented work.

Our isoprene emission estimate of 3.5 Tg is about 1 Tg lower than previous estimates for Europe that are based on European bottom-up inventories (Simpson et al., 1995, 1999; Steinbrecher et al., 2009). Likely reasons for the lower isoprene emissions in our inventory include the use of different meteorology data, lower temperatures and light abundance in the selected years, and the application of a biomass correction factor for main tree species. The impact of the bioclimatic correction factor on our European emission estimate will be discussed in Sect. 4.4.

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. 2.4. Global inventories are known to incorporate a lower degree of detail and are commonly used for global estimates of vegetation emissions. In the scope 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 was used with the same horizontal resolution as applied for the presented emission estimate. Using the G97 algorithm together with the GEIA isoprene emission inventory resulted in 10 Tg isoprene emissions per year in Europe, while using the MEGAN algorithm together with the global MEGAN input variables resulted in 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. The annual European isoprene emissions calculated with the global isoprene emission inventory of the MEGAN model (Guenther et al., 2006) are in exact agreement with the European inventory of Simpson et al. (1999) which is likely due to their use of similar plant species distribution data. In general, the MEGAN inventory agrees well with recent European bottom-up estimates (Table 8), while the former GEIA inventory overestimates isoprene emissions in Europe by more than factor 2 compared to European bottom-up 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 are 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 MEGAN inventory uses geo-referenced plant species distribution data where these are available (e.g. in the US, in Canada and in Australia) while more generic data is used in other world regions. In Europe, national tree data provided by Simpson et al. (1999) was employed in MEGAN to derive the plant distribution functions for forest land use.

The generalized way to define the geographic distribution of 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 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. A1b, Electronic Supplement: http://www.biogeosciences.net/6/1059/2009/bg-6-1059-2009-supplement.pdf). 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. There is a clear need for future research on the chemical speciation and emission factors of oxygenated VOC for different crop and tree species. Oxygenated 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) and should respond differently to light, drought or herbivore attack.

Biogenic emissions among plants of the same species or even among parts of the same plant may vary considerably. 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 from two different branches of the same Scots pine tree differed by a factor of two. Monoterpene emission rates among different Scots pine trees of the same age and origin, growing under similar conditions, even varied by more than one order of magnitude (Komenda and Koppmann, 2002). 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).

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). Annual monoterpene emissions from agriculture in our inventory sum up to about 0.9 Tg and are lower than the estimate of about 2 Tg given by Steinbrecher et al. (2009) 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.). Agriculture is an important source for OVOCs and monoterpenes in our inventory, comprising about 35% of the total annual OVOC and monoterpene emissions.

In our inventory, OVOC due to the high default emission factor of $2.0\,\mu g\,g_{DW}^{-1}\,h^{-1}$ 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% of large parts of France, England, Germany and Italy and locally cover about 40% in Spain (see map in Fig. A4, Electronic Supplement),

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.

To quantify the impact of uncertain monoterpene emissions from agriculture for our inventory, we performed a simulation of BVOC emissions for the year 2005 with increased monoterpene emissions from rape cultivations. For this test, the rape standard emission factors for MT_{pool} and MT_{synt} were increased by a factor of four and set to $2.0 \, \mu g \, g_{DW}^{-1} \, h^{-1}$. The MT standard emission potentials assigned to all other agriculture crops remained unchanged. Total European monoterpene emissions from agriculture increased by 3% in this test. Emissions from agriculture in the Atlantic vegetation zone increase by roughly 3%, while the agriculture emissions from the Boreal, Continental and Mediterranean zone are less affected.

The regional impact on BVOC emissions from agriculture depends on the agricultural area fraction covered with rape cultivations. Agriculture BVOC emissions for 2005 increased by 1% in Spain, 2% in Great Britain, 3% in Germany and 4% in Finland. Rape is cultivated in Southern Finland and increased monoterpene standard emission factors slightly affect the agriculture BVOC emissions. However we note that agriculture plays a minor role in Finland, contributing only 1% to the total BVOC emissions in Finland.

Though only small changes of agricultural emissions are observed in this test for monoterpene emissions from rape cultivations, we conclude that the estimate of agricultural emissions in Europe is currently biased by the uncertainties in monoterpene and OVOC standard emission potentials for crops.

4.4 Bioclimatic correction

To adjust foliar biomass densities for the main tree species and crops in 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 3% higher than the amount calculated with bioclimatic correction factors according to Tables 1 and 2. For single BVOC classes annual European emissions changed less than 5%.

However this factor is important when estimating BVOC emissions from major vegetation zones and countries within Europe. In the Atlantic vegetation zone, total BVOC emissions for 2005 are 17% higher and agriculture BVOC emissions are 26% higher when considering the bioclimate correction of foliar biomass densities. This can be explained with bioclimatic correction factors larger than 1 for the main agricultural crops in the Atlantic vegetation zone, leading to elevated foliar

biomass densities in Western Europe (see Fig. A1a, Electronic Supplement: http://www.biogeosciences.net/6/1059/2009/bg-6-1059-2009-supplement.pdf). This is also reflected in the emissions from Great Britain, which are higher by 12%. In the Mediterranean vegetation zone, total BVOC emissions for the year 2005 are 5% lower when considering the bioclimate correction of foliar biomass densities. Agriculture BVOC emissions are 20% lower, indicating that bioclimatic correction factors below 1 for main crops in the Mediterranean zone are the cause for the discrepancy. In Spain, emissions are only 2% lower due to the minor importance of agriculture emissions. In the Boreal vegetation zone, BVOC emissions for 2005 are only 1% lower when taking into account the bioclimatic correction of foliar biomass densities. Though bioclimatic correction factors for the main tree species in the Boreal zone are less than 1, the impact on total BVOC emission is limited. As expected, BVOC emissions of Germany remained unchanged, since this country is within 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

The commonly observed temperature and light dependence of BVOC emissions seems to hold also at high latitudes in boreal and subarctic regions. It has been shown that the light and temperature dependent parameterization of BVOC emissions is applicable to northern boreal environmental conditions (Rinne et al., 2000; Tarvainen et al., 2005, 2007; Hakola et al., 2006). Tiiva et al. (2008) demonstrated the increase of isoprene emission due to temperature increase in subarctic heath land. The effect was found to be a direct response to increased air temperature, which indicates a rapid physiological effect of current temperature on isoprene production as outlined in Lerdau and Gray (2003). The mean isoprene emissions from subarctic heath land were comparable to the emissions found earlier from a subarctic peatland ecosystem (Tiiva et al., 2007). The emissions from the subarctic peatland increased 10-fold during an exceptionally warming

period, again giving evidence for the validity of the proposed temperature- and light-dependence (Tiiva et al., 2007).

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 photosynthesis shortly after budbreak, emission of isoprene only starts after a retardation of several days. On the other hand, older leaves produce isoprene less efficiently. Reduced emissions in autumn have been found to be correlated with the activity of some terpene synthases (Lehning et al., 1999) and a seasonality for monoterpene synthase activity has been observed for *Quercus ilex* (Fischbach et al., 2002). Based on long term laboratory experiments with *Pinus pinea* trees, Staudt et al. (2000) 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 μg g$_{DW}^{-1}$ h^{-1} during the course of the year (Staudt et al., 1997). The algorithm of Staudt et al. (2000) has been applied in this work to determine the (long-term) seasonal variation of emissions from deciduous and evergreen vegetation.

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, depending on whether BVOCs are emitted from current photosynthesis like in case of isoprene and MT$_{synt}$ or from reservoir pools (MT$_{pool}$). 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. (2007) 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* which are both MT$_{pool}$ emitter. Monoterpene emissions of water stressed *Rosmarinus officinalis* remained stable (Ormeño et al., 2007). Species like *Cistus* and *Rosmarinus* contain aromatic oils in external glandular hairs which allow monoterpene emissions to be maintained during drought conditions until the reservoir gets depleted. In case of BVOC emission from current photosynthesis, a severe drought with prolonged reduction of photosynthesis may reduce emission due to a depletion of resources (Bertin and Staudt, 1996).

At ambient ozone levels, reactive terpenoids like ocimene, linalool, limonene and most sesquiterpenes are partly removed within the canopy or within leaf or branch cham-

bers, if flushed with ambient air (Seufert et al., 1997). Above canopy fluxes are much smaller than emissions derived from branch enclosures due to losses by deposition and oxidation within the canopy (Ciccioli et al., 1999). 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 are more representative of the sum of parent hydrocarbon, its oxidations products and particles released to the atmosphere. Transformation and 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 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 developed in this work can be used together with less biased emission factors and with a more sophisticated canopy emission model in the future to obtain more accurate BVOC emission estimates for Europe with a high temporal and spatial resolution.

5 Conclusions

Agriculture land use types are identified in our study as an important source for OVOCs and monoterpenes. However, large uncertainties remain for the OVOC class 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 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 – 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 agriculture in the Mediterranean while emissions

from agriculture 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 BVOCs 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 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 may 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 portal (http://afoludata.jrc.ec.europa.eu/index.php/ dataset/info/121). To access the dataset on the web portal it is necessary to register (http://afoludata.jrc.ec.europa.eu/index. php/new_user).

Resulting European emission fields can be used in the future to investigate secondary particle formation from isoprene, monoterpenes and sesquiterpenes with regional or global chemistry transport models.

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