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EMISSIONS FROM NATURAL SOURCES

Contribution of the Nature Expert Panel to the
EMEP/CORINAIR Atmospheric Emission Inventory Guidebook
(SNAP Code 11)

Vienna, 1998

Federal Ministry for Environment, Youth and Family

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SUMMARY

Within the UN-ECE Task Force on emission inventories, the Nature Expert Panel has compiled guidelines for the assessment of emissions from nature and forestry in Europe. These guidelines are to be included in the EMEP/CORINAIR guidebook on emission inventories, after acceptance at the Task Force meeting in Wismar, Germany, April 1998. Sectors dealt with are emissions from forests and forest fires, emissions from soil, grassland and other low-vegetation emissions, emissions from wetlands and waters, from animals, volcanoes, natural gas seeps and from lightning. Procedures for calculating emissions are described separately for each of the sectors, following the strict format of the guidebook. Further work of the Expert Panel, which includes a contribution to the discussion on human responsibility towards natural emissions, and a first assessment of natural emissions in Europe applying the methods described, is referred to.

This document thus contains the first edition of the Guidebook Chapter 11. This chapter, along with the rest of the Guidebook, can be found at the European Environment Agency web-site http://www.eea.dk/aegb. This site will be updated periodically, so for the latest version of any part of the Guidebook users are recommended to consult the online version.

A mirror of the EEA site, which also contains suggested changes as well as officially accepted updates, can be found at:

http://www.aeat.co.uk/netcen/airqual/TFEI/unece.htm.

KURZFASSUNG

Im Rahmen der UN-ECE Task Force über Emissionsinventuren hat das "Nature Expert Panel" Richtlinien erarbeitet, wie in Europa die Emissionen aus natürlichen Quellen sowie aus der Forstwirtschaft abgeschätzt werden sollen. Diese Richtlinien sollen beim kommenden Treffen der Task Force in Wismar, BRD (April 1998) akzeptiert werden und in das EMEP/CORINAIR Handbuch für Emissionsinventuren Eingang finden. Die hierbei erarbeiteten Kapitel behandeln die Bereiche Wald, Waldbrände, Boden, Grasland und andere niedrige Vegetation, Emissionen von Feuchtgebieten und Wasserflächen, von wildlebenden Tieren, Vulkanen, oberflächennahen Lagerstätten organischen Materials sowie von Blitzschlag. Die Vorgangsweise zur Ermittlung der Emissionen wird getrennt für jeden Bereich beschrieben, wobei das Format des Handbuches genau eingehalten wird. Auf weitere Arbeiten des "Expert Panels", nämlich eine Diskussion der Frage, ob und wieweit eine Verantwortung der menschlichen Gesellschaft bezüglich dieser Emissionen besteht, sowie eine erste Abschätzung der natürlichen Emissionen in Europa unter Verwendung der beschriebenen Methoden, wird hingewiesen.

Das vorliegende Dokument enthält somit die erste Version des Kapitels 11 für das erwähnte Handbuch. Dieses Kapitel ist genauso wie das ganze übrige Handbuches im Internet unter der Adresse der Europäischen Umweltagentur (EEA) zu finden: http://www.eea.dk/aegb. Unter dieser Adresse erfolgen, auch periodische Aktualisierungen, daher wird empfohlen, für den jeweils aktuellen Stand die Internet-Version heranzuziehen.

Die jeweils offizielle Version und zusätzlich die vorgeschlagenen Änderungen sind auch unter der folgenden Adresse verfügbar: http://www.aeat.co.uk/netcen/airqual/TFEI/unece.htm.

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PREFACE

Emissions from natural sources contribute significantly to the European emission totals. In order to better understand the behavior and fate of these compounds in the atmosphere, the available information about their incorporation has to be improved. Also and even more important in terms of the political implications, the fate of anthropogenic air pollution is not sufficiently known without an adequate treatment of natural emission sources.

The Nature Expert Panel to the UN-ECE Task Force on emission inventories has been set up in order to help fill the gaps in the emission information from natural sources. In the first version of the EMEP/CORINAIR Emission Inventory Guidebook[1] (McInnes, 1996), the standard document for European emission inventories, the chapters on natural emissions had been left blank. It was the task of the expert panel to provide guidelines to national experts, how to derive such inventories.

When the work of the Nature Expert Panel started with its formation at the fifth meeting of the UN-ECE / European Environment Agency's Task Force on Emission Inventories in Oxford, March 1996, the area of responsibility was defined according to the "Nature" section of the CORINAIR SNAP Code (sector 11). During the further development, also due to recommendations of this expert panel, the responsibilities were considerably increased. Sector 11 has recently been renamed to "Other sources and sinks" for the draft versions of the SNAP 97 code. Tab. 1 shows the correspondence between SNAP 94 and SNAP 97 for sector 11 (SNAP 97 version 1.0 from March 20, 1998 has been prepared by CITEPA and RISØ for the European Topic Centre on Air Emissions).

Table 1: Proposed SNAP 97 sub-categories of sector 11 in relation to SNAP 94 categories

SNAP 97		SNAP 94 (previous representation)	
11	**OTHER SOURCES AND SINKS**	**11**	**NATURE**
11 01	**Non-managed deciduous forests**	**11 01**	**Non-managed deciduous forests**
11 01 04	European oak	11 01 01	High isoprene emitters
11 01 05	Sessile oak	11 01 02	Low isoprene emitters
11 01 06	Other deciduous oaks	11 01 03	None isoprene emitters
11 01 07	Holm oak		
11 01 08	Cork oak		
11 01 09	Other evergreen oaks		
11 01 10	Beech		
11 01 11	Birch		
11 01 15	Other deciduous broadleaf species		
11 01 16	Other evergreen broadleaf species		

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[1] McInnes G.; The Joint EMEP/CORINAIR Atmospheric Emission Inventory Guidebook, 1st Edition. European Environment Agency, Copenhagen, 1996.

11 01 17 Soils (excluding CO_2)	
11 02 Non-managed coniferous forests	**11 02 Non managed coniferous forests**
11 02 04 Norway spruce	11 02 01 High isoprene emitters
11 02 05 Sitka spruce	11 02 02 Low isoprene emitters
11 02 06 Other spruce	11 02 03 None isoprene emitters
11 02 07 Scots pine	
11 02 08 Maritime pine	
11 02 09 Aleppo pine	
11 02 10 Other pines	
11 02 11 Fir	
11 02 12 Larch	
11 02 15 Other conifers	
11 02 16 Soils (excluding CO_2)	
11 03 Forest and other vegetation fires	**11 03 Forest fires**
11 03 01 Man induced	
11 03 02 Other	
11 04 Natural grassland and other vegetation	**11 04 Natural grassland**
11 04 01 Grassland	
11 04 02 Tundra	
11 04 03 Other low vegetation	
11 04 04 Other vegetation (Mediterran. scrub,...)	
11 04 05 Soils (excluding CO_2)	
11 05 Wetlands (marshes - swamps)	**11 05 Wetlands (marshes - swamps)**
11 05 01 Undrained marshes	11 05 01 Undrained and brackish marshes
11 05 02 Drained marshes	11 05 02 Drained marshes
11 05 03 Bogs	11 05 03 Raised bogs
11 05 04 Fens	
11 05 05 Swamps	
11 05 06 Floodplains	
11 06 Waters	**11 06 Waters**
11 06 01 Lakes	11 06 01 Lakes
11 06 02 Shallow saltwaters (< 6m)	11 06 02 Shallow saltwaters
11 06 03 Ground waters	11 06 03 Ground waters

11 06 04	Drainage waters	11 06 04	Drainage waters
11 06 05	Rivers	11 06 05	Rivers
11 06 06	Ditches and canals	11 06 06	Ditches and Canals
11 06 07	Coastal waters (> 6m)	11 06 07	Open sea (> 6m)
11 07	**Animals**	**11 07**	**Animals**
11 07 01	Termites	11 07 01	Termites
11 07 02	Mammals	11 07 02	Mammals
11 07 03	Other animals		
11 08	**Volcanoes**	**11 08**	**Volcanoes**
11 09	**Gas seeps**	**11 09**	**Near surface deposits**
11 10	**Lightning**		(missing in SNAP 94)
11 11	**Managed deciduous forests**		(SNAP 94: part of agriculture)
11 11 04	European oak		
11 11 05	Sessile oak		
11 11 06	Other deciduous oaks		
11 11 07	Holm oak		
11 11 08	Cork oak		
11 11 09	Other evergreen oaks		
11 11 10	Beech		
11 11 11	Birch		
11 11 15	Other deciduous broadleaf species		
11 11 16	Other evergreen broadleaf species		
11 11 17	Soils (excluding CO_2)		
11 12	**Managed coniferous forests**		(SNAP 94: part of agriculture)
11 12 04	Norway spruce		
11 12 05	Sitka spruce		
11 12 06	Other spruce		
11 12 07	Scots pine		
11 12 08	Maritime pine		
11 12 09	Aleppo pine		
11 12 10	Other pines		
11 12 11	Fir		
11 12 12	Larch		
11 12 15	Other conifers		
11 12 16	Soils (excluding CO_2)		

11 21	**Changes in forest and other woody biomass stocks**	(SNAP 94: part of agriculture)
11 21 01	Tropical forests	
11 21 02	Temperate forests	
11 21 03	Boreal forests	
11 21 04	Grassland / tundra	
11 21 05	Other	
11 22	**Forest and grassland conversion**	(SNAP 94: part of agriculture)
11 22 01	Tropical forests	
11 22 02	Temperate forests	
11 22 03	Boreal forests	
11 22 04	Grassland / tundra	
11 22 05	Other	
11 23	**Abandonment of managed lands**	(SNAP 94: part of agriculture)
11 23 01	Tropical forests	
11 23 02	Temperate forests	
11 23 03	Boreal forests	
11 23 04	Grassland / tundra	
11 23 05	Other	
11 24	**CO_2 emissions from / or removals into soils (except 10.06)**	(SNAP 94: part of agriculture)
11 25	**Other**	

According to the requirements for the guidebook, emission of the following compounds was included: SO_2, NO_x, NMVOC, CH_4, CO, CO_2, N_2O, NH_3. Furthermore, emissions of heavy metals and persistent organic pollutants should have been considered, but this was beyond the resources of the Panel. No final decision is available currently, however, as which of these compounds will finally be included in international protocols.

The following chapters, presenting the default methodologies for calculating and reporting emissions by national experts, follow the strict structure given by the guidebook. References and authors are given at the end of each chapter. The chapters are expected to be officially accepted at the upcoming Task Force meeting in Wismar, Germany, in June 1998. Possible updates of chapters will be accessible via internet. The pages of the Nature Expert Panel as well as other proposed changes to the guidebook will be kept at the following address: http://www.aeat.co.uk/netcen/airqual/TFEI/unece.htm. The official version of the guidebook is available at the European Environment Agency: http://www.eea.dk/aegb. These pages will also contain the future official versions of the chapters. Here also the results of the Agri-culture Expert Panel will be documented, dealing with emissions from SNAP code 10. The

work of the Nature Expert Panel consisted also in supporting the agriculture expert panel, in terms of soil NO_x emissions and NMVOC from plants.

In addition to the emission assessment as such, also an attempt has been made to apply the approaches and to quantify the emissions of Europe[2]. The results have been submitted to an international scientific journal. It is expected that the distribution of the guidebook and subsequent discussion also of the results given in that paper will lead to a significant improvement of the understanding of European natural emissions.

Also prepared for publication is an attempt to attribute emissions towards anthropogenic or natural sources, which is not quite as straightforward as it may look initially. This paper[3] is meant to provide information in terms of policy options for emission reductions, as it gives indications in which direction target values may be drawn with respect to natural emissions.

Funding for this work has primarily been performed by EMEP and by the Austrian Federal Environment Agency. All the input of numerous experts, also those in addition to the members of the expert panel (see Appendix), is gratefully acknowledged.

David Simpson and Wilfried Winiwarter, March 1998.

[2] Simpson, D., Winiwarter, W., Börjesson, G., Cinderby, S., Ferreiro, A., Guenther, A., Hewitt,C.N., Janson, R., Khalil, M.A.K., Owen, S., Pierce, T.E., Puxbaum, H., Shearer, M., Steinbrecher, R., Tarrason, L., and Öquist, M.G., Inventorying emissions from Nature in Europe. Submitted to J.Geophys.Res., March 1998.

[3] Winiwarter, W., Fontelle J.-P., Haberl H., Simpson, D., On the boundary between man-made and natural emissions: Problems in defining European ecosystems. To be submitted to J.Geophys.Res., April 1998.

SNAP CODE :   **1101**
                                                                         1102
                                                                         1111
                                                                         1112

SOURCE ACTIVITY TITLE :   **Non-managed broadleaf forest**
                                                   Non-managed coniferous forest
                                                     Managed broadleaf forest
                                                     Managed coniferous forest

PARCOM-ATMOS CODE :

NACE CODE :

1.   ACTIVITIES INCLUDED

All types of foliar forest emissions will be considered, non-managed and managed, broadleaf and coniferous. Forest foliage is primarily a source of VOC, and we distinguish here between isoprene, monoterpenes, and 'other VOC'. Emissions from forest soils are covered in the chapter dealing with activities 110117, 110216, 111117 and 111216. Note that for methane the flux is believed to be from the atmosphere to the forest floor, so in any case a zero emission factoris recommended for this species. Emissions from forest fires are covered in 1103 "Forest and other vegetation fires". Emissions from the forest undergrowth and root system have not yet been included, although may be added at a later stage. Emissions from shrub-like vegetation, maquis, garrique, or other vegetation types are covered in SNAP 1104 "Natural grassland and other vegetation".

2.   CONTRIBUTIONS TO TOTAL EMISSIONS

According to CORINAIR-90, forests (deciduous and coniferous) contributed 19% of total European NMVOC emissions, 4.4% of CH_4 emissions, 14.3% of N_2O emissions and 0.8% of NH_3 emissions.

However, as noted below the natural emission estimates for VOC as supplied for CORINAIR-1990 must now be regarded as outdated. Table 2.1 compares the more recent estimate of Simpson et al. (1995) and Guenther et al. (1995) with estimates of anthropogenic emissions.

Table 2.1 Comparison of estimated isoprene, OVOC, and monoterpene emissions from forests with man-made VOC. Units: ktonnes per year

Country	Isoprene	OVOC	Monoterp.	Man-made VOC**
Albania	6	9	16	30
Austria	32	78	30	418
Belgium	30	13	7	364
Bulgarian	135	44	41	178
Czechoslov.***	70	95	124	
Denmark	7	7	4	167
Finland	82	354	398	209
France	480	216	215	2393
Germany	121	190	249	3154
Greece	21	35	62	293
Hungary	82	16	23	205
Iceland	0	0	7	6
Ireland	2	6	11	102
Italy	53	89	142	2080
Luxembourg	2	1	0.4	19
Netherlands	8	6	5	424
Norway	29	104	143	266
Poland	63	176	113	802
Portugal	36	61	70	202
Romania	154	83	55	567
Spain	137	248	272	1050
Sweden	108	389	370	528
Switzerland	5	17	30	284
Turkey	213	460	175	
Russia	2006*	3197*	1060-3490[I]	3566
UK	53	27	39	2287
Sum	4000	6000	3700-6100	20000

Notes: All isoprene and OVOC emissions are from Simpson et al., 1995.

All monoterpene emissions (except Russia) are from Guenther et al., 1995, in ktonne carbon. * 1989 estimates were made for whole Soviet Union, however, Russia is expected to account for the majority of emissions. **Man-made emissions are unofficial estimates, generally derived by subtracting estimated Natural and Agricultural emissions from total emissions. *** Former Czechoslovakia

Other references: I - Isidorov, 1992, sum of pine+fir emissions

3.   GENERAL

3.1. Description

The subject of emission inventories for emissions from vegetation is still very much in its infancy in Europe, and the design of an inventory procedure should reflect this. Indeed, NMVOC inventories prepared for the CORINAIR 1990 data-base have already been outdated by recent re-evaluations of the emission factors on which these have been based (Guenther et al., 1993, 1995, 1998, Simpson et al., 1995, Seufert et al., 1997). Generally, the mix of

emissions varies greatly both in and between vegetation types, and knowledge of this mix is constantly being updated and in some cases completely revised.

*** It is more important at this stage to assemble the land-use information than to estimate the emissions directly. ***

This is especially true for NMVOC as models are almost completely reliant on good land-use data-bases for their biogenic emissions estimates. Hopefully the procedures suggested here will lead to a Europe-wide data-base which will greatly improve emission estimates for model calculations and policy decisions.

Biogenic VOC is also a rather loose term for a wide range of compounds, of which only a few are generally of most interest. Isoprene is generally the compound of most importance for ozone modelling for example, and it is useful to inventory this compound specifically. Emissions of the various terpenes may also be important, although there are great uncertainties associated with their atmospheric behaviour. Similarly, the remaining VOC species ('other VOC', or OVOC) doubtless play some role in atmospheric chemistry problems, but little is known about the chemistry of many components or the quantitative emissions of individual species. Emissions may be large, however.

A review of the sources and chemistry of biogenic VOCs has recently been given by Fehsenfeld et al., 1992. A special-issue Atmospheric Environment dealing with a large number of European measurements has recently been published (Seufert et al., 1997).

Emissions vary greatly from one tree species to another. And as knowledge has increased some species previously classified as non-isoprene emitters have actually now been found to emit isoprene in significant quantities. Conversely, oaks were previously thought to be always high isoprene emitters, whereas now it is recognised that some evergreen oaks emit little isoprene but very high amounts of terpenes (Seufert et al., 1997).

These considerations have been reflected in the new SNAP codes adopted for this chapter which assign codes to specific types of trees, rather than to "high-isoprene emitters" etc.

Light and temperature controls on emissions

For all types of vegetation, an appropriate system describing the emissions flux on an hourly basis is that of Guenther et al. (1996):

$$\text{Flux} (\mu g\ m^{-2}\ yr^{-1}) = \int \varepsilon . D . \gamma\ dt \qquad (1)$$

where ε is the average emission potential ($\mu g\ g^{-1}\ h^{-1}$) for any particular species, "D" is the foliar biomass density (g dry weight foliage m^{-2}), and γ is a unitless environmental correction factor representing the effects of short-term (e.g. hourly) temperature and solar radiation changes on emissions.

Guenther et al.(1991, 1993) showed that to a very good approximation the short-term (hourly) variations in emissions of isoprene could be described by the product of a light

dependent factor, C_L and a temperature dependant factor, C_T. Thus, the so-called ISOG algorithm:

$$\gamma_{iso} = C_L \cdot C_T \qquad\qquad (2, \text{ISOG})$$

The light factor, C_L is given by:

$$C_{L_{iso}} = \frac{\alpha c_{L1} L}{\sqrt{1 + \alpha^2 L^2}} \qquad\qquad (3)$$

where α (= 0.0027) and c_{L1} (= 1.066) are empirical constants, and L is the PAR flux (μmol photons (400-700nm) $m^{-2} s^{-1}$). Temperature dependence $C_{T_{iso}}$ is described by:

$$C_{T_{iso}} = \frac{\exp C_{T1}(T - Ts) / RT_sT)}{1 + \exp(C_{T2}(T - T_M) / RT_sT)} \qquad\qquad (4)$$

where R is the gas constant (= 8.314 J K^{-1} mol^{-1}), and c_{T1} (= 95000 J mol^{-1}), c_{T2} (= 230000 J mol^{-1}), and T_M (= 314 K) are empirical coefficients based upon measurements of three plant species: eucalyptus, aspen, and velvet bean, but which seem to be valid for a variety of different plant species (Guenther et al. 1993, Guenther 1997).

The environmental correction factor for monoterpene emissions from most plants are parameterised using the following equation (Guenther et al. 1993):

$$\gamma_{mts} = \exp (\beta \bullet (T - T_s)) \qquad\qquad (5a, \text{MTS})$$

where β (= 0.09 K^{-1}) is an empirical coefficient based on non linear regression analysis of numerous measurements present in the literature. This type of emission is associated with vaporisation of terpenes from stores within the plant tissue, and this algorithm is referred to here as MTS.

Recently it was shown that some evergreen oaks, and also Norway spruce, show a light-dependency of monoterpene emissions. At least for *Q.ilex* this dependency seems to be well described by the Guenther isoprene algorithms (Kesselmeier et al., 1996, Seufert et al., 1997). Denoting this behaviour by MTL, we have:

$$\gamma_{mtl} = \gamma_{iso} \qquad\qquad (5b, \text{MTL})$$

These emission algorithms represent our current knowledge of terpenoid emission by plants. These algorithms will likely need to be revised in the future, when a better biological understanding of the biosynthesis and emission of terpenoids is available, since there remains an uncertainty in the resulting emission estimates that is about a factor of 3 or more. This variation is mainly due to the (1) differences in the emissions from branch to branch and from

tree to tree, (2) variation with season, (3) nutrient condition of the plant, (4) stress and (5) experimental errors. Suggestions for improved algorithms have been made by Schuh et al. (1997) and Schnitzler et al. (1997); but the generality of these suggestions need further testing before we can recommend a change from the basic Guenther algorithms.

The relationship between environmental conditions and emission of OVOC is even less understood than isoprene and monoterpenes. Emissions of some of these compounds, including a group of C_6 unsaturates, are strongly influenced by external factors other than light and temperature, such as plant wounding by microbes, insects or mechanical stress. Given the lack of other information regarding the factors controlling oxygenated hydrocarbon emission, the use of equation (5) for parameterisation of oxygenated hydrocarbon emission is recommended (Guenther et al, 1994, Geron et al., 1994, König et al. 1995). i.e.:

$$\gamma_{ovoc} = \gamma_{mts} \qquad\qquad (6)$$

These light and temperature dependencies are illustrated in Figures 3.1 and 3.2.
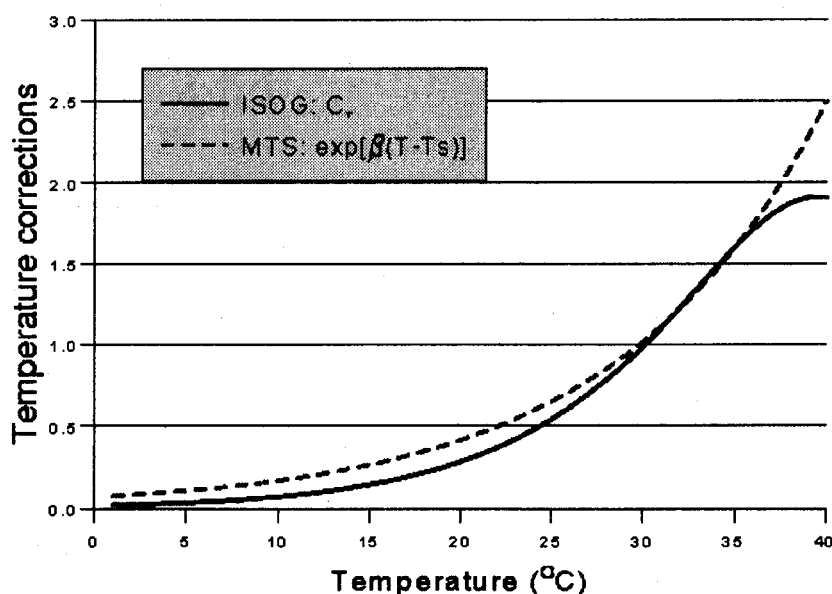

Figure 3.1 Temperature dependency of isoprene (ISOG) and of terpene stores (MTS) emissions.
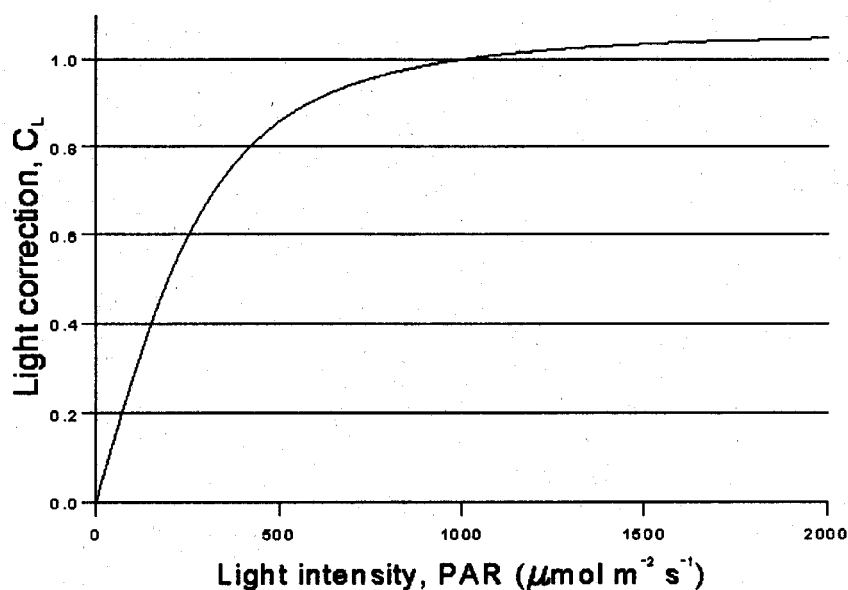
Figure 3.2 Light dependency for emissions of compounds, which are emitted as they are synthesized (e.g. isoprene)

Calculation of annual emissions then requires in principal both temperature and radiation data over the whole year with appropriate spatial resolution. However, many simplifications are possible and the simpler methodology (section 4) proposes a seasonal approach. The use of equations 1-6 above is covered in the detailed methodology (section 5).

3.2. Definitions

Some relevant terms are:

Forest - for the purposes of this guidebook the definition of forest should be as inclusive as possible. In theory all trees should be included, although in practice other definitions of forest may be included in statistical definitions, e.g.:

UNECE/FAO Forest means land with tree crown cover of more than about 20% of the area, with trees usually growing to more than about 7 m in height and able to produce wood. This includes both closed forest formations where trees of various storeys and undergrowth cover a high proportion of the ground and open forest formations with a continuos grass layer in which tree synusia cover at least 10% of the ground.

Branch-level - refers to emissions or measurements where the ambient radiation and temperature is an average over a whole branch, including both sun leaves and shade leaves.

Leaf-level data refer to data appropriate to a single leaf. Leaf-level emission potentials are on average 1.75 times higher than branch-level rates because the latter are mores shaded (Guenther et al., 1994). Emission potentials in this chapter are only given as branch level. (U.S. papers tend to give leaf-level, which requires modelling the shading within a forest canopy)

Coniferous = all trees classified botanically as *Gymnospermae*, generally referred to as softwoods or needle-leafed species.

Non-coniferous = all trees classified botanically as *Angiospermae*, generally referred to as hardwood or **broad-leaved** species. Note that such species can be other deciduous or evergreen.

Deciduous = all plants which shed leaves, usually in the Autumn.

DW - dry weight of plants (used for emission rates), as opposed to fresh weight.

Foliar Biomass densities as used here give the mass of foliage per unit projected ground area, and must not be confused with total biomass densities which have the same units (g m^{-2}) but include wood mass.

OVOC = Other volatile organic compound. Any non-methane VOC species other than isoprene or monoterpenes emitted by vegetation, including oxygenated VOC but also non-oxygenated.

PAR = photosynthetically active radiation, typically about 45-50% of total global radiation, covering the wavelength range 400-700nm.

3.3   Techniques

3.4   Emissions

Biogenic emissions consist of a wide variety of species. Attention has mainly focused on isoprene and the class of monoterpene compounds (alpha-pinene, beta-pinene, limonene, etc.). The remaining 'other' VOC (OVOC) species consist of a large number of species including hydrocarbons and oxygenated compounds (alcohols, aldehydes, etc.), and have proven difficult to quantify in atmospheric samples. See section 9.

3.5   Controls

'Control measures' is not usually an applicable concept for forest emissions. However, it can be mentioned that much of the current forest cover in Europe is artificial, in the sense that the selection of species has been decided by human intervention. Thus, Sitka forest plantations in the U.K. represent an emissions increase over the coniferous forest which they replaced, so control in terms of species selection could be envisaged. Such action to reduce 'natural' emissions has so far only been undertaken in California as far we are aware!

4. SIMPLER METHODOLOGY

All methodologies for calculating biogenic emissions essentially involve multiplying an emissions factor for a type of vegetation by a statistic giving the amount of vegetation in the country or grid square. Two major alternatives for this are (1) to perform these calculations at a genera or preferably species specific level (requiring for example separate statistics for Norway spruce, Douglas fir, etc.), or (2) to perform the calculations for different ecosystem types. In this latter method, each ecosystem is assumed to consist of a number of species, and the assigned emission rates attempt to give the average emissions from this category.

The rest of this chapter follows a species orientated method (1) approach as far as possible. The main justification for this is that the recent European measurements have differed sufficiently from their American counterparts on an ecosystem basis that where possible detailed species measurements should form the basis of the data-base. Of course, data still does not exist for many vegetation types in Europe, in which case some ecosystem-assumptions are necessary anyway. These will be based as far as possible on knowledge of European species.

As noted in section 3, an appropriate system describing the emissions flux on an hourly basis is that of Guenther et al. (1996):

$$\text{Flux } (\mu g \, m^{-2} yr^{-1}) = \int \varepsilon . D . \gamma \, dt \qquad (1)$$

where ε is the average emission potential ($\mu g \, g^{-1} h^{-1}$) for any particular species, "D" is the foliar biomass density (g dry weight foliage m^{-2}), and γ is a unitless environmental correction factor representing the effects of short-term (e.g. hourly) temperature and solar radiation changes on emissions. For isoprene emissions, and light-activated terpene emissions (so far only quantified for two forest species, *Picea abies* and *Quercus ilex*), γ is a function of light and temperature, and is denoted γ-iso. Terpene and OVOC emissions from most vegetation types are simply dependant on temperature, in which case γ is temperature-only dependant, and denoted γ-mt.

The simplified methodology consists of modifying equation (1) to be a seasonal rather than an hourly calculation.

$$F = \varepsilon . D . \Gamma \qquad (7)$$

Where Γ represents the integrated value of γ over the growing season of the vegetation concerned.

Using meteorological data from the EMEP MSC-W models the integrated values, Γ-iso and Γ-mts, have been calculated for both 6 monthly (May-October) and 12 monthly growing seasons, as averages over each country. These have been calculated from hourly γ values, and thus have units of hours. The Γ values are tabulated in Table 4.1. With this simplified methodology we could estimate for example the OVOC emissions from 1 km^2 of deciduous oak (e.g. *Q.robur*) as simply:

Emission = Area x ε . D . Γ-iso

$\qquad$ = 10^6 (m^2) x 60 (μg g^{-1} h^{-1}) x 320 (g m^{-2}) x Γ-iso (h)

For Austria, for example, Table 4.1 gives Γ-iso for 6-months as 452, therefore we have:

Emission = 10^6 (m^2) x 60 (μg g^{-1} h^{-1}) x 320 (g m^{-2}) x 452 (h) = 8.67 tonne km^{-2}

Table 4.1: Country average values of integrated environmental correction factors, Γ-iso and Γ-mts for 6 and 12 month growing seasons (unit= hours).

	Γ-mts = Γ-ovoc		Γ-iso	
	6-month	12-month	6-month	12-month
Albania	745	976	563	719
Austria	588	734	452	540
Belarus	753	895	581	684
Belgium	739	969	580	712
Bosnia_Herz.	709	893	561	686
Bulgaria	824	1029	620	755
Croatia	883	1121	667	815
Czech Republic	712	885	533	633
Denmark	518	704	373	485
Estonia	565	669	422	491
Finland	458	523	339	379
France	840	1107	669	829
Germany	698	890	525	632
Greece	1076	1440	816	1057
Hungary	966	1188	730	874
Ireland	467	713	337	478
Italy	904	1208	711	902
Latvia	636	757	486	572
Lithuania	675	813	516	613
Luxembourg	786	1003	620	745
Macedonia,F.Y.R.	631	783	492	597
Moldova, Rep. of	858	1040	649	771
Netherlands	676	901	513	643
Norway	327	397	240	284
Poland	736	912	558	669
Portugal	1015	1388	853	1093
Romania	783	964	587	706
Russia, Fed.	808	917	637	717
Slovakia	797	977	607	724
Slovenia	745	940	562	682
Spain	982	1301	806	1004
Sweden	423	508	315	368
Switzerland	465	580	368	432
Turkey	976	1263	783	983
United_Kingdom	493	720	358	492
Ukraine	856	1023	656	771
Yugoslavia	752	937	557	674

5.   DETAILED STATE OF THE ART METHODOLOGY

The detailed methodology still relies on the basic equations (1-6) given above, but allows for the use of better input information and a more refined calculation if local meteorological data are available. We give details for calculations at either a monthly or hourly resolution.

5.1   Monthly calculation

For the monthly calculation we make the following assumptions for the integration of the ISOG-type emissions:

1.   The light-intensity variation given by equation 2 can be replaced by a simple step-function, where $C_L = 1$ during most of the day and zero otherwise.
2.   The calculation of the temperature correction (Eqns. 4,5) need not be done every hour, but instead may be approximated by a monthly average daytime temperature.
3.   Ambient temperature and light-intensity provide a reasonable approximation to leaf-level light and temperature.

Approximation (1) is generally rather good, as light levels quickly reach 1000 μmol m^{-2} s^{-1} during the morning hours in most locations, even with moderate cloud cover. (200 μmol m^{-2} s^{-1} is set as the cut-off for defining daylength as this corresponds to aprox. $C_L = 0.5$). Approximation (2) introduces larger errors, but only of order 20% or so, which is much less than the uncertainties in the emission potentials. Approximation (3) has been tested by Simpson et al.(1995) and shown to introduce only moderate uncertainties for European conditions, again much less than those of the emission potentials.

The number of light-hours per day corresponding to the above definition can be calculated as a simple function of latitude and month:

Table 5.1:   Number of light-hours* per day (N_L) as a function of latitude and month.

Lat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
80	0.0	0.0	0.0	13.1	24.0	24.0	24.0	15.2	6.1	0.0	0.0	0.0
78	0.0	0.0	4.4	12.9	20.5	24.0	24.0	14.6	7.2	0.0	0.0	0.0
76	0.0	0.0	5.8	12.7	18.6	24.0	20.2	14.1	7.9	0.0	0.0	0.0
74	0.0	0.0	6.8	12.6	17.5	20.9	18.6	13.8	8.5	0.0	0.0	0.0
72	0.0	0.0	7.4	12.5	16.7	19.1	17.6	13.6	8.9	0.0	0.0	0.0
70	0.0	0.0	7.9	12.4	16.1	18.0	16.8	13.4	9.2	2.5	0.0	0.0
68	0.0	1.6	8.4	12.3	15.6	17.2	16.2	13.2	9.4	4.2	0.0	0.0
66	0.0	3.6	8.7	12.2	15.2	16.6	15.8	13.0	9.6	5.2	0.0	0.0
64	0.0	4.7	8.9	12.2	14.9	16.1	15.4	12.9	9.8	5.9	0.0	0.0
62	0.0	5.4	9.1	12.1	14.6	15.7	15.0	12.8	9.9	6.4	1.5	0.0
60	2.4	6.1	9.4	12.1	14.3	15.4	14.7	12.7	10.1	6.9	3.3	0.0
58	3.7	6.6	9.5	12.0	14.1	15.0	14.4	12.6	10.2	7.3	4.3	2.2
56	4.6	7.0	9.7	12.0	13.9	14.7	14.2	12.5	10.3	7.7	5.1	3.5
54	5.3	7.3	9.8	11.9	13.7	14.5	14.0	12.4	10.4	7.9	5.7	4.4

52	5.8	7.7	9.9	11.9	13.5	14.2	13.8	12.3	10.4	8.2	6.2	5.1
50	6.3	7.9	10.0	11.9	13.4	14.0	13.6	12.2	10.5	8.4	6.6	5.7
48	6.7	8.2	10.1	11.8	13.2	13.8	13.4	12.2	10.6	8.6	7.0	6.2
46	7.1	8.4	10.2	11.8	13.1	13.6	13.3	12.1	10.6	8.8	7.3	6.6
44	7.4	8.6	10.2	11.8	12.9	13.5	13.1	12.1	10.6	9.0	7.6	6.9
42	7.7	8.8	10.3	11.7	12.8	13.3	13.0	12.0	10.7	9.1	7.9	7.3
40	7.9	9.0	10.4	11.7	12.7	13.1	12.9	11.9	10.7	9.3	8.1	7.6
38	8.2	9.1	10.4	11.6	12.6	13.0	12.8	11.9	10.8	9.4	8.4	7.8
36	8.4	9.3	10.5	11.6	12.5	12.9	12.6	11.8	10.8	9.6	8.6	8.1

Notes: Day-lengths (in hours) calculated for the 15th of each month from Latitudes 80 degrees N to 36 degrees N. *Period of light-hours defined for PAR>200 μmol m^{-2} s^{-1}.

If we let mm1 and mm2 be the start and end of the growing season for a particular vegetation type , N_d (mm) be the number of days per month, N_L (mm) be the number of light-hours per day (Table 5.1), and T_{mm} be the monthly mean temperature, for month "mm", yearly emissions can be evaluated with:

$$\text{Emis(isoprene)} = \sum_{mm=mm1}^{mm2} A.D.\gamma_{iso}(T_{mm}).N_d(mm).N_L(mm)$$

Emissions of terpenes from species displaying MTL behaviour are also described by this equation.

For the yearly emissions of species displaying the MTS-type behaviour there is no light-dependency, and we perform the calculation for 24 hours per day:

$$\text{Emis(monoterpenes)} = \sum_{mm=mm1}^{mm2} A.D.\gamma_{mt}(T_{mm}).N_d(mm).24$$

Similarly,

$$\text{Emis(OVOC)} = \sum_{mm=mm1}^{mm2} A.D.\gamma_{ovoc}(T_{mm}).N_d(mm).24$$

5.2   Hourly calculation

If desired, and appropriate meteorological data are available, the environmental correction factors (γ) may be evaluated on an hourly basis using local surface temperature and sunlight conditions. The algorithms, temperature and light corrections, C_T and C_L , are as given in Equations 1-7 above.

Refinements:

Age distribution of forest

Isidorov et al. (1993) have pointed out that a land-use data-base built up with knowledge of not only the area but also the age distribution within each region can give a better description of the biomass densities. This approach requires more data but helps to eliminate a potentially large area of uncertainty.

Seasonal variation

Foliar density varies markedly over the year, and this can be straightforwardly incorporated into the above calculations if data are available through the use of seasonal-dependent foliar biomass density.

Altitude temperature correction

Atmospheric temperature generally decreases with height at a rate of ca. 6 degrees C per km. Thus, data obtained from a meteorological station at a given height may be corrected to temperatures in another location (e.g. on a mountainside) before applying any of the detailed methodologies.

6. RELEVANT ACTIVITY STATISTICS

Vegetation coverage in terms of the vegetation types discussed in section 8 are required, together with foliar biomass estimates (D), and estimates of growing seasons. Commercial forestry at least is usually well documented. Other wooded land is a common category where definitions are more problematic.

For a good inventory it is actually most important to specify the correct foliar biomass density to accompany any given area of vegetation. This is because "area" is an ill-defined quantity in many instances, e.g. 1 km^2 of wooded area may include very dense forest with an average foliar biomass density of, say, 1400 g m^{-2}, or it may contain scattered trees with only 100g m^{-2}.

The new SNAP codes have been designed to encourage the use of data for each tree species separately for at least the most common trees. Very nice examples of this type of compilation are provided by Andreani-Aksoyoglu and Keller (1995) for Switzerland, and Ortiz and Dory (1990) for Spain, the latter tabulating area coverage and mean biomass factors for all 50 level III territorial units.

Categories such as mixed forest should be avoided as this gives no information on species content. If species-specific data are not available, then genus-level data should be used. Only as a last resort should more general categories be supplied.

As pointed out by Veldt (1989) common vegetation names are often confusing, and care should be taken to provide Latin names of species as well as common names of all species. Translations of some common tree species names are included in Table 14.1, taken from EC (1996).

Foliar Biomass densities

For the simpler methodology, seasonal average foliar biomass densities may be used. Default values are suggested below, and in section 8. These suggestions appear to fit quite well a wide range of measurements, but the variability of Mediterranean vegetation may cause some problems. For example, Ortiz & Dory (1990) mention a land-use class, Monte hueco, which consists of a mixture of species, with biomass densities as low as 100 g m^{-2}. For coniferous forests, Veldt suggests densities of 700-1400 g m^{-2} for different species < 60 deg N latitude, whereas Ortiz and Dory use 400 g m^{-2}. Even further north, variations are great. Andreani-Aksoyoglu and Keller, 1995, quote a biomass factor for oak species of 530 g m^{-2}. Some variations are systematic; Isidorov et al. (1993) points out that foliar biomass as a proportion of total tree biomass increases in harsher conditions, and with age.

*** Therefore, it is STRONGLY RECOMMENDED that foliar biomass densities appropriate to the local vegetation are used. These may well be a factor of 2 or three different to the default values. ***

Table 6.1:   Default foliar biomass densities (adapted from Veldt, 1989)

Land Use Type		Foliar Biomass Density, D (g m^{-2})
Broadleaf:		
Deciduous Oaks		320
Birch (*Betula*)		320
Poplar, aspen (*Populus*)		320
Default deciduous broadleaved		300
Evergreen broadleaved		500
Conifers		
Norway spruce (*Picea abies*)	> 60° N lat.	800
	55-60° N lat.	1400
	< 55° N lat.	1600
Sitka spruce (*Picea sitchensis*)		1400
Other spruce		1400
Scots pine (*Pinus sylvestris*)	> 60° N lat.	500
	< 60° N lat.	700
Other *Pinus ssp.*		700
(Fir) *Abies ssp.*		1400
Douglas Fir (*Pseutotsuga menziessi*)		1000
Larch (*Larix*)		300
Other coniferous		1000

Comment on Satellite data

Satellites provide a spatially comprehensive method of mapping vegetation with very high-resolution. Use of such data is encouraged, but a strong warning should be issued that ground-validation is essential if biogenic emissions are to be estimated. The apparent beauty and detail of a satellite image should not be mistaken for accuracy! Satellite data are easily mis-interpreted (wrong species, problems with non-dominant vegetation, etc.) and even in the United States where biogenic emission inventories are very advanced, discrepancies of up to a factor of 5 are still found between satellite-derived isoprene emissions and ground-based determinations (Lamb et al., 1997).

7. POINT SOURCE CRITERIA

No point sources

8. EMISSION FACTORS, QUALITY CODES AND REFERENCES

Emission potentials (ε) are required separately for isoprene, monoterpenes and OVOC. Further, for monoterpenes two classes of behaviour are distinguished. For most trees emissions are temperature-only dependant, controlled by the γ-mts environmental factor (equation 5a). For evergreen oaks the MTL algorithm is used (eqn. 5b).

Emission potentials for a wide variety of species have recently been compiled by Guenther et al. (1994, 1997), Geron et al.(1994) for American woodlands, and by Steinbrecher (1997) and Seufert et al. (1997) for European species. Very little reliable experimental data on the emissions of OVOCs is available, and consequently Guenther et al. (1994) recommended the use of a uniform emission rate of 1.5 $\mu g\ g^{-1}\ h^{-1}$ for all tree species, recognising that this was a first order approximation to a ten-fold range (0.5-5 $\mu g\ g^{-1}\ h^{-1}$). The data of König et al.(1995) fall within this range, and so until further European data are available then 1.5 $\mu g\ g^{-1}\ h^{-1}$ also seems a reasonable choice for preliminary, first-order, estimates of OVOC emissions in Europe.

The emission potentials are given in Table 8.1.

Table 8.1: Standard emission potentials (μg g^{-1} h^{-1} at 30 deg. C and PAR=1000 μmol m^{-2} s^{-1}) for European trees. Isoprene and monoterpene emission potentials are taken from Guenther et al., 1994, 1997, or Geron et al., 1994, except where European measurements can provide a basis, as indicated by additional refs. For terpenes ε-mtl denote emissions controlled by light and temperature (using γ-mtl), whereas ε-mts denote emissions controlled by light only. All isoprene rates are branch-level, often derived from leaf-level U.S. estimates by division by 1.75.

		Type	Foliar	Iso.	Terpenes		O-VOC	Additional Refs.	
Common name	Latin name		biomass	ε-iso	ε-mtl	ε-mts	ε-ovoc	Iso.	Terp.
(example)			density, D						
			g m^{-2}						
Fir	*Abies*	e	1400	0	0	3	1.5		
Maple/Sycamore*:	*Acer*	d	320	0	0	3	1.5	S93	S93
Common Alder	*Alnus*	d	320	0	0	1.5	1.5	S93	S93
Birch	*Betula*	d	320	0	0	0.2	1.5	K	P,K
Hornbeam	*Carpinus*	d	320	0	0	0.65	1.5	K	K
Cedar	*Cedrus*	e	700	0	0	1.5	1.5		
Orange	*Citrus sp.*	d	320	0	0	1.5	1.5		
Italian cypress	*Cupressus*	d	700	0	0	0.65	1.5		
Blue gum	*Eucalyptus sp.*	e	400	20	0	3	1.5	Str97b	H
European beech	*Fagus*	d	320	0	0	0.65	1.5	P,S93,K,Sh	K,Sh
Ash	*Fraxinus*	d	320	0	0	0	1.5	S93	S93
Walnut	*Juglans*	d	320	0	0	3	1.5		
Common juniper$	*Juniperus*	e	700	0	0	0.65	1.5	O	O
European larch	*Larix*	d,c	300	0	0	1.5	1.5	S93	S93
Olive	*Olea*	e	200	0	0	0	1.5		
Date palm	*Phoenix*			20	0	0	1.5		
Spruce$	*Picea sp.*	e	Varies	1	1.5	1.5	1.5	As P.abies	
Norway spruce$	*Picea abies*	e	Varies	1	1.5	1.5	1.5	S94,Ke;	J,Ke, S94,LP
	Picea omorika	e	Varies	10	0	0.65	1.5		
Blue spruce	*Picea pungens*	e	Varies	1	0	0.65	1.5		
Sitka spruce$	*Picea sitchensis*	e	Varies	6	0	3	1.5	Str96,97b,Sm	
Pines:	*Pinus sp.*	e	700	0	0	3	1.5		-
Aleppo pine$	*Pinus halepensis*	e	700	0	0	0.65	1.5		H
Umbrella pine$	*Pinus pinea*	e	700	0	0	6	1.5	Ks,Std,Str97a,Sf	
Maritime pine$	*Pinus pinaster*	e	700	0	0	0.2	1.5		Si
Scots pine$	*Pinus sylvestris*	e	Varies	0	0	1.5	1.5		J
Pistachio	*Pistacia sp.*			0	0	3	1.5	H,Ha	H,Ha
Americ. sycamore*	*Platanus*	d	320	34	0	0	1.5		
Poplar	*Populus*	d	320	60	0	0	1.5	H	
Cherry#4	*Prunus*	d	300	0	0	0	1.5		
Douglas Fir$	*Pseudotsuga*	e	1000	0	0	1.5	1.5		D
Oaks:	-			-	-	-	-	-;	-
Default deciduous oak#1 $	-	d	320	60	0	0.2	1.5	Sf	Sf

Default evergreen oak#2 $	-	e	500	0	20	0	1.5	Sf	Sf,
Turkey oak $	Quercus cerris	d	320	0	0	1	1.5	S97	S97
Kermes/Holly oak $	Quercus coccifera	e	500	0	20	0	1.5	SH	SH
Hungarian oak $	Quercus frainetto	d	320	100	0	0.2	1.5	S97,Sf,	Sf
Holm oak $	Quercus ilex	e	500	0	20	0	1.5	Be,Ks96,Str97,Sf	
Sessile oak	Qercus petraea	d	320	60	0	0.2	1.5	K,S97,Str97b,Sf	
Downy oak	Quercus pubescens	d	320	60	0	0.2	1.5	S97	S97
European oak#3	Quercus robur	d	320	60	0	0.2	1.5	S93,I	S93
Cork oak $	Quercus suber	e	500	0	0	0.2	1.5	Sf	Sf
Locust	Robinia pseudoacacia	d	320	10	0	-	1.5		
Willow	Salix	d	150	34	0	0.2	1.5	O	S93
Saw-palmetto	Serenoa	d	320	10	0	0	1.5		
Lime tree/Basswood	Tilia	d	320	0	0	0	1.5		
Elm	Ulmus	d	320	0	0	0.2	1.5		

Notes:

Type gives evergreen (e),deciduous (d), or (d,c) for Larix deciduous coniferous

#1 e.g. Q. rubra, Q.faginea, Q.lusitanica.

#2e.g. Q.rotundifolia, Q.callipiprinos,Q.ithhaburiensis, Q.coccifera

#3 also known as English oak, Pendunculate oak

#4 includes almond,apricot, blackthorn (sloe), peach.

* Sycamore = Acer pseudoplatanus, not to be confused with the American sycamore, Platanus occidentalis

Refs:

Be Bertin et al, 1997; D   Duyzer, 1993; H   Hewitt, C.N. and Owen, S., pers.comm.; I Isidorov et al., 1985; J   Janson, 1993; K   Koenig et al., 1995; Ks96,97 Kesselmeier et al., 1996, 1997; LP Lindskog and Potter, 1995; Ha Hanson et al., 1997; O Owen et al., 1997; P Puxbaum, 1997; Sh Schuh et al., 1997; Si   Simon et al., 1994; Sf   Seufert et al., 1997; Sm Simpson et al., 1995; Std Staudt et al., 1997; S94 Steinbrecher, R., 1994; S93,97 Steinbrecher et al., 1993, 1997; Str96,97a,97b Street et al., 1996,1997a,1997b.

9.   SPECIES PROFILES

Emission (γ) potentials have been given separately for isoprene, terpenes, and OVOC, and this division represents the most important level of speciation. However, there are many species represented within the class of terpenes and OVOC covering a wide range of chemical behaviour. This section attempts some guidance as to likely breakdowns among the monoterpene and OVOC classes.

Monoterpenes

Although many types of monoterpenes exist, most plants emit only 2-3 major species, with the reactive α-pinene often dominating emissions from species such as Norway spruce and Scots pine (Janson, 1993). The ratio of one compound to another is very variable, both with season and temperature, so it is very difficult to specify the speciation in a quantitative way (Janson, 1993). In order to illustrate the major compounds, Table 9.1 compares the ratios of several monoterpenes to α-pinene obtained from several studies. Table 9.2 groups a number of species in order of their relative frequency of emission.

Table 9.1: Relative composition of hydrocarbon-mix emitted by vegetation as reported by different authors, adapted from Duyzer (1993). Numbers in % are given relative to α-pinene (α-pinene is 100%)

	Veldt:91	Janson:93	Janson:93	Steinb.'93	Simon:93	Duyzer:93
	Average of several pines	Scots pine	Norway spruce	Norway spruce	Maritime pine	Douglas fir
β-pinene	40	33	5	17	105	40-100
3-carene	30	111	6-800		50	30-80
limonene	26	61	5-15	13	44	20-60

Table 9.2: Examples of monoterpenes emitted by vegetation into the atmosphere (Zimmerman, 1979; Isidorov, 1985, as given by Guenther et al., 1994).

Major	Frequent	Occassional
Δ^3 - Carene	αThujene	αFenchene
d-Limonene	Tricyclene	β-Fenchene
Myrcene	Terpinolene	δ-Fenchene
α-pinene	α-Terpinene	ε-Fenchene
β-pinene	β-Terpinene	Bornylene
Sabinene	γ-Terpinene	Alloocimene
Camphene	p-Cymene	Methyl chavicol
1,8-Cineole	α-Phellandrene	p-Cymen-8-ol
β-Phellandrene	trans-Ocimene	Linalool
	cis-Ocimene	2-Methyl-6-methylene-1,7-octadiene-3-one
	2-Carene	Pinocarvone
		Verbenone
		Fenchone
		Thujone
		Camphor

OVOC

The identification and quantification of OVOC emissions from plants has proven one of the most difficult problems in evaluating total biogenic emissions. OVOC consists of a wide variety of compounds, many of which have been difficult to measure. Examples are alcohols, ketones, esters, ethers, aldehydes, alkenes and alkanes. Useful reviews can be found in Puxbaum (1997), Bode et al. (1997), Guenther et al. (1994) and Kotzias et al. (1997). The most extensive quantitative European data-set appears to be that of König et al. (1995), otherwise some screening studies are also available (Hewitt and Street, 1992, Steinbrecher, 1994, Isidorov, 1992, Goldstein et al., 1996, Arey et al., 1991a,b).

10.   UNCERTAINTY ESTIMATES

None of the biogenic emission inventories used in Europe can be compared in terms of complexity or accuracy with those generated in the U.S.. All European methodologies have been severely limited by the availability of data on a European scale. Several key items are either missing or known to only a limited extent, necessitating some rather arbitrary choices.

Assessment of the uncertainties inherent in calculations of biogenic VOC emissions in Europe is rather difficult. As a starting point, estimates of the uncertainty of even recent U.S. inventories have suggested up to a factor of 3 for isoprene (Guenther et al., 1994). Further, even though much progress has been made in emission potentials and algorithms (Guenther et al., 1993, 1997, Seufert et al., 1997), awareness has grown of the large uncertainties associated with specifying land-cover for particular species. Even in the U.S., where land-use data-bases exist over the whole country in consistent format, uncertainties associated with specifying forest coverage are still significant (Guenther et al., 1994). In Europe such uncertainties are very much greater because such coherent land-use data sets have not yet become available.

We discuss some of the important factors contributing to the total uncertainty of the European emission estimates below.

Emission potentials

Even with large campaigns such as BEMA (Seufert et al., 1997) emission factors for European species are very few, and taken from a very limited set of conditions and samples. Genus-level potentials derived in the U.S. are often not appropriate for Europe because the species mix within a genus is often very different. It is clear that many more measurements are required before emissions in Europe can be described with any confidence, but meanwhile the first positive steps that can be taken are to collect good land-use data as a basis for any inventory.

Land-use data

The focus of most forest statistics appears to be the area of productive, coniferous forest, rather than the categories of most interest for biogenic inventories. Even for the coniferous forest category definitions vary greatly; 1 km^2 of coniferous forest appears to mean that 50% of the stem-volume is coniferous in Finland and Norway, 70% in Sweden, 80% in Ireland, and 100% in the U.K. (UN ECE, 1985). Whichever definition is used, the aim should be to get the best description of foliar biomass for the area and tree species concerned.

Biomass data

Although the biomass data given in the simpler methodology can be used as default values if no other information is available, factor of two uncertainties can easily be introduced. Clearly

the best solution is for each country to specify biomass densities appropriate to local conditions.

OVOC emissions

Guenther et al. (1993) noted that the recommended emission rate of 1.5 µg g^{-1} h^{-1} is associated with a 10-fold range (0.5 - 5 µg g^{-1} h^{-1}) in possible emissions, and that even this may underestimate some emissions.

Final remarks

It has been recognised that the minimum level of uncertainty in global biogenic emission estimates is a factor of 3 (Guenther et al., 1995), but this is likely to represent a lower limit for the accuracy of European emission estimates. Further, this figure relates to estimates of annual emissions. Uncertainties for episodic calculations must obviously be substantially greater.

11. WEAKEST ASPECTS/PRIORITY AREAS FOR IMPROVEMENT IN CURRENT METHODOLOGY

The emission factors and knowledge of land-use within each region are certainly the weakest aspects. The emission factors can only be improved with more measurements. The land-use problem is primarily one of data collection, as presumably forestry and agricultural Institutes hold quite detailed data for most countries. Collection of this land-use data is of the greatest priority.

12. SPATIAL DISAGGREGATION CRITERIA FOR AREA SOURCES

Follows from land-use and climate data.

13. TEMPORAL DISAGGREGATION CRITERIA

The details of hourly calculations are given in section 5, detailed methodology.

It is worth noting that annual emissions of biogenic emissions give only a limited insight into the importance of these compounds. For assessing their impacts on photochemical ozone formation it is the biogenic emissions during the warmest and sunniest days which are of interest. In practice therefore, photochemical oxidant models all calculate their own biogenic emission rates internally using short period temperature, radiation data in conjunction with land-use data.

14. ADDITIONAL COMMENTS

Recent developments and re-evaluations of previous methodologies have resulted in significant changes in the emission factors which should be used in inventorying biogenic VOC emissions. This chapter has presented information on the new emission factors for a range of species derived from the latest American and European evaluations. In addition, much progress has been made in developing algorithms to describe the emission-temperature-sunlight relationships for isoprene, monoterpenes and other VOC. Still, these algorithms will certainly be changed in the future as knowledge of the underlying processes improves. Suggestions for modifications to include long-term (seasonal changes) to the emission potentials, or other improvements have been presented by Guenther (1997), Schnitzler et al., 1997, and Schuh et al. (1997), although more work is needed to evaluate these algorithms before they can be recommended for the Guidebook.

Canopy models

It is possible to apply complex `canopy' approaches in which forest canopy models are used to estimates levels of temperature and radiation at different heights within a canopy (e.g. Pierce and Waldruff, 1991, Lamb et al., 1993), and such an approach was tested in Simpson et al. (1995). Canopy approaches should be used together with 'leaf-level' emission factors, as opposed to the 'branch-level' factors given in section 8. However, the difference in emissions estimates between a canopy model and simple use of branch-levels estimates is relatively small (up to 20%). Given the much larger uncertainties in the emission potentials, uncertainties introduced by the forest-canopy model itself (eg. in temperature profiles within the canopy), and the lack of evaluation of such models in European conditions, we do not recommend applying such a model for European emissions at this stage.

The emission factors given in section 8 are therefore exclusively for use where emission-canopy models are not used.

It should be noted that this section still presents a simpler methodology for calculating emissions than can be found in Guenther et al., 1995. We make no attempt to account for factors such as net primary production, leaf-area index, or vegetation index. No canopy radiative model is used. Such factors might improve the accuracy of the estimates somewhat, but until the basic emission factors for European vegetation are more firmly established too much sophistication in the inventory procedure seems unnecessary. Groups having the data and resources to implement such methods are referred to Guenther et al., 1994, Guenther et al., 1995 or Geron et al., 1994.

Table 14.1: Generic names of tree species in different European languages

Botanical Name	French	German	Greek	Italian
Fagus sylvatica	Hêtre	Rotbuche	Οξυα δασικη	Faggio
Quercus petraea	Chêne rouvre	Traubeneiche	Δρνς αποδισκο	Rovere
Quercus robur	Chêne pédonculé	Stieleiche	Δρνς ποδισκοφορος	Farnia
Quercus ilex	Chêne vert	Steineche	Αρια	Leccio
Quercus suber	Chêne liège	Korkeiche	Φελλοδρνς	Sughera
Pinus sylvestris	Pin sylvestre	Gemeine Kiefer	Δασικ πενκη	Pino silvestre
Pinus nigra	Pin noir	Schwarzkiefer	Μανη πενκη	Pino nero
Pinus pinaster	Pin maritime	Seestrandkiefer	Οαλασσια πενκη	Pino marittimo
Pinus halepensis	Pin d'Alep	Aleppokiefer	Χαλεπιος πενκη	Pino d'Aleppo
Picea abies	Epicéa commun	Rotfichte	Ερνθρελατη νψηλη	Abete rosso
Picea sitchensis	Epicéa de Sitka	Sitkafichte	Ερνθρελατη	Picea di Sitka
Abies alba	Sapin pectiné	Weißtanne	Λενκη ελατη	Abete bianco
Larix decidua	Mélèze d'Europe	Europäische Lärche	Λαριξ ενρωπαικη	Larice

Botanical Name	Portuguese	Russian	Spanish	Swedish
Fagus sylvatica	Faia	бук лесной	Haya	Bok
Quercus petraea	Carvalho branco Americano	дуб скалъный	Roble albar	Bergek
Quercus robur	Carvalho roble	дуб черещатый	Roble común	Ek
Quercus ilex	Azinheira	дуб каменный	Encina	Stenek
Quercus suber	Sobreiro ·	дуб пробковый	Alcornoque	Korkek
Pinus sylvestris	Pinheiro silvestre	сосна обыкновенная	Pino silvestre	Tall
Pinus nigra	Pinheiro Austriaco	сосна чёрная	Pino laricio	Svarttall
Pinus pinaster	Pinheiro bravo	сосна приморская	Pino negral	Terpentintall
Pinus halepensis	Pinheiro de alepo	сосна алеппская	Pino carrasco	Aleppotall
Picea abies	Picea	ель европейская	Abeto rojo	Gran
Picea sitchensis	Picea de Sitka	ель ситхинская	Picea de Sitka	Sitkagran
Abies alba	Abeto branco	пихта белая	Abeto común	Sivergran
Larix decidua	Larício Europeu	лиственница европейская	Alerce	Europeisklärk

Botanical Name	Danish	Dutch	English	Finnish
Fagus sylvatica	Bøg	Beuk	Common beech	Pyökki
Quercus petraea	Vintereg	Wintereik	Sessile oak	Talvitammi
Quercus robur	Stilkeg	Zomereik	European oak	Metsätammi
Quercus ilex	Steneg	Steeneik	Holm oak	Rautatammi
Quercus suber	Korkeg	Kurkeik	Cork oak	Korkkitammi
Pinus sylvestris	Skovfyr	Grove den	Scots pine	Metsämänty
Pinus nigra	Østrisk fyr	Oostenrijkse/ Corsicaanse zwarte den	Corsican/Austrian black pine	Euroopanmusta-mänty
Pinus pinaster	Strandfyr	Zeeden	Maritime pine	Rannikkomänty
Pinus halepensis	Aleppofyr	Aleppoden	Aleppo pine	Aleponmänty
Picea abies	Rødgran	Fijnspar	Norway spruce	Metsäkuusi
Picea sitchensis	Sitkagran	Sitkaspar	Sitka spruce	Sitkankuusi
Abies alba	Ædelgran	Zilverden	Silver fir	Saksanpihta
Larix decidua	Lærk	Europese lariks	European larch	Euroopanlehti-kuusi

15. SUPPLEMENTARY DOCUMENTS

The American Biogenic Emission Inventory System (BEIS) has resulted in extensive lists of emission potentials. The latest published version is Geron et al. (1994). The updated BEIS-3 version is currently under preparation by Guenther et al. (1998). (Some of these rates have been already adopted in Table 8.1).

A qualitative list of isoprene and monoterpene emitting species is held at:

Hewitt, C. N., R.A. Street and P.A. Scholefield (1998):
Isoprene and monoterpene-Emitting Species Survey 1998.
http://www.es.lancs.ac.uk/es/people/pg/pas/download.html

16. VERIFICATION PROCEDURES

If satellite data have been used in the land-use mapping process it is essential that these are independently verified by on-the-ground surveys. Large errors are possible in the identification of vegetation types and biomass from remote sensing methods.

In general all of the emission potentials are built upon very few data. More measurements are required of at least the major sources, and several different measurement techniques need to be applied in order to eliminate the artefacts (usually enhanced emissions) easily generated by disturbances to the vegetation.

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19.   RELEASE VERSION, DATE AND SOURCE

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SNAP CODE :   **110117**
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SOURCE ACTIVITY TITLE :   **Non-managed broadleaf forest soils**
                                   Non-managed coniferous forest soils
                          Natural grassland and other vegetation soils
                                     Managed broadleaf forest soils
                                     Managed coniferous forest soils

1.   ACTIVITIES INCLUDED

This chapter covers emissions from non-agricultural areas that are produced biogenically in soils. Although the magnitude of emissions from soils may be perturbed and controlled by human activities, the actual processes are considered natural. This version of the chapter deals with only NO_x emissions, mainly in the form of nitric oxide (NO), which are produced by micro-organisms in soil. Natural ecosystems tend to have modest fluxes, but soils that are nitrogen-enriched, especially agricultural regions, may have NO_x fluxes approaching those of anthropogenic sources (Williams et al., 1992). Fluxes of CH4 are not dealt with here as fluxes are expected to be to the ground, not to the atmosphere.

This chapter contains the information required to calculate emissions from soils in five SNAP categories (non-managed and managed, broadleaf and coniferous, forests, and natural grasslands). Emissions from agricultural soils are covered in 100100 (cultures with fertilisers) and 100200 (cultures without fertilisers), although the methodologies are similar.

2.   CONTRIBUTIONS TO TOTAL EMISSIONS

Emissions of NO_x from soils are estimated to be as much as 16% of the global budget of NO_x in the troposphere (Logan, 1983). The contribution of soil NO emissions from agricultural lands has previously been estimated to be 15% of the total European NO_x emissions inventory (Simpson et al., 1995), but emissions from non-agricultural areas are certainly much smaller than this.

3.   GENERAL

3.1   Description

Nitric oxide (as well as N_2 and N_2O) are produced as intermediate steps in microbial nitrification and denitrification processes. As emissions depend on the amounts of nitrogen going through these processes, agricultural soils, subject to direct fertilisation and manure, are responsible for the great majority of emissions, and in some regions may have NO_x fluxes approaching those of anthropogenic sources (Williams et al., 1992).

Soils emit NO_x mainly through biological pathways, and emission rates can be categorised by land use. The quantity of NO_x emissions from agricultural land is dependent on the rate of fertiliser application and the subsequent microbial nitrogen processing in the soil, together with a multitude of other environmental factors. A large number of studies have been discussed in relation to possible controlling factors in Skiba et al. (1997).

Although the magnitude of soil NO_x emissions may be small in overall comparison to anthropogenic NO_x emissions, there is considerable uncertainty in the estimates. Further, soil NO emissions occur in low-NO_x regions where ozone formation is most sensitive to NO_x availability, and the highest fluxes of NO occur in the warmer months of the year--times when photochemical smog is of concern.

3.2   Definitions

Soil NO emissions: nitric oxide produced by micro-organisms in soils, which ultimately "leaks" into the atmosphere.

3.3   Techniques

Current estimation techniques are based on empirical algorithms that account for land use cover and possibly N-inputs and/or soil temperature. These algorithms are based on a limited number of field chamber measurements.

Soil emissions of NO_x are dependent on the crop type and fertilisation rate and on a multitude of other environmental factors. The simple technique is provides an annual estimate based upon N-inputs only, whereas the detailed technique is intended more for modelling purposes and uses the algorithm of Novak and Pierce (1993) that calculates emissions of NO based on land use and temperature.

3.4   Emissions

The current draft of this chapter considers only NO emissions. Other trace gases, such as methane, N_2O, and CO, are known to be emitted from soils but are not yet included in this methodology. For methane, soils, especially within forests, are probably a major sink so it is not clear how emissions should be defined.

3.5   Controls

Nitric oxide emissions from soils are emitted by a natural process, microbial activity in soils. This activity may be influenced by the amount of nitrogen-based fertiliser added to soils, but this discussion is mainly relevant to agricultural emissions, as discussed in chapter 100100 and Skiba et al. (1997).

4.   SIMPLER METHODOLOGY

The simpler methodology is derived from the work of Skiba et al. (1997), who suggested that 0.3% of applied N is returned to the atmosphere as NO. For non-agricultural areas applied N would consist of animal manure and atmospheric deposition. Additionally, a background N-emission rate of 0.1 ng NO-N m^{-2} s^{-1} is assumed. (For agricultural areas the fertiliser application is considered, see 100200 and 100100).

Despite its simplicity, the Skiba et al. approach has the advantage of explicitly relating emissions to applied N amounts.

5.   DETAILED METHODOLOGY

Given the lack of evaluation of any paramaterisations in Europe, a detailed methodology is probably not worthwhile for estimates of annual emissions. However, in case hourly changes in emissions are required (e.g. for modelling) the following methodology is proposed. Unfortunately, the simple and detailed methodologies are not consistent - they produce quite different annual estimates. However, until more is known about the merits of either method a consistent description cannot be provided.

This methodology is taken from Novak and Pierce (1993) and is known commonly as the second-version of the Biogenic Emissions Inventory System (BEIS-2). BEIS-2 can estimate NO emissions for forests, agricultural crops, urban trees, and grasslands. BEIS-2 calculates a range of emission flux rates based on land use types and soil temperature. The basis of the BEIS-2 calculation for soil NO emissions originates with the following equation (Williams et al., 1992):

$$F_{NO} = A \times \exp(0.071 \times T_s)$$

where

F_{NO}	=	NO flux, (ng N m^{-2} s^{-1})
T_s	=	Soil temperature, degrees Celsius
A	=	Experimentally derived constant for the land use types of grasslands and pasture, forests and wetlands.

The parameter A is given in Table 8.1. Emissions from soils at sub-zero temperatures can be assumed to be zero for inventory purposes.

6.   RELEVANT ACTIVITY STATISTICS

For all approaches land use coverage is required, at least to distinguish agricultural and forest and other soils. For the simple methodology an estimate of N-inputs is required. This can be obtained from national deposition estimates or EMEP modelling. For the detailed approach air temperature statistics are needed.

7.   POINT SOURCE CRITERIA

No point sources.

8.   EMISSION FACTORS, QUALITY CODES AND REFERENCES

A large number of emission factors based on field measurement data are given in the literature. Williams et al. (1992), Yienger and Levy (1995) and Skiba et al. (1997) provide excellent reviews on these data. Emission factors are given as a function of land use and other environmental conditions, such as temperature, soil moisture, and soil nitrate levels. The variation in these measurements is considerable, resulting in a wide range of uncertainty in current emission factors. Williams et al. estimates an annual uncertainty of about a factor of three. The quality code for soil NO emission factors thus should be considered a D.

The factors required for the application of the detailed methodology (recommended for modelling hourly emissions, rather than annual) are given in Table 8.1.

Table 8.1:   Empirical coefficients for BEIS-2 system, from Novak and Pierce, 1993

Land use category	A	Function to compute T_s (°C) from ambient temperature (T_a).
Grasslands + pasture	0.9	$T_s = 0.67\ T_a + 8.8$
Forest	0.07	$T_s = 0.84\ T_a + 3.6$
Wetlands	0.004	$T_s = 0.92\ T_a + 4.4$

Valid for $0 < T_s < 35$ (°C).

9.   SPECIES PROFILES

Nitric oxide (NO) is considered to be the predominant NO_x compound emitted from soils.

10.   UNCERTAINTY ESTIMATES

The uncertainty of soil NO emission estimates is reported by Williams et al (1992) to be about a factor of three, when averaged over the United States on an annual basis. In view of the poor coverage of data across Europe, especially in Mediterranean areas, a factor of five uncertainty seems reasonable. Additional field studies comparing atmospheric measurements of NO_x fluxes with soil emissions derived from chamber measurements are needed to reduce this uncertainty.

11.   WEAKEST ASPECTS/PRIORITY AREAS FOR IMPROVEMENT IN CURRENT METHODOLOGY

In developed areas of the world, such as Europe, the greatest uncertainty in total soil NO emissions is the amount of NO emitted from heavily-fertilised farmland. Little information is available on emissions from natural grasslands (see e.g. Skiba et al., 1997). Studies are needed

to determine the fraction of nitrogen inputs that are subsequently released into the atmosphere as NO. The role of plant canopies in mitigating the flux of NO into the free atmosphere also needs to be explored.

12. SPATIAL DISSAGGREGATION CRITERIA FOR AREA SOURCES

The spatial disaggregation of soil NO emissions depends on the spatial distribution of land use, with agricultural cropland being the most important.

13. TEMPORAL DISSAGGREGATION CRITERIA

Many meteorological processes affect the temporal distribution of soil NO emissions. These processes and parameters include soil temperature and rainfall (which affects soil moisture).

14. ADDITIONAL COMMENTS

Emissions of NO from soils is both a natural and anthropogenic-influenced source. Although emissions occur as a result of biogenic processes, the magnitude of soil-generated NO is influenced by human cultivation, fertiliser application, animal management and deposition onto the soil.

A more detailed method than those suggested here has been presented in Yienger and Levy (1995) and was initially used for global soil NO_x emissions. In this approach, the variation in soil NO emissions is associated with biomass burning, history of soil moisture (pulsing), temperature, soil moisture, vegetation cover type (biome), canopy reductions, and fertilisation rate. Temperature is calculated from air temperatures using the same empirical relationships used in Novak and Pierce for wet soils, and by adding 5° C to dry soils, based on observations reported in Johansson et al., 1988. In dry soils, rather than an exponential increase, emissions increase with temperature, in a weak linear relationship.

Apart from the differences in methodology, the Yienger-Levy and Skiba approaches differ greatly in their assumption of the fraction of applied N (fertiliser, etc.) which is released as NO. Yienger and Levy assume 2.5%, whereas Skiba et al. assume 0.3% (NO as N). As the Skiba et al. figure is based upon a larger literature than Yienger and Levy and includes many European measurements it is probably a better estimate for European inventories, but the range illustrates well the uncertainties associated with this emission source.

15. SUPPLEMENTARY DOCUMENTS

16. VERIFICATION PROCEDURES

Because the emission factors are largely based on soil chambers, independent verification of the fluxes into the free atmosphere is needed. This verification is expensive, but may be accomplished using micrometeorological techniques that examine either the gradient in NO_x concentration differences with height or direct eddy correlation of NO_x fluxes. The rapid conversion of freshly-emitted NO into NO_2 in the presence of O_3 complicates the measurement and interpretation of micrometeorological flux data.

17. REFERENCES

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18. BIBLIOGRAPHY

19. RELEASE VERSION, DATE AND SOURCE

SNAP CODE :   **1104**
                                                                                    110401
                                                                                    110402
                                                                                    110403
                                                                                    110404

SOURCE ACTIVITY TITLE :   **Natural Grassland and Other Vegetation**
                                                                              Grassland
                                                                                Tundra
                                                                    Other Low Vegetation
                                                                       Other Vegetation

PARCOM-ATMOS CODE :

NACE CODE :

1.   ACTIVITIES INCLUDED

This chapter deals with NMVOC emissions from all types of grasslands and other types of vegetation (natural, semi-natural and in some cases cultivated) which do not fit easily into the forest classification. This includes especially the Mediterranean maquis/garrique and other low scrub-type vegetation, heathland, Tundra, etc. Table 1.1 outlines some examples within the SNAP codes.

Most of the grasslands in mid- and northern Europe are agriculturally used for either harvesting hay (meadows) or for grazing (pastures). Natural grasslands can be found in alpine regions above the timberline (alpine Tundra), at lower elevation northwards of the timberline (boreal Tundra), in dry climatic regions with poor soil (Steppe), on saltfloors and on moorland.

Low vegetation (< 5 m height) , apart from grassland, is widespread across Europe. For example, in many parts of Europe moorland and heathland cover large areas, with *Erica sp,* *Ulex sp., Calluna sp., Pteridium sp.,* and similar species being common. In the Mediterranean region maquis, garrique and jaral are characteristic landscapes (see definitions, 3.2).

Many types of vegetation could be covered within this system, and many overlap with other SNAP categories. E.g. reed vegetation, or maritime coastal vegetation (halopsammophytic), could be included here or under SNAP1105 (wetlands). Unfortunately, we have no information on emission rates yet, so this particular problem does not arise. More importantly, methods are given here for calculating VOC emissions from Agricultural crops such as wheat, as the methodology is identical to that for other vegetation. These emissions should be entered under SNAP-level 10-Agriculture, and not SNAP-11 - Other sources and sinks.

Emissions of N_2O are assumed to follow IPCC methodologies and so are not covered here. Emissions of NO_x from the soil are dealt with in a separate chapter covering all types of forests and grasslands. Emissions arising from fires are covered in SNAP 1103 (Forest and

other vegetation fires). Emissions of CH_4 should strictly be treated also in the soils section, but in any case are assumed to be zero (the flux is probably to the ground, not to the atmosphere).

Table 1.1:   Classification scheme for grassland and other non-forest vegetation in Europe

110401	Natural grassland
	Pastures, Meadows,
	Steppe
110402	Tundra
	alpine Tundra, boreal (treeless) Tundra
110403	Other low vegetation
	Heathland, Moorland
	Miscellaneous dwarf shrub vegetation(Garrique etc.)
110404	Other vegetation
	Maquis
100205	Grasslands (Agricultural)
	Agricultural grassland of low and medium productivity (< 8 t ha^{-1} yr^{-1} yield),
	Agricultural grassland with high productivity (> 8 t ha^{-1} yr^{-1} yield)

2.   CONTRIBUTIONS TO TOTAL EMISSIONS

According to the CORINAIR-1990 inventory, natural grassland accounts for 0.6% of European NMVOC emission, 0.4% of CH_4 emissions, 2.9% of N_2O emissions and 0.3% of NH_3 emissions. However emission rates for NMVOC need to be substantially revised. Simpson et al., 1998, using the recommended defaults in this chapter estimate that pastures and meadows may contribute nearly 1 Mt to European NMVOC emissions (ca. 4%) and crops also ca. 1 Mt. Uncertainties are still very large and in some other areas emissions might be appreciable, e.g. the NH_3 emission from pastures (due to animal droppings) and meadows (in particular when fertilised with manure).

The area coverage of grasslands in Europe is second highest after forests, however the biomass density of grasslands is often lower than the foliar biomass density of forests.

The emissions from other low vegetation were not covered in CORINAIR-90/94, however their emissions may have been included by some countries under the "forest" SNAP codes.

3.   GENERAL

3.1   Description

Emissions of NMVOC from plants are usually divided into isoprene, monoterpene, and OVOC (other VOC) emissions for inventory purposes. In general isoprene and monoterpene emissions are the most photochemically reactive and hence of most interest for ozone studies. However, for grasslands the major emission probably consists of OVOC, and these may be significant in mass terms.

Only a small number of screening studies have been undertaken until now to survey biogenic VOC emissions from non-forest vegetation.

Hewitt & Street (1992) tested the 21 most abundant grass and herbaceous species in the U.K with a qualitative method. Only purple moor grass (*Molinia caerulea*), bracken (*Pteridium aquilinum*) and common gorse (*Ulex europaeus*) were found to emit isoprene, and only ivy (*Hedera helix*) and cocksfoot grass (*Dactylis glomerata*) found to emit monoterpenes. 28 species of agricultural crops were also screened, of which only blackcurrant (*Ribes nigrum* v. Ben Sark and Ben Lomond) produced any significant emissions. The only major species, in terms of abundance, of which no varieties were tested was winter barley (*Hordeum vulgare*). As pointed out by Hewitt & Street, genetically different varieties of the same species may display different emission characteristics to those found above, but these data strongly suggest that isoprene as well as terpene emissions from crops and grasses are not important in the U.K. This result supports the previous findings that grasses and grass related crops are generally no or low emitters for isoprene and terpenes. (However, other VOC emissions are probably very significant).

A compilation of biogenic VOC emissions from crops and "hay" (meadows for hay production) from US sites is found in Lamb et al. (1993). Except for Tomato and Maize (Corn) all agricultural crops tested as well as "hay" were classified as "low emitters" (emission rate of all VOC determined < 1 µg g^{-1} h^{-1} DW) in the Lamb et al. (1993) study (Table 8.4). However, in their compilation the chemical nature of VOC other than isoprene and terpenes (OVOC) has not been specified, though for several crop species the OVOC emission rate exceeded the emission rates of the "classical" biogenic VOCs isoprene and terpenes. Arey et al. (1991) and Winer et al. (1992) investigated emission rates from a number of agricultural crops and from a perennial grassland plot in the US in more detail (Table 8.1). They specified the "OVOCs" and found (Z)-3-hexenol ("leaf alcohol") and (Z)-3-hexenylacetate ("leaf ester") in many crops as the two most dominant compounds of the group of "OVOCs".

Very little is known of emissions from shrubs and bushes, except that obtained as a result of a limited number of intensive field campaigns held at a few locations in the north-western Mediterranean region, as part of the Biogenic Emissions in the Mediterranean Region (BEMA) project (e.g. Owen et al, 1997) and in the U.K. (e.g. Cao et al., 1997). Additionally a limited amount of screening work has been carried out on these ecosystems (e.g. Hewitt and Street, 1992).

However, the vegetation species found in these ecosystems are often very aromatic and hence may be expected to emit a very wide and complex range of volatile organic compounds. This is especially so for Mediterranean vegetation. By far the majority of efforts to date have been focused on the emissions of isoprene and monoterpenes, so it is difficult to quantify the emissions of these other VOC, including the oxygenated compounds. Additionally, nothing is known of the emission of nitrogen and sulphur compounds from these plants.

There are very few data about VOC emissions from single herbaceous species which may occur in certain areas in relatively large quantities. An example is *allium ursinum* (wild garlic) which grows in mid and northern Europe in beech and other mixed hardwood forests in spring with biomass densities up to 300 g m^{-2}. Although wild garlic emits no isoprene and only a little of terpenes, the emission rate of OVOCs was found to be 2.6 µg g^{-1} h^{-1} DW (Puxbaum & König 1997) and thus it can be classified as "high OVOC - emitter". Similarly Tanner & Zylinska (1994) found relatively high emission rates of oxygenated terpenoids (> 4 µg g^{-1} h^{-1} DW) in undercover vegetation (tarweed) in the San Joaquin Valley. Although these examples are for species under forests - and not in grasslands, they might indicate that there might be grassland biomes which contain herbaceous plants with higher emission rates than those to be recommended in section 8.

König et al. (1995) tested VOC emissions from agricultural plants such as wheat, rye, rape, grape and three types of grassland in East Austria. They used the Arey et al. (1991) approach to include also specified OVOC emissions. In terms of prevalence of one of the groups of emitted VOCs (isoprene, terpenes, OVOC) wheat, rye, oilseed rape, grape and two of the grass plots examined were "OVOC" - emitters. However, for one of the examined grass plots, terpene and OVOC - emissions were of equal importance (grassland A3, Table 8.2). After mowing of one of the grass plots the emissions of terpenes and OVOCs increased roughly by a factor of three. The same group performed a measurement campaign in Northern Germany in 1995. Although the results are not published until now, we include the data for an examined grass plot (grassland G in Table 8.2, Puxbaum et al., in preparation). The data fit well into the results for grasslands from the above mentioned studies from the US and Austria.

3.2   Definitions

OVOC - Other non-methane VOC, excluding isoprene and terpene. Usually used to encompass a wide range of emitted VOC - see section 9.

BMD - Biomass density (g m^{-2} DW) averaged over vegetation period

DW - dry weight of plants(used for emission rates), as opposed to fresh weight.

NPP - Net primary production (g Carbon m^{-2} yr^{-1}) Buildup of biomass carbon during a year

PAR- Photosynthetically active radiation, typically about 45-50% of total global radiation.

Grasslands are areas which are dominated by grassy plants, but usually also containing other herbs. There are mainly two families of grassy plants: *poaceae* ("sweet grasses") and

cyperaceae ("acidic grasses"), the first of the two occurring most frequently in European grasslands.

Tundra - vast level treeless (almost) Arctic region where subsoil is frozen.

Names and definitions of Mediterranean landscape classes vary from country-to-country and from author-to-author (Di Castri et al., 1981). However the following are in common usage:

Maquis
-       also known as matorral denso, espinal (ES), chaparral (UK, USA), macchia alta (IT).
-       comprising evergreen shrubs and small trees, typically olive (*Olea oleaster*),   carob (*Ceratonia siliqua*), dwarf *Quercus ilex* and *Erica multiflora*

Garrique
-       also know as maturral claro (ES), scrub (UK), macchia bassa (IT)
-       comprised of mid-height shrubs, 0.6-2 m high on calcerous soils, typically *Pistachia lentiscus*, *Arbutus unedo*, *Myrtus communis* and *Ulex sp.*

Garrique is sometimes used for vegetation less than 0.6 m high also, in which case **lande** (FR), **tomillar** (ES), **gairriga** (IT), **phyrgana** (GR) are alternative names.

Jaral
-       similar sized shrubs on siliceous soils, e.g. *Erica sp.*, *Cistus sp.*

3.3   Techniques

Not applicable

3.4   Emissions

This chapter deals with NMVOC - emissions of grassland and other low vegetation including crops. As for forests, NMVOC species are classified into three groups: Isoprene,   Terpenes (Mono- and Sesquiterpenes), OVOC (other VOC). The composition of OVOC is discussed in section 9.

3.5   Controls

Principally there seems to be no control to natural emissions by definition, however land-use changes obviously can significantly affect total emissions (e.g. very early changes which date back to the bronze age, when forests were cleared in Europe to gain agricultural land and meadows, or more recent changes due to nitrogen deposition where heather gets converted to grassland).

4.   SIMPLER METHODOLOGY

Grasslands and other low vegetation ecosystems consist generally of plant communities (except for crops which are usually monocultures). Often a few species dominate the community. We introduce a classification scheme for grassland and other low vegetation in Europe (Table 8.2), but emission rate data for grasslands are not available for the different types. Similarly for Mediterranean shrubland landscapes it does not seem possible at present to subdivide into species for inventory purposes, and northern moorlands and heathlands must also be treated together.

We therefore recommend the use of ecosystem-wide rates for dealing with these types of vegetation. However, we give emission rates for individual species where known. These may be used to devise more appropriate ecosystem rates for particular regions, or to conduct a species-specific approach if desired.

For all types of vegetation, an appropriate system describing the emissions flux on an hourly basis is that of Guenther et al. (1996):

$$\text{Flux } (\mu g \, m^{-2} \, yr^{-1}) \;=\; \int \varepsilon . D . \gamma \;\; dt \qquad\qquad (1)$$

where ε is the average emission potential ($\mu g \, g^{-1} \, h^{-1}$) for any particular species, "D" is the foliar biomass density (g dry weight foliage m^{-2}), and γ is a unitless environmental correction factor representing the effects of short-term (e.g. hourly) temperature and solar radiation changes on emissions. For isoprene emissions, and light-activated terpene emissions (so far only quantified for two forest species, *Picea abies* and *Quercu ilex*), γ is a function of light and temperature, and is denoted γ-iso. Terpene and OVOC emissions from most vegetation types are simply dependant on temperature, in which case γ is temperature-only dependant, and denoted γ-mt.

The simplified methodology consists of modifying equation (1) to be a seasonal rather than an hourly calculation.

$$F = \varepsilon . D . \Gamma \qquad\qquad (2)$$

Where Γ represents the integrated value of γ over the growing season of the vegetation concerned.

The total emission from an area is then obtained in a detailed methodology by calculating F every hour for each vegetation category and group of VOC compounds and multiplying by the appropriate areas.

Using meteorological data from the EMEP MSC-W models the integrated values, Γ-iso and Γ-mts, have been calculated for both 6 monthly (May-October) and 12 monthly growing seasons, as averages over each country. These have been calculated from hourly γ values, and thus have units of hours. The Γ values are tabulated in Table 4.1. With this simplified

methodology we could estimate for example the OVOC emissions from 1 km^2 of grassland as simply:

Emission   = Area x ε . D . Γ-mts

= 1000 000 m^2 x 1.5 $\mu g \, g^{-1} \, h^{-1}$ x 500 g m^{-2} x Γ-mts h

For Austria, for example, Table 4.1 gives Γ-mts (=Γ-ovoc) for 6-months as 588, therefore we have:

Emission = 1000 000 m^2 x 1.5 $\mu g \, g^{-1} \, h^{-1}$ x 500 g m^{-2} x 588 h = 441 kg km^{-2}

Table 4.1: **Country average values of integrated environmental correction factors, Γ-iso and Γ-mts for 6 and 12 month growing seasons (unit= hours).**

	Γ-mts (= Γ-ovoc)		Γ-iso	
	6-month	12-month	6-month	12-month
Albania	745	976	563	719
Austria	588	734	452	540
Belarus	753	895	581	684
Belgium	739	969	580	712
Bosnia Herzegovina	709	893	561	686
Bulgaria	824	1029	620	755
Croatia	883	1121	667	815
Czech_Republic	712	885	533	633
Denmark	518	704	373	485
Estonia	565	669	422	491
Finland	458	523	339	379
France	840	1107	669	829
Germany	698	890	525	632
Greece	1076	1440	816	1057
Hungary	966	1188	730	874
Ireland	467	713	337	478
Italy	904	1208	711	902
Latvia	636	757	486	572
Lithuania	675	813	516	613
Luxembourg	786	1003	620	745
Macedonia,F.Y.R.	631	783	492	597
Moldova, Rep. of	858	1040	649	771
Netherlands	676	901	513	643
Norway	327	397	240	284
Poland	736	912	558	669
Portugal	1015	1388	853	1093
Romania	783	964	587	706
Russia, Fed.	808	917	637	717
Slovakia	797	977	607	724
Slovenia	745	940	562	682
Spain	982	1301	806	1004
Sweden	423	508	315	368
Switzerland	465	580	368	432
Turkey	976	1263	783	983

	Γ-mts (= Γ-ovoc)		Γ-iso	
	6-month	12-month	6-month	12-month
United_Kingdom	493	720	358	492
Ukraine	856	1023	656	771
Yugoslavia	752	937	557	674

5.   DETAILED STATE OF THE ART METHODOLOGY

For a more detailed calculation the environmental correction factors (γ-iso, γ-mts) may be calculated explicitly on a monthly or an hourly basis if relevant meteorological data are available. The procedure is identical to that presented for forest emissions in 1101, 1102, and is not repeated here.

6.   RELEVANT ACTIVITY STATISTICS

The relevant statistics are vegetation cover, foliar biomass density, and possibly monthly and/or hourly temperature and radiation parameters if the detailed methodology is to be pursued.

Vegetation coverage in terms of the vegetation types discussed in section 8 are required, together with foliar biomass estimates (D), and estimates of growing seasons. Grasslands are found in land use statistics generally under grassland, pastures and possibly meadows. Care should also be taken not to double count species/vegetation types.

We have not found a comprehensive discussion of biomass densities. However, there is information about the annual net primary production (Ruimy et al., 1994, Lieth and Whittaker, 1975). Data for natural grasslands are compiled in Table 6.1.

Table 6.1: Compilation of Annual Net Primary Production for Grasslands (g C m^{-2} yr^{-1}) according to Ruimy et al. (1994) and Lieth and Whittaker (1975) and estimate for default biomass density values. BMD = Biomass density.

	"REF" Ruimy et al.	"MEAN" Lieth&W	default BMD g m^{-2} DW
Tundra	100	50	100
Savanna	530	400	500
Temperate grasslands	470	300	450

Notes: The default biomass densities (BMD) are derived in the following way: The net primary production is the build up of new biomass in the vegetation period in g C m^{-2} yr^{-1}. The conversion factor from C (Carbon) to biomass DW is 2.2 (Ruimy et al., 1994). It is assumed that 50 g m^{-2} biomass is remaining from the past year. The new (at the end of the vegetation period) and old biomass value is averaged over the vegetation period.

For Alpine grasslands the following defaults are recommended:

	D (g m^{-2} DW)
Alpine pastures above timberline:	50
Mid productivity alpine grassland (1-3 cuts)	200

For heathlands and moorlands very little data is available. We recommend a default based upon the biomass density of Gorse, which is widespread in the UK, assuming 50% coverage:

	D (g m^{-2} DW)
Heathland /moorland	175

For Mediterranean scrublands, the following are recommended:

Maquis	400
Garrique/low-scrubland	200
Monte-hueco*	100

* mixed pastures and trees, mainly Holm and Cork oaks.

For Karelian (Russian) spruce forests (marshy-grassy-types) the following data are available. The ground-biomass densities of Russian forests are probably larger though than those of many managed forests in other parts of Europe:

	D (g m^{-2} DW)
Forest grass-biomass	90
Forest ferns	14
lichen+mosses	100-300
shrub, including berries	10-30

For a more detailed evaluation of D, local information is required. Some insight about the biomass of meadows can be obtained from harvest yields of hay. In Austria the yield of hay is of the order of 6-10 t ha^{-1} and more, which is equivalent to 600-1000 g m^{-2} harvested dry biomass. The frequency of harvests per year is 1-6, depending of altitude and fertilisation. If we assume that after harvest a biomass density of 50 g m^{-2} remains, and there is a linear growth rate between harvests, the annual average biomass density is estimated to 200-300 g m^{-2}. This number is for medium productive grassland in the alpine region and is lower than Lamb et al's (1987) estimate for meadows for hay production in the US of 540 g m^{-2}. However, in highly productive grasslands in flat terrain in Europe the biomass density might be as high as the Lamb et al. 1987 estimate.

For agricultural grassland an estimation of the vegetation period averaged biomass density can be obtained by the following formula:

$$BMD = [Y * 100/2 * n] + 50$$

Where BMD is biomass density (g m^{-2} DW), Y is yield of biomass DW per vegetation period (t ha^{-1}), n is the number of cuts per year, and 50 is the biomass remaining after cutting

7.   POINT SOURCE CRITERIA

No point sources

8.   EMISSION FACTORS, QUALITY CODES AND REFERENCES

NMVOC

For grassland areas the emission potentials (ε, equation 1) should be given as standardised values at 30 °C and for full sunlight=1000 μmole photons m^{-2} s^{-1} PAR. A summary of default ecosystem-type emission factors which seem appropriate especially for European species is given in Table 8.1 below

Table 8.1. Ecosystem-default emission potentials (ε) for isoprene (iso), terpenes (mts) and OVOC, and biomass densities. ε (μg g^{-1} DW h^{-1}) is given for 30°C and 1000μmol PAR.

Ecosystem	D (g m^{-2} DW)	ε-iso	ε-mts	ε-ovoc	Main reference
Grass	400*	0	0.1	1.5	K
Maquis	400	8	0.65	1.5	O,G95
Garrique	200	8	0.65	1.5	O, G95
Monte-hueco	100	1	10**	1.5	***
Moorland/heathland	350	8	0.65	1.5	C

Notes: * but see section 6 for Alpine grasslands; ** Calculate with γ-iso. All other terpenes with γ-mts; *** Assumes ca. 50% *Q.ilex*, 50% *Q.suber*; K=König et al., 1985, C=Cao et al., 1997, G95=Guenther et al., 1995, O=Owen et al. 1997

It is important to note that the 1.5 μg g^{-1} h^{-1} rate for OVOC given here is a default (from Guenther et al., 1995) with a wide uncertainty range. Almost all measurements have used methods for the determination of VOCs, which are not capable of finding and quantifying polar compounds with less than four carbon atoms (e.g. methanol, formaldehyde, etc.). For this reason the OVOC results in these tables also list separately OVOC $\geq C_4$ and OVOC$<C_4$ if known. Recently it was shown that plants may emit methanol (MacDonald & Fall 1993), low molecular weight aldehydes (Kotzias et al. 1997) and low molecular weight organic acids (Bode et al. 1997) in relevant quantities. For grasslands and crops no data are available however to quantify this further.

The following tables give species-specific emission potentials and some more detail about the OVOC split.

Table 8.2: Species-specific emission potentials in μg g^{-1} h^{-1} dry weight of plants for grassland (SNAP 110401) normalised to 30°C, PAR levels not specified

	Biomass density g m^{-2}	ε-iso	ε-mts	ε-ovoc	OVOC split ($>C_4,<C_4$)	Refs
USA:						
"hay"	540	0.07	0.175	1.5	(0.11*,n.a.)	L
Grassland[#]		n.d.	0.015	1.5	(0.06,n.a.)	A/W
Europe:						
Grassland A1		0.001/C[§]	0.02	1.5	(0.015,n.a.)	K
Grassland A2	300	0.002/S[§]	0.015	1.5	(0.06,n.a.)	K
Grassland A3	420	0.003/S[§]	0.07	1.5	(0.08,n.a.)	K
Grassland A3m (after mowing)	420	0.002/S[§]	0.20	1.5	(0.27,n.a.)	K
Grassland G	230	n.d./xx[§]	0.03	1.5	(0.15,n.a.)	P/
Recommended default for grassland	**400****	**0**	**0.1**	**1.5**		

Notes: n.d. not detected; n.a. not analyzed; S[§] measured under sunny conditions; C[§] measured under cloudy conditions; *OVOC not specified; ** see also section 6. ; [#] perennial natural grassland; A1) grassland under oak forest; A2) grassland with no flowers, 35 cm height; A3) grassland with some flowers, 25 cm height; A3m) grassland 3 mowed; G grassland in northern Germany.

Refs: L: Lamb et al. 1987, 1993, A/W: Arey et al. 1991, Winer et al. 1992, K: König et al. 1995, S: Street et al. 1997, P: Puxbaum and König 1997, P/: Puxbaum et al. in preparation, Tanner and Zylinska 1994.

Table 8.3: Species-specific emission potentials in μg g^{-1} DW h^{-1} for shrubs and low vegetation, standardised to 30 °C and 1000 μmol m^{-2} s^{-1} PAR.

NOTE: Many tree species can be shrub like - their emission potentials may be found for these in the chapter covering forests (SNAP1101,etc.)

Common name (example)	-	ε-iso.	ε-mts	ε-ovoc$	References Iso	Terp.
Wild garlic	Allium_ursinum	0	0	3	P	P
-	Anthyllis	0.1	0.2	1.5	O	O
Strawberry tree-	Arbutus	0.1	0.2	1.5	B3,O	O
-	Arundo	60	0.2	1.5	O,H90,B3	B3
	Artemisia	0	0.2	1.5	P/	P/
Dwarf_boxwood	Buxus	10	0.2	1.5	O,B3	B3
Carob	Ceratonia	0.1	0.65	1.5	O	O
	Chrysanthenum	0.1	0.65	1.5	O	O
rockrose	Cistus	0.1	0.2	1.5	O	O
Broom	Cytisus	20	0.2	1.5	S:Sf;B3	B3,-O
Tree_heath	Erica	5	0.2	1.5	S:Sf:O	B3,O
	Helichrysum	0.1	3	1.5	O	O
Tarweed	Holocarpha	0	3	3	TZ	TZ
Juniper	Juniperus	0.1	0.65	1.5	S:Sf;B3	B3,O
Lavender	Lavendula	0.1	0.65	1.5	S	O
Common_myrtle	Myrtus	34	0.2	1.5	S:Sf;B3	O
	Phillyrea	0.1	0.65	1.5	O	O
	Rhamus	20	0	1.5	O,B3	B3
Rosemary	Rosmarinus	0	1.5	1.5	S:Sf	Ha
Sage	Salvia	0.1	1.5	1.5	B3	B3
Broom	Spartium	5	0.2	1.5	S:Sf;O	B3,O
Bil/blueberry	Vaccinium	0.1	0	1.5	B3	B3
Gorse	Ulex	8	0.65	1.5	S:B,i6;C;B3	B
Grape	Vitis	0.1	0.1	1.5	B3	A,-K

Notes: $We have used a default ε-OVOC of 1.5 μg g^{-1} h^{-1} for all compounds except Wild garlic, which includes 1.6 μg g^{-1} h^{-1} oxygenated compounds, 1.0 μg g^{-1} h^{-1} h carbon from sulphurous organics, and tarweed for which TZ give higher rates. References as for Table 8.1, plus B3=Guenther et al. 1998, O=Owen et al.,1997, Sf=Seufert et al., 1997.

Table 8.3: Emission rates in µg h^{-1} g^{-1} dry weight of plants for crops, normalised to 30°C, PAR levels not specified

	Biomass density g m^{-2}	ε-iso	ε-mts	ε-ovoc	Measured OVOC split ($>C_4,<C_4$)	Authors
Wheat (*Triticum*):						
USA	740	0.002	0.008	1.5	(0.03*,n.a.)	L
USA	n.a.	0	0	1.5	(0.05,0.5*)	A/W
Europe (after bloom)	800	0/S§	0	1.5	(0.016,n.a.)	K
Rye *(Secale)*:						
USA	2430	0.003	0.008	1.5	(0.005*,n.a.)	L
Europe	400	0/S§	0.10	1.5	(0.25,n.a.)	K
Barley ():						
USA	1290	0.006	0.015	1.5	(0.009,n.a.)	L
Oats *(Avena)*:						
USA	750	0.01	0.026	1.5	(0.0015*,n.a.)	L
Recommended default for grass related crops	**800**	**0.002**	**0.1**	**1.5**		
Other crops:						
"High emitters":						
Maize/Corn US	1610	0	0.22	1.5	(0.88*,n.a.)	L
Maize/Corn Europe	n.a.	0	0	1.5	6.4 1.0	S R
Tomato (S.)	n.a.	0	13.2	1.5	(0.4,n.a.)	A/W
Tomato (C.)	n.a.	0	21.8	1.5	(1.2,n.a.)	A/W
Miscellaneous						
Alfalfa	3250	0.005	0.2	1.5	(0.6,n.a.)	L, A/W
Safflower	n.a.	0	0.3	1.5	(0.7,n.a.)	A/W
Sorghum	3180	0.002	0.03	1.5	(1.0,n.a.)	L, A/W
Rice	1050	0.10	0.24	1.5	(0.15*,n.a.)	L
Tobacco	490	0	0.12	1.5	(0.48*,n.a.)	L
Soybeans	740	0.03	0	1.5.	(n.a.,n.a)	L
Sunflower	n.a.	0.05	0.7	1.5	(0.3,n.a.)	SCH
Oilseed Rape	400	0/S§	0.12	1.5	(0.23,n.a.)	K
Grape:						
USA (T.S.)	n.a.	0	0	1.5	(1.4,n.a.)	A/W
USA (F.C.)	n.a.	0	0.07	1.5	(1.3,n.a.)	A/W
Europe (Ch.)	410/l.o.	0.002/S§	0.002	1.5	(0.05,n.a.)	K
Misc. crops default	**1335**	**0.09**	**0.13**	**1.5**	**(0.6,0.9)***	

Notes: 0 not detected. n.a. not analyzed. S§ measured under sunny conditions.

*OVOC not specified; *** the OVOC <4C emission rate is a guess based on very little data l.o. leaves only.

Refs: L: Lamb et al. 1987, 1993, A/W: Arey et al. 1991, Winer et al. 1992, K: König et al. 1995, S: Street et al. 1997, R: Rudolph et al. (in press).

9.   SPECIES PROFILES

As with forest NMVOC emissions, biogenic emissions from grasslands consist of a wide variety of species, including isoprene, monoterpenes, (alpha-pinene, beta-pinene, limonene, etc.), and 'other' VOC. The 'other' VOC (OVOC) species consist of a large number of oxygenated compounds (alcohols, aldehydes, etc.), and have proven difficult to quantify in atmospheric samples. Progress in quantification of OVOC from European vegetation has been made recently (König et al. 1995, Puxbaum 1997), although many more measurement data will be required before reliable attempts to inventory specific OVOC can be made.

Section 8 has already presented separate emission rates for isoprene, terpenes, and $<C_4$, $>C_4$ OVOC. However, within each of these groups a wide range of species are emitted, as indicated by Table 9.1.

Table 9.1. Main emitted single VOC species (Rank 1-3) emitted from grassland plots and various crops (compiled from König et al. 1995 and Puxbaum et al. in preparation). Note that $<C_4$ organic compounds have not been determined in these studies.

Plot	Rank 1	Rank 2	Rank 3
Grassland A1	a-Pinene	Leaf ester	Hexanal
Grassland A2	Leaf ester	Leaf alcohol	Limonene
Grassland A3	Leaf ester	1,8-Cineol	a-Pinene
Grassland G	Pentanal	Leaf ester	Limonene
Wheat	Leaf ester	Hexanal	2-Pentanone
Rye	1-Hexanol	Leaf alcohol	2-Methyl-1-propanol
Rape	Leaf ester	Limonene	Sabinene
Grape (Chardonnay)	Butanone	Leaf ester	Hexanal

Leaf ester: (Z)-3-hexen-1-ol-acetate, Leaf alcohol: (Z)-3-hexen-1-ol

10.   UNCERTAINTY ESTIMATES

With so few data it is very difficult to quantify the uncertainties. Quality codes for all grassland vegetation should probably be "E".

11.   WEAKEST ASPECTS/PRIORITY AREAS FOR IMPROVEMENT IN CURRENT METHODOLOGY

Very few measurements are available of VOC emissions from natural grasslands. Emissions of "other" VOC" $< C_4$ in particular (see e.g. aldehyde and ketone emissions from corn as determined by Street et al. 1997) are possibly significant but virtually unquantified for grasslands. In the same way emissions of "other" VOC" $< C_4$ for crops are unknown.

More data are needed about NMVOC emissions for major grassland and shrub-type biomes in Europe, in particular also from Northern, Eastern, and Southern Europe. E.g. there is hardly any information about heather , Tundra, grasslands in the mountainous regions in Northern Europe with ferns and other scrub, alpine pastures, Steppe, etc.

12.   SPATIAL DISAGGREGATION CRITERIA FOR AREA SOURCES

Given by vegetation coverage and climate.

13.   TEMPORAL DISAGGREGATION CRITERIA

Given by equation (1) if required. It has to be kept in mind, that grassland vegetation in Europe is generally perennial, although in some cases snow-covered. However no data about emissions in the cold season are known.

A detailed treatment could also take into account the changes in biomass density over the growing season. Methods are given in Guenther et al., 1995, for many vegetation types which allows for the gradual changes in biomass dependant on NPP. A more extreme temporal variation is caused by cutting on agricultural or semi-natural areas: an example an alpine meadow at lower elevation with 3 cuts in a season is shown in Figure 13.1.
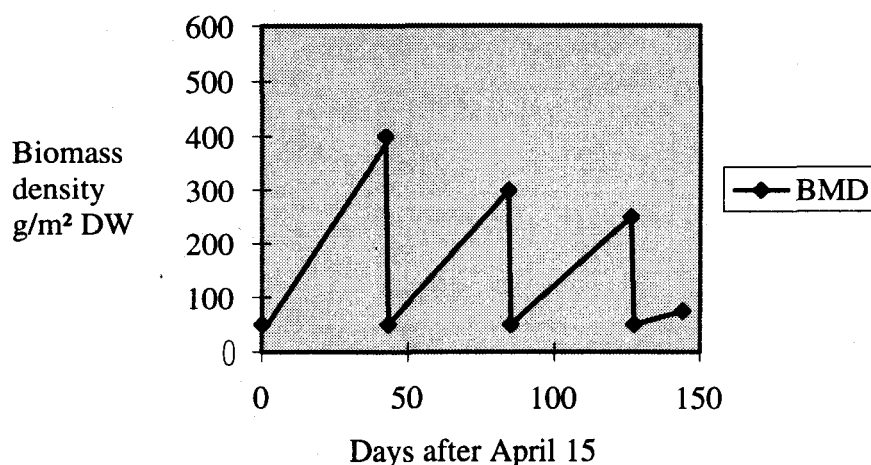
Figure 13.1: Biomass development on a 3-cut alpine meadow

14. ADDITIONAL COMMENTS

For modelling purposes the terpenes and OVOC emissions have to be speciated in some way. As the major emission is OVOC, one could use methanol for the $<C_4$ OVOC and hexenylacetate for $>C_4$ OVOC.

15.   SUPPLEMENTARY DOCUMENTS

A land surface characterisation for global mapping purposes is described by DeFries et al. (1995). An interesting feature in this approach is the discrimination between C3 and C4 plants.

The American Biogenic Emission Inventory System (BEIS) has an extensive list of emission potentials. The latest version is documented by Guenther et al. (1998).

16.   VERIFICATION PROCEDURES

If satellite data have been used in the land-use mapping process it is essential that these are independently verified by on-the-ground surveys. Large errors are possible in the identification of vegetation types and biomass from remote sensing methods.

In general all of the emission potentials are built upon very few data. More measurements are required of at least the major sources, and several different measurement techniques need to be applied in order to eliminate the artefacts (enhanced emissions) easily generated by disturbances to the vegetation.

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SNAP CODE :   **1103**
                                                                        110301
                                                                        110302

SOURCE ACTIVITY TITLE :   **Forest and Other Vegetation Fires**
                                                                  Man Induced
                                                                        Other

PARCOM-ATMOS CODE :

NACE CODE :

1.   ACTIVITIES INCLUDED

Burning (naturally or man-induced) of non-managed and managed forests and other vegetation, excluding agricultural burning of stubble, etc.

2.   CONTRIBUTIONS TO TOTAL EMISSIONS

On a global scale biomass burning in all its forms is estimated to make very significant contributions to greenhouse gases (Andreae et al., 1988, Andreae, 1991). However, most of this burning is human-initiated, and takes place in the tropics. Of an estimated 3550 Tg CO_2 (as C) formed yearly from biomass burning, only 117 Tg C is ascribed to fires in the temperate and boreal regions, and only a small fraction of these take place in Europe (Levine, 1994).

Considering the European continent as a whole, the vast majority of these fires occur in the Eurasian part of Russia, where recent estimate suggest annual areas burnt of between 2-7 million ha (Conard and Davidenko, 1997, and references contained therein).

However, we here deal with the European part of the Russian Federation, along with the other European countries, where the area burnt is estimated at 0.5-1 million ha (range is from several years, Stannars and Bourdeau, 1995).

According to the CORINAIR-1990 inventory, forest fires account for 0.2% of European NO_x emissions, 0.5% of NMVOC emission, 0.2% of CH_4 emissions, 1.9% of CO emissions, 1.2% of N_2O emissions and 0.1% of NH_3 emissions. On the whole forest fires appear to contribute only a small percentage of emissions. However, uncertainties are very large and in some areas emissions might make appreciable contributions to ground level concentration, especially as fires occur over short periods of the time.

On a global scale biomass burning is a very significant source of CO_2 and a number of other gases to the atmosphere. However, most burning takes place in the tropical and subtropical regions, so emissions from European fires have received very little attention.

3.   GENERAL

3.1. Description

Forest fires have always been a feature of forest ecosystems. However, although 'natural' forest fires may be initiated by lightning, recent estimates indicate that on a global scale almost all biomass burning is human-initiated and is increasing with time (Andreae, 1991, Levine, 1994). Much of the global emission results from so-called slash-and-burn agriculture in the tropics, but such practices are much less common in Europe. Prescribed burning, a management practice common in North America, and upon which most emission-factor measurements are based, is also not common in Europe. However, fires in Europe are still heavily associated with human influence, although often by accident rather than design.

The frequency and extent of fires in Europe is very variable from year to year, reflecting year-to-year climatological variability.

3.2. Definitions

Biomass - for forest fires the biomass of interest is the mass of all living and dead vegetation per unit area, in units of kg/m^2. Both above-ground and below-ground biomass are significant and must be distinguished. This use of the term biomass should be distinguished from the 'foliar biomass' of importance for VOC emission estimates from foliar activity (e.g. SNAP 1101,1102).

3.3. Techniques

3.4   Emissions

The major products of biomass burning are CO_2 and water vapour. However a large number of particulates and trace gases are produced, including the products of incomplete combustion (CO, NMHCs) and nitrogen and sulphur species. These arise partly from nitrogen and sulphur contained in the vegetation and organic matter in the surface soils. Additionally, emissions can arise from the re-volatilisation of substances which have been deposited (Hegg et al., 1987, 1990).

Some emissions are not considered further here as they have little relevance for tropospheric chemistry, but they are worth mentioning for their stratospheric impacts. These include H_2, COS and to a lesser extent CH_3Cl (Crutzen et al., 1979, Andreae, 1991).

Many other trace emissions have been measured, but which seem to contribute little to total emissions, e.g. methanesulphonate (MSA), aldehydes, organic acids (Andreae et al., 1988).

A secondary effect of fires is that emissions from the land-area after burning can be significantly enhanced relative to unburned areas. Such effects are not considered here.

3.5   Controls

Many forest fires are set deliberately or accidentally as a result of human activities. For example, data from Russia suggests that 68% of fires occur within 5 km of a road (Korovin, 1996). The main control options then consist of improved fire-prevention and fire-extinction.

Little information appears to be available on methodologies to reduce emissions during controlled forest burns. However, in the Agricultural sector it is known that time of burning and meteorological conditions have important effects on both emissions and ground level concentrations.

4.   SIMPLER METHODOLOGY

From annual statistics of forest burnt one may simply multiply the area burnt by the emission factors given in Table 8.1. These emission factors are in fact identical to those given in the detailed methodology if default biome characteristics are used.

5.   DETAILED METHODOLOGY

Emissions are obtained in a two-step process:

(i)   Estimate the emissions of carbon from the burned land.
(ii)   Estimate the emissions of other trace gases using emission ratios with respect to carbon.

The basic calculation of the mass of carbon emitted, M(C), follows the methodology of Seiler and Crutzen (1980):

$$M(C) = 0.45 \times A \times B \times \alpha \times \beta$$

Where

0.45 is the average fraction of carbon in fuel wood
"A" is the area burnt (m^2)
"B" is the average total biomass of fuel material per unit area (kg/m^2),
"α" is the fraction of the above average above-ground biomass
relative to the total average biomass B,
"β" is the burning efficiency (fraction burnt) of the above-ground biomass.

Values of B, "α" and "β" are given for relevant biomes in Table 5.1. These data are taken from Seiler and Crutzen (1980), although we have added a new forest category, "Mediterranean forest" to account for the low biomass density of this region. The "α" and "β" fractions

assumed for this biome are derived from the Spanish CORINAIR 1990-93 inventories, see also Rodriguez Murrilo (1994).

Table 5.1:   Biome characteristics for forest-fire emission estimates

Biome	Biomass (kg/m^2)	Above ground biomass fraction	Burning efficiency
	B	"α"	"β"
Boreal forest	25	0.75	0.2
Temperate forest	35	0.75	0.2
Mediterranean forest (1)	15	0.75	0.25
Scrubland (2)	7.5	0.64	0.5
Grassland (Steppe)(2)	2	0.36	0.5

Notes: all data from Seiler+Crutzen (1980), except:

(1) new forest category, assuming lower biomass density

(2) which is a subjective estimate, assuming burning efficiency of European grass/shrublands is less than the data on tropical biomes for which Seiler+Crutzen suggest 0.8

The emission of any particular species can then be obtained by multiplying the mass of carbon formed by the emission ratios (in g/kg C) from section 8.

As an example, if we use the factors presented above for Boreal forests, we can evaluate the mass of carbon generated in one hectare of burned boreal forest:

M(C)   =   0.45 x A   x   B   x   a   x   b

= 0.45 x 10000 m^2 x 25 kg/m^2 x 0.75 x   0.2 = 16875 kg

The emission ratio for NO$_x$ is given in section 8 (Table 8.1) as 8 g/kg C emitted, therefore the emission factor to be applied is 135 kg NO$_x$/ha.

This factor is somewhat higher than the factor recommended for CORINAIR-90, namely 75 kg/ha for oceanic climate type forest, but as the background to the previous recommendation is not known we cannot discuss this further.

6.   RELEVANT ACTIVITY STATISTICS

The area of forest burnt (A) must be known. The ecosystem-dependent biomass and burning "B", "α" and "β" should ideally be estimated from local data, otherwise the values given in Table 5.1 provide a default.

7.   POINT SOURCE CRITERIA

No point sources.

8.   EMISSION FACTORS, QUALITY CODES AND REFERENCES

Emission factors of trace gases relative to CO_2 formed in burning are given in Table 8.1, based upon the recommendations of Andreae, 1991.

Table 8.1:   Emission ratios for biomass fires, relative to carbon emitted as CO_2.

	moles X per 100 moles CO_2 emitted			g X/kg C emitted as CO_2
	Field Measurements	Laboratory Studies	"Best Guess"	"Best Guess"
CO	6.5-140	59-105	100	230
CH_4	6.2-16	11-16	11	15
NMHCs	6.6-11	3.4-6.8	7	21
NO_x	2-8	0.7-1.6	2.1	8
NH_3	0.9-1.9	0.08-2.5	1.3	1.8
N_2O	0.18-2.2	0.01-0.05	0.1	0.4
SO_x	0.1-0.34	-	0.3	1.6

Notes: average mass of NMHC assumed to be 37, derived from speciation obtained by Radke et al., 1991. NO_x as NO_2, SO_x as SO_2.
Source: Andreae (1991)

For the simplified methodology we can use the data given in Tables 5.1 and 8.1 to calculate default emission factors per hectare of land. These default emission factors are given in Table 8.2.

Table 8.2:   Default emission factors (kg/ha) for forest and vegetation fires.

	CO	CH_4	NMVOC	NO_x	NH_3	N_2O	SO_x
Boreal forest	3881	253	354	135	30	8	30
Temperate forest	5434	354	496	189	43	6	43
Mediterranean forest	1456	95	133	51	11	3	11
Shrubland	828	54	76	29	7	1.6	7
Grass/Steppe	373	24	30	13	3	0.7	3

Notes: NO_x as NO_2, SO_x as SO_2.

Quality codes for all forest fire emissions should probably be "D".

9.   SPECIES PROFILES

For NMHC emissions from a number of forest fires, Radke et al. (1991) obtained an average species profile of 35% C_3H_6, 30% C_2H_6, 16% C_2H_2, 14% C_3H_8, 5% n-C_4H_{10} (by mass).

10.   UNCERTAINTY ESTIMATES

Andreae (1991) suggests that the emissions of CO_2 are uncertain by about 50% and a factor of 2 for the other trace gases. The fact that emission ratios so far determined seem to be consistent from Brazil to Canada (see Andreae, 1991, and references therein) lends some confidence to extrapolating results into Europe. However, one possible cause for concern lies in results reported by Hegg et al. (1987) which suggested that areas which had experienced substantial N-deposition emission ratios for NO_x could be an order of magnitude greater than those obtained in rural areas. Indeed, emissions of purely man-made species such as F12 are also observed from forest fires, again the result of resuspension of previously deposited pollutants (Hegg et al., 1990). Such re-suspension is very likely in many areas of Europe,

Overall, a factor of 3 uncertainty would seem a reasonable first guess for emissions of gases such as NO_x from Europe.

11.   WEAKEST   ASPECTS/PRIORITY   AREAS   FOR   IMPROVEMENT   IN CURRENT METHODOLOGY

Very few measurements are available of emissions from natural forest fires, and all emission rates and biome-factors reported here are based upon studies in North America or the Amazon. Evaluation of these data against European conditions
should be a priority.

Despite all the complex interactions involved in forest fire emissions, the emission ratios as given in Table 2 do seem quite consistent between various workers.

The burning efficiency is here set to 0.2 for forest fires, following Seiler and Crutzen (1980). However, efficiencies of 0.76 have been reported from wild fires in Australia (Hurst et al., 1996), or 0.1 for fires in Siberia (Dixon and Krankino, 1993).

Additionally, the uncertainty in the area burned can be one of the limiting factors in establishing emissions. Estimates for Russia for example have varied by a factor of ten, partly due to the fact that official statistics do not include fires in areas not receiving fire-protection (Conard and Davidenko, 1996).

12. SPATIAL DISSAGGREGATION CRITERIA FOR AREA SOURCES

From statistics, satellite observation, etc.

13. TEMPORAL DISSAGGREGATION CRITERIA

14. ADDITIONAL COMMENTS

Some estimates of emissions from biomass burning distinguish between different phases of burning. In the 'smouldering' phase emissions tend to be higher than in the burning phase (Cofer et al., 1991), as it is the most easily combustible material which burns in the early phases. During the smouldering phase the less oxidised products (CO, HCs, etc.)are produced in higher proportions (Cofer et al., 1989, 1991). However, all phases of burning display a mixture of complete and incomplete combustion. Given the lack of data on typical European fires, and the lack of significant emissions from this source sector, such distinctions are not recommended for inventory development at this stage.

15. SUPPLEMENTARY DOCUMENTS

16. VERIFICATION PROCEDURES

17. REFERENCES

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18.   BIBLIOGRAPHY

19.   RELEASE VERSION, DATE AND SOURCE

Version: 1.1

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SNAP CODE :   **1105**
                                                                        110501
                                                                        110502
                                                                        110503
                                                                        110504
                                                                        110505
                                                                        110506
                                                                        110601

SOURCE ACTIVITY TITLE :   **Wetlands (Marshes-Swamps)**
                                                              Undrained Marshes
                                                                Drained Marshes
                                                                           Bogs
                                                                           Fens
                                                                         Swamps
                                                                     Floodplains
                                                                  Shallow Lakes

PARCOM-ATMOS CODE :

NACE CODE :

1.   ACTIVITIES INCLUDED

This chapter covers emissions of methane (CH_4) and to a lesser extent sulphur produced in naturally saturated soils, in areas either permanently or seasonally flooded with fresh water. Note that this chapter covers shallow lakes (110601), typically defined by depths of less than 2 m, as well as the wetland (1105) SNAP-codes. Lakes of greater than 2m depth should not generally be treated as wetlands. The chapter does not cover agricultural wetlands such as rice fields, though the biogeochemical processes are the same. (See Schütz et al., 1989, for experimental measurements from Italian rice fields.)

The main emission, CH_4, is produced by anaerobic bacteria (methanogens) in the soil, diffused through soil water and transported to the atmosphere by plants, ebullition, or diffusion. Type of vegetation soil characteristics, and local climate are three important factors affecting methane emissions; data about these factors are used to make global and regional estimates.

Natural sulfur gases such as OCS (carbonyl sulfide), DMS (dimethyl sulfide), H_2S and CS_2 are emitted from brackish wetlands and wetlands with high soil sulfur, usually as the result of microbiological activity, though partly by chemical reduction of sulfate (some H_2S) or possibly by algae or other plants (DMS). These gases will be briefly discussed as they are not considered a significant source of pollutants. The bacteria which produce the sulfur gases usually out-compete methanogens, so methane production is inhibited by saline conditions. Brackish marshes have usually been omitted from inventories of methane emissions.

Wetland areas are affected by human management when drained for agriculture or construction; maintained for wildlife habitat or water treatment; or built/converted for water storage and transport such as canals or farm ponds. These changes in area may be estimated if adequate data are available from local sources.

2. CONTRIBUTIONS TO TOTAL EMISSIONS

Wetlands are estimated to produce about 20% of the annual global methane emissions. Recent global estimates have been 100 - 110 Tg (10^{12} g) per year, with a range of about 50 - 150 Tg CH_4 emitted per year. These estimates are reviewed in Matthews (1993).

Biogenic sulfur gases emitted from wetlands and soils are estimated to be less than 2% of the total sulfur budget; 5-12 Tg S per year out of a total of 310 Tg. Less than 10% of the world's soils are in brackish marsh, so sulfur emissions from saline marshes are on the order of 1-2 Tg; insignificant compared to anthropogenic sources (Warneck, 1988; Andreae, 1984). Early studies which indicated a much larger source of biogenic sulfur gases from wetlands were either not reproduced, or may have been an artifact of the sampling process (see Chin and Davis, 1993, for further discussion).

3. GENERAL

3.1 Description

CH_4 is produced by anaerobic bacteria (methanogens) in the soil, diffused through soil water and transported to the atmosphere by plants, ebullition, or diffusion. Ground water table position, type of vegetation, soil characteristics, available substrates and local climate are all important factors affecting methane emissions. Further, methanogenesis is the final step in the anaerobic degradation chain, requiring organic by-products from other bacteria as food, and emitting methane as a waste (Gujer and Zehnder, 1983). For this reason, methane emission usually requires days to weeks to become significant at the beginning of the season. Methane in turn is a food source for aerobic bacteria called methanotrophs, so it can be oxidised in the aerobic root zone of plants or aerobic layers in soil or water. Approximately 10 - 40% of the methane produced in saturated soil is eventually emitted to the atmosphere. (See Conrad, 1996, and references therein.)

Biogenic sulfur gases are formed during anaerobic decomposition, from chemical reactions with the sulfate ion, and possibly also by some species of marsh vegetation (Patrick and DeLaune, 1977; Warneck, 1988; Chin and Davis, 1993).

3.2 Definitions

Many terms are used to describe naturally occurring flooded areas: wetland, mire, bog, fen, wet tundra, swamp, wet meadow and marsh are among the most common. In common usage the terms are imprecise and sometimes interchangeable. For the purposes of this chapter:

Wetland is used as an overall term for any area of permanently or seasonally flooded soils, where soils are saturated long enough for the soil to become reduced, a methanogen population established, and methane emitted from the soil. The types of wetlands are differentiated by their vegetation, which affects the amount of organic substrate available and transport of CH_4; and by season of flooding or thawing.

The following definitions are derived from Zoltai and Pollet (1983), Aselmann and Crutzen (1989), though a similar scheme was used by Matthews and Fung (1987).

A bog is a peat forming wetland, usually with mossy vegetation, sometimes with boreal forest, waterlogged from precipitation only.

A fen is a peat forming wetland with water flowing through the system, usually with grasses and sedges in addition to moss; less acidic than a bog and more productive.

Bogs and fens make up most of the boreal wetlands in tundra ecosystems, though they may be found at other latitudes.

Swamps are forested wetlands, with much less accumulated organic matter than bogs, usually found in temperate or tropical latitudes.

A marsh is a wetland with grass, sedges or reed vegetation.

A flood plain is the area seasonally covered by water along rivers or lakes. They are significant sources of methane principally in South America and Africa.

A shallow lake is a body of water warm enough for methane to be produced in sediment and shallow enough (<2m) that methane can diffuse or bubble to the surface. Canals and farm ponds might also be considered in this category as well as natural bodies of water.

The SNAP classifications "undrained and brackish marshes", "drained marshes" are preserved for consistency with previous work, but essentially all marshes which still fit unto the definition of wetland are treated identically in the following.

3.3   Techniques

Methane fluxes from wetlands have commonly been estimated by measuring its accumulation in closed chambers. In the past few years, area estimates from various types of eddy correlation measurements have become more common. Areas of wetlands have been estimated from maps, Gore (1983) for example, and from digitized databases of soils and vegetation. Season of methane emission is usually estimated from local climate data.

3.4   Emissions

Wetlands emit methane, carbon dioxide and biogenic sulfur gases, together with minor quantities of N_2O and NO. However, methane is the only gas emitted that is globally significant. Biogenic CO_2 is simply recycled (although wetlands do play a role in the global carbon cycle as the amounts of C stored in peatlands are significant - ca 412 Gt of C world wide; Woodwell et al., 1995). Biogenic sulfur gases are insignificant compared to anthropogenic sulfur emissions.

3.5   Controls

Natural wetlands have commonly been drained in temperate and tropic zones for agriculture, construction and peat harvest. These activities have "controlled" emissions by destroying the wetlands. Arctic and high latitude boreal wetlands are not drained because the ground is frozen much of the year; no controls appear reasonable.

4.   SIMPLER METHODOLOGY

Methane emission from wetlands (W_{CH4}, in mass units) is estimated by:

$$W_{CH_4} = \sum_{i}^{7} \left(A_i \cdot F_i \cdot S_i \cdot cf \right) \qquad (01)$$

Where $i = 1, \dots , 7$ for the 7 wetland types; A_i is the area in each wetland type; F_i is the seasonal average flux (in mass/area/time units, usually mg CH_4 m^{-2} day^{-1}); S_i is the length of the season of methane emission. The season is the time the soil is thawed for boreal and northern temperate wetlands, and the length of time the soil is inundated for flood plains and seasonal marshes and swamps. "cf" is the appropriate units conversion factor.

5.   DETAILED STATE OF THE ART METHODOLOGY

The detailed methodology is essentially the same as the simple methodology. The estimates may be improved by introducing wetland types characterized specifically by country; or using local flux measurements rather than the averaged ones given in section 8. Any information specific to a country rather than a global database should improve the precision of the estimate.

6.   RELEVANT ACTIVITY STATISTICS

Wetland area data are found in a series of tables in Aselmann and Crutzen, 1989. They show percent wetland area in 2.5° latitude x 5° longitude cells. Matthews and Fung (1987) used a different classification scheme and divided their estimate into 1°x 1° cells. Their data base is documented by Matthews (1989) and is available by FTP from the US NCAR (National Center for Atmospheric Research) data site: ncardata.ucar.edu.

Maps of some wetland areas in Europe may be found in Gore (1983) volume 4A: General Studies and volume 4B: Regional Studies. Great Britain, Ireland, Finland and Sweden are covered in particular detail. Most of these maps are based on research done in the country of origin.

Local government agencies and researchers may be able to provide rainfall and temperature data to determine seasonality; and more precise land use data for wetland areas.

7.   POINT SOURCE CRITERIA

All wetland sources are considered area sources.

8.   EMISSION FACTORS, QUALITY CODES AND REFERENCES

Methane:

Bartlett and Harriss (1993) did a thorough review of flux measurements from wetlands and shallow lakes for the purpose of making global estimates. The following table is adapted from their work. They combined measurements from fens and bogs.

Climate Zone	Flux by Wetlands Type $(mgm^{-2}d^{-1})$					
	Bogs	Fens	Marsh	Swamp	Flood-plain	Shallow Lakes
Arctic	96	96				
Boreal	87	87	87	87		35
Temperate	135	135	70	75	48	60
Tropical	199	199	233	165	182	148

The climate zones are arctic: 60 - 90° latitude; boreal: 45 - 60° latitude; temperate: 20 - 45° latitude; tropical: 0 - 20° latitude. These climate zones apply best to the American continents, as most of the northern hemisphere studies are from Canada and the U.S., and most southern hemisphere studies were done in Brazil.

Biogenic Sulfur gases:

Steudler and Peterson estimated a total annual emission of 5.8 g S m^{-2} yr^{-1} in a study which measured all principal biogenic sulfur gases emitted from a brackish marsh over the period of a year.

9.   SPECIES PROFILES

10.   UNCERTAINTY ESTIMATES

The data quality for making an estimate of methane emissions from wetlands is moderate (D rating).

Wetland flux estimates are probably the greatest source of uncertainty in making global estimates of methane. Although there are measurements in all wetland types from the principal wetland areas, fluxes may vary over several orders of magnitude at a single site. Inter-annual variation of seasonal averages can vary as much as an order of magnitude. Most boreal and temperate zone flux measurements have been made in North America and Scandinavia, and most tropical zone measurements have been made in Central and South America. Since there are few or no other measurements of methane flux from other parts of the world, the uncertainty of using the available measurements cannot be calculated, but may be large. Measurements of methane flux in Europe have fit in the range of other boreal and high temperate zone measurements, however.

The estimated areas of wetlands may differ greatly depending on the underlying vegetation databases. The differences in area estimates between Matthews and Fung (1987) and Aselmann and Crutzen (1989) are discussed at length in the latter paper and in Bartlett and Harris (1993). Their total areas are very close but their distribution differs greatly, particularly in the tropics. Their estimates of total area for the northern hemisphere temperate and boreal zones are very close, but their vegetation classes are not strictly comparable.

The flux estimates for biogenic sulfur gases is poorer (an E rating). There are few measurements of all sulfur gases and the measured emissions are extremely variable.

The comments on the uncertainties of flux measurements of methane also apply to the biogenic sulfur gases. Additional variability is due to flux which varies with the tide (H_2S), or with daylight (DMS). Since not all researchers have measured all gases, it is difficult to get a total sulfur estimate. Since there is still possible contamination of the samples during measurement for the earlier data, there can be four orders of magnitude difference between measurements made in the same area by different researchers.

11. WEAKEST ASPECTS/PRIORITY AREAS FOR IMPROVEMENT IN CURRENT METHODOLOGY

As noted in 10, the emissions flux estimates are probably the greatest source of uncertainty. Additionally, linking flux estimates to wetland classification is an important problem. As it is not known exactly which parameters affect flux, then it is difficult to devise good parameterisation schemes. A further problem arises from differences in techniques used in measuring fluxes - such factors may explain some of the variability found of measurements.

Development of better techniques for remote sensing and evaluation is probably an essential component of inventory improvement.

12. SPATIAL DISAGGREGATION CRITERIA

Methane emissions are estimated by the different types of wetlands defined in section 3.2.

13. TEMPORAL DISAGGREGATION CRITERIA

Methane emissions vary seasonally, usually following soil temperature, plant growing season or saturation season, though exceptions may be found (Svensson and Rosswall, 1984; Whalen and Reeburgh, 1992; Westermann, 1993). For example, in the high northern latitudes wetlands are usually classified as bogs, forested bogs, and fens with maximum emissions from June to September. Methane emission increases when soil temperature increases above 0 degrees but has been measured at very low levels from frozen soil . Seasonal wetlands such as flood plains will only emit methane during the wet season, and methane emissions vary within wetlands along moisture gradients (Svensson, 1976; Moore et al., 1990; Granberg et al., 1997). Dry, aerated soils are usually sinks of methane; drought or other change in water table may cause a source area to become a sink (Harriss et al., 1982, Whalen et al., 1991, Oechel, 1993).

All fluxes given in section 8 are averaged diurnally and seasonally.

14. ADDITIONAL COMMENTS:

Very recently, Cao et al. (1996) and Christensen et al. (1996) have modeled the carbon system and methane emissions from wetlands. This type of model is considerably more complicated but allows modeling changes of methane emissions due to changes in climate. At present these models are validated against global estimates using measured fluxes (Matthews and Fung, 1987; Aselmann and Crutzen, 1989; Bartlett and Harris, 1993). The models are not yet generally available.

15. SUPPLEMENTARY DOCUMENTS

16. VERIFICATION PROCEDURES

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19.   RELEASE VERSION, DATE AND SOURCE

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SNAP CODE :   **1107**

SOURCE ACTIVITY TITLE :   **Animals and Humans**

PARCOM-ATMOS CODE :

NACE CODE :

1.   ACTIVITIES INCLUDED

This section covers the emissions from wild-living animals. Both the emissions from the intestines and from excreta are included. Not covered are emissions from animal husbandry (chapter 10.4: Enteric fermentation) or from pets, which are partly similar, but may be considered influenced by human behavior in many respects. Still included here however are emissions from humans (breath, sweat, etc.; excreta are dealt with in chapter 9.1.7, latrines, or 9.10.2, waste water treatment), as they do not appear anywhere else and should be perceived differently to other anthropogenic emissions.

2.   CONTRIBUTIONS TO TOTAL EMISSIONS

The information available is very sparse. With respect to the global situation, animal methane emissions have been attributed to termites, which are hardly relevant for Europe. The relatively high emissions of ammonia given for humans in some publications include emissions from pets, and thus need to be considered with caution for the purpose of this chapter. Nevertheless the figures presented may give some guidance which levels of emissions are to be expected.

For the UK [1], ammonia emissions from humans (without pets) have been estimated at 0.7 % of total ammonia emissions, and wild animals (deer and birds) at 0.2 %. Global emissions of ammonia were estimated at 4.8 % for humans, and at 0.2 % for wild animals [2]. The estimate for humans here however includes emissions from pets (which in [1] are estimated to total three times the amount of human emissions) and from latrines. Estimates for methane are not available for Europe, but using global estimates [3] or the emission factors provided below the contribution of emissions appears to be smaller than 1% of the total.

3.   GENERAL

3.1. Description

Metabolic processes especially in the intestines of animals, but also processes in their excretions are responsible for gas formation. One important pathway leading primarily to methane formation is the anaerobic degradation of plant cellulose by symbiotic microflora (methanogenic bacteria, but also acetogenic bacteria) in the intestines. Major kinds of animals that are known to emit methane are mammals (primarily ruminants and rodents) and termites.

A completely different pathway of emissions is the decay of urea or uric acid to ammonia in animal manure (mammals or birds). This pathway may also lead to N_2O formation. Emissions however are much more pronounced for domestic animals, where manure is actually collected and kept liquid for longer periods of time, or other sites where animals live in a very dense population (point emissions from bird breeding colonies on small islands, e.g. in the North Sea). Other relevant emissions are volatile organic compounds like isoprene, however no specific information could be obtained as this source is probably negligible.

It is very important to discuss the difference and the reasons of the difference between domestic and wild animals. Domestic animals are generally kept more densely, such that manure management is needed and the manure has to be stored for a longer period of time. Chemical processes in the manure (decay of urea to ammonia) are completely different and much less relevant for natural animals. Also, the diet is quite different between natural and domestic animals, influencing the feed nitrogen content, which is important for ammonia formation. The diet also affects the methane yield, the proportion of food energy content emitted in the form of methane. Nevertheless emissions need to be considered comparable to some extent, especially due to the absence of any better data (see section 8).

For a gas which deposits quite efficiently as ammonia, also a canopy effect may be taken into account. Gases released effectively from the animals may well be absorbed immediately in the forest canopy or in the grass before ever actually escaping to the lowest layers of the atmosphere. These emissions will never have any apparent effect on the atmosphere.

3.2. Definitions

Wild-living animals: Animals which are not severely affected in their feeding behavior or their mobility by anthropogenic influences, and are not controlled by humans.

3.3. Controls

Not applicable.

3.4 Emissions

Emissions are mainly methane and ammonia. Some NMVOC emissions are also possible, but probably small. Considering similar processes as for domestic animals, also nitrous acid emissions should be expected. For instance, formic acid emissions have been attributed to formicine ants [4]. These emissions have never been actually quantified and may not be relevant anywhere outside the tropical rain forests.

3.5 Controls

There is no controls to natural emissions by definition.

4. SIMPLER METHODOLOGY

Apply emission factors given in section 8.

5.   DETAILED METHODOLOGY

For detailed emission assessment, emission factors as given in section 8 should be adapted towards national particularities. Such an approach has been used in [5]. Animal weights may vary within a species as much as a factor of 2, leading to considerably different emission scaling factors, depending on which variety of a species is dominant in a certain country. Also, the feeding habits should be taken into account, both in terms of energy content in order to assess methane emissions [3], and in nitrogen content for scaling ammonia emissions [2].

6.   RELEVANT ACTIVITY STATISTICS

Information from wildlife specialists, hunting statistics etc. on number and kind of animals present. For big game species, hunting accounts for about 20-30% of the winter population (which resembles the annual population minimum).

7.   POINT SOURCE CRITERIA

There are no point sources.

8.   EMISSION FACTORS, QUALITY CODES AND REFERENCES

As measuring emission factors for wild living animals is almost by definition very difficult, the data quality is poor (D-E). Most information is taken from similarities and analogies between domestic and wild animals. The choice of emission factors for ammonia has been discussed in detail [1]. Ammonia emission rates have been given for red deer (0.9 kg/individual and year, [1]) and for reindeer (1 kg N per individual and year, [2]). The emission factors seem to be similar enough to be combined for Table 1. Not considered here however was possible redeposition of ammonia in forests at plant surfaces before emissions actually can reach the atmosphere (canopy effect), as discussed in [2].

For methane, data presented in this guidebook for enteric fermentation were used [6]. Large uncertainty is associated with deriving deer emissions from cattle emission factors. Scaling of these emissions for moose and for red deer was performed using estimated excretion of nitrogen [2] as an indicator of their metabolic activity. These emission factors are about 50 % larger than those suggested previously [3]. However as methane emissions from animal droppings are not included in either of the data given (an additional 25 % according to[6]), the emission factors proposed here still should not be considered upper limits. Methane emissions from humans, mainly in human breath, have been assessed from measured values [3]. The resulting emission factor of 0.07 kg/person and year is notably lower to that of pigs, which may have a comparable metabolism. Considering the food uptake of humans, which is about one third of that of pigs, an emission factor of 0.5 kg/person would be expected. Much of this

discrepancy may be due to a different diet but no full explanation is possible. We thus propose to apply an emission factor of 0.1 kg/person and year.

As weights for different game species vary considerably, we recommend to further scale the emissions by the life weight in a linear fashion. A more complex scaling proportional to the ¾ power of weight has been suggested [3], which may describe the food demand more closely, but other parameters also contribute to methane emissions such that it does not seem justified to perform an increase in complexity. The average weights of species have been simplified from much more detailed literature data [7]. Thus the average weight of red deer and reindeer is taken at 100 kg, fallow deer and white-tailed deer 90 kg, roe deer 15 kg, chamois 35 kg, ibex 70 kg and mufflon 25 kg. Moose emissions were assumed to be twice those of reindeer, according to estimates of nitrogen excretion [2]. The resulting methane emission factors are consistent with estimations by the Swiss Federal Office of Environment [8]. Ammonia emission factors agree in part with data from the Czech Republic [5]. There are discrepancies of almost a factor of 3 for red deer however, as the dominant variety is the unusually heavy Carpathian deer (170 kg).

Table 8.1:   Emission factors for wild animals' emissions (in kg per animal/person and year)

	Assumed life weight [kg]	CH_4	NH_3	Literature
deer (red deer, reindeer)	100	25	1.1	derived from [6],[1]
moose	350	50	2.2	derived according to [2]
roe deer	15	4	0.2	scaled from red deer*
boar		1.5	1	[6], derived from [1]
birds	0.8	--	0.12	[1]
large birds	2.4	--	0.36	[1]
humans		0.1	0.05	derived from [3], [1]

*) Use animal weights to similarly scale emissions for other species

No information at all was available for rodents. Here also linear scaling by weight should be performed. While this probably underestimates the metabolic activity of small animals somewhat, the methane yield, given in [3] as the fraction of food energy content that is emitted as methane, has been assumed to be clearly smaller for any species other than ruminants. A Czech study [5], taking into account the nitrogen content of feed, assumes ammonia emissions from hares to be about 8 times of what should be expected from weight scaling. On the other hand, for smaller animals living close to or under the ground, the canopy effect should be expected very large. All of this is to be considered part of overall uncertainty. Not included were termite emissions, which are currently assumed negligible for the European continent, even if termites have become established in Southern Europe, or emissions from other invertebrates.

9.   SPECIES PROFILES

No profiles are needed for methane or ammonia emissions. Information on NMVOC is missing.

10. UNCERTAINTY ESTIMATES

Uncertainty is to be considered very high (data quality D, for methane emissions from deer E).

11. WEAKEST ASPECTS/PRIORITY AREAS FOR IMPROVEMENT IN CURRENT METHODOLOGY

Emission rates are primarily inferred from domestic animals.

12. SPATIAL DISSAGGREGATION CRITERIA FOR AREA SOURCES

Forest area or grassland area, depending on animal species considered.

13. TEMPORAL DISSAGGREGATION CRITERIA

Source is too small such that no detailed temporal disaggregation is needed.

14. ADDITIONAL COMMENTS

Wild living animals are generally to be considered as causing natural emissions, even if their number is to a large extent dependent of human interest (in both directions: animals in competition to domestic animals, but also animal feeding in winter because of hunting interests). The reason is that anthropogenic influence should not be considered overwhelming in this respect.

More problematic is the question of human emissions. The human metabolism clearly is associated with anthropogenic activities, and the number of humans on earth (or in Europe) clearly is out of its natural boundary. Nevertheless it seems ethically not correct to submit this type of emissions to those which are effectively controllable by man. Human control in that respect, i.e. regulation of the number of people on earth for the sake of limiting emissions to the atmosphere, can not be acceptable. Therefore also these emissions should be considered "natural".

15. SUPPLEMENTARY DOCUMENTS

16. VERIFICATION PROCEDURES

17. REFERENCES

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19. RELEASE VERSION, DATE AND SOURCE

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SNAP CODE :   **1108**

SOURCE ACTIVITY TITLE :   **Volcanoes**

PARCOM-ATMOS CODE :

NACE CODE :

1.   ACTIVITIES INCLUDED

The current chapter includes emissions from geothermal activities, both eruptive and non-eruptive. Sources include volcanoes, but also fumaroles, geysers, metamorphic degassing or other activities related to molten magma in the earth's crust. Heated magma under pressure contains gases like sulfur dioxide, carbon dioxide, hydrogen sulfide, mercury and chlorine. These gases may be released when magma gets close to the surface and the pressure may be discharged.

With respect to the different sources, non-eruptive volcanoes that outgas at relatively constant rates seem to be more important than those from sporadic eruptions, both for CO_2 [1] and SO_2 [2]. However the sporadic emissions are much more difficult to assess

Some of the emissions may also be considered anthropogenic, when produced at geothermal power plants where artificial holes are drilled to obtain hot water from the earth's interior. These emissions however are treated in SNAP 0507 and are assumed to be rather small.

2.   CONTRIBUTIONS TO TOTAL EMISSIONS

The emissions from volcanoes show great regional and temporal variation. Most affected are volcanic areas, and also volcanic activity tends to be highly variable. The number of active subaerial volcanoes per year based on a 5-year running average is approximately 60 [2, 3]

In Europe, significant volcanic emissions are currently limited to Italy and to Iceland. For Italy, the SO_2 emissions from Mt. Etna have been estimate to amount to 1.5+/-0.3 Mt per year [4], while globally for all non-eruptive volcanoes 9 Mt have been reported [2, 5]. On a global scale and including the highly variable annual contribution of eruptive volcanism of about additional 4 Mt per year, SO_2 from volcanoes is estimated to account for about 5-10 % of the anthropogenic flux [5] (in Japan about 50 % of the total [6]). H_2S Emissions are considered to be quickly oxidized to SO_2 in the atmosphere [7] and have been assumed negligible by some authors [7, 8]. In contrast, a very recent compilation [2] estimates the global emissions of S from H_2S and other species at about 3.5 Mt/yr additionally. Then the volcanic sulfur flux is about 13 % of the anthropogenic flux.

For CO_2, emissions from subaerial volcanoes are considered greater than those from the submarine ones (mostly mid-oceanic ridge system) and are in the range of $0.01\text{-}0.05 \times 10^{12}$ mol/yr (0.44-2.2 Mt/yr) for one major volcano [9] and are globally at 65

Mt/yr [10], clearly two orders of magnitude lower than the anthropogenic output of CO_2 [1]. Values for the Etna plume have been measured at about 13 Mt/yr, with a similar amount of diffusive emissions [4]. Possibly due to the low solubility of CO_2 in silicate melts at upper crustal depths, the annual quiescent release of CO_2 from all active volcanoes seems to be more than an order of magnitude greater than that annually emitted directly from all forms of erupting lava.

Considerable emissions of aerosols are present in most volcanic plumes [11]. Aerosol emissions are however not subject of the current guidebook. Emissions of Hg and Cl_2 or F_2 have been measured occasionally, but are very difficult to generalize. [7, 12]

3. GENERAL

3.1. Description

Heated rocks in the earth's crust may be chemically transformed such that gases are released. Carbonates may thus release CO_2, and Sulfates SO_2. These gases may be dissolved at a high pressure in the molten magma. Reaching the surface (either at the sea floor for submarine volcanoes, or at the atmosphere) the pressure decreases and the gases are emitted into the atmosphere.

3.2. Definitions

Volcano: Site where molten magma / lava occasionally reaches the surface

Non-arc volcano: Volcano on a hot spot or rift zone - erupts more frequently, total number is smaller

Arc volcano: Volcano at a subduction zone - eruptions are more violent

Fumarole: Gas vent caused by leaks from magma underneath

Geyser: Water fountain driven by venting gas due to hot magma

3.3. Techniques

A differentiation of techniques is not applicable to natural emission sources. However different source categories exist. Volcanoes are sources that have magma outflow. By contrast, fumaroles and other sources only vent gases through cracks in the rocks.

There are significantly different emission patterns also among volcanoes. Outgassing may occur continuously (globally the larger portion of emissions), or are episodic in the course of an eruption. Differentiation can also be made among eruptive emissions: Eruptions in an arc tectonic regime tend to be more violent, but seem to have a more predictable pattern of explosivity strength vs. SO_2 emissions.

The different types of volcanoes are well known and data are available. Generally, continuous flow volcanoes have a low viscosity magma and also for that reason have flat slopes, while eruptive volcanoes are comparatively steep.

3.4   Emissions

Volcanic activities release gases from the minerals being heated to form magma. Most important emissions are SO_2 and CO_2, but also H_2S. Trace constituents include Hg (mostly as sulfur complexes, Cl_2 and F_2.

3.5   Controls

There is no controls to natural emissions by definition.

4.   SIMPLER METHODOLOGY

Primary source of geothermal emissions are active volcanoes. These volcanoes are well known and geologically described. Emissions from explosive volcanism can be assessed based on the Volcanic Explosivity Index (VEI) of volcanoes. The Smithsonian Global Volcanism Network catalogues each eruption during the past 200 years. Differentiation is to be made between arc-volcanoes and non-arc volcanoes. CO_2 emissions may be derived from SO_2 emissions, considering the additional uncertainties Emissions from many continuous emitting volcanoes have been listed [2], other volcanoes should be scaled to one of those listed.

The secondary sources (fumaroles, geysers) are hardly ever significant sources. Emissions should be estimated from approximations of the number of sources, the volume gas flow and the concentrations.

5.   DETAILED METHODOLOGY

Emissions from specific volcanoes can be assessed using spectrometric data [13] from ground assessments also in combination with available satellite data [14]. Evaluations may take advantage of the existing dataset of the Total Ozone Mapping Spectrometer (TOMS) aboard NASA satellite Nimbus 7, which allows evaluation of SO2 emissions [5], or the SBUV/2 instrument carried by NOAA-11 [15].

6.   RELEVANT ACTIVITY STATISTICS

There are no statistical data available. Instead, geological information needs to be obtained from the respective national geological survey.

Satellite data can in principle be obtained from NASA or NOAA, respectively. The exact procedures however have not been checked.

7.   POINT SOURCE CRITERIA

Each active volcano is to be considered a point source.

8.   EMISSION FACTORS, QUALITY CODES AND REFERENCES

SO_2:
Explosive emissions:

Arc volcanoes: $\log E = -0.25 + 0.76$ VEI [5]
         where E is emission of SO_2 (kt)
         VEI is the volcanic explosivity index

Non arc-volcanoes: emitted SO_2 is typically much higher and less dependent on the VEI. An order of magnitude higher emissions should be assumed for eruptions of non-arc volcanoes, using the same formula as for arc volcanoes. The uncertainty is very high however. Global emissions are considered to be around 4 Mt/yr [5].

Non-explosive emissions:

9 Mt/yr globally for non-explosive volcanoes (Etna-type), which emit at steady state. More specific information has been compiled [2]. Data given specifically therein should be applied.

CO_2-emissions are in the range of $0.01-0.05 \times 10^{12}$ mol/yr (0.44-2.2 Mt/yr) for one major volcano [9], but occasionally much higher (Mt. Etna: plume emissions and diffusive emissions combined 25 Mt/yr). The ratio of CO_2/SO_2 is considered to be around 1.5 for arc emissions, but globally up to 4 or 5 on the molar scale [9], part of the difference caused by the unusually high CO_2 emissions from Mt. Etna. These figures may be taken if no other information is available.

F and Cl emission data are available for Mt. Erebus, Antarctica, which is has a very uncommon alkaline magma, rich in halogens and various trace metals. These data therefore need to be seen as an indication of an upper boundary rather than as an emission factor as such. The average F/S ratio (by weight) in Erebus gas reported is 0.69, for Cl/S it is 0.55 [7]. Similarly Hekla (Iceland) is renowned for its high concentration of F and Cl during eruption. However these results should only be taken if specific information is available, as they are known to be on the upper end.

Emissions of 4-20 mg Hg / kg fumarole vapors have been reported and may be applied [11]. According to [2], the ratio of SO_2-S to S in other sulfur species is about 2:1, with 71 % of the sulfur contained in H_2S. The mass ratio of H_2S/SO_2 is 0.21 and may be applied for estimating H_2S emissions.

CO_2 Emissions from geothermal fields have been reported in [16]. Strictly these emissions are anthropogenic and should be reported in connection with power generation (SNAP 1)

9.   SPECIES PROFILES

Table 9.1: Profiles for sulfur compounds in % S (from [2])

SO_2	63
H_2S	24.5
CS_2	2.4
OCS	1.5
SO_4^{2-}	1.4
particulate S	0.8
other:	6.6

10.   UNCERTAINTY ESTIMATES

The measured variability of diffusive emission fluxes may be in the order of 20 % (relative standard deviation [4]). The uncertainty with the emission factors however is assumed to be in the range of one order of magnitude.

11.   WEAKEST   ASPECTS/PRIORITY   AREAS   FOR   IMPROVEMENT   IN CURRENT METHODOLOGY

Surrogate parameters to establish emission factors are rather week. Other surrogates than the Volcanic eruptivity index, which are linked more closely to the emissions, need to be identified. Validation of TOMS data for assessing eruptive emissions is needed.

12.   SPATIAL DISSAGGREGATION CRITERIA FOR AREA SOURCES

Emission areas should be limited to geologically active areas, like calderas.

13.   TEMPORAL DISSAGGREGATION CRITERIA

No generalization possible; temporal disaggregation may be performed for past periods according to available records of volcanic activity.

14.   ADDITIONAL COMMENTS

Volcanic emissions are the typical example of emissions not at all influenced by man. Nevertheless there may be cases where this is not quite true, especially in connection with geothermal power use or other deep drills. These emissions however are to be taken into account elsewhere.

15. SUPPLEMENTARY DOCUMENTS

16. VERIFICATION PROCEDURES

Emissions from volcanic sources may be estimated from spectroscopic measurements (correlation spectrometer, COSPEC: [14]; LIDAR [12]).

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SNAP CODE :   **1109**

SOURCE ACTIVITY TITLE :   **Gas Seeps**

PARCOM-ATMOS CODE :

NACE CODE :

1.   ACTIVITIES INCLUDED

Natural gas as a product of microbial degradation derives from a variety of geological periods and therefore is stored under very different conditions in the earth's crust. While the very old storage chambers tend to be very well sealed (otherwise they would have been emptied in the time since formation), seeping of natural gas may occur at storage sites of more recent times, like from the glaciation periods. Several of such gas seeping sites have been observed, most easily under water when methane bubbles rise from a lake or the sea floor.

Gas seeps from natural gas reservoirs can not easily be distinguished from gas being developed from organic material buried in the sediment. However differentiation should be made to methane production in soils, which is described in the "wetlands" chapter (proposed SNAP 1105). The difference between these two sources of freshly produced methane is primarily in the age of the organic material to be processed, which may be thousands of years old in the first case, but is fresh material (also with respect of ^{14}C content) in the latter case. Also, the amount of material can be assessed from vegetation density in the latter case.

2.   CONTRIBUTIONS TO TOTAL EMISSIONS

Due to the irregular emission patterns, only rough estimations are possible. A compilation of reports on gas seepages indicates that globally emissions may be between 8 and 65 Tg CH_4 per year [1] (approx. 2-13 % of global annual CH_4 emissions).

3.   GENERAL

3.1. Description

Gas seeps from natural gas reservoirs or from reservoirs of organic matter occur both under shallow sea surfaces as well as at land surfaces. However only seeps under water are easily identified due to formation of gas bubbles.

Natural gas reservoirs may start seeping gas after seismic activities (earthquakes) or also depending on the outside temperature. Emissions depend on the emission rate and the size of the seep area. While a number of gas seeps have been observed, in general they seem to be highly limited in extent.

In order to be able to quantify emissions from this source, steady flow and homogeneous composition of the seeps need to be assumed. This is however not the real situation. In fact, outbursts of activity have been observed that indicate some methane formation is still active and the reservoirs are being emptied periodically. This would indicate that maximum observed emission rates should not be considered typical [2].

Submarine emissions may occur also from the deep ocean. Here only seeps from the continental shelves are considered, as most of deep ocean emissions will be dissolved in sea water long before reaching the surface.

3.2. Definitions

3.3. Techniques

Emissions from underground gas storage would be expected to be steady flow. Observed gas flow however is strongly variable, in some instances taking place primarily during summer and fall, and preferably during low tide [3]. In these cases, methane is assumed to be produced by on-going processes from buried organic material. ^{14}C depletion in the resulting methane emission proves that this material is from fossil origin [1]. In addition to bacterial production, thermogenic production is assumed, with the associated emissions being accompanied by oil seeps.

While gas formation, especially for bacterial production, may depend on the ambient temperature and decrease considerably during wintertime, gas release may also depend on other parameters. High pressure (as at high tide) or a low degree of filling of the underground storage (after a previous outburst) may halt emissions for some time.

3.4 Emissions

Natural gas emissions are primarily methane (CH_4), but at a lower rate also other alkanes may be released.

3.5 Controls

There is no controls to natural emissions by definition.

4. SIMPLER METHODOLOGY

Size and location of seeping areas need to be obtained from geological offices, research institutions or petrol companies. The emissions are then calculated for each of these areas separately by:

$$E = F \times A$$

A is the area in m^2, F the average flux per m^2 (see section 8).

5.   DETAILED METHODOLOGY

There is no state-of-the-art methodology.

6.   RELEVANT ACTIVITY STATISTICS

There are no statistical data available. The activity (number and size of fields where seeping is taking place) may obtained from research institutions, geological offices, or petrol companies.

7.   POINT SOURCE CRITERIA

No point sources.

8.   EMISSION FACTORS, QUALITY CODES AND REFERENCES

As indicated earlier, emission factors are highly uncertain due to the irregularity of the emissions taking place. Emission rates of 10 l/h from one single seep hole have been reported near the California South Coast [4], but also the area-based value of 1 l/h/m^2 in the Danish coastal waters [5]. These values need to be considered absolute maxima, with typical values at least a factor of 20 lower [1, 3].

According to a compilation of all known source areas [1], the highest overall seepage rate is given for the California South Coast (Santa Barbara Channel) at 400 g/yr/m^2. As a typical emission factor, the numbers given for the Gulf of Mexico, the North Carolina coast and the Danish Kattegat and Skagerrak should be used: 50 g/yr/m^2. These factors refer to active areas only. Whenever available local information should be used however, as this number can only give a rough guidance for orientation.

For those emissions taking place at larger depths, the dissolution of methane in sea water from rising gas bubbles needs to be considered. This uptake has been discussed in more detail [1] with respect to bubble size. As a first guideline, it may be assumed that only 50 % of the emissions at 100 m depth will reach the surface.

9.   SPECIES PROFILES

A typical profile for gas seeps is suggested in [4], at 75 % methane, 7 % each propane and n-butane and 6 % ethane (by weight).

10.   UNCERTAINTY ESTIMATES

The uncertainty with the emission factors is assumed to be in the range of at least one order of magnitude, data quality E.

11. WEAKEST ASPECTS/PRIORITY AREAS FOR IMPROVEMENT IN CURRENT METHODOLOGY

More information on activity rates have to be obtained. Especially flux measurements are needed in areas where these emissions are known to take place. Ambient methane concentrations near potential emission areas should be observed for a prolonged period of time in order to determine duration and strength of possible active and quiet periods.

12. SPATIAL DISSAGGREGATION CRITERIA FOR AREA SOURCES

Even distribution within each field.

13. TEMPORAL DISSAGGREGATION CRITERIA

Constant emission flux is assumed, as otherwise temporal disaggregation would have to be based on observations, event based.

14. ADDITIONAL COMMENTS

Natural gas seeps are not at all influenced by humans.

15. SUPPLEMENTARY DOCUMENTS

16. VERIFICATION PROCEDURES

17. REFERENCES

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SNAP CODE :   **1110**

SOURCE ACTIVITY TITLE :   **Lightning**

PARCOM-ATMOS CODE :

NACE CODE :

1.   ACTIVITIES INCLUDED

Lightning and corona discharge during thunderstorm events cause atmospheric chemical reactions to take place at high voltages and high temperatures. These reactions cause the production of NO_x in the atmosphere. Such production processes are, strictly speaking, not real emissions as the compounds involved (primarily N_2 and O_2) are not injected into the atmosphere but are present anyway. However as these processes can not adequately be described by conventional atmospheric models on one hand, and their impact is eventually identical to those from (anthropogenic) emissions on the other hand, they are easy to be compared on the emission level and thus are frequently treated as such.

2.   CONTRIBUTIONS TO TOTAL EMISSIONS

Global NO_x production by lightning has been estimated in the range of 3-5 TgN/yr [1]. For the U.S., 40% of the yearly lightning-generated NO is estimated to be produced during the summer months [2]. Other estimates using the calculation schemes given below indicate that the lightning NO comprises only 3% of the total NO_x emissions budget, with a maximum contribution of 24% at the maximum hour with respect to anthropogenic emissions at a definite period in summer for the U.S. North-East [3].

These figures apply to emissions within the whole troposphere. Emissions in the boundary-layer (circa lowest 1 km) are obviously considerably less. In reporting emissions under the joint EMEP/CORINAIR system, care must be taken to report only emissions between the ground and 1 km - see section 8.

3.   GENERAL

3.1. Description

The electrical discharge of lightning creates plasma channels in the atmosphere characterized by the high fraction of ionic loads and high temperatures. Major compounds of the atmosphere, notably nitrogen, oxygen, and water, may be ionized and then undergo chemical transformation. While the exact pathway of such transformations is largely unknown, a few assessments have been made [4, 5]. A major species to be produced is nitric oxide (NO), but also other compounds containing nitrogen, oxygen and hydrogen atoms are being formed. Crucial for the formation is the high temperature during the flash (up to 30000 K) and the

subsequent rapid cooling below 1500 K which prevents the freshly formed NO from immediate destruction.

3.2 Definitions

Lightning: Atmospheric discharge during thunderstorm events

CG - discharge: Flash starting in the cloud, bringing several coulomb of negative charge to earth within about 0.5 s (negative discharge)

IC - discharge: Flash that does not connect to earth: intracloud, intercloud and cloud-to-air flashes

3.3 Techniques

While lightning exhibits different characteristics depending on whether it is cloud-to-ground (CG), cloud-to-cloud or within-cloud (inter- and intra-cloud, IC), emission estimation techniques have not been resolved to this level of detail. It has been reported that IC discharges may be up to ten times less efficient in producing NO_x than the CG discharges [4]. However, newer information suggests that these discharges may be nearly equal [1, 5]. The amount and distribution of NO produced is believed to be dependent on the energy and the frequency of lightning strokes, which in turn is dependent on cloud temperatures and cloud heights. IC lightning is known to be more frequent than CG lightning. The ratio has been correlated to the cold cloud thickness (cold cloud = below freezing), representing the size of the electric field involved that may determine the number of IC flashes [6]. Despite of generally large variations of this ratio, a dependence on geographical latitude has been found using cold cloud thickness as a parameter.

3.4   Emissions

Out of the compounds being formed in lightning discharges, numbers are given only for NO and NO_2 as NO_x. These emissions seem to be the most relevant.

Differentiation needs to be made for IC and CG lightning, especially with respect to their injections into the atmosphere as relevant for models. IC lightning occurs at altitudes above about 5 km and may be neglected in some boundary layer models, while CG lightning is expected to reach from the ground to about 7 km high (north of 30 deg. Latitude) or 10 km high (south of 30 deg. Latitude). The NO formed is distributed decreasing with height as a function of air density [7]. For a 7 km flash, about 20% of the emissions would then occur in the lowest 1000m, and 80% between ground level and 5 km.

In [3] the IC component -- here only calculated in the detailed methodology -- is assumed to add an extra 21% NO at 60 deg. N and 61% at the equator. All IC flashes are assumed to occur above a height of 5 km.

3.5   Controls

There is no controls to natural emissions by definition.

4.   SIMPLER METHODOLOGY

The number of lightning flashes can be obtained from measurements (see section 5), or from estimations. In the latter case, the flashes are estimated from meteorological data on thunderstorm occurrence and from the geographical latitude of the area considered. Support for these estimations may be given by satellite data [8]. Emissions are then calculated according to [3] :

$$CG_{NO} = E \times M$$

where CG_{NO} is the NO produced by the cloud-to-ground part of the lightning flash
$\quad\quad E = 4 \times 10^8$ J per cloud-to-ground flash and
$\quad\quad M = 9 \times 10^{16}$ molecules NO / J

Calculated in mass units, this yields 2.75 kg NO_x (calculated as NO_2) per flash of lightning. About 20% of this amount is assumed to be emitted below 1 km altitude, 80 % below 5 km altitude.

5.   DETAILED METHODOLOGY

The difference of the detailed methodology is that the number of lightning flashes is actually counted and cloud-to-cloud flashes are included. Data for the U.S. are available from the East Coast lightning detection network, or from the lightning strike data archive from Global Atmospherics, Inc. in Tucson, AZ. In many European countries, especially in Western Europe, national networks are operative and may be accessible through the respective national meteorological service. These networks do not include cloud-to-cloud (IC) flashes however.

Emissions now are calculated as [9]:

$$LNO = (N_{CG} \cdot EF_{CG} / \epsilon_{CG}) + [(N_{CG} / \epsilon_{CG}) \cdot (10/(1 + (\Phi/30)^2) - 1)] \cdot EF_{IC}$$
where:
LNO	= NO emissions for lightning flashes in study area, molecules NO
N_{CG}	= Number of cloud-to-ground (CG) flashes recorded
ϵ_{CG}	= Efficiency of the CG network
EF_{CG}	= Emission factor for NO for each CG lightning flash
Φ	= Latitude of the study area in degrees
EF_{IC}	= Emission factor for NO for each inter- or intra - cloud (IC) lightning flash

The emission factors needed for calculation are given in section 8. For the U.S. East Coast, the efficiency has been reported to be 0.7 [9]. The equation takes care of the fact that IC

lightning is, dependent on the latitude, about four times as frequent as CG lightning. While recent investigations [6] indicate a less pronounced latitude dependence than the one given here, the results are virtually identical at 40 deg. Latitude.

Emissions from IC flashes are assumed to take place above 5 km altitude only. In contrast, 80% of the CG-lightning emissions are expected at altitudes below 5 km, and 20% even below 1 km.

6.   RELEVANT ACTIVITY STATISTICS

Meteorological data on lightning frequencies need to be obtained. Lightning climatologies are being produced or are available in the meteorological offices of many countries. The data may either derive from reporting thunderstorm events, from observation networks, or from satellite information.

7.   POINT SOURCE CRITERIA

No point sources.

8.   EMISSION FACTORS, QUALITY CODES AND REFERENCES

A large variety of emission factors is given in the literature from laboratory as well as field investigations. According to [10], the low, median and high end of these estimates may be given at 0.36×10^{26}, 4×10^{26}, and 30×10^{26} molecules NO per flash. As indicated in [10] and also discussed in [3], the highest of these figures (from [11]) is not supported by studies modelling nitrate deposition. [1] estimates global NO_x production from a best fit approximation between a global model and observations from regions where lightning is expected to be a major source. This study yields results close to the lowest of the three factors given, thus we recommend to apply the factor of 0.36×10^{26} molecules NO (2.75 kg NO_x) for each flash of lightning as EF_{CG}. Only part of these emissions should be reported: See Table 8.1.

Literature data [4, 9] suggest an emission factor for IC lightning of an order of magnitude lower than for CG lightning. We tentatively are recommending that EF_{IC} be set equal to 0.36×10^{25} molecules NO (275 g NO_x). Recent theoretical considerations [5] however indicate that such a low emission factor might not be realistic. The total energy dissipated in an IC flash should then be at least as high as in GC flashes. Even considering the decreased NO formation at high altitude the EF_{IC} should be considerably higher then (maybe a factor 5). However quantification is missing, and the emissions only concern altitudes above 5 km anyway (where they are relevant primarily on the global scale). Thus an update will only be given at a later stage, when new evidence emerges.

All recommended emission factors are compiled in the following table for the respective altitudes. Note that reporting will only be necessary for lightning emissions up to one km at this stage. The upper layer emissions may be needed at a later stage only.

Table 8.1: Recommended emission factors per flash of lightning in molecules NO and kg NO$_x$ (calculated as NO$_2$), respectively.

ALTITUDE	EF$_{CG}$ (molecules)	EF$_{CG}$ (kg)	EF$_{IC}$ (molecules)	EF$_{IC}$ (kg)	COMMENT
below 1 km	0.72×10^{25}	0.55	0	0	report
1km to 5 km	2.16×10^{25}	1.65	0	0	do not report !
above 5 km	0.72×10^{25}	0.55	0.36×10^{25}	0.275	do not report !
total	3.6×10^{25}	2.75	0.36×10^{25}	0.275	do not report !

Because of the uncertainty in the NO production factors, we assume a quality code of D. Additional information on uncertainties can be obtained from [1] and [12].

9.   SPECIES PROFILES

Emissions are given for NO$_x$. While virtually all of the oxidation product is originally NO, a considerable part is transformed to NO$_2$ very quickly (depending on ozone availability etc.). This part may be in the order of 25% of the original NO [11].

10.   UNCERTAINTY ESTIMATES

The uncertainty with the emission factors has been estimated a factor of three, however the validity of these results have to be checked with respect to those literature estimates giving results different by up to an order of magnitude (see [5] and [10]).

11.   WEAKEST ASPECTS/PRIORITY AREAS FOR IMPROVEMENT IN CURRENT METHODOLOGY

Depending on the methodology of assessing the emission factors, there are still large discrepancies. These have to be settled before any more detailed estimations can be performed. In addition, the chemical conversion processes in lightning need to be better understood, especially with regard to IC lightning.

12.   SPATIAL DISSAGGREGATION CRITERIA FOR AREA SOURCES

Spatial disaggregation can be performed according to the distribution of lightning and thunderstorm events.

13.   TEMPORAL DISSAGGREGATION CRITERIA

Temporal disaggregation should be done according to diurnal and annual cycle of thunderstorm / lightning activity.

14. ADDITIONAL COMMENTS

Lightning is not known to be influenced by humans at all, thus it should be considered as a purely natural source.

15. SUPPLEMENTARY DOCUMENTS

16. VERIFICATION PROCEDURES

17. REFERENCES

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