WORKING PAPER

A MODEL TO CALCULATE NATURAL VOC EMISSIONS FROM FORESTS IN EUROPE

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Wolfgang Schöpp

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PREFACE

This Working Paper presents the results of an innovative combination of two ongoing efforts within the Transboundary Air Pollution Project. Firstly, the growing concern about the regional effects of photochemical oxidants has made necessary better inventories of the emissions of oxidant precursors, including volatile organic compounds (VOC). Forests are an important natural source of VOC emissions. Secondly, to estimate these emissions, use has been made of GEOMAN, a geographically based environmental data storage, retrieval and display system that is being developed by our Project. This is the first use that has been made of GEOMAN, and a successful one at that. Finally, it is worth noting that this work was carried out in close cooperation with the Forest Study of the Biosphere Dynamics Project in the Environment Program.

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ABSTRACT

A significant portion of the total emissions of volatile organic compounds (VOC) may come from natural sources and, in particular, from forests. It is important to quantify these emissions because their share influences the magnitude of reductions that will have to be undertaken in the anthropogenic emission sectors in order to reduce secondary air pollution problems such as photochemical smog and acid deposition.

This paper describes a model to calculate geographically-resolved VOC emissions from forests in Europe for different seasons, months or average days. We review briefly the method on how to calculate biogenic emissions from trees and available emission factor functions, including a discussion of the dependence of emissions on latitude, altitude, time of the day and temperature. Subsequently, the geographically-resolved forest and temperature data bases for Europe, as used in this model to derive the emission estimates, are described. The forest data are verified against other published forest inventories for Europe or parts of Europe. The resulting total VOC emissions are compared with existing country- or region-specific estimates, and some sensitivity analyses are carried out in order to show where the emission model could be simplified or where it needs to be improved.

Based on our total forest coverage of approximately 2.2 million km^2, we calculate an average total annual emission rate of VOC's from these forests of 7.5 Megatonnes, based on typical European temperatures averaged over 30 years. This is equivalent to an areal average of 3.4 tonnes per year per km^2 forest or 0.9 tonnes per year per km^2 land area in the modeling domain. Until now, this forest emission model represents the only available basis for geographically-resolved emission calculations of VOC's from forests for all Europe for varying time periods.

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1. INTRODUCTION

The need for major emission reductions of the predominant air pollutants, i.e. sulfur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOC), is becoming widely accepted among policymakers of many countries. In order to create realistic and feasible strategies for such emission reductions, it is necessary to quantify, in a reliable way, past and current emission levels and to predict future levels with some confidence. It is, as well, important to know the types of emission sources and their associated emission quantities so that reductions can be proposed based on actually available control technologies for the relevant source sectors.

Air pollutants are emitted not only from man-made, but also from natural sources. On a global scale, the natural emissions often even outweigh those from human activities. In developed countries, however, the reverse is generally true, and most air pollution comes from fuel burning and other human and industrial activities. One exception are naturally emitted VOC's which can be significant, and which contribute to the formation of photochemical oxidants, predominantly ozone (O_3), and play a role in the acidification of the environment. The importance of these naturally-emitted VOC's is dependent on a region's or country's forests coverage compared with the abundance of man-made sources, such as automobiles, the use of organic solvents, and the petrochemical industry. For example, in Scandinavian countries, it is estimated that more than 50 percent of total national VOC's come from forests. In OECD-Europe, on average, 30 percent of all VOC's are estimated to be emitted annually from forests (OECD, 1989; Lübkert and de Tilly, 1989).

Although the total amount of VOC from forests may in some regions of Europe be comparable to or greater than that of anthropogenic emissions, the environmental impact of VOC's, and thus their role in ozone formation and acidification of the environment, depends also on the individual VOC species and their reactivity. Atmospheric chemistry and transport models are used to study this relationship between pollutant emissions and the resulting environmental burden. Over the past years, much attention in Europe and North America has been given to the modeling of both acid deposition and photochemical smog. Such models are also used to devise realistic emission control scenarios to reduce the environmental burden. In the case of VOC it is thus important to know which fraction of the reactive species comes from natural sources because this source sector cannot be "controlled", and consequently emission reductions to control secondary air pollution problems may have to be greater in the man-made source sectors.

Atmospheric chemistry and transport models are available for greatly varying spatial and temporal scales, and for various levels of detail. The reliability of the results of these models depends not only on the model formulation but also on the available input data. Not surprisingly, sensitivity analyses have shown that the emission inputs are key variables (e.g., Derwent and Hov, 1987). If model results are to represent real-world conditions, and are not only to be used for relative comparison between different scenarios, then key input data such as emissions have to be of high quality.

This paper describes the development of an emission model of VOC emitted from forests in Europe. In general, results from this model are intended as input into atmospheric chemistry and transport models, and, in particular, as input into the European Acid Deposition (EURAD) model (Ebel et al., 1989). The EURAD model is a European adaption of the Regional Acid Deposition Model (RADM) (NCAR, 1986) as part of the EUROTRAC program. For details, the reader is referred to Ebel et al.,(1989) and NCAR (1986).

In this paper, we review briefly the method to calculate biogenic emissions from trees and available emission factor functions, including a discussion of the dependence of emissions on latitude, altitude, time of the day and temperature. Subsequently, the geographically-resolved forest and temperature data bases for Europe which are used here to derive the emission estimates are described. The forest data base is verified against other published forest inventories for Europe or parts of Europe. The resulting total VOC emissions are then compared with other existing estimates, and lastly, some sensitivity analyses are carried out to test the importance of certain model input parameters. The results of these sensitivity runs are used to suggest some simplifications of the model input, and to point to areas where more refined input would be desirable.

2. METHOD

2.1. Review of Method for Calculating a Biogenic Emission Inventory for VOC's from Forests

Emission calculations are usually made for individual source sectors or categories, which lump together a conglomerate of individual sources of similar nature with respect to their emissions (see, for example: OECD, 1989; Lübkert and de Tilly, 1989; Veldt et al., 1988). Within these categories, total emissions are typically calculated by simply multiplying an average emission factor with a total production or use rate of the respective fuel or raw material. For the development of a biogenic emission inventory, basically three components are necessary (Zimmerman, 1979):

1. emission factors for the vegetative species;
2. prevailing conditions such as temperature, season, etc.;
3. biomass density factors.

For the VOC emission model developed here, we use emission factor functions derived from Zimmerman's (1979) and Tingey's (1978a,b) work. In our model, we take into account the following prevailing conditions: (1) regionally and temporally interpolated local temperatures, (2) the month of the year, (3) the time of the day (i.e. we distinguish between day- and night-time), (4) latitude, and (5) altitude. Biomass densities are derived from the total forest coverage per unit area and the wood volumes per species category in the same unit area.

The data have a spatial resolution of one degree longitude and half a degree latitude; in our emission model, they cover the area between 12° West and 42° East longitude and between 35° and 72° North latitude (Figure 1). A temporal resolution of one day is accomplished by a cubic spline interpolation of monthly average temperature data available between 1950 and 1984. The model is thus apt to calculate natural VOC emission rates for different seasons as well as for "typical" days. It is possible to incorporate more recent meteorological years into the emission model.

Model users may also wish to incorporate their own temperature data. Since temperature is probably the most important variable influencing the total emission rate of natural VOC from forests, this would be especially advisable where the results from this emission model are to be used in episodic atmospheric transport models for photochemical oxidant formation and/or acid deposition calculations. In this case, the model user can incorporate his/her own surface temperature field and may thereby improve the temporal resolution to one, or several hours.

2.2. Emission Factor Algorithms

Since emission measurements are usually not carried out on a routine basis for all individual sources, emission rates are generally based on mass balance calculations and specific point source measurements. This knowledge is translated into emission factors which (1) represent an extrapolation of point-specific data to an entire emission source category, and (2) are representative of typical conditions.

We know that the resulting average emission rates can vary greatly caused by (1) different operating conditions and/or sizes, etc., of emitting sources, and (2) fluctuations in environmental conditions such as temperature and time of the day, etc. This is the main reason why emission factors often vary considerably from one literature source to the next, and the user should have a good understanding of the underlying assumptions about the main influencing variables before using them.

Emission factors for VOC's from trees are generally very scarce. Actual field measurements of emissions were conducted by Zimmerman (1979) in the US states of Washington, North Carolina, Florida and California in the late 1970's. He found that the tree species sampled exhibited clear emission patterns. Conifers emitted primarily terpene-type compounds such as alpha-pinene, beta-pinene and delta-carene, whereas oaks emitted mainly isoprene. Zimmerman (1979) also observed that temperature, season, elevation and light affected the emission rates measured. These dependences were determined in more detail from laboratory experiments by Tingey et al. (1978 a,b). Their work shows terpene-type emissions tend to be greater at higher temperatures, low elevations and early in the growing season. Isoprene is only emitted from certain plants and only in daylight.

The results for the different VOC compounds measured by Zimmerman (1979) and Tingey et al., (1978a, b) have been aggregated into total VOC emission factor algorithms (e.g., Veldt et al., 1988). Figure 2 illustrates the relationship between the total VOC emissions and temperature for coniferous and deciduous trees, and for day- and night-time, respectively. The resulting equations are:

$$E_{h\ \mathrm{conif\ day}} = 10^{(0.05\ T_h\ -\ 0.6815)} \tag{1}$$

$$E_{h\ \mathrm{conif\ night}} = 10^{(0.05\ T_h\ -\ 0.7593)} \tag{2}$$

$$E_{h\ \mathrm{decid\ day}} = 10^{(0.1\ T_h\ -\ 2.15)} \tag{3}$$

$$E_{h\ \mathrm{decid\ night}} = 10^{(0.1\ T_h\ -\ 2.5556)} \tag{4}$$

where

$E_h =$ hourly species-specific VOC emission factor
for day or night time, respectively [kg VOC/km^2 · h];
$T_h =$ ambient temperature at hour h [° C].

This shows a considerable difference between the magnitude of emissions from deciduous and coniferous trees; pine trees emit an order of magnitude more VOC's at ambient temperatures commonly encountered in Europe than do broad-leafed species. The figure also shows the strong dependence of emissions on ambient temperature. It is therefore important to calculate emission rates based on actual observations of the main influencing variables. This paper will investigate how far one can rely on average temperature values compared to actual measurements.

Since our basic temperature data were monthly averages which we interpolated to daily average values by use of a cubic spline (see Section 3.2), we had to aggregate the day- and night-time emission factors for both conifers and broad-leafed trees. We assumed that the trees emitted for 12 hours according to day-time rates and for the other 12 hours according to night-time emission rates. This then results in the following two equations which are used in our model:

$$E_{d\ conif} = 144.0 \cdot 10^{(0.05\ T_d\ -\ 1.5)} \tag{5}$$

$$E_{d\ decid} = 3.415 \cdot 10^{(0.1\ T_d\ -\ 1.5)} \tag{6}$$

where

E_d = daily species-specific VOC emission factor [kg VOC/km^2 · d];
T_d = average ambient temperature on day d [° C];

and no distinction was made between day- and night-time temperature. As discussed later (see Section 5.2), this may result in some significant underprediction where a large temperature gradient exists between day- and night-time.

3. DATA BASES

3.1. Geographically-Resolved Forest Data Base

In the framework of the integrated Regional Acidification Information and Simulation (RAINS) model developed at IIASA (Alcamo et al. (in press); Alcamo et al., 1987), a geographically-resolved forest data base for large parts of Europe was established (Posch, 1989) for developing the direct forest impact submodel (Mäkelä et al., 1987). This data base was modified, and completed for all Europe, and then served as input into the natural VOC emission calculations.

3.1.1. Forest Coverage Data

For RAINS, total forest coverage data were taken from survey maps (e.g., Instituto Geográfico Nacional de España, 1982; DSurvey, War Office and Air Ministry, 1962), or where not available, from an atlas (National Geographic, 1981) for the following 13 altitude classes: <0 m, 0–150 m, 0–300 m, 150–300 m, 300–450 m, 300–600 m, 450–600 m, 600–900 m, 900–1200 m, 900–1500 m, 1200–1500 m, 1500–2100 m, >2100 m. The spatial resolution was one degree longitude and half a degree latitude. The method used was to overlay a grid of small squares and to count those over the green (i.e. wooded) fraction in each altitude class of each grid cell versus the total number of squares in the same class. This resulted in a fraction of forest coverage in each altitude class.

As seen above, the altitude classes were not unique but depended on the maps available. For example, some maps distinguished only between altitude classes from 0 to 300 m, 300 to 600 m, and so forth, whereas others made distinctions every 150 meters. The maximum altitude in all cases was ">2100 m". In this work, the 13 different altitude classes were newly aggregated into the following six unique classes: (1) <0–300 m, (2) 300–600 m, (3) 600–900 m, (4) 900–1500 m, (5) 1500–2100 m, and (6) >2100 m.

For this work, the forest coverage data were converted to actual km^2 wooded area by calculating the surface area per grid cell for grids of 1° longitude and 0.5° latitude according to the following equation:

$$A_g = cc \cdot \cos(\Phi + 0.25) \tag{7}$$

where

$$cc = (4 \cdot \pi \cdot R^2 \ \sin 0.25) \ / \ 360 \tag{8}$$

and:

$A_g =$ grid area [km^2];
$R =$ radius of the earth, 6370 km;
$\Phi =$ ° latitude.

Forest area in mountainous terrain calculated in this way can be underestimated because the surface area of the grid is assumed to be a flat surface.

3.1.2. Forest Species Data

For a large part of Europe, total wood volumes of coniferous and deciduous trees were available on a region or country basis (Nilsson et al., forthcoming). These wood volumes had been spatially interpolated for use in RAINS. If a grid cell fell entirely into one region, the same forest density was assumed for the region as a whole. If a grid cell fell into two or more regions, the different forest densities were weighted by the relative area from each region covered by the grid cell. The so-obtained wood volumes per grid cell were converted into relative fractions of conifers and broad-leafed trees. By simply assuming a linear relationship between wood volume and areal coverage, the square kilometers of coniferous versus deciduous forest in each grid cell could be determined. The assumption of such a linear relationship may introduce some error into the calculations. However, Nilsson and Posch (forthcoming) found little difference when comparing wood volumes with areal coverage data on a grid of our resolution. These differences seem to be important only in a much finer grid than 1° longitude and 0.5° latitude.

Where the data on total wood volumes for conifers and broad-leafed trees were missing, species information was obtained from a forestry atlas (Weltforstatlas, 1975) which distinguishes between the relative portions of coniferous and deciduous trees on a regional scale [in hectares]. Spatial interpolation was done in the same way as above; if a model grid cell fell into two or three different regions, the relative shares were weighted by areal coverage, otherwise the average densities from the region as a whole were assumed.

The next step was to reallocate the species information now available on a grid basis into the six different altitude classes. We have assumed that north of 47° latitude only conifers grow in the two highest altitude classes; so the total wooded area in these two classes was filled with coniferous trees. South of 47° latitude (i.e. the south side of the Alps), we have assumed deciduous trees to grow up to 2100 m altitude, and thus only filled the highest class > 2100 m with conifers. The remainder of conifers was evenly distributed in the remaining four or five classes. Deciduous trees were evenly distributed in the four or five lower altitude classes (see Annex A1).

3.2. Regionally and Temporally Interpolated Temperature Data Base

Monthly average temperature data from about 600 surface observations in Europe were available for 34 years between 1950 and 1984 (Henttonen and Mäkelä, 1988) for use in the RAINS model. Information included data on longitude, latitude, and altitude of each measurement station. This information was used in our emission model as base data for temperature input. However, since we needed temperature values for each grid cell and on a daily basis, available surface data had to be interpolated spatially and temporally.

3.2.1. Regional Interpolation of Temperature

Spatial interpolation was done by the so-called Combined Method described by Ojansuu and Henttonen (1983). This method makes use of the statistical dependence of temperature on latitude and altitude. The following non-linear regression model was used to describe this dependence:

$$T_{ki} = \beta_{k0} + \beta_{k1} y_i + \beta_{k2} z_i^{\beta_{k3}} + \epsilon_{ki} \tag{9}$$

where

T_{ki} = average temperature for month k at station i;
y_i = latitude of station i;
z_i = altitude of station i;
ϵ_{ki} = estimation error of temperature for month k at station i.

The parameters $\beta_{k0,\ldots,k3}$ were estimated for each month separately (Henttonen and Mäkelä, 1988), using the method of least squares (Dixon et al., 1985). Spatial correlation between stations was not taken into account in this regression model. The estimation error term ϵ_{ki} denotes the difference between observed and calculated temperatures and was determined at each station for each month. This term signifies a regional bias due to effects such as coastal influences, etc. In order to appropriately account for these regional differences, the following distance formula was used to weigh the error term ϵ_{ki}:

$$w_i = \begin{cases} (1 - d_i / d_{max})^2 & \text{for } d_i \leq d_{max}; \text{ and } (z_i - z) < 500 \text{ m;} \\ 0 & \text{otherwise;} \end{cases} \tag{10}$$

where

w_i = weight for the observation at station i;
d_i = distance between the station and the subject point;
d_{max} = 250 km;
z_i = altitude of station i;
z = altitude of the subject point.

The resulting weights w_i are used to calculate the weighted average regional bias at any desired point. As the formula indicates, the regional bias of the temperature at a particular station was only considered to influence calculated temperatures when the station was within a radius of 250 km and within a maximum altitude difference of 500 meters; these maxima were determined from sensitivity analyses.

Now, the temperature at any point could be calculated by specifying the respective latitude and altitude in the regression model, and by correcting this result with the weighted average regional bias. For our emission model, we calculated the temperatures at all grid cell midpoints in each of the six different altitude classes described above (compare Section 3.1.1). In general, the larger the distance between measurement stations, the stronger the influence of the regression on the resulting calculated temperatures.

In practice this means that we used a spatial interpolation method which makes use of a regression model to locally improve temperature estimates. Compared to only using spatial interpolation (Method of Moving Average), we avoid the problem of having to find the optimum number of measurement stations that influence the subject point. Whereas too many as well as too few stations in the Moving Average Method give relatively quickly comparably large errors, the Combined Method gives relatively stable results. Using the Jackknife Method (Quenouille, 1956; Tukey, 1958), Henttonen and Mäkelä (1988) found a maximum absolute error of less than 3° C. They determined no systematic error (i.e. the bias is almost 0) and a maximum root mean square error (RMSE) of 1.5° C in January.

3.2.2. Temporal Interpolation of Temperature

As we wanted to calculate natural VOC emissions not only for monthly periods but also for individual "typical" days or during "typical" several-day episodes, we had to again interpolate the monthly temperature data. This temporal interpolation was made by using a cubic spline function (Henttonen and Mäkelä, 1988), which is a smooth interpolation scheme that gives consistent results but misses any irregular peaks or lows.

Using the cubic spline method (Press et al., 1986), we derived six daily average temperature values in each grid cell for each of the six altitude classes. These temperatures were either based on a specific inventory year, or on a "typical" year which constitutes a 30-year mean of the monthly averages. The latter may be of value in trying to predict "typical" emissions that might be expected during a particular season or month.

3.2.3. Limitations of the Temperature Interpolation Methods

The temperature interpolation schemes used here represent climatological approaches in which local or short-term phenomena are neglected. For example, small scale (i.e. an extent of less than 250 km) or short-term weather situations (e.g., local inversions), as well as steep temperature rises or falls from day to day, are not accounted for by these methods. That means that the subsequently calculated natural VOC emission rates are representative if the period considered is (1) at least around one month duration, or (2) supposed to represent a "typical" short-term episode of only a few days, or a "typical", e.g., 3rd of June-day itself. However, interpolated temperature data should not be used to try to reproduce emission rates as they actually occurred on a specific day or days. Instead, only actual temperature data should be used as model input.

4. RESULTS

4.1. The European Forest Inventory

The forest coverage data for conifers and broad-leafed trees were summed up to calculate the total European forest area. This results in 2198 * 10^3 km^2 of forest in total, and in 1472 * 10^3 km^2 of coniferous and 726 * 10^3 km^2 of deciduous trees. Figure 3 shows the total forest coverage density in the one degree longitude and half a degree latitude grid in Europe, whereas Figures 4 and 5 depict the densities of coniferous and deciduous trees separately.

We verified our forest data base by comparison with published or otherwise available forest inventories (Andryukov and Timofeev, 1989; UN ECE, 1987; Posch, 1989; Veldt et al., 1988). Where available, we compared the inventories for conifers and broad-leafed trees separately (Andryukov and Timofeev, 1989; UN ECE, 1987). In contrast to our inventory, PHOXA (Veldt et al., 1988) has a separate class for "mixed" forest, so that a species-specific comparison was not possible with their inventory.

We also made a country-by-country comparison in the cases where sufficient data were available (Andryukov and Timofeev, 1989; UN ECE, 1987; Posch, 1989; Veldt et al., 1988). For the PHOXA forest inventory, this was only partly possible because the PHOXA region does not include all European countries and some of them only partly. For the Soviet Union, no verification was possible because our model domain does not cover the entire European part of the country, but only extends to 42° East. The UN ECE (1987) data, on the other hand, cover the Asian as well as European part of the country, and Andryukov and Timofeev (1989) cover the entire European part up to about 60° East in the North and to around 55° East in the South.

An overview of these comparisons is presented in Tables 1 and 2. Whereas Table 1 compares species-specific estimates for various regions in Europe, Table 2 compares national estimates for total forest coverage. Table 1 shows that our data are in good agreement with data by Posch (1989) but, for some countries, show relatively large deviations from the UN ECE data (1987). In countries of mountainous terrain, this may be explained by the fact that we calculate the forest coverage as a relative fraction of the grid cells and assume these to be flat. In countries with relatively flat terrain, we have a high confidence in our data because most of them were taken from detailed survey maps (e.g., Instituto Georgráfico Nacional de España, 1982; DSurvey, War Office and Air Ministry, 1962). Some deviations may result because the definition used for forest may not always be the same. When added up into entire regions, our data compare very well with other estimates (see Table 1).

4.2. Natural VOC Emissions from Forests in Europe

Once we had calculated the daily average temperature, as well as the areal coverage of conifers and broad-leafed species for each altitude class in each grid cell, we could then determine the total natural VOC emission rates from forests. This was done by a series of computer programs using DBase and C language.

First, emission factors for coniferous and deciduous trees were calculated for each altitude class and grid element, and for the entire time period according to the following equations (see Annex A2):

$$E_{conif} = \sum_{d=N_F}^{N_L} \left(144.0 \cdot 10^{(0.05\, T_d - 1.5)}\right) \tag{11}$$

$$E_{decid} = \sum_{d=N_F}^{N_L} \left(3.415 \cdot 10^{(0.1\, T_d - 1.5)}\right) \tag{12}$$

where

E_{conif}	=	VOC emission factor for coniferous forest for time interval N_F - N_L [tonnes per km^2 per desired time interval];
E_{decid}	=	VOC emission factor for deciduous forest for time interval N_F - N_L [tonnes per km^2 per desired time interval];
T_d	=	daily average temperature [°C];
N_F	=	first day of time interval;
N_L	=	last day of time interval.

Next, these emission factors were multiplied with the respective forest coverage data so that emission rates per species per altitude class and per grid element could be calculated as follows (see Annex A3):

$$e_{gz_i\, conif} = E_{conif} \cdot A_{gz_i\, conif} \tag{13}$$

$$e_{gz_i\, decid} = E_{decid} \cdot A_{gz_i\, decid} \tag{14}$$

where

$e_{gz_i\ conif}$	=	emission rate for coniferous forest in grid g at altitude z_i [tonnes per grid per desired time interval];
$e_{gz_i\ decid}$	=	emission rate for deciduous forest in grid g at altitude z_i [tonnes per grid per desired time interval];
$A_{gz_i\ conif}$	=	area covered with coniferous forest in grid g at altitude z_i [km^2];
$A_{gz_i\ decid}$	=	area covered with deciduous forest in grid g at altitude z_i [km^2];
z_i	=	average altitude per altitude class i [m];
i	=	1 to 6.

The output at this stage is used for the graphical representation and can be displayed. As a last step, emissions were summed up over the modeling domain and over all altitude classes so that total VOC emissions from each species category are computed (see Annex A4):

$$e_{conif} = \sum_{g} \sum_{z_i} e_{g_{zi}\ conif} \tag{15}$$

$$e_{decid} = \sum_{g} \sum_{z_i} e_{g_{zi}\ decid} \tag{16}$$

where

e_{conif}	=	emissions from coniferous forest in model domain [tonnes per model area per desired time interval];
e_{decid}	=	emissions from deciduous forest in model domain [tonnes per model area per desired time interval].

With the emission model developed in this paper, we calculate a total of 7,089 ktonnes for 1982 as an example year, and 7,473 ktonnes per year for a 30-year average of natural VOC emissions from forests in Europe between 11° West and 42° East longitude, and between 35 and 72° North latitude (compare Figure 1). This is equivalent to an areal average of 3.4 tonnes per year per km^2 forest or 0.9 tonnes per year per km^2 land area in the modeling domain. Figure 6 shows the geographical distribution of these emissions for a 30-year average and Annex A5 depicts separately for the different regions in Europe all gridded emissions by number. Figures 7 and 8 depict the spatial emission densities, also for a 30-year average of VOC's from coniferous and deciduous forests, separately. In total, 6,821 ktonnes are emitted annually from conifers and 652 ktonnes from broad-leafed trees. Tables 3 and 4 summarize region- and country-specific estimates made with our model, and compare them with natural VOC estimates made by other groups.

Figure 9 shows the typical emissions for the three-month period between May and July 1982 and Figure 10 the daily emissions for a "typical" 3rd of June. For all Europe, these add up to 3,078 ktonnes for the May–July period and to 25 ktonnes for the 3rd of June.

5. DISCUSSION

5.1. Comparison with Other Natural VOC Emission Estimates

Until now, not many reliable emission estimates exist in Europe for natural VOC's from forests. Most of these estimates are annual averages and not necessarily specific to a particular year. More recent estimates include those by the PHOXA group (Veldt et al., 1988), the OECD (Lübkert and de Tilly, 1989; OECD, 1989) and Andryukov and Timofeev (1989).

The PHOXA data are available for a limited area which covers northern Europe between 10° West and 24° East longitude and between 47.5 and 60° North latitude (see Figure 11). They are available from the literature as totals per nation or national region included in the PHOXA domain for 1980 (Veldt et al., 1988). Since these data have been used in the modeling of episodes of large-scale formation and long-range transport of photochemical oxidants, they are also available for particular episode days. In order to verify the emission model proposed in this paper, we compared our estimates within the PHOXA domain with those available from Veldt et al. (1988).

The OECD data (OECD, 1989; Lübkert and de Tilly, 1989) are available for 17 western European countries as national total estimates also for the year 1980, and they were compared with our calculations for the same 17 countries. The estimates by Andryukov and Timofeev (1989) are country-specific and for all Europe, but not for a specific inventory year. We compared these with our model estimates for the 30-year average. As our model region only extends to 42° East, it does not comprise the entire region of the European part of the Soviet Union which, in the North, extends up to 60° East and, in the South, to around 55° East. We therefore compared emissions for the European area with and without the contribution from Soviet forests.

With these data available, it was thus possible to check our calculations against several independent estimates, on different averaging time scales and for various regions in Europe. The first comparison was with the total annual 1980 PHOXA estimate. Temperature inputs in our calculation are based on measured monthly averages from 1980, interpolated by the method described above to daily average temperatures. The emission model calculates a total amount of VOC's from coniferous and deciduous trees of 1688 ktonnes. This compares quite well with the PHOXA estimate of 1613 ktonnes for the same region and year (i.e. a 4 percent difference) (see Table 3).

The next comparison was made as well within the PHOXA area, but on a daily basis during the 22-26 July 1980 photochemical smog episode. In this case, relatively good agreement was achieved during the first days of the episode, but the model failed to reproduce the high levels towards the end. On 22 July 1980, our model calculates an emission rate of 10,772 tonnes whereas PHOXA calculated 9,746 tonnes (i.e. only a 10 percent difference); and on 26 July 1980 we calculate 10,798 tonnes whereas PHOXA estimated 21,322 tonnes (i.e. almost twice as high an emission). It is not surprising that our model does not reproduce this steep emission increase because we base our calculation on interpolated monthly temperature data whilst PHOXA used actual daily temperatures.

Table 4 gives an overview of the comparison of country-wide natural VOC emissions from forests as calculated by our model and those by Andryukov and Timofeev and by the OECD. In general, Andryukov and Timofeev calculate significantly higher emissions than estimated by our model or by the OECD. The OECD estimates agree relatively well with ours. When considering the total European OECD region, our emissions are 10 percent lower than those given by the OECD for 1980 (see Table 3). The comparison with Andryukov and Timofeev again shows a consistent difference for the various region chosen in Table 3 of about a factor of 3.5. Since they do not give any details of how they calculated their emissions, we cannot comment on, or explain, this large discrepancy.

5.2. Sensitivity Analyses

As Equations (1)–(4) and Figure 2 show, VOC emissions from trees are mostly influenced by the ambient temperature, type of forest, and time of the day. In our model, we have established a forest data base that distinguishes between deciduous and coniferous trees on a spatial scale of one degree longitude and half a degree latitude, and on a vertical scale of 300 and 600 m intervals up to 2100 m. We then combined these data with local temperature information.

Although we knew that temperature is probably the most important influencing variable, we did not have access to better temporally-resolved temperature data and therefore used monthly average observations as our basis. We used smooth interpolation schemes to obtain daily values for all grid cells. By doing so, we excluded consideration of any short-term or local effects which may be very important when calculating VOC emissions for a specific meteorological event in a particular region. Because of the exponential temperature increase, this is of special importance for short-term high temperature periods. On the other hand, our model is not so much intended to reproduce exact data of the past, as to predict seasonal and "typical" short-term natural VOC emissions anywhere in Europe, based on a consistent set of forest and meteorological data.

Although we distinguished between day- and night-time emission factor functions, we used the same constant average daily temperature in both equations. This allowed us to combine equations (1) and (2) into equation (5) for conifers, and (3) and (4) into equation (6) for deciduous trees. In doing so, we are prone to overestimate night-time emissions and underestimate day-time rates, with a net effect of underestimating total daily VOC emissions because of their exponential increase with higher temperatures. If sufficient knowledge on the existing daily temperature patterns in the various regions and climate zones of Europe is available elsewhere, this information might significantly improve our model. We could then prescribe typical daily temperature gradients to each grid element of our modeling domain. In the framework of our study, we have only carried out a few example calculations here, intended to illustrate the important effect of different daily temperature gradients.

We compared the aggregated daily VOC emission factors, for conifers only, for the following three cases of temperature gradients: (1) a constant daily average temperature $\bar{T}_d$; (2) a step-function with a 12-hour day-time temperature T_{max} and a 12-hour night-time temperature T_{min}; and (3) a triangular function with a maximum temperature T_{max} at 15 h, a minimum T_{min} at 3 h, and a constant temperature increase or decrease each hour. For these three types of daily temperature curves, we assumed two different lengths of daytime: (1) a 12-hour day and 12-hour night, and (2) an 18-hour day and 6-hour night. We carried out the calculation of $E_{d\ conif}$ for two reference temperatures $\bar{T}_d$: (1) 20°C, and (2) 10°C. The resulting emission factors are listed in Table 5, and the percentage difference to the reference case of a constant temperature of 20°C or 10°C throughout the day are given for each case. This shows a maximum deviation of over 25 percent for the case of an 18-hour day with a T_{max} of 25°C for 12 hours and a T_{min} of 15°C for the remainder. Also for a $\bar{T}_d$ of 20°C, assuming a triangular-shaped temperature gradient over the day with 18 day-time hours, and with an increase or decrease of 1°C per hour, we get a difference of over 15 percent in the aggregated daily emission factor.

However, 20° C is probably too high an average daily temperature, especially for northern Europe, and 10 or 12° C too high a variation between day and night in areas influenced by maritime climates. When repeating the same calculations but with a $\bar{T}_d$ of 10° C and only a 6° C variation between daily minimum and maximum, the relative difference is maximally 15 percent (see Table 5). For European countries of the mid-latitudes, 10°C is a realistic daily average as, for example, in the Federal Republic of Germany, the annual average temperature is about 9° C (Veldt et al., 1988). Here we see that the differences are much smaller than in the above case of $\bar{T}_d = 20°C$, although the net effect is still an underestimation.

Qualitatively, we know that the daily temperature varies most closely to such a triangular-shaped function and would probably be even better represented by a sinusoidal function in the following way:

$$T_h = T_d + \alpha \sin [2 \pi (h - 9) / 24] \qquad (17)$$

where

$T_h =$ temperature at hour h;
$T_d =$ average daily temperature;
α = amplitude (i.e. 2 α = difference between the maximum and minimum daily temperatures).

Since we did not have enough information available to quantify this behavior in the various climatic zones of Europe, we did not attempt to incorporate it into our model at this stage. We therefore only know that we somewhat underestimate the total daily emission rate.

In order to investigate the dependence of temperature on altitude and latitude, we carried out a few sensitivity tests. For these, we restricted the areal coverage to the PHOXA domain.

In the first case, we evaluated the influence of using actual altitude classes for forest coverage versus only average altitudes in each grid cell. From work in IIASA's Biosphere Program (Leeman, 1989), we had available average grid heights for each gird cell in our model. Results were compared on a one-year and one-day basis; we chose 1982 and the 3rd of June 1982.

For 1982, detailed calculations with all altitude classes result in 1754 ktonnes of natural VOC in the PHOXA area, whereas calculation with only the average altitude per grid cell results in 1795 ktonnes (i.e. a 2 percent difference) (Figures 12 and 13).

Calculations for only one day (3 June 1982) show the same overall 2 percent difference (Figures 14 and 15). Figure 16 shows for 3 June 1982 those grid cells where the difference between calculation with average heights versus 6 altitude classes is larger than 10 percent. From this figure we see that most of the large relative differences occur where the absolute emissions are very small (around 0), i.e. along the coast lines. As expected, the remaining relatively large differences occur in the areas with high mountain ranges (e.g. Riesengebirge in Czechoslovakia, Jotunheim in Norway, Erzgebirge in GDR, the Alps in FRG).

The maximum absolute difference for an individual grid square that we calculated on this day was 6.2 tonnes; we should see this in relation to the maximum grid emission of 35 tonnes. In more than 90 percent of all grids in the PHOXA area, the absolute difference was less than 1 tonne, and in more than 75 percent of all grids the relative difference was less than 10 percent. In conclusion, overall as well as grid-specific differences are small, so that the error introduced by calculating with average grid heights can be considered minor, and the model could be simplified by only using one average grid-specific altitude class. However, in extremely mountainous areas, such as the Alps, the altitude-dependent calculation of emissions should be preferred.

The next sensitivity test was made to evaluate the influence of using a cubic spline function in order to obtain daily temperature averages and subsequently calculating relatively long-term average emissions, versus using monthly average temperatures directly in the emission rate calculations. As an example, we selected a three-month period from May through July 1982.

Calculation without a cubic spline interpolation result in 799 ktonnes (Figure 17) whereas computation with a spline interpolation gives 693 ktonnes (Figure 18), i.e. an estimate 13 percent lower. This is a relatively large difference and may be explained by the fact that as a result of the spline interpolation, the early May temperatures are still influenced by the cooler April average and the late July temperatures already by the August average, which probably does not show any considerable change compared to July. The spatial variability of the relative differences between calculation with and without spline interpolation is illustrated in Figure 19. This shows that in areas of mostly maritime climate, the differences are relatively small (less than 10–12 percent), whereas in areas of more continental climate, they become larger (up to 22 percent). This is consistent with the above argument, since the difference between monthly averages for April and May is probably larger in the region of continental climate than in the zones close to the coast. It could therefore be expected that in the fall, or in all cases where temperatures continously decrease, calculations without spline interpolation would be lower than those with spline interpolation, and in all cases where the average monthly temperature rises, calculation without this interpolation would be higher. Since spline interpolation better represents reality for periods of several weeks to months, it is preferable to the use of simple monthly average temperatures.

As already assumed at the outset of our study, we found that actual daily temperature gradients have the largest effect on resulting VOC emission rates. The second most important influence for relatively short periods, such as several weeks to several months, is caused by the use of a temporal spline interpolation of monthly temperature averages versus the use of only monthly averages. On the other hand, additional detail in the forest data base such as species allocation with altitude, has only a small overall, as well as local effect. It has thus been shown that the cubic spline interpolation to derive daily temperature values is essential and that a further improvement in our emission model could be achieved by specifying daily temperature gradients for all grid cells, thus creating hourly temperature input for the model.

6. SUMMARY AND CONCLUSIONS

In this paper, we have developed an emission model to calculate spatially resolved natural VOC's from forests in Europe for different seasons, months or average "typical" days. We have described in detail the derivation of the necessary geographically-resolved forest and temperature input data bases for all Europe between 12° West and 42° East longitude and between 35 and 72 ° North latitude.

The emission model calculates natural VOC emissions from conifers and broad-leafed species in six different altitude classes, the first three of which cover 300 meter-intervals and the last three 600 meter-intervals up to 2100 m, and in a grid of one degree longitude and half a degree latitude. The model can calculate natural VOC emissions for individual "typical" days, as well as for several days, weeks, months, seasons and years, based on monthly temperature averages. The model is further built in such a way that the user can easily incorporate his/her own temperature data in order to improve the temporal resolution.

The emission model incorporates a spatially resolved forest inventory with a total forest coverage of 2.2 million km^2 within our modeling domain. Of this, 1.5 million km^2 are covered with conifers and 0.7 million km^2 with broad-leafed trees.

Our forest data base has been verified by comparison with other forest inventories. This has been done for specific regions and countries, and for coniferous and deciduous trees separately. These comparisons show deviations between our inventory and others for individual countries, but agree very well when summed up over various regions. Some of these deviations may be explained by the fact that we have more up-to-date information compared to the other already published inventories. Also, our deviations for individual countries are of the same order of magnitude as differences between the other inventories themselves. Nevertheless, in mountainous terrain, a better estimate of forest surface area could be achieved by accounting for the slope of the landscape rather than assuming it to be flat.

Our temperature data base consists of geographically interpolated monthly averages for a total of 34 years between 1950 and 1984. Temperature data are separately available for the six different altitude classes, as well as for the average grid height of each grid square. For VOC emission calculations, these data are temporally interpolated by a cubic spline function to give daily temperature values. Based on the daily averages, VOC emissions can be calculated for any period between 1950 and 1984, as well as for a "typical" day, month, season, etc. In the latter case temperatures are derived from a 30-year average of observed monthly temperatures.

Using 30-year average temperatures, we calculate 7,473 ktonnes per year of natural VOC's from forests of which 6,821 ktonnes came from conifers and 652 ktonnes from broad-leafed forest. This is equivalent to an annual average of 3.4 tonnes per km^2 forest or 0.9 tonnes per km^2 land area in the modeling domain. For a typical summer-day (3 June), the total VOC's from forests are 25 ktonnes, and for a typical May–June period, they are 3,078 ktonnes.

Our emission calculations have been verified by comparison of VOC totals for specific regions in Europe or for particular countries with other published estimates of natural VOC for the same areas. These comparisons show good agreement between our emission calculations and those by PHOXA and OECD, whereas they are considerably lower (about a factor of 3.5) than those by Andryukov and Timofeev. Until now our forest emission model represents the only available basis for geographically-resolved calculation of VOC's from forests in all Europe; therefore no comparison of the spatial distribution of forests or emissions is possible.

Sensitivity analyses have shown that, based on available monthly average temperatures, it is better to use a cubic spline interpolation method when calculating VOC emissions for a several months-period than to use the monthly average temperatures themselves. It has further been demonstrated that our model could be improved by prescribing daily temperature gradients to all grid cells, thus creating hourly temperature input into the emission factor algorithms. However, the model user can also incorporate his/her own temperature field, for example, for actual hourly data, thereby improving the input.

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Table 1. Comparison of Different Forest Inventories.

Region	Total Forest Area [km²]	Coniferous Forest [km²]	Deciduous Forest [km²]	Reference
PHOXA	476,413	356,937	119,476	This Work
	487,076	-	-	Veldt et al., 1988
OECD Europe w/o Yugoslavia	1,140,145	854,665	285,480	This Work
	1,179,000	499,000*	-	Andryukov and Timofeev, 1989
	1,103,040	699,450	403,590	UN ECE, 1987
	1,135,589	-	-	Posch, 1989
OECD Europe	1,235,893	868,258	367,635	This Work
	1,253,000	514,000*	-	Andryukov and Timofeev, 1989
	1,194,290	711,550	482,740	UN ECE, 1987
	1,231,338	-	-	Posch, 1989
Europe w/o USSR**	1,475,049	1,008,761	466,288	This Work
	1,527,000	662,000*	-	Andryukov and Timofeev, 1989
	1,470,930	864,040	606,890	UN ECE, 1987
	1,487,601	-	-	Posch, 1989
Europe w/ USSR**	2,198,159	1,472,440	725,719	This Work***
	3,043,000	1,622,000*	-	Andryukov and Timofeev, 1989
	2,229,675	-	-	Posch, 1989***

* this estimate excludes Sweden which, according to Andryukov and Timofeev (1989), has a total forest coverage of 234,000 km^2.

** refers to the European part only.

*** covers the USSR only up to 42° East.

Table 2. Comparison of Different Estimates of Forest Coverage per Country.

Country	Total Forest Area [km²] according to				
	This Work	Posch, 1989	Andryukov and Timofeev, 1989	UN ECE, 1987	Veldt et al., 1988
Albania	13,930	13,930	-	-	-
Austria	30,310	30,290	37,000	37,540	17,190*
Belgium	4,600	4,610	6,000	6,800	9,020
Bulgaria	34,260	38,460	37,000	33,000	-
CSSR	38,460	38,470	45,000	45,780	47,010
Denmark	2,390	2,400	5,000	4,660	8,010
Finland	224,540	225,370	187,000	200,590	-
France	110,700	114,580	130,000	144,400	47,350*
FRG	61,650	61,320	68,000	73,600	77,210
GDR	27,380	27,640	30,000	29,550	35,600
Greece	26,360	24,210	58,000	57,540	-
Hungary	9,370	9,370	15,000	16,370	6,330*
Ireland	880	940	-	3,800	7,260
Italy	51,730	51,830	77,000	86,750	-
Luxembourg	900	900	-	880	1,130
Netherlands	2,200	2,280	3,000	3,110	4,060
Norway	112,360	112,610	83,000	66,600	32,387*
Poland	67,710	67,710	85,000	86,540	71,350
Portugal	30,300	29,810	36,000	29,760	-
Romania	48,050	60,690	62,000	65,400	-
Spain	151,910	152,190	227,000	117,890	-
Sweden	300,690	300,660	234,000	237,000	90,973*
Switzerland	12,180	12,180	9,000	11,860	-
United Kingdom	11,740	9,410	19,000	20,180	32,196
USSR	723,110**	742,074**	1,516,000***	8,109,000****	-
Yugoslavia	95,750	95,750	74,000	91,250	

*only parts of these countries are contained in the PHOXA region.
**covers the USSR only up to 42° East.
***refers to the European part only.
****refers to the entire USSR.

Table 3. Comparison of Region-Specific Estimates of VOC's from Forests.

Region	Total Natural VOC [Ktonnes]	VOC from Coniferous Forest [Ktonnes]	VOC from Deciduous Forest [Ktonnes]	Reference
PHOXA	1,688 (1980)	1,625	63	This Work
	1,613 (1980)	-	-	Veldt et al., 1988
OECD Europe w/o Yugoslavia	4,484	4,175	309	This Work
	15,370	-	-	Andryukov and Timofeev, 1989
	4,955 (1980)	-	-	OECD, 1989
OECD Europe	4,648	4,253	395	This Work
	16,570	-	-	Andrykov and Timofeev, 1989
Europe w/o USSR*	5,561	5,060	501	This Work
	19,240	-	-	Andryukov and Timofeev, 1989
Europe w/USSR*	7,473	6,821	652	This Work**
	29,040	-	-	Andryukov and Timofeev, 1989

* refers to the European part only.

** includes emissions in the USSR only up to 42° East.

Table 4. Comparison of Country-Specific Estimates of VOC's from Forests.

Country	Total VOC Emissions [ktonnes] according to		
	This Work*	Andryukov and Timofeev, 1989	OECD, 1989**
Albania	45	-	-
Austria	109	370	140
Belgium	15	17	35
Bulgaria	118	700	-
CSSR	144	360	-
Denmark	6	15	51
Finland	601	480	522
France	524	1,800	999
FRG	224	680	220
GDR	118	290	-
Greece	155	2,300	130
Hungary	21	70	-
Ireland	3	-	17
Italy	170	1,300	550
Luxembourg	3	-	6
Netherlands	8	8	14
Norway	299	200	180
Poland	309	720	-
Portugal	257	850	277
Romania	157	630	-
Spain	1,115	6,600	943
Sweden	890	600	750
Switzerland	40	100	50
United Kingdom	39	50	71
USSR	1,912***	9,800****	-
Yugoslavia	164	1,200	-

*emission calculations are based on 30-year average temperatures.
**emissions refer to 1980.
***includes emissions in the USSR only up to 42° East.
****refers to the European part only.

Table 5. Effects of Different Temperature Gradients on Daily Emission Factor for VOC from Conifers, $E_{d\ conif}$

Temperature Gradient					Number of Day-Time Hours	A	B	100 × (A-B)/B
Function Type	$\bar{T}_d$ [°C]	T_{max} [°C]	T_{min} [°C]	ΔT [°C/hr]		$E_{d\ conif}$ [kg VOC/km²-d]	$E_{d\ ref}$ [kg VOC/km²-d]	[%]
Constant	20	20	20		12	45.54	45.54	0.0
Constant	20	20	20		18	47.92	45.54	5.2
Step	20	25	15		12	56.18	45.54	23.4
Step	20	25	15		18	57.33	45.54	25.9
Triangular	20	26	14	1	12	50.74	45.54	11.4
Triangular	20	26	14	1	18	52.72	45.54	15.8
Constant	10	10	10		12	14.40	14.40	0.0
Constant	10	10	10		18	15.15	14.40	5.2
Step	10	13	7		12	15.84	14.40	10.0
Step	10	13	7		18	16.30	14.40	13.2
Triangular	10	13	7	0.5	12	15.07	14.40	4.7
Triangular	10	13	7	0.5	18	16.59	14.40	15.2

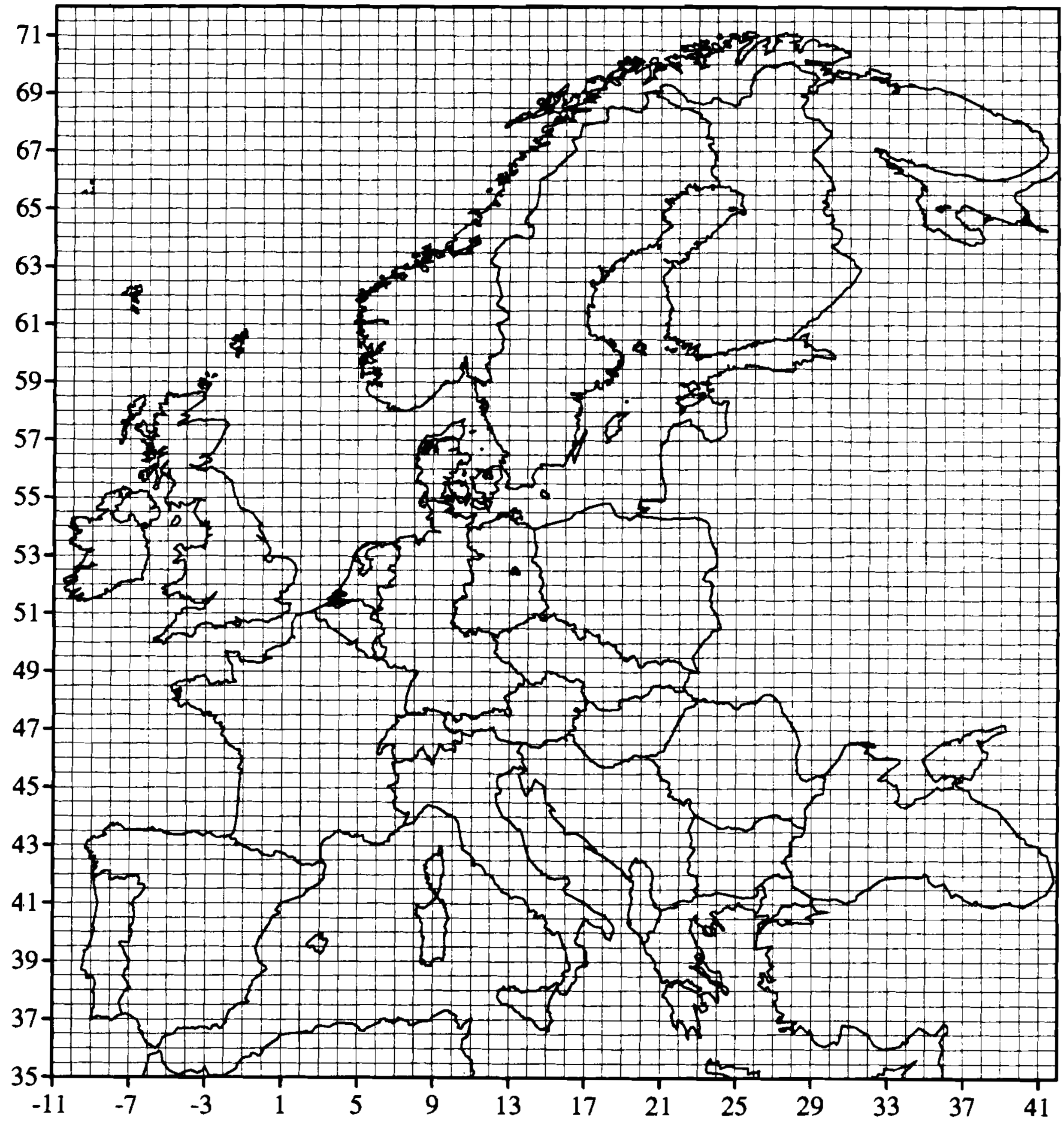

Figure 1. Model domain Europe.

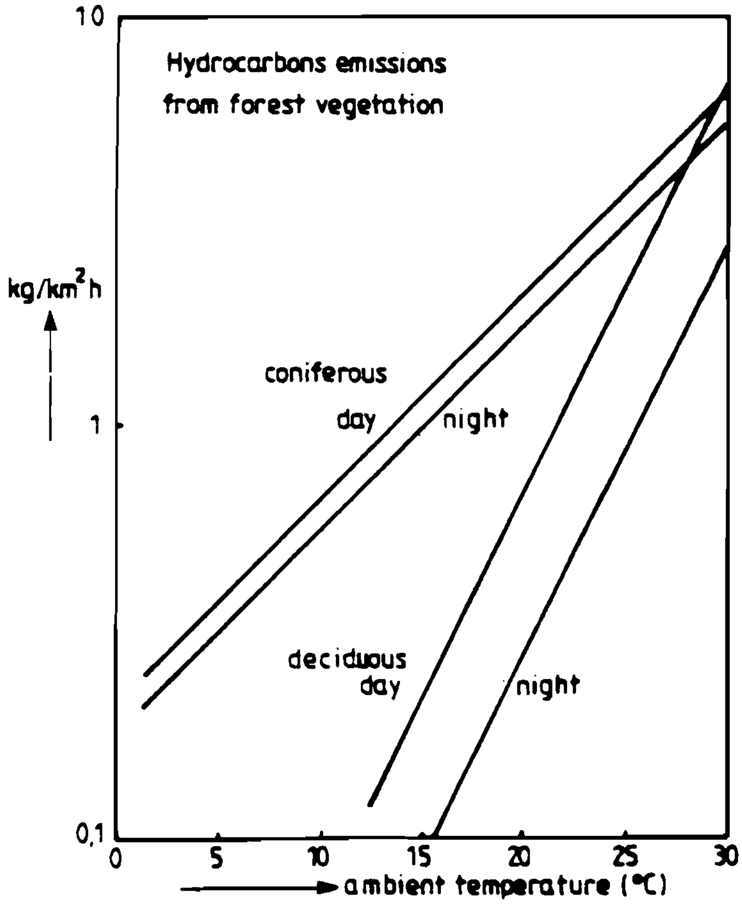

Figure 2. Emission factor algorithms for VOC's from forests.

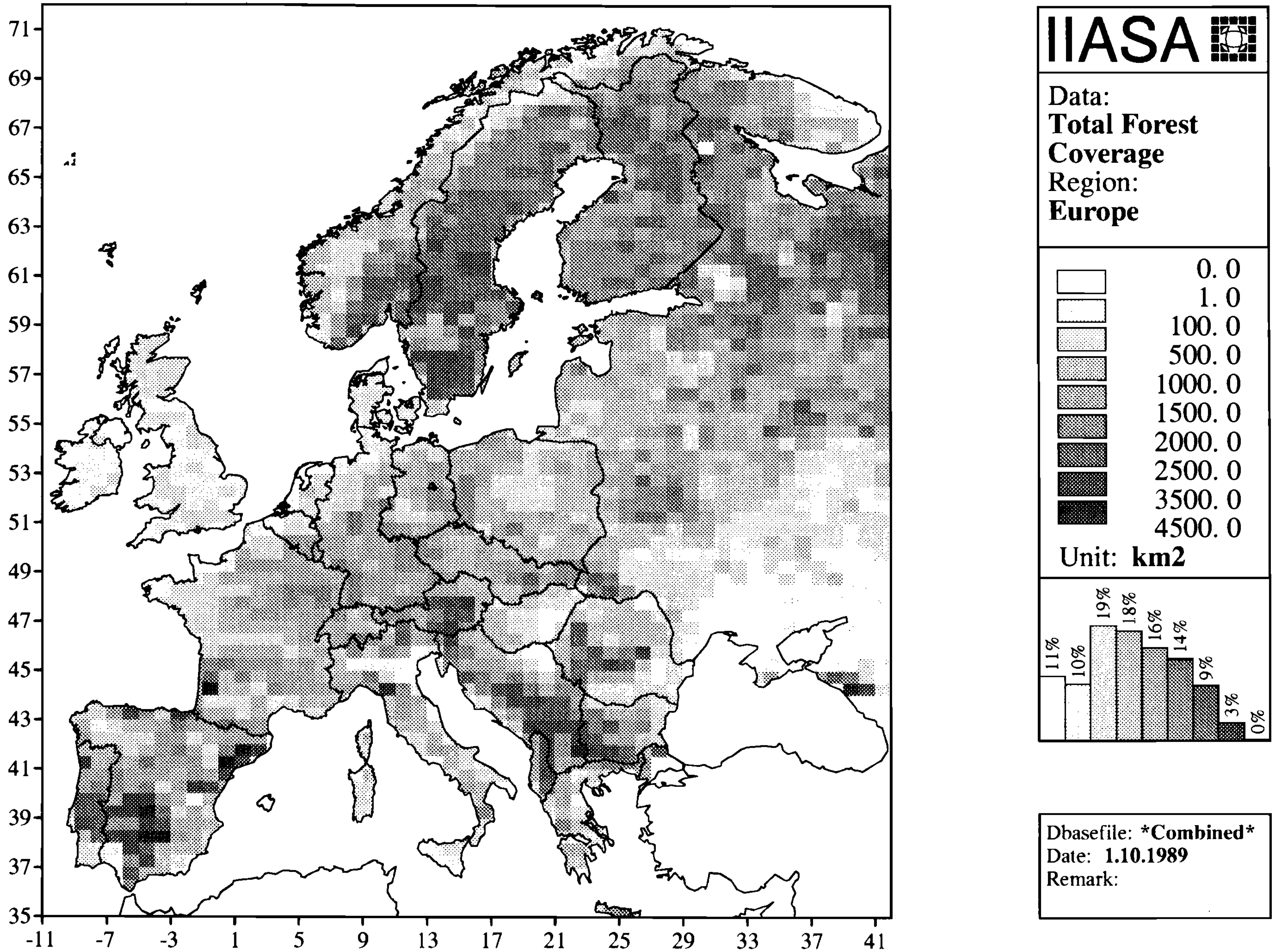

Figure 3. **Total forest coverage densities in Europe.**

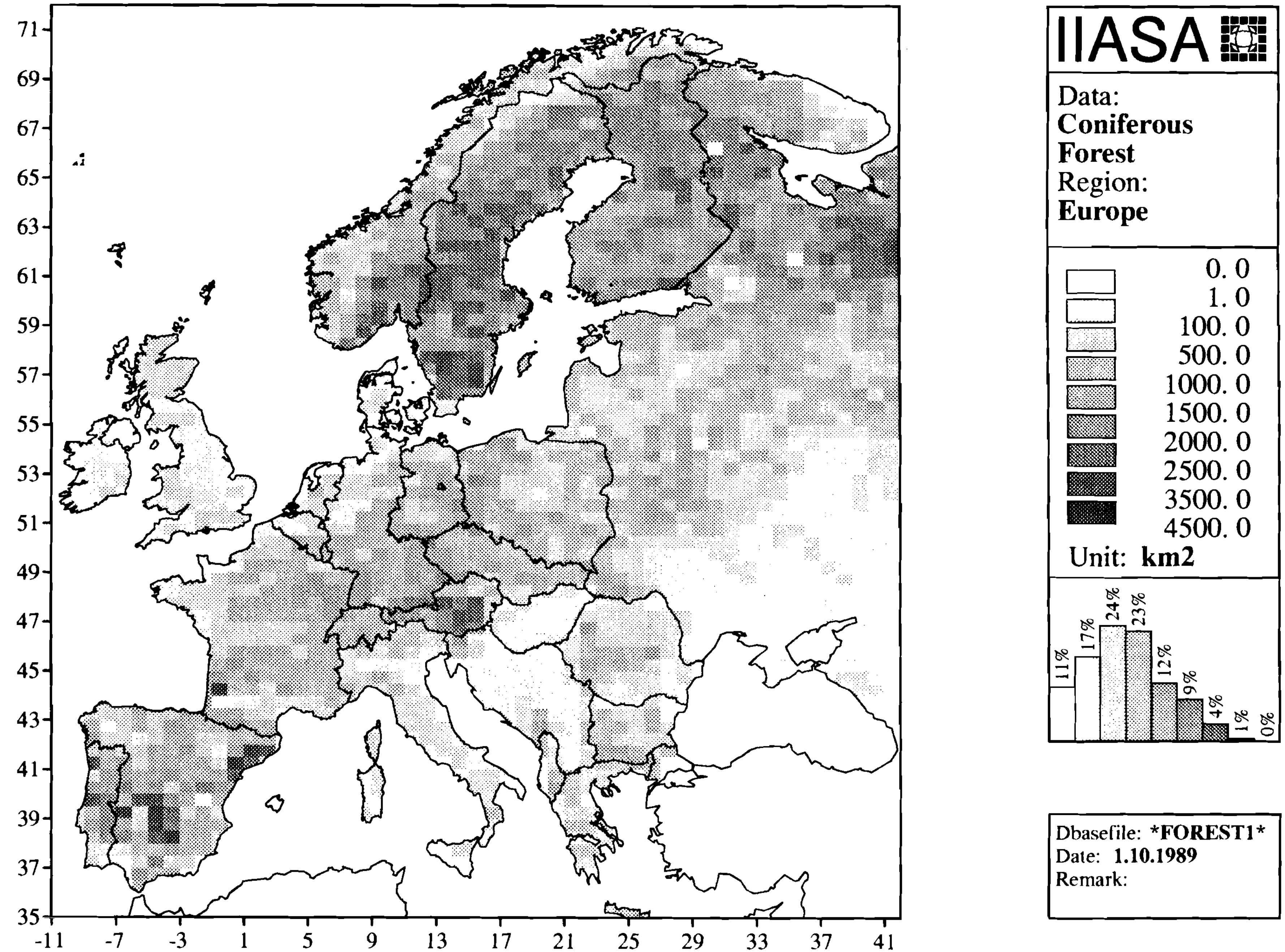

Figure 4. **Coniferous forest coverage densities in Europe.**

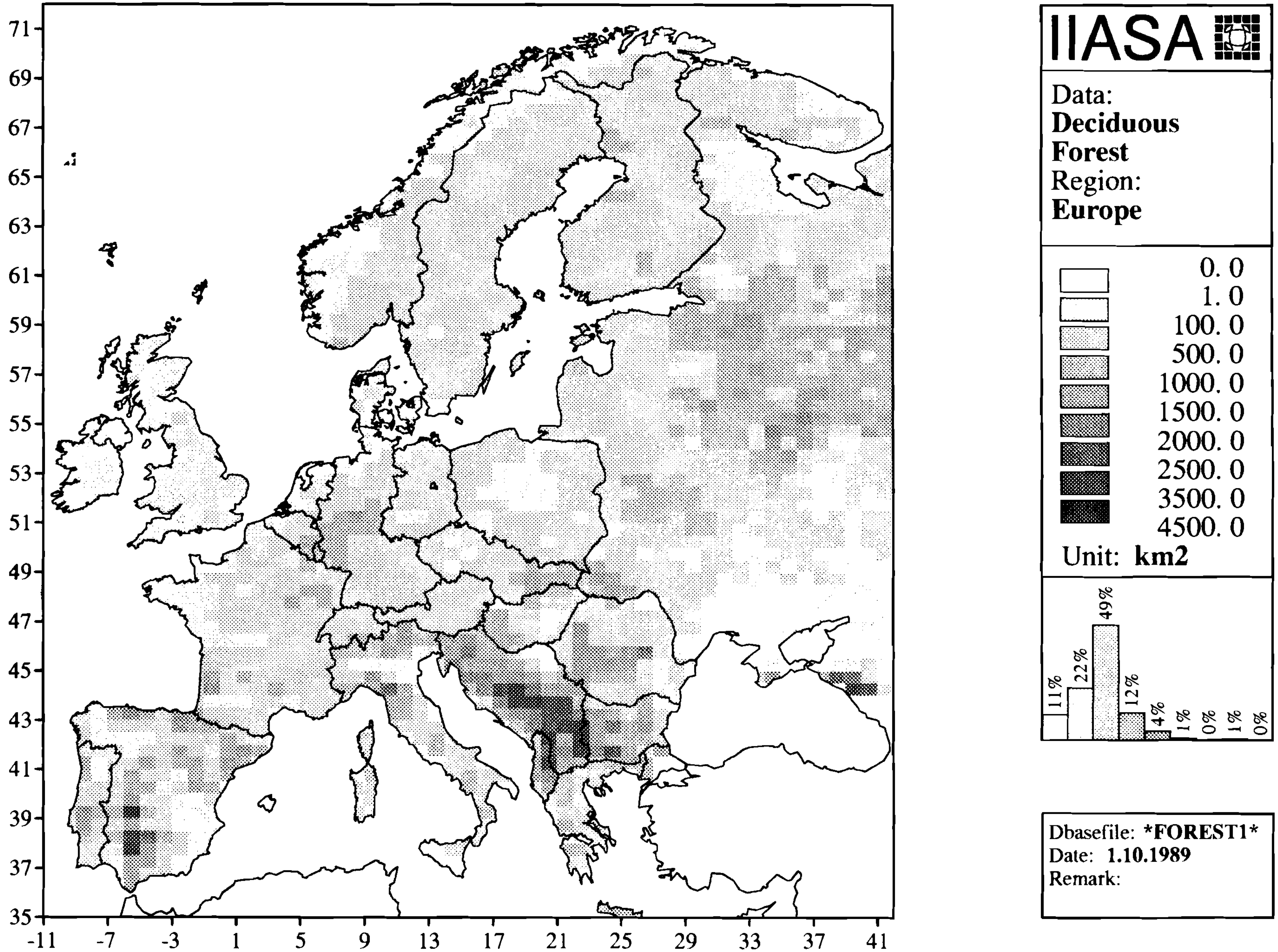

Figure 5. **Deciduous forest coverage densities in Europe.**

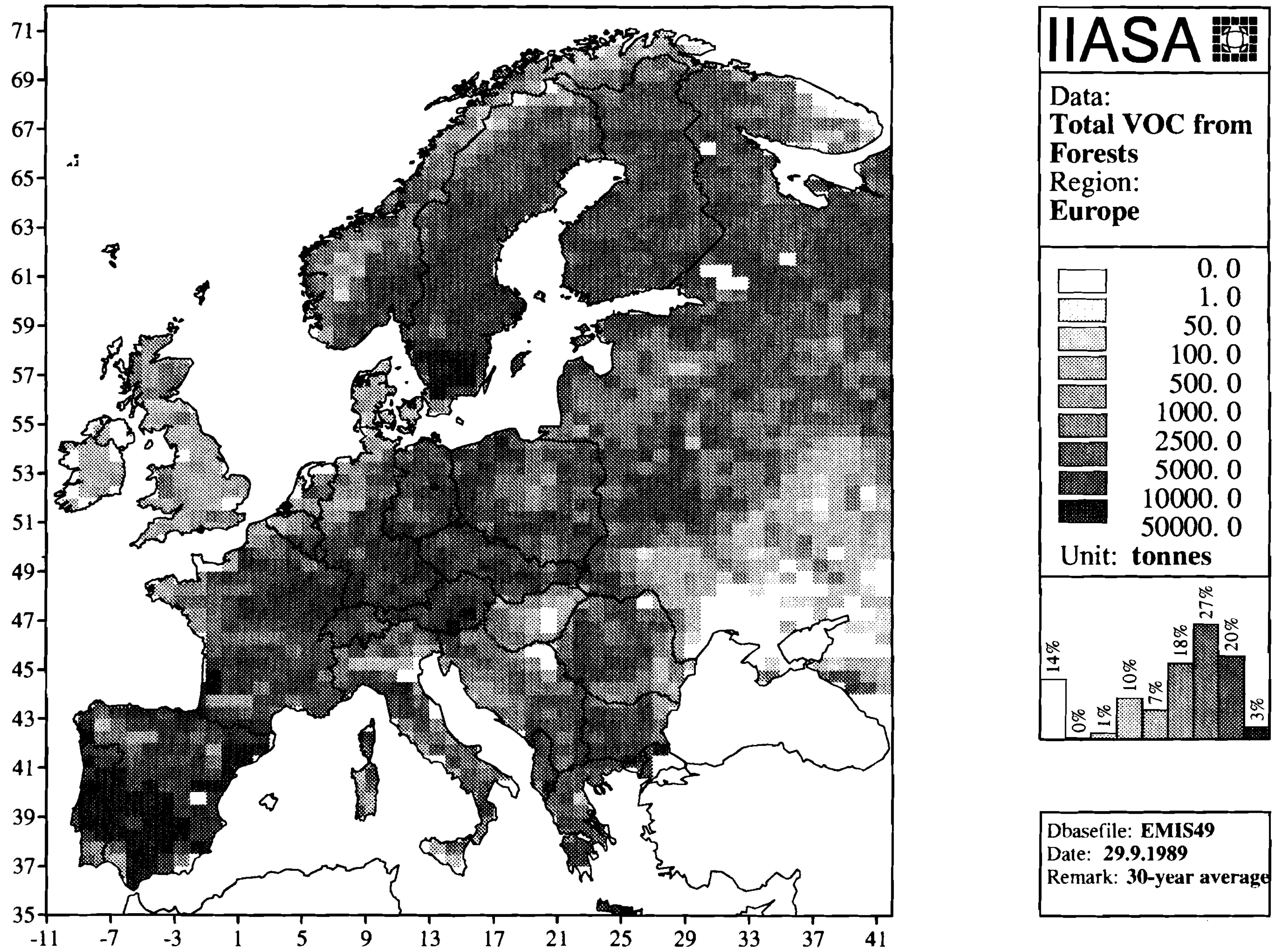

Figure 6. **Natural VOC emissions from forests in Europe, 30-year average.**

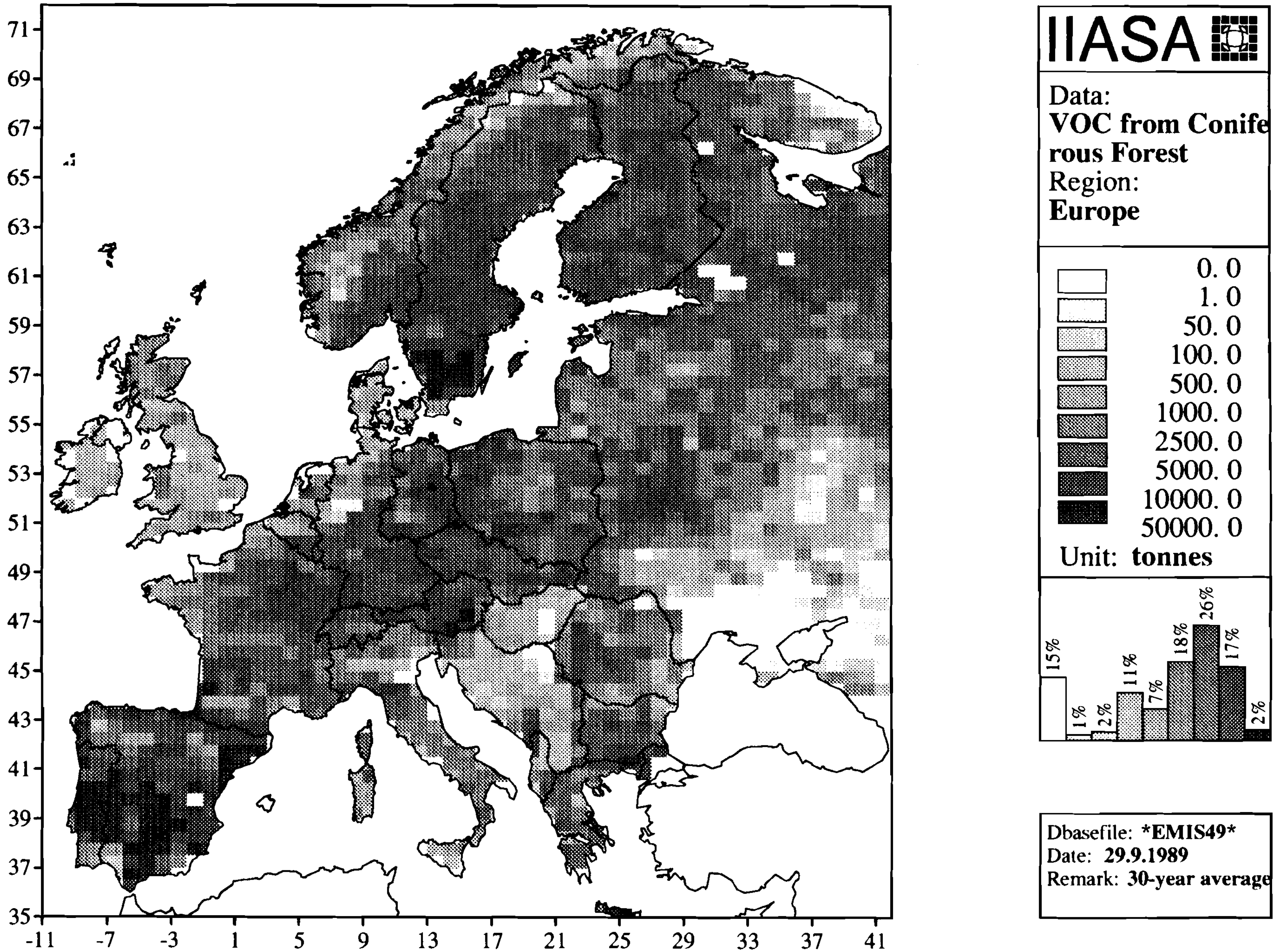

Figure 7. Natural VOC emissions from coniferous forests in Europe, 30-year average.

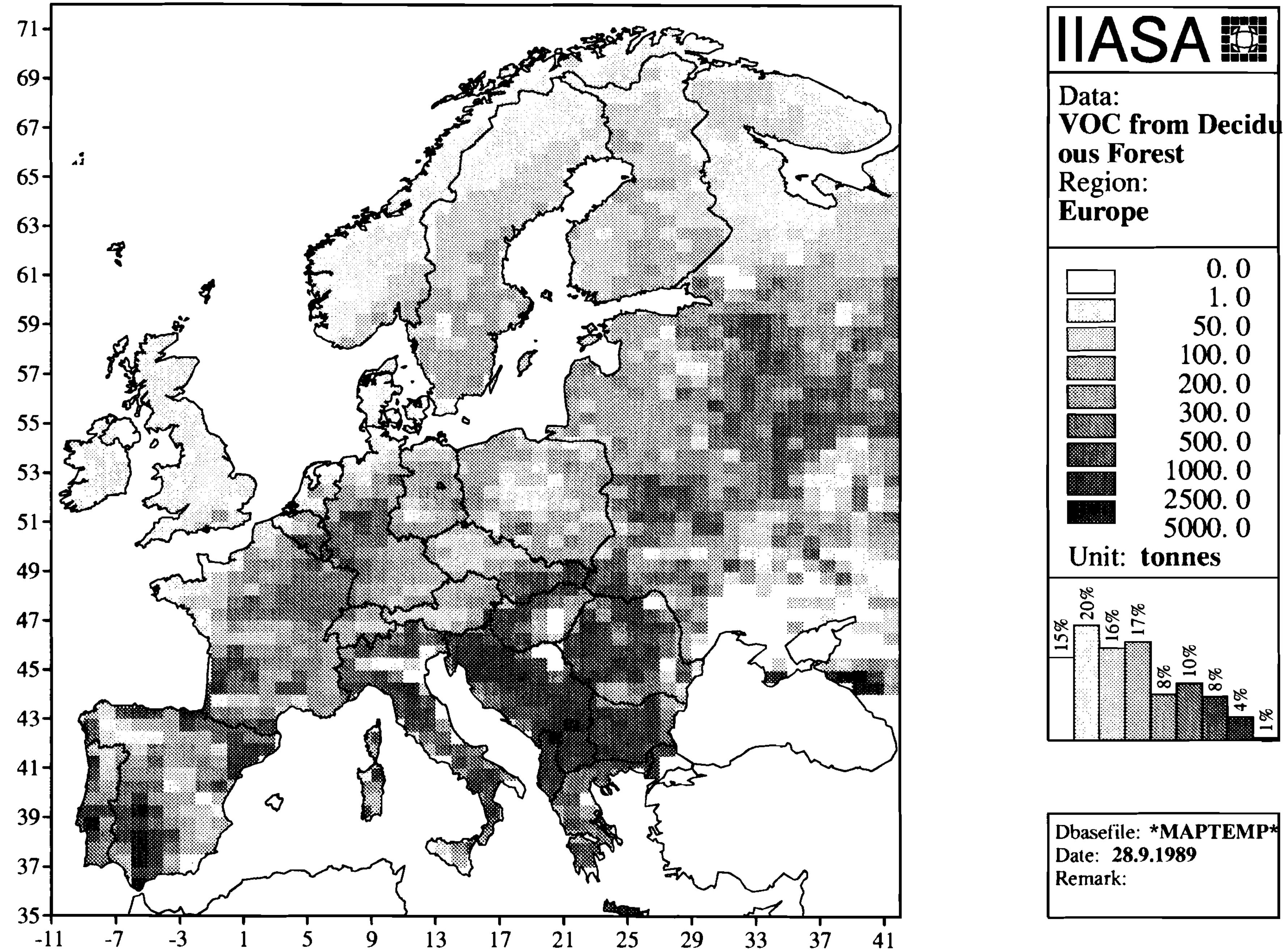

Figure 8. **Natural VOC emissions from deciduous forests in Europe, 30-year average.**

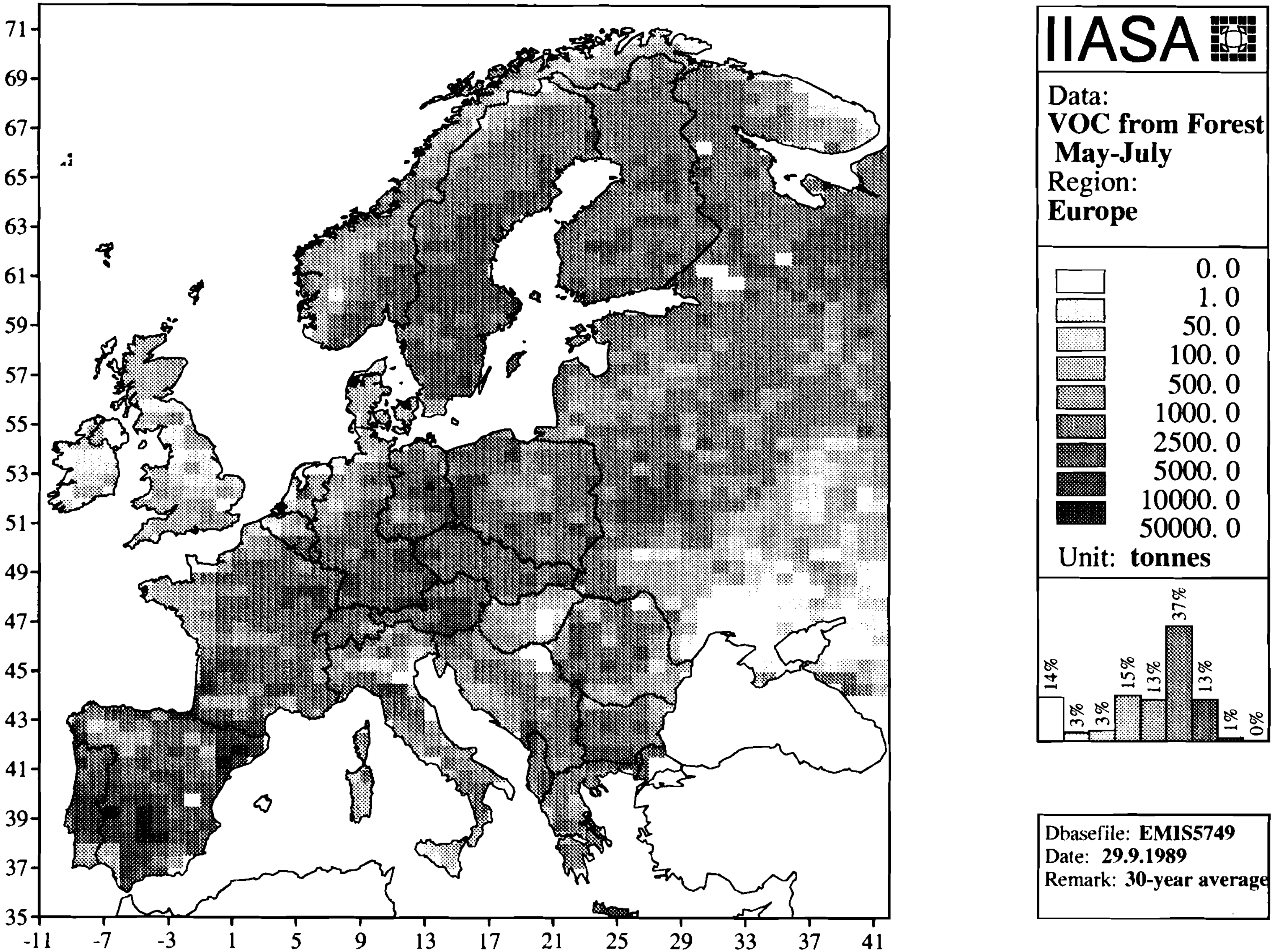

Figure 9. **Natural VOC emissions from forests in Europe, May–July, 30-year average.**

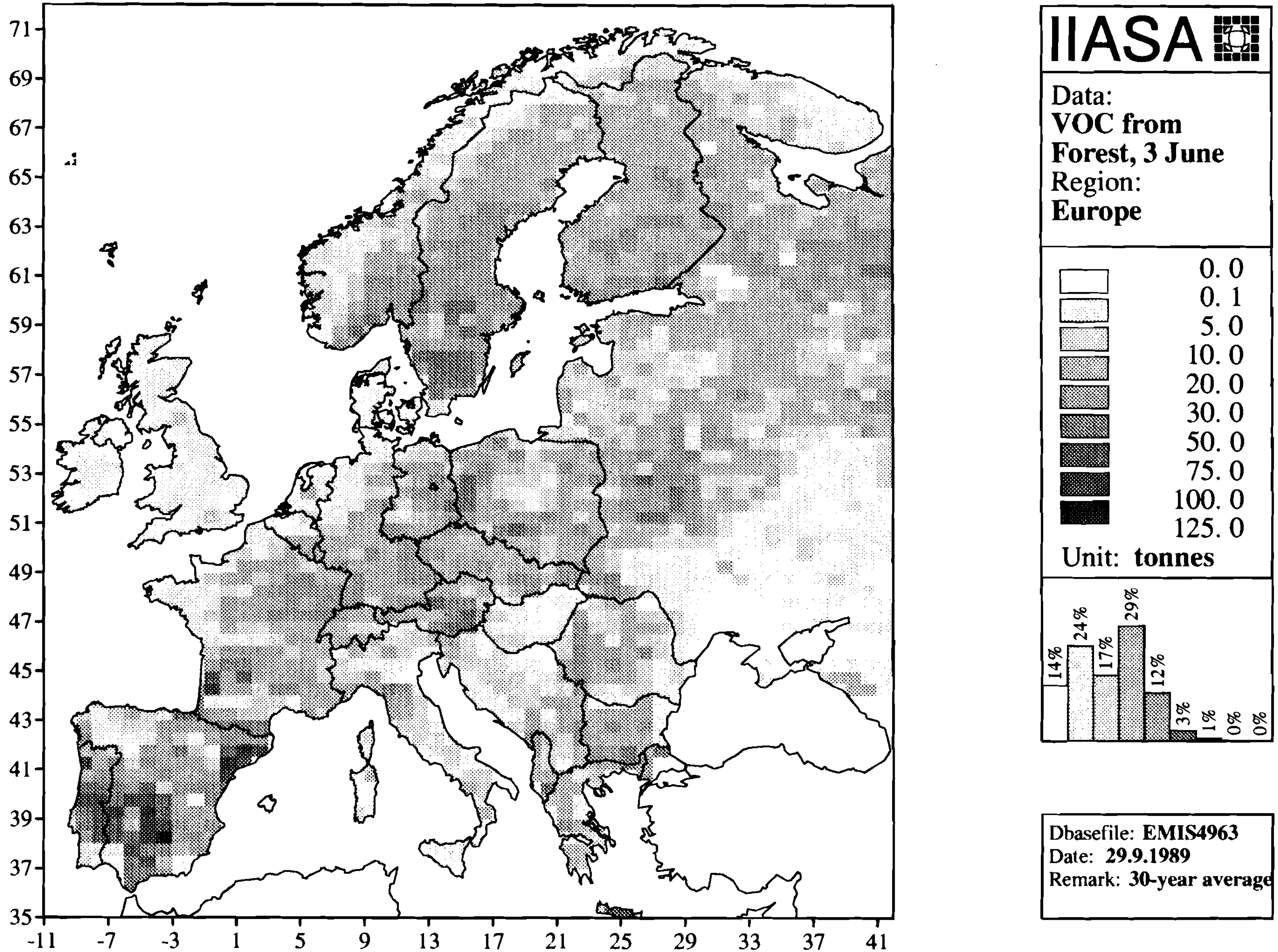

Figure 10. Natural VOC emissions from forests in Europe, a "typical" 3rd of June-day, 30-year average.

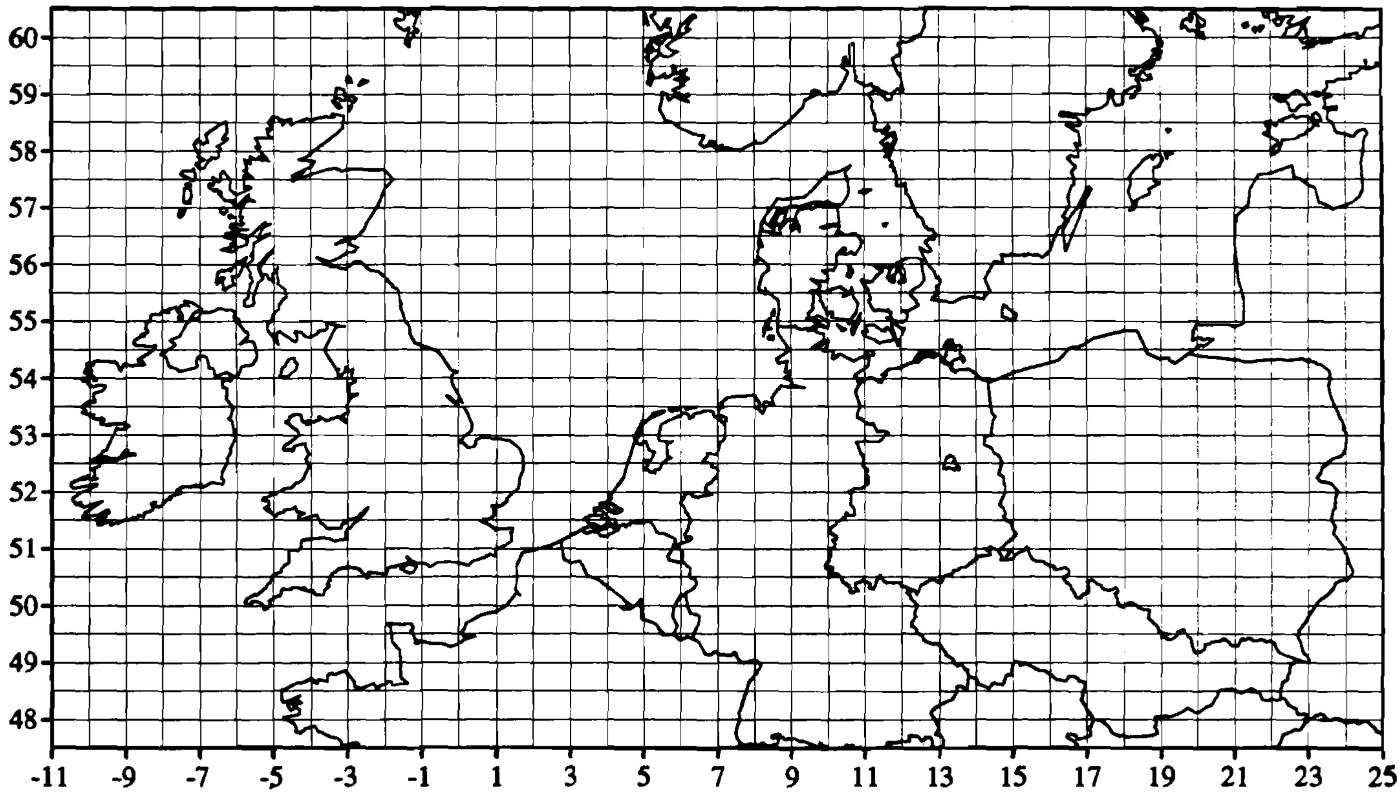

Figure 11. PHOXA model domain.

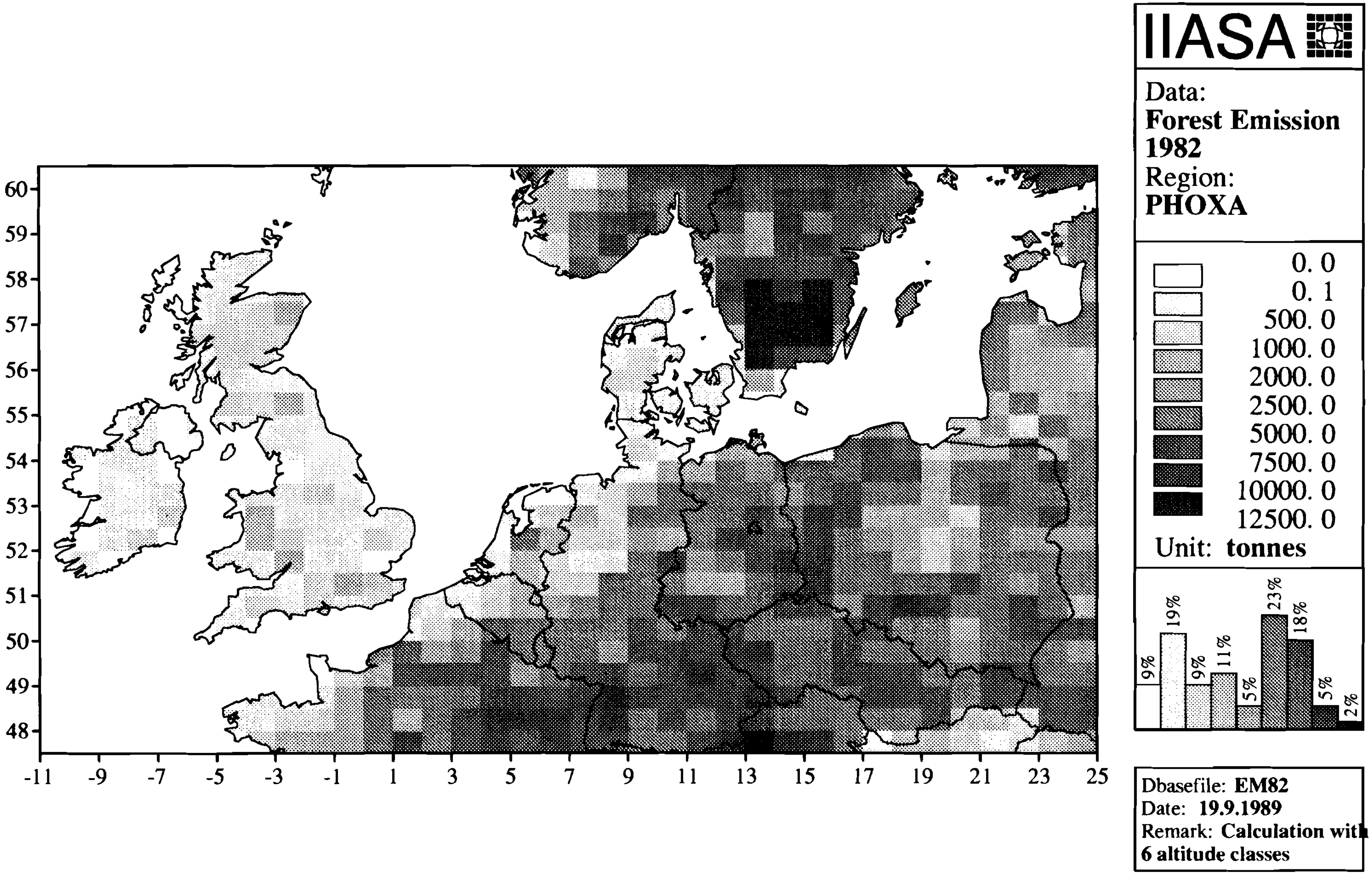

Figure 12. Natural VOC emissions from forests in the PHOXA model domain, 1982 - six different altitude classes.

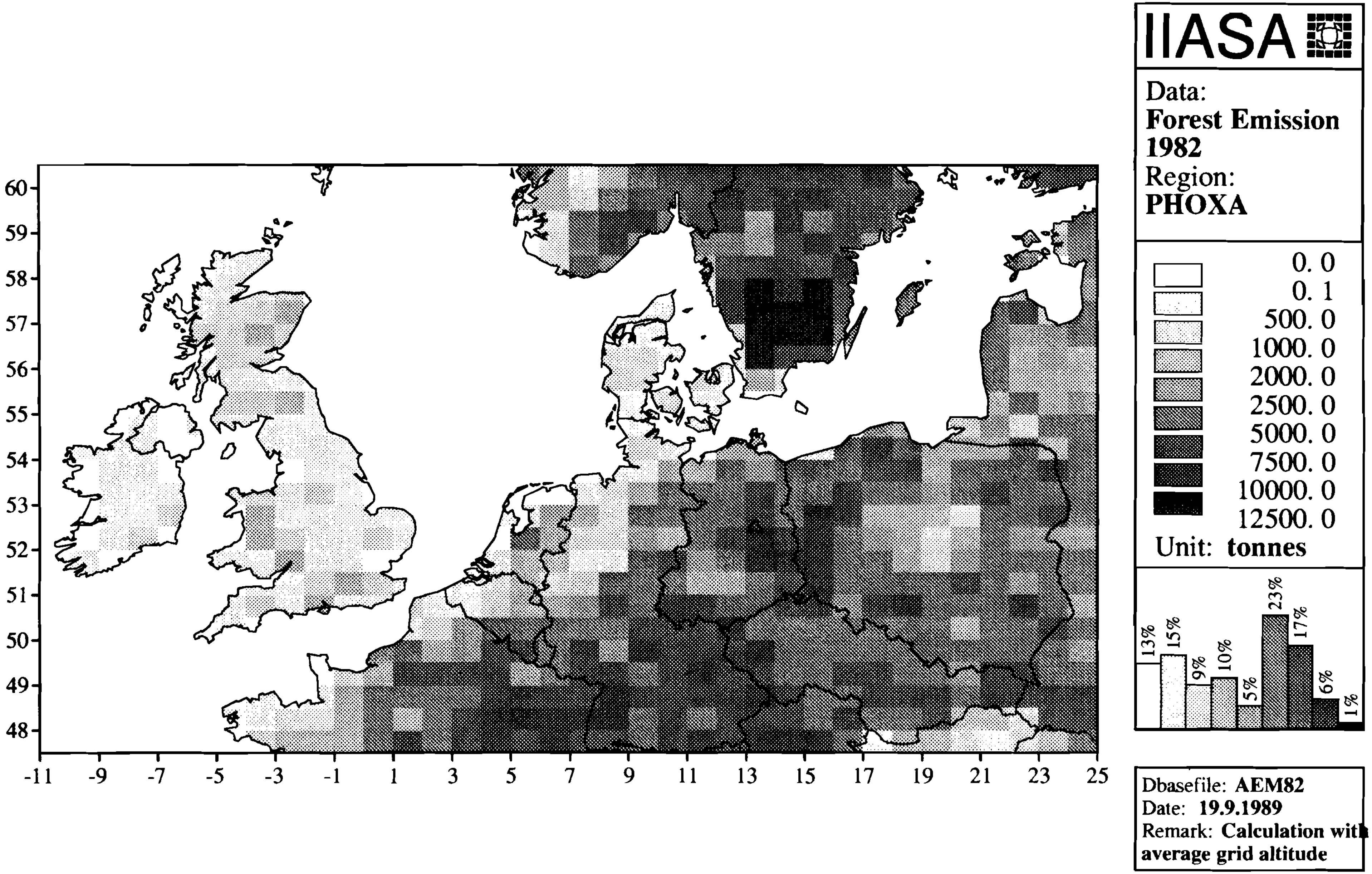

Figure 13. Natural VOC emissions from forests in the PHOXA model domain, 1982 - average grid altitude.

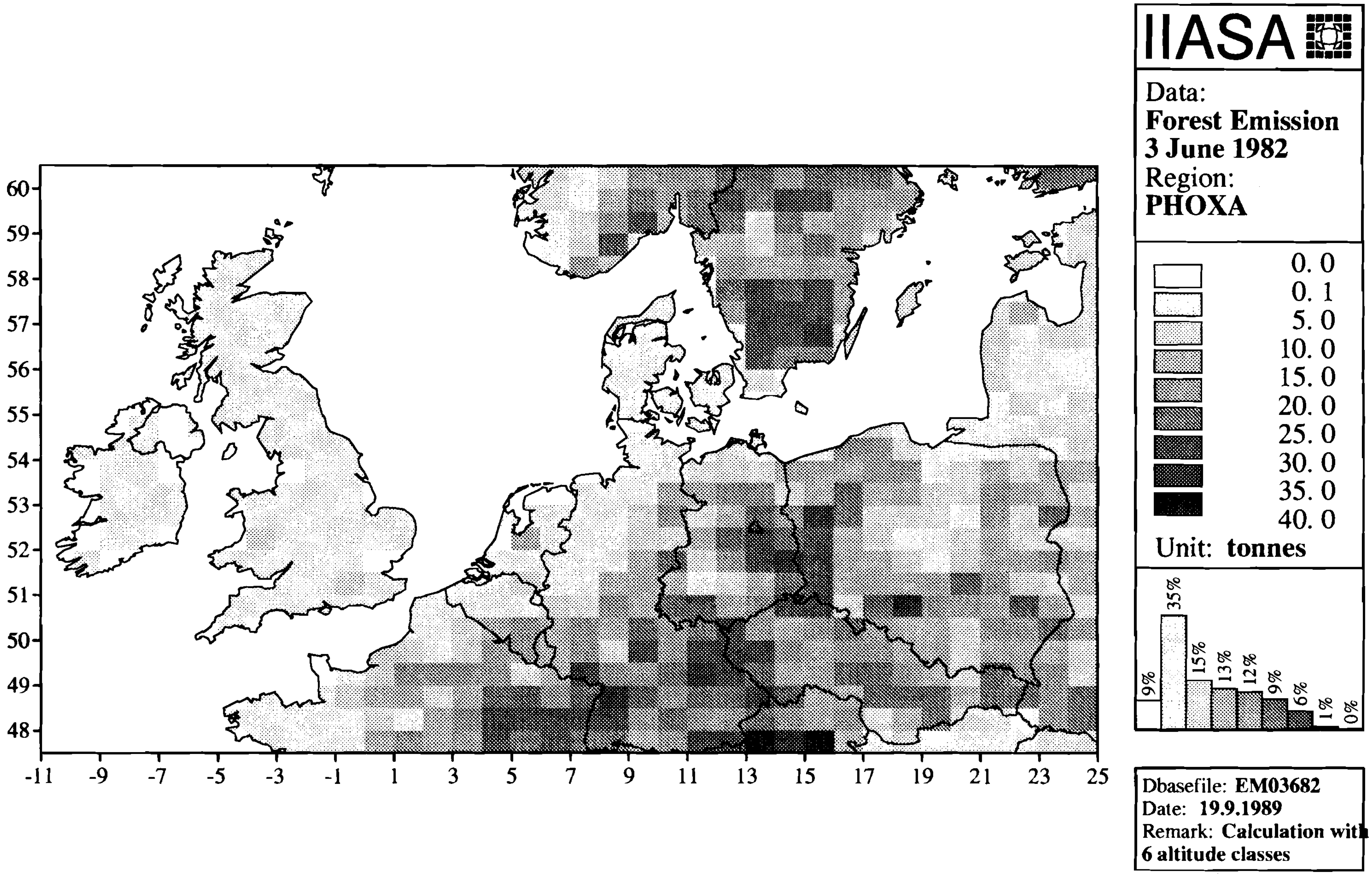

Figure 14. Natural VOC emissions from forests in the PHOXA model domain, 3 June 1982 - six different altitude classes.

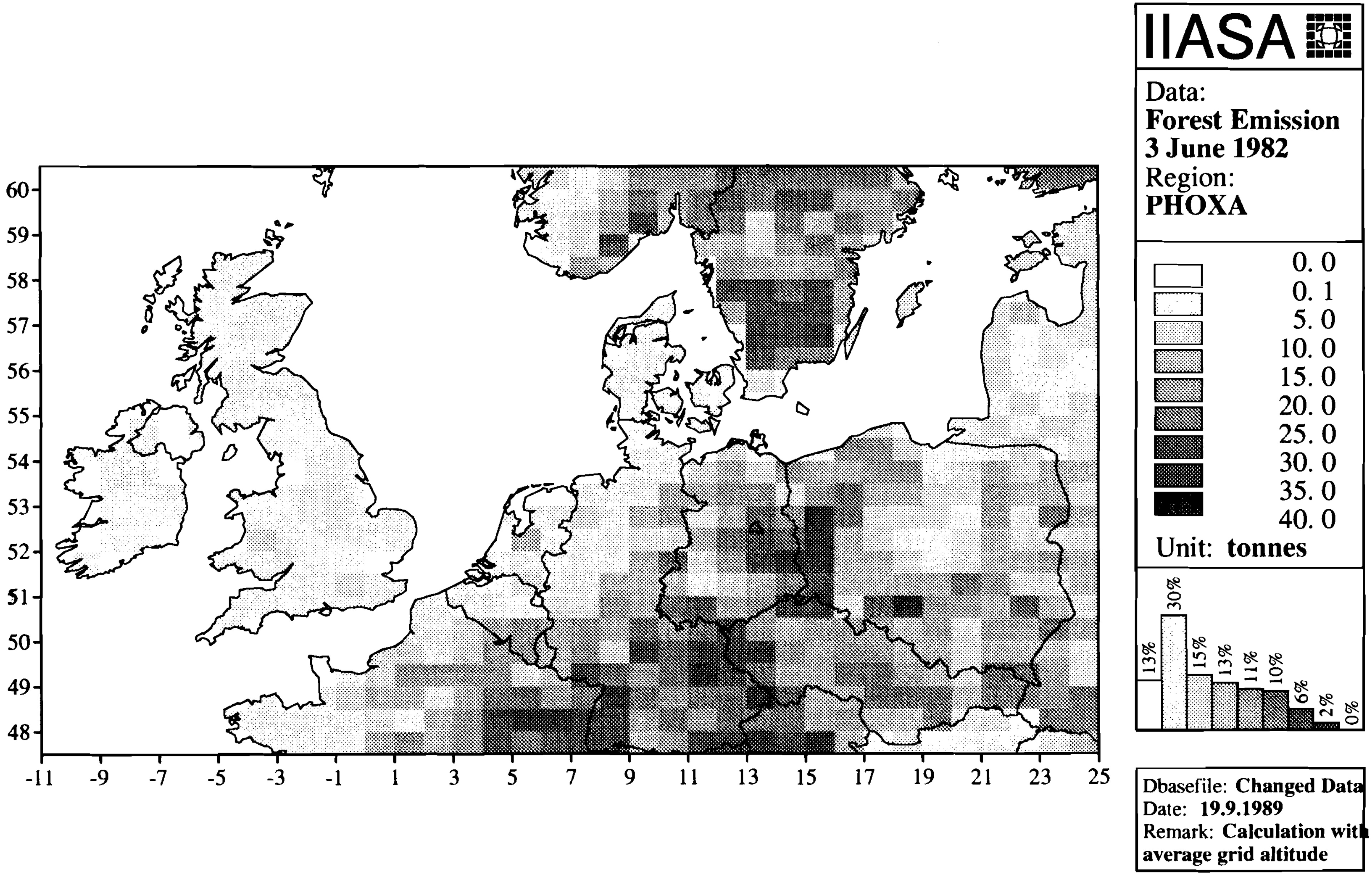

Figure 15. Natural VOC emissions from forests in the PHOXA model domain, 3 June 1982 - average grid altitude.

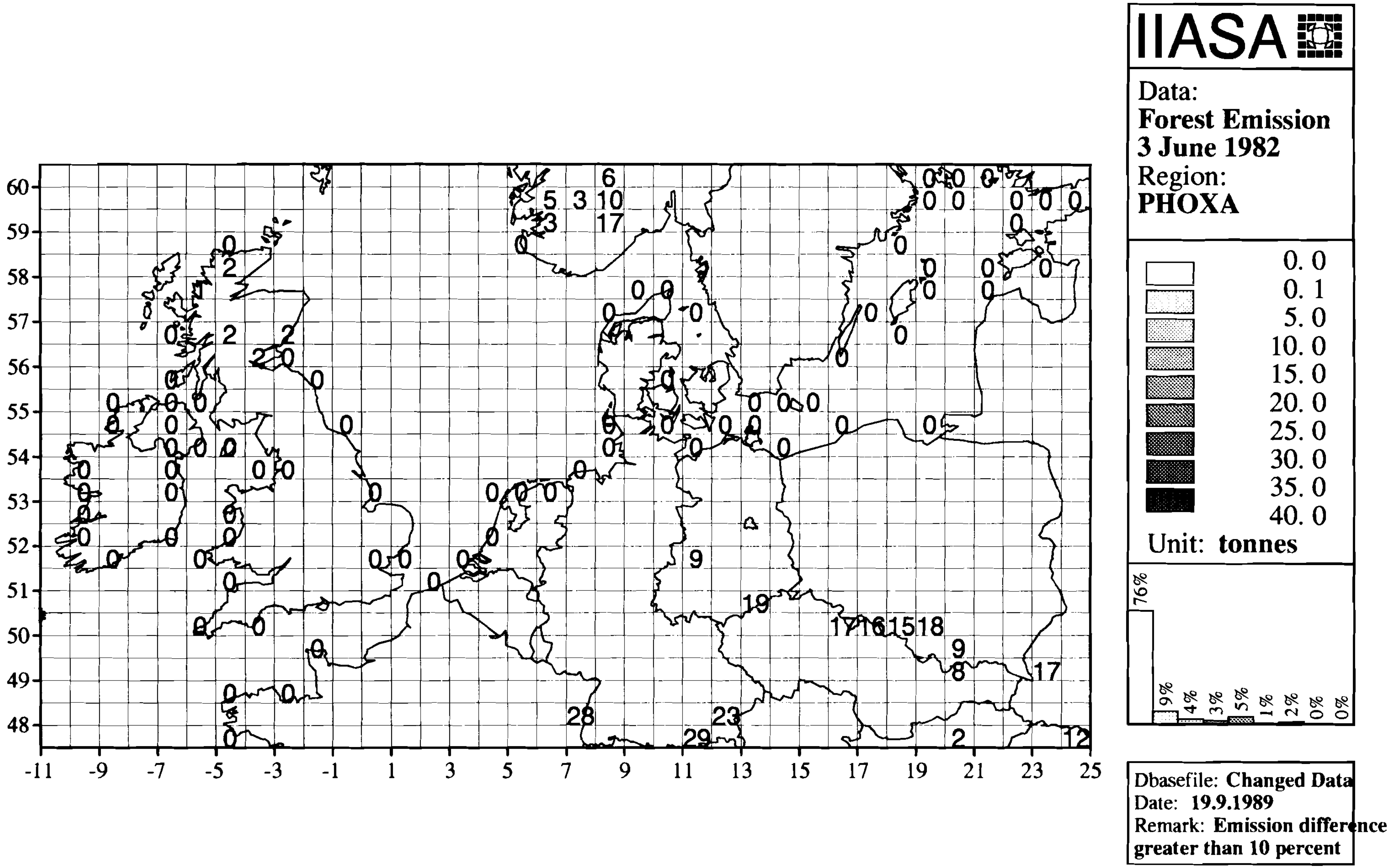

Figure 16. Emission difference (greater than 10 percent) between calculation with 6 atltitude classes versus average grid height.

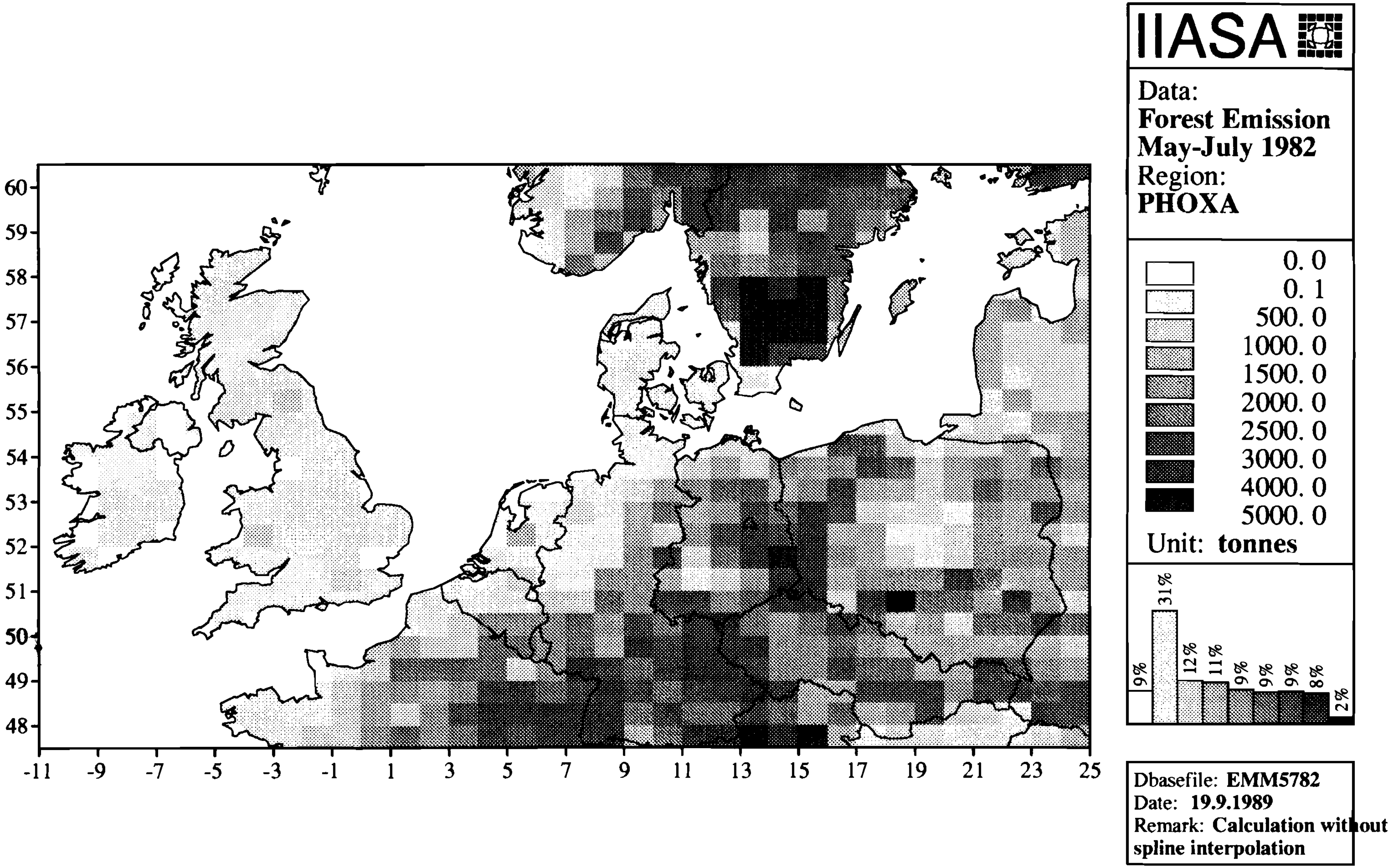

Figure 17. Natural VOC emissions from forests in the PHOXA model domain, May–July 1982 - calculation without spline interpolation

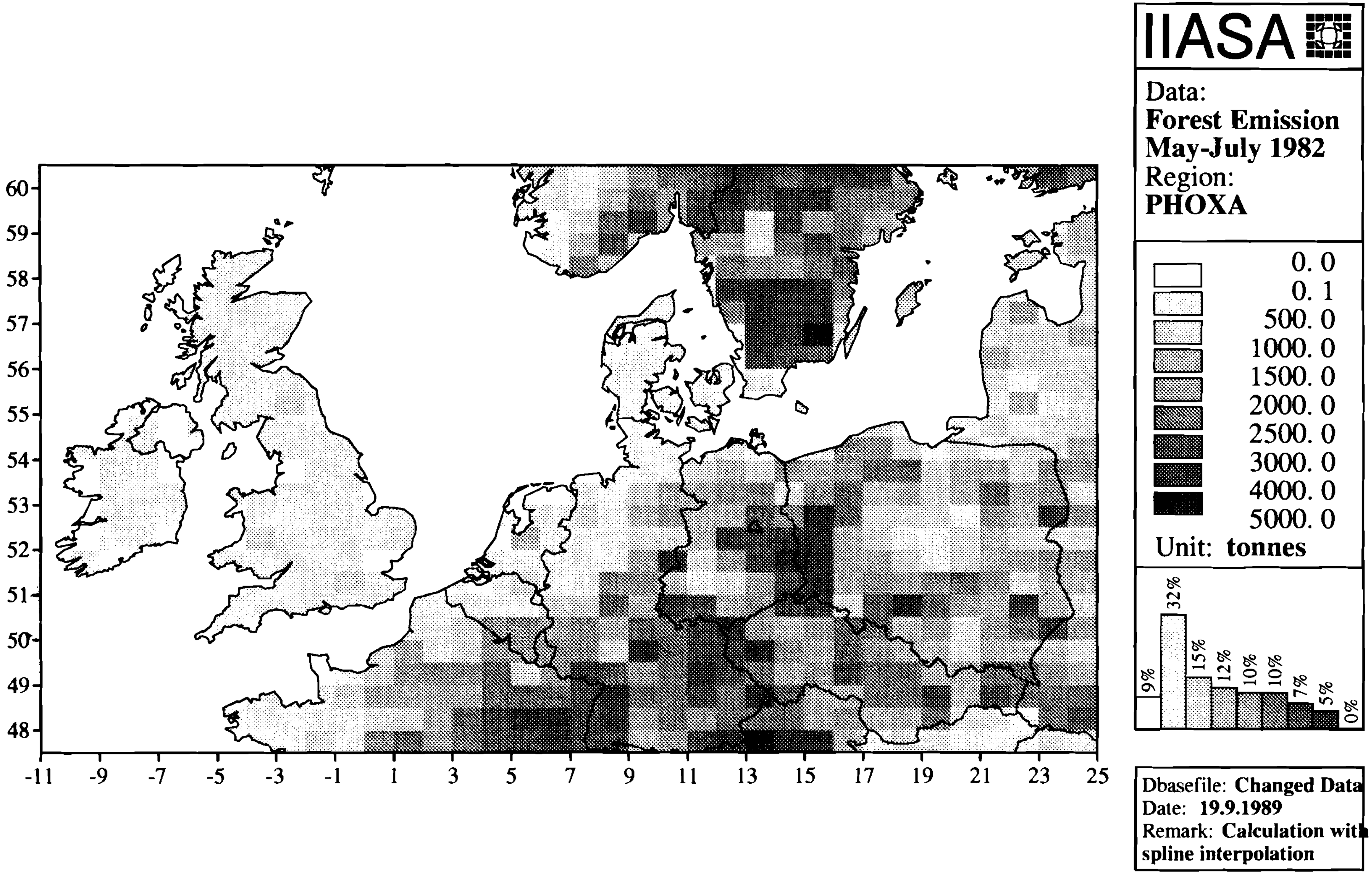

Figure 18. Natural VOC emissions from forests in the PHOXA model domain, May–July 1982 - calculation with spline interpolation.

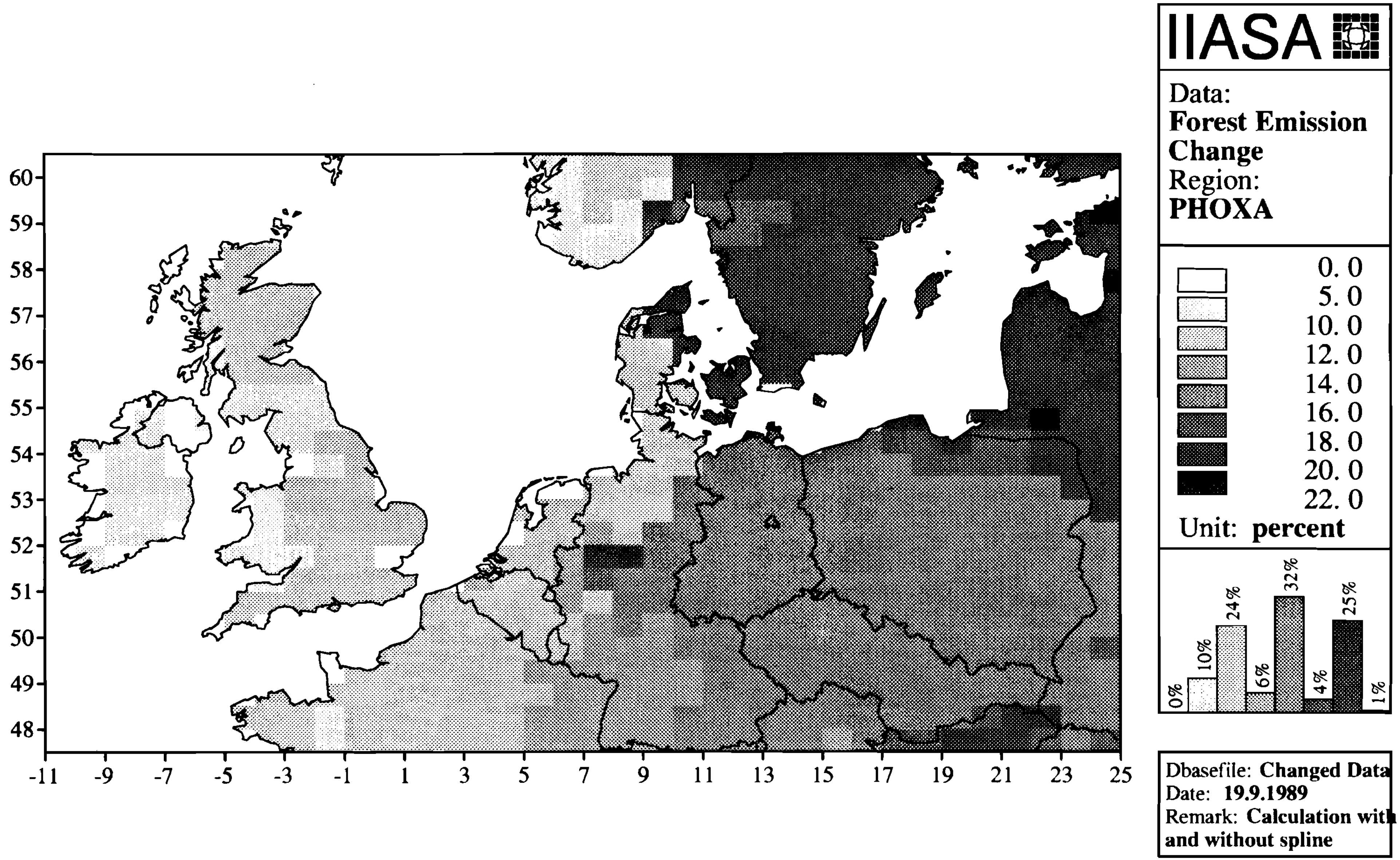

Figure 19. Emission difference between calculation with and without spline interpolation.

ANNEXES

Annex A1.	DBase-Program to Reallocate Forest Species into Six Altitude Classes.
Annex A2.	C-Program to Calculate E_{conif} and E_{decid} from Temperature Data for Each Altitude Class and Grid Element.
Annex A3.	DBase-Program to Calculate Natural VOC Emissions from Emission Factors and Forest Coverage Data.
Annex A4.	DBase-Program to Sum up Coniferous and Deciduous Emissions per Grid Cell and in the Entire Grid Area.
Annex A5.	Gridded VOC Emissions from Forests in Europe, 30-Year Average.

Annex A1. DBase-Program to Reallocate Forest Species into Six Altitude Classes.

```
close all databases
clear
use <forest file*>
goto top
* convert forest volume data into fraction of coniferous and deciduous forest coverage:
do while .not. eof()
if conifm3 <> 0 .and. decidm3 <> 0
   replace conif with conifm3 / (conifm3 + decidm3)
   replace decid with decidm3 / (conifm3 + decidm3)
else
   replace conif with 0
   replace decid with 0
endif
skip 1
enddo
goto top
* if forest coverage data is available, calculate total forest coverage as well as total coverage
  per species over all altitude classes:
set filter to a0300m <> -9999.00
replace all suma with (a0300m + a300600m + a600900m + a9001500m + a15002100m + a2100m)
replace all sumc with (a0300m + a300600m + a600900m + a9001500m + a15002100m + a2100m) ×
conif
replace all sumd with (a0300m + a300600m + a600900m + a900150m + a15002100m + a2100m) ×
decid
goto top
* fill top altitude class with conifers and for all latitudes worth of the Alps, also fill second-highest
  altitude class with conifers:
do while .not. eof()
if (suma <> 0)
   replace c2100m with a2100m
   replace d2100m with 0
   if (lat >= 47)
     replace c15002100m with a15002100m
     replace d15002100m with 0
   endif
endif
 skip 1
 enddo
 goto top
* calculate remaining amount of conifers to be distributed and resulting ratio of coniferous to
  deciduous forest:
 do while .not. eof()
 if (lat >= 47)
   newsumc = sumc - a15002100m - a2100m
 else
   newsumc = sumc - a2100m
 endif
 newsumd = sumd
 if (newsumc + newsumd) <= 0
   newconif = 0
```

```
   newdecid = 0
 else
   newconif = max (0, newsumc/(newsumc + newsumd))
   newdecid = 1 - newconif
 endif
* distribute remaining species-specific forest over the lower four (or five) altitude classes:
 if (lat < 47)
   replace c15002100m with newconif × a15002100m
   replace d15002100m with newdecid × a15002100m
 endif
replace c9001500m with newconif × a9001500m
replace c600900m with newconif × a600900m
replace c300600m with newconif × a300600m
replace c0300m with newconif × a0300m
replace d9001500m with newdecid × a9001500m
replace d600900m with newdecid × a600900m
replace d300600m with newdecid × a300600m
replace d0300m with newdecid × a0300m
skip 1
enddo
return
```

*Forest File Description:

Field	Field Name	Field Description	Unit
1	LONG	longitude	°
2	LAT	latitude	°
3	GRIDKM2	grid surface area	km^2
4	A0300M	forested area below 300 m altitude	km^2
5	A300600M	forested area between 300 and 600 m altitude	km^2
6	A600900M	forested area between 600 and 900 m altitude	km^2
7	A9001500M	forested area between 900 and 1500 m altitude	km^2
8	A15002100M	forested area between 1500 and 2100 m altitude	km^2
9	A2100M	forested area above 2100 m altitude	km^2
10	CONIFM3	volume of coniferous forest	m^3
11	DECIDM3	volume of deciduous forest	m^3
12	CONIF	fraction of coniferous forest	
13	DECID	fraction of deciduous forest	
14	CO300M	area covered by coniferous forest below 300 m	km^2
15	C300600M	area covered by coniferous forest between 300 and 600 m	km^2
16	C600900M	area covered by coniferous forest between 600 and 900 m	km^2
17	C9001500M	area covered by coniferous forest between 900 and 1500 m	km^2
18	C15002100M	area covered by coniferous forest between 1500 and 2100 m	km^2
19	C2100M	area covered by coniferous forest above 2100 m	km^2
20	D0300M	area covered by deciduous forest below 300 m	km^2
21	D300600M	area covered by deciduous forest between 300 and 600 m	km^2
22	D600900M	area covered by deciduous forest between 600 and 900 m	km^2
23	D9001500M	area covered by deciduous forest between 900 and 1500 m	km^2
24	D15002100M	area covered by deciduous forest between 1500 and 2100 m	km^2
25	D2100M	area covered by deciduous forest above 2100 m	km^2
26	SUMA	total forest coverage	km^2
27	SUMC	total area covered by coniferous forest	km^2
28	SUMD	total area covered by deciduous forest	km^2

Annex A2. C-Program to Calculate E_{conif} and E_{decid} from Temperature Data for Each Altitude Class and Grid Element for Specified Time Periods.

```
/*input and output files are DBase 3Plus files */

#include <stdio.h>
#include <sys/file.h>
#include <math.h>
#include <fcntl.h>

#define FALSE 0
#define TRUE 1
#define MaxRecordLen 512
#define MaxColors 16


typedef unsigned char byte;
typedef unsigned short int word;
typedef byte bool;
typedef struct Date { int month ;
               int day ;
               };
typedef char string[12];
typedef byte DateType[3];
/* structure of dbase header */
typedef struct DbaseHeaderType { byte version;
                    DateType LastUpdate;
                    long records;
                    word HeaderLength,RecordLength;
                    byte reserved[20];
                    };
/* structure of records for field types */
typedef struct DbaseFieldType { char name[11];
                    char type;
                    long adr;
                    byte length,dezimals;
                    byte reserved[14];
                    };

/* Length of Months for: Dec,Jan, ... Dec,Jan */
int MonthLength[14] = {31,31,28,31,30,31,30,31,31,30,31,30,31,31};

main(argc,argv)
int argc;
char *argv[];
{
int a,b;
char *dbasi,*dbaso,*fieldn;
float p1,p2;
struct Date von,bis;
/* begin */
   if (argc == 10) {
```

```
/* getting arguments from command line */
      dbasi = argv[1] ;
      dbaso = argv[2] ;
      fieldn = argv[3] ;
      sscanf(argv[4],"%f",&p1);
      sscanf(argv[5],"%f",&p2);
      p2 = p2 * pow(10.,-1.5);
      sscanf(argv[6],"%d",&von.month);
      sscanf(argv[7],"%d",&von.day);
      sscanf(argv[8],"%d",&bis.month);
      sscanf(argv[9],"%d",&bis.day);
      }
   else
      {
/* wrong number of arg in command line ask user */
      dbasi = calloc(40,1);
      dbaso = calloc(40,1);
      fieldn = calloc(11,1);
      printf("Enter: Dbase-input, Dbase-output,Output-field, p1, p2, von(mm dd), bis0);
      scanf("%s%s%s%f%f%d%d%d%d",dbasi,dbaso,fieldn, &p1,&p2,&von.month,
      &von.day,&bis.month,&bis.day); p2 = p2 * pow(10.,-1.5) ;
      }
/* call function to read a dbase file and write results to an other */
   CalcSpline(dbasi,dbaso,"LONG","LAT",fieldn,&von,&bis,p1,p2);
};
/* end */


StringCopy (dest,source,anf,len)
/* copy part of a string */
  char *dest,*source;
  int anf,len;
  {
  int n;
  char *d,*s;
  /* begin */
  d= dest;
  s= source+anf;
  for (n=0; (n<len)&(*s!=' '); n++)
    *(d++)= *(s++);
  *d= ' ';
  }
/* end */


/* function to read a dbase file and write results to an other */

CalcSpline (FileIN,FileOUT,LongName,LatName,OutVar,von,bis,p1,p2)
  char *FileIN,*FileOUT,*LongName,*LatName,*OutVar;
  struct Date *von,*bis;
  float p1,p2;
  {
  struct DbaseHeaderType headeri,headero;
  struct DbaseFieldType field;
```

```
int a,x,y,ix,LongPos,LongLen,LatPos,LatLen,DataPos[14],DataLen[14];
int LongPoso,LongLeno,LatPoso,LatLeno,OutPos,OutLen;
int none,Data,DataPos2[14],DataLen2[14];
FILE *fi;
int fo;
byte b;
char buf[MaxRecordLen];
char s[16],fLat[9],fLong[9],fOut[9];
char *DataName[14];
char *DataName2[14];
float fx,fy,fd,ya[14],ya2[14],fxo,fyo;
float efact();
long posi;

/* initial data */
DataName[0] ="M22";
DataName[1] ="M11";
DataName[2] ="M12";
DataName[3] ="M13";
DataName[4] ="M14";
DataName[5] ="M15";
DataName[6] ="M16";
DataName[7] ="M17";
DataName[8] ="M18";
DataName[9] ="M19";
DataName[10] ="M20";
DataName[11] ="M21";
DataName[12] ="M22";
DataName[13] ="M11";
DataName2[0] ="I22";
DataName2[1] ="I11";
DataName2[2] ="I12";
DataName2[3] ="I13";
DataName2[4] ="I14";
DataName2[5] ="I15";
DataName2[6] ="I16";
DataName2[7] ="I17";
DataName2[8] ="I18";
DataName2[9] ="I19";
DataName2[10] ="I20";
DataName2[11] ="I21";
DataName2[12] ="I22";
DataName2[13] ="I11";

/* begin */
printf("Loading Data .... ");
LongPos= -1;
LatPos= -1;
Data = 0;
/* open dbase files */
if ((fi= fopen(FileIN,"r")) == NULL )
  {
/* input file must exist */
   printf("%s Inputfile does not exist0,FileIN);
```

```
    exit(1);
    };
  if ((fo= open(FileOUT,O_RDWR)) == -1 )
    {
/* at least header of input file must exist */
    printf("Outputfile does not exist0);
    exit(1);
    };
/* read header input file */
  fread(&headeri,sizeof(struct DbaseHeaderType),1,fi);
  fread(&b,1,1,fi);
  a= 0;
  while (b!=13)
    {
    fread(&(field.name[1]),sizeof(struct DbaseFieldType)-1,1,fi);
    field.name[0]= b;
    printf("%c,%s0,b,field.name);
/* check for longitude field */
    if (strcmp(field.name,LongName)==0)
      {
      LongPos= a;
      LongLen= field.length;
      };
/* check for latitude field */
    if (strcmp(field.name,LatName)==0)
      {
      LatPos= a;
      LatLen= field.length;
      };
    for (ix=0;ix<14;ix++) {
/* check for temperature date and spline coef. */
      if (strcmp(field.name,DataName[ix])==0)
        {
        DataPos[ix]= a;
        DataLen[ix]= field.length;
        };
      if (strcmp(field.name,DataName2[ix])==0)
        {
        DataPos2[ix]= a;
        DataLen2[ix]= field.length;
        };
      };
    a+= field.length;
    fread(&b,1,1,fi);
    };
  for (ix=0;ix<14;ix++)
    Data -= (DataPos[ix] == 0 || DataPos2[ix] == 0)? 1 : 0 ;

/* read output header */
  read(fo,&headero,sizeof(struct DbaseHeaderType));
  read(fo,&b,1);

/* number of records must be 0 or the same as on input */
  if(headero.records != 0 && headero.records != headeri.records)
```

```
    {
    printf("Number of records in Input and Outputfile are different0);
    exit(1);
    };
  none = FALSE ;

/* make number of record in output same as on input */
  if(headero.records == 0)
    {
    lseek(fo,0L,L_SET) ;
    headero.records = headeri.records ;
    write(fo,&headero,sizeof(struct DbaseHeaderType));
    write(fo,&b,1);
    none = TRUE ;
    } ;

  LatPoso = -1;
  LongPoso = -1;
  OutPos = -1;
  a= 0;
/* look for fields LONG,LAT,<result> */
  while (b!=13)
   {
   if(read(fo,&(field.name[1]),sizeof(struct DbaseFieldType)-1) == 0)
    {
    printf("Outputfile readerror0);
    exit(1);
    };
   field.name[0]= b;
   if (strcmp(field.name,LongName)==0)
     {
     LongPoso= a;
     LongLeno= field.length;
     sprintf(fLong,"%c%d.%df",'%',field.length,field.dezimals);
     };
   if (strcmp(field.name,LatName)==0)
     {
     LatPoso= a;
     LatLeno= field.length;
     sprintf(fLat,"%c%d.%df",'%',field.length,field.dezimals);
     };
   if (strcmp(field.name,OutVar)==0)
     {
     OutPos= a;
     OutLen= field.length;
     sprintf(fOut,"%c%d.%df",'%',field.length,field.dezimals);
     };
   a+= field.length;
   read(fo,&b,1);
   };
/* all fields are found ? */
  if ((LongPos!=-1)&(LatPos!=-1)&(Data==0)&(LongPoso!=-1)&(LatPoso!=-1)&(OutPos!=-1))
     {
```

```
/* start calculation */
/* none is TRUE if no record is in output file */
    printf("readwrite Records0);
    for (a=0; a<headeri.records; a++)
     {
     fread(&b,1,1,fi);
     if (none==TRUE) ix=write(fo,&b,1);
     if (none==FALSE) ix=read(fo,&b,1);
     fread(buf,headeri.RecordLength-1,1,fi);
     StringCopy(s,buf,LongPos,LongLen);
     sscanf(s,"%f",&fx);
     StringCopy(s,buf,LatPos,LatLen);
     sscanf(s,"%f",&fy);
/* read input & output file */
     for (ix=0;ix<14;ix++)
       {
       StringCopy(s,buf,DataPos[ix],DataLen[ix]);
       sscanf(s,"%f",&(ya[ix]));
       StringCopy(s,buf,DataPos2[ix],DataLen2[ix]);
       sscanf(s,"%f",&(ya2[ix]));
       };
     if (none==FALSE)
       {
       ix=read(fo,buf,headero.RecordLength-1);
       posi = (long)OutPos-(long)headero.RecordLength+1L;
       posi=lseek(fo,posi,L_INCR);
       StringCopy(s,buf,LongPoso,LongLeno);
       sscanf(s,"%f",&fxo);
       StringCopy(s,buf,LatPoso,LatLeno);
       sscanf(s,"%f",&fyo);
/* the order in input and output file must be the same */
       if (fx!=fxo || fy!=fyo) {
         printf("Coordinates out of order0);
         exit(1);
         }
       }
     else
       {
/* write LONG LAT if no records on output file */
       lseek(fo,(long)LongPoso,L_INCR);
       sprintf(s,fLong,fx);
       write(fo,s,LongLeno);
       lseek(fo,(long)LatPoso-(long)LongPoso-(long)LongLeno,L_INCR);
       sprintf(s,fLat,fy);
       write(fo,s,LatLeno);
       lseek(fo,(long)OutPos-(long)LatPoso-(long)LatLeno,L_INCR);
       };
/* write result to output record */
     printf("%f %f0,fx,fy);
/* call function with calculate efactors */
     sprintf(s,fOut,efact(ya,ya2,von,bis,p1,p2));
     ix=write(fo,s,OutLen);
     posi=lseek(fo,(long)headero.RecordLength-1L-(long)OutPos-(long)OutLen,L_INCR);
     };
```

```
    if (none==TRUE)
     {
     write(fo," ",1);
     }
    printf("0);
    }
  else
    {
    printf("Die erforderlichen Felder wurden nicht gefunden !0);
    };
 };
/* end */

/* function to calculate efactor */
float efact(ya,ya2,von,bis,p1,p2)
  float p1,p2;
  float *ya,*ya2;
  struct Date *von,*bis;

  {
  struct Date dat,plus();
  float a,b,datDay,datDay2,efac,temp;
  int dM,ic,stop;
/* begin */
  ic = 0 ;
  efac = 0.;
  stop = 1 ;
  for(dat= *von;stop==1;dat=plus(dat))
    {
/* find spine coef */
    stop = (dat.day!=bis->day||dat.month!=bis->month);
    datDay = (float)dat.day-(float)MonthLength[dat.month]  / 2. ;
    datDay2 = (float)dat.day+(float)MonthLength[dat.month-1]  / 2. ;
    dM = dat.month + (datDay <= 0 ?  -1 : 0);
    datDay = datDay < 0 ? datDay2 : datDay ;
    datDay = datDay/(float)(MonthLength[dM]+MonthLength[dM+1])/2. ;
    b = datDay ;
    a = 1. - datDay ;
/* calc value from spine */
    temp =a* ya[dM]+b* ya[dM+1]+((a* a* a-a)* ya2[dM]+(b* b* b-b)* ya2[dM+1])/6.;
/* calc efactor */
    efac += pow(10.,(p1* temp));
    ic++;
    }
  return p2 * efac ;
  }
/* end */

/* calender function */
struct Date plus(dat)

  struct Date dat;

/* begin add one day */
```

```
  {
  ++dat.day;
  dat.day = dat.day > MonthLength[dat.month] ? 1 : dat.day ;
  if (dat.day==1)
    {
    dat.month++;
    dat.month = dat.month > 12 ? 1 : dat.month ;
    }
  return dat;
  }
/* end */
```

Annex A3. DBase-Program to Calculate Natural VOC Emissions from Emission Factors and Forest Coverage Data.

```
close all databases
clear
select 3
* use empty file which contains structure for emissions per grid element, altitude class, and species
  type:
use <emission file*>
* enter coordinates for all grid elements from forest coverage file:
append from <forest file>
select 1
use <efactor file**> alias ef
* index data bases on longitude and latitude:
index on (long + lat / 100) to efactor
select 2
use <forest file***> alias ph
index on (long + lat / 100) to forest
set relation to (long + lat / 100) into ef
select 3
* for identical grid elements, multiply forest coverage data per species from forest file with emission
  factors per altitude class from efactor file, and write into emission file for each altitude class and
  species type:
set relation to (long + lat / 100) into ph
replace all cem0300 with (ph->c0300m × ef->ef150c / 1000)
replace all cem300600 with (ph->c300600m × ef->ef450c / 1000)
replace all cem600900 with (ph->c600900m × ef->ef750c / 1000)
replace all cem9001500 with (ph->c9001500m × ef->ef1200c / 1000)
replace all cem1500210 with (ph->c15002100m × ef->ef1700c / 1000)
replace all cem2100 with ph->c2100m × ef->ef2100c / 1000)
replace all dem0300 with (ph->d0300m × ef->ef150d / 1000)
replace all dem300600 with (ph->d300600m × ef->ef450d / 1000)
replace all dem600900 with (ph->d600900m × ef->ef750d / 1000)
replace all dem9001500 with (ph->d9001500m × ef->ef1200d / 1000)
replace all dem1500210 with (ph->d15002100m × ef->ef1700d / 1000)
return
```

*Emission File Description:

Field	Field Name	Field Description	Unit
1	LONG	longitude	°
2	LAT	latitude	°
3	CEM0300	VOC emission from coniferous forest below 300 m	tonnes
4	CEM300600	VOC emission from coniferous forest between 300 and 600 m	tonnes
5	CEM600900	VOC emission from coniferous forest between 600 and 900 m	tonnes
6	CEM9001500	VOC emission from coniferous forest between 900 and 1500 m	tonnes
7	CEM1500210	VOC emission from coniferous forest between 1500 and 2100 m	tonnes
8	CEM2100	VOC emission from coniferous forest above 2100 m	tonnes
9	DEM0300	VOC emission from deciduous forest below 300 m	tonnes
10	DEM300600	VOC emission from deciduous forest between 300 and 600 m	tonnes
11	DEM600900	VOC emission from deciduous forest between 600 and 900 m	tonnes
12	DEM9001500	VOC emission from deciduous forest between 900 and 1500 m	tonnes
13	DEM1500210	VOC emission from deciduous forest between 1500 and 2100 m	tonnes
14	DEM2100	VOC emission from deciduous forest above 2100 m	tonnes
15	SUMEMC	total VOC emission from coniferous forest	tonnes
16	SUMEMD	total VOC emission from deciduous forest	tonnes

**EFactor File Description:

Field	Field Name	Field Description	Unit
1	LONG	longitude	°
2	LAT	latitude	°
3	EF150C	emission factor for coniferous forest at 150 m	kg/km^2
4	EF450C	emission factor for coniferous forest at 450 m	kg/km^2
5	EF750C	emission factor for coniferous forest at 750 m	kg/km^2
6	EF1200C	emission factor for coniferous forest at 1200 m	kg/km^2
7	EF1700C	emission factor for coniferous forest at 1700 m	kg/km^2
8	EF2100C	emission factor for coniferous forest at 2100 m	kg/km^2
9	EF150D	emission factor for deciduous forest at 150 m	kg/km^2
10	EF450D	emission factor for deciduous forest at 450 m	kg/km^2
11	EF750D	emission factor for deciduous forest at 750 m	kg/km^2
12	EF1200D	emission factor for deciduous forest at 1200 m	kg/km^2
13	EF1700D	emission factor for deciduous forest at 1700 m	kg/km^2
14	EF2100D	emission factor for deciduous forest at 2100 m	kg/km^2

***see Annex A1.

Annex A4. DBase-Program to Sum up Coniferous and Deciduous Emissions per Grid Cell and in the Entire Grid Area.

```
close all databases
clear
use<emission file*>
* sum all coniferous emissions over six altitude classes per grid element:
replace all sumemc with (cem0300 + cem300600 + cem600900 + cem9001500 + cem1500210
 + cem2100)
* sum all deciduous emissions over six altitude classes per grid element:
replace all sumemd with (dem0300 + dem300600 + dem600900 + dem9001500 + dem1500210
 + dem2100)
* sum up species-specific emissions over entire grid:
sum sumemc to memc
sum sumemd to memd
return
```

*see Annex A3.

Annex A5. Gridded VOC Emissions from Forests in Europe, 30-Year Average.

Figure A5.1. Gridded VOC Emissions from Forests in Scandinavia.
Figure A5.2. Gridded VOC Emissions from Forests in Northwest Europe.
Figure A5.3. Gridded VOC Emissions from Forests in Central Europe.
Figure A5.4. Gridded VOC Emissions from Forests in Southwest Europe.
Figure A5.5. Gridded VOC Emissions from Forests in Southeast Europe.
Figure A5.6. Gridded VOC Emissions from Forests in Northern USSR.
Figure A5.7. Gridded VOC Emissions from Forests in Southern USSR.

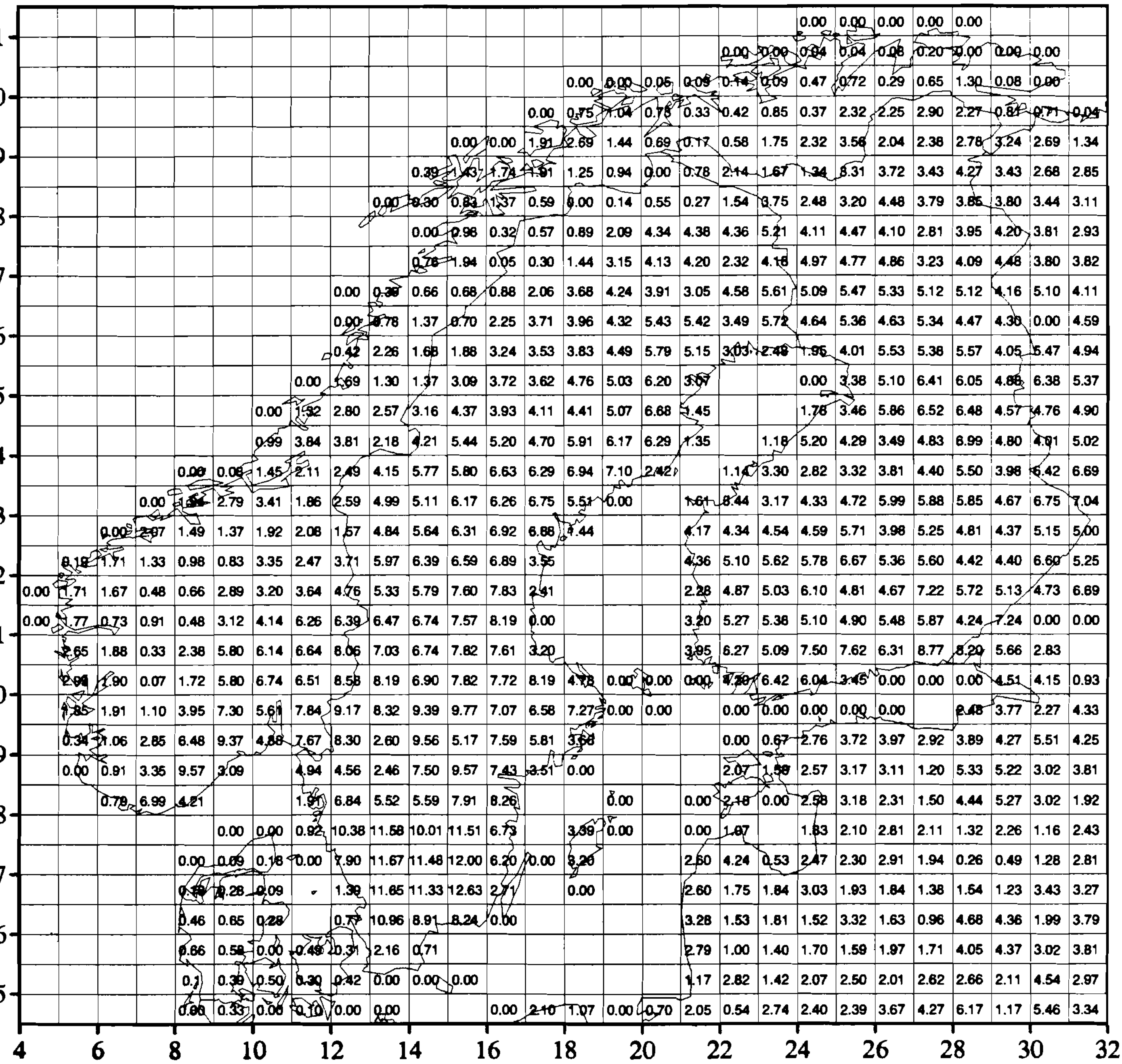

Figure A5.1. Gridded VOC Emissions from Forests in Scandinavia [ktonnes].

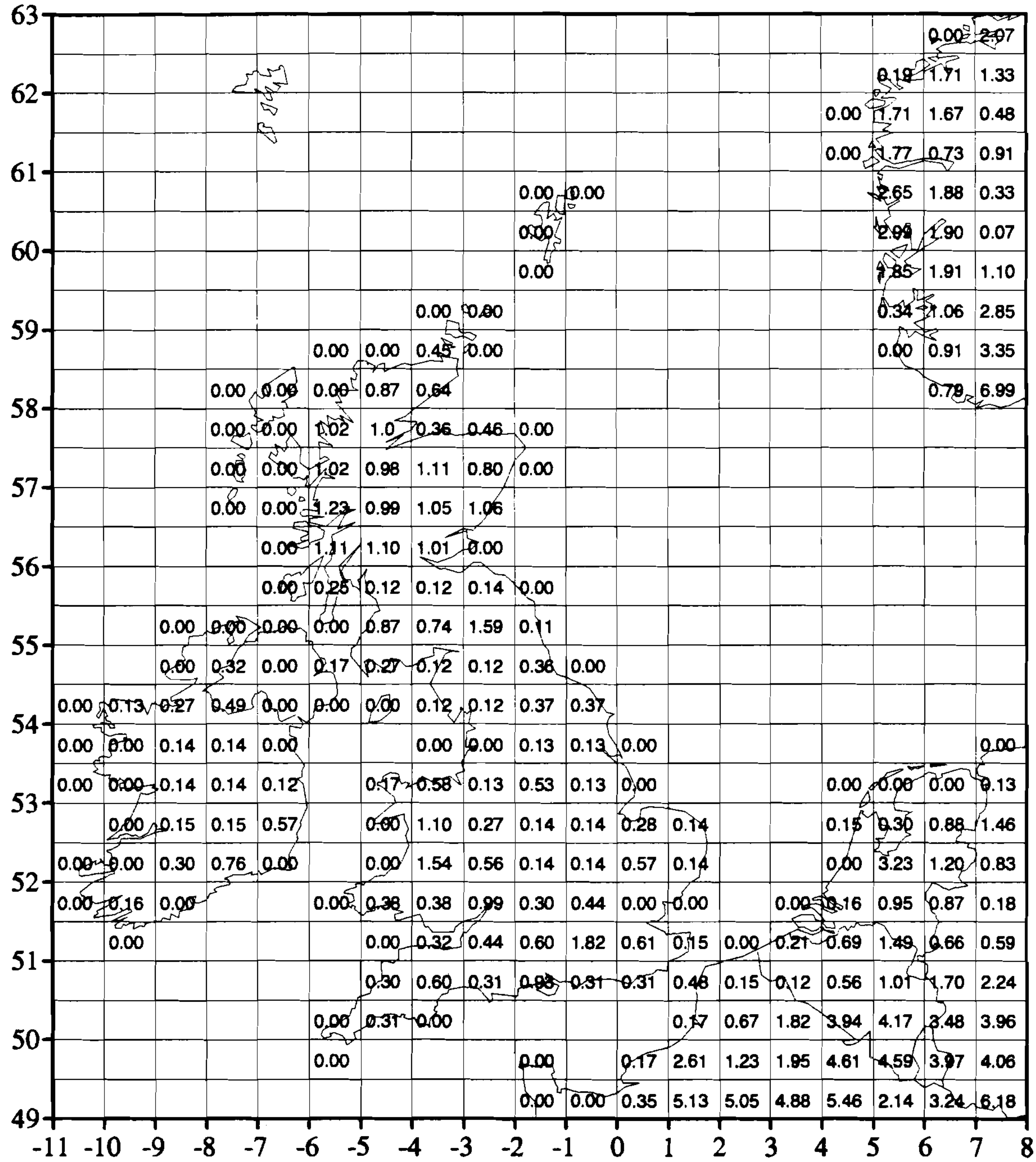

Figure A5.2. Gridded VOC Emissions from Forests in Northwest Europe [ktonnes].

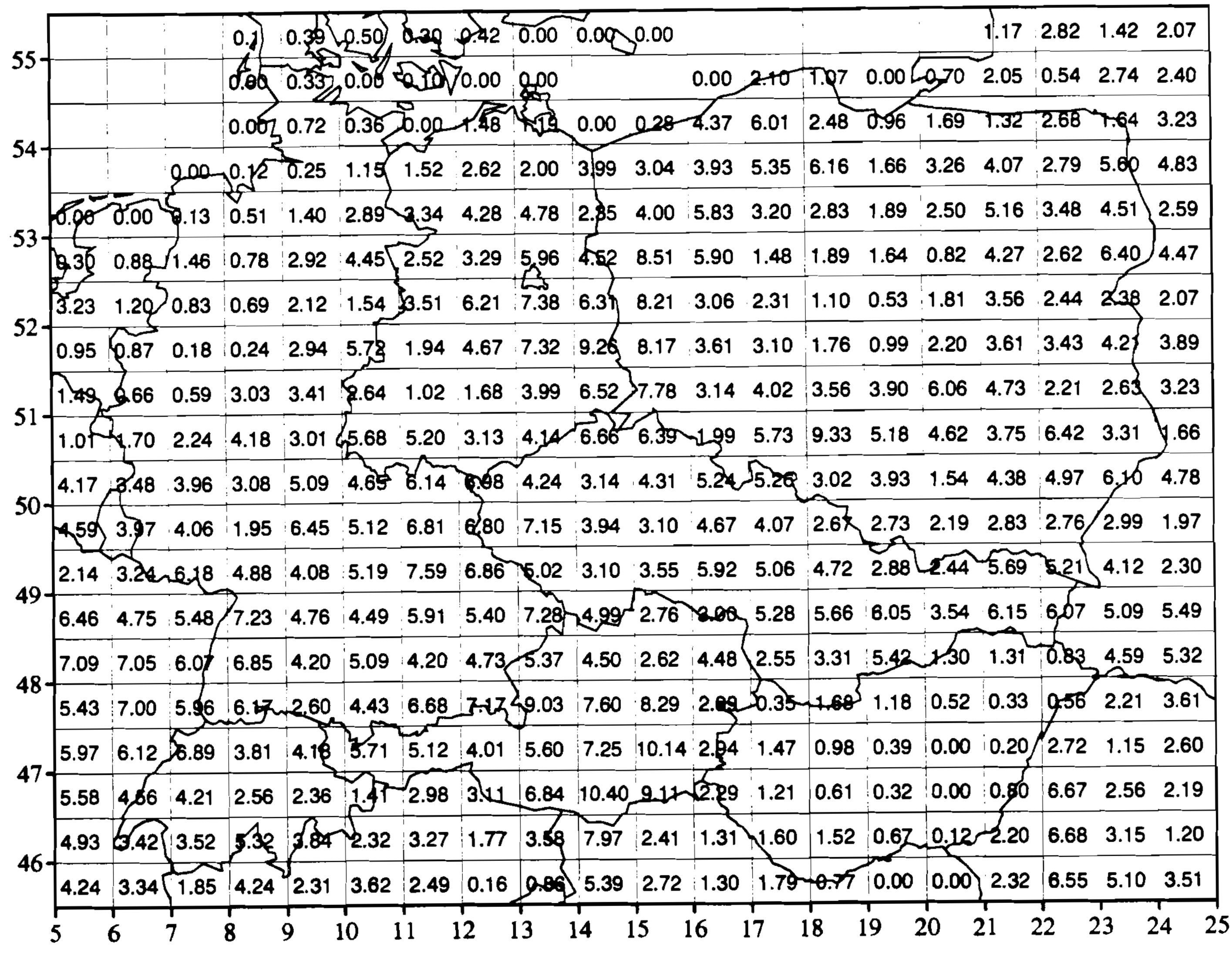

Figure A5.3. Gridded VOC Emissions from Forests in Central Europe [ktonnes].

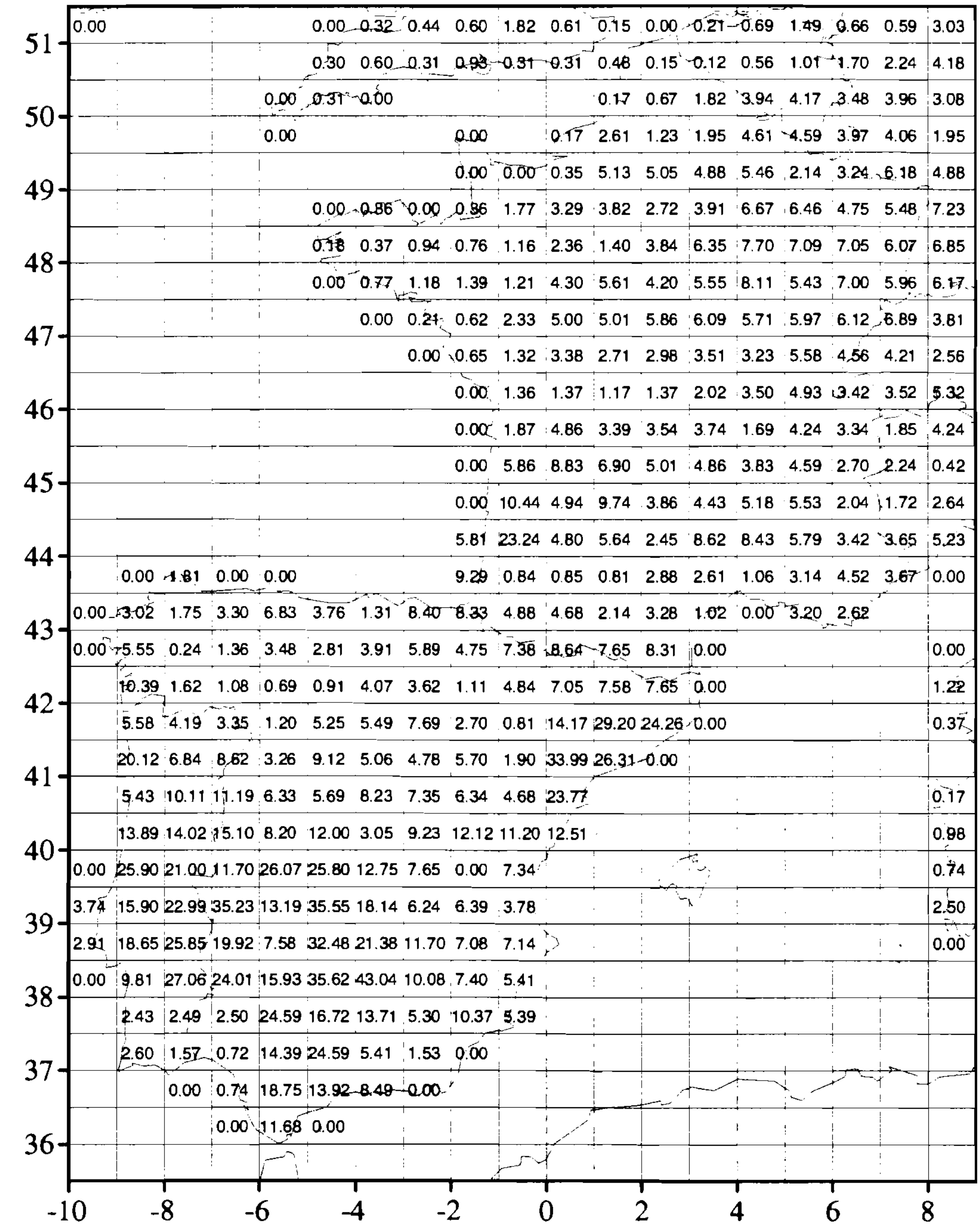

Figure A5.4. Gridded VOC Emissions from Forests in Southwest Europe [ktonnes].

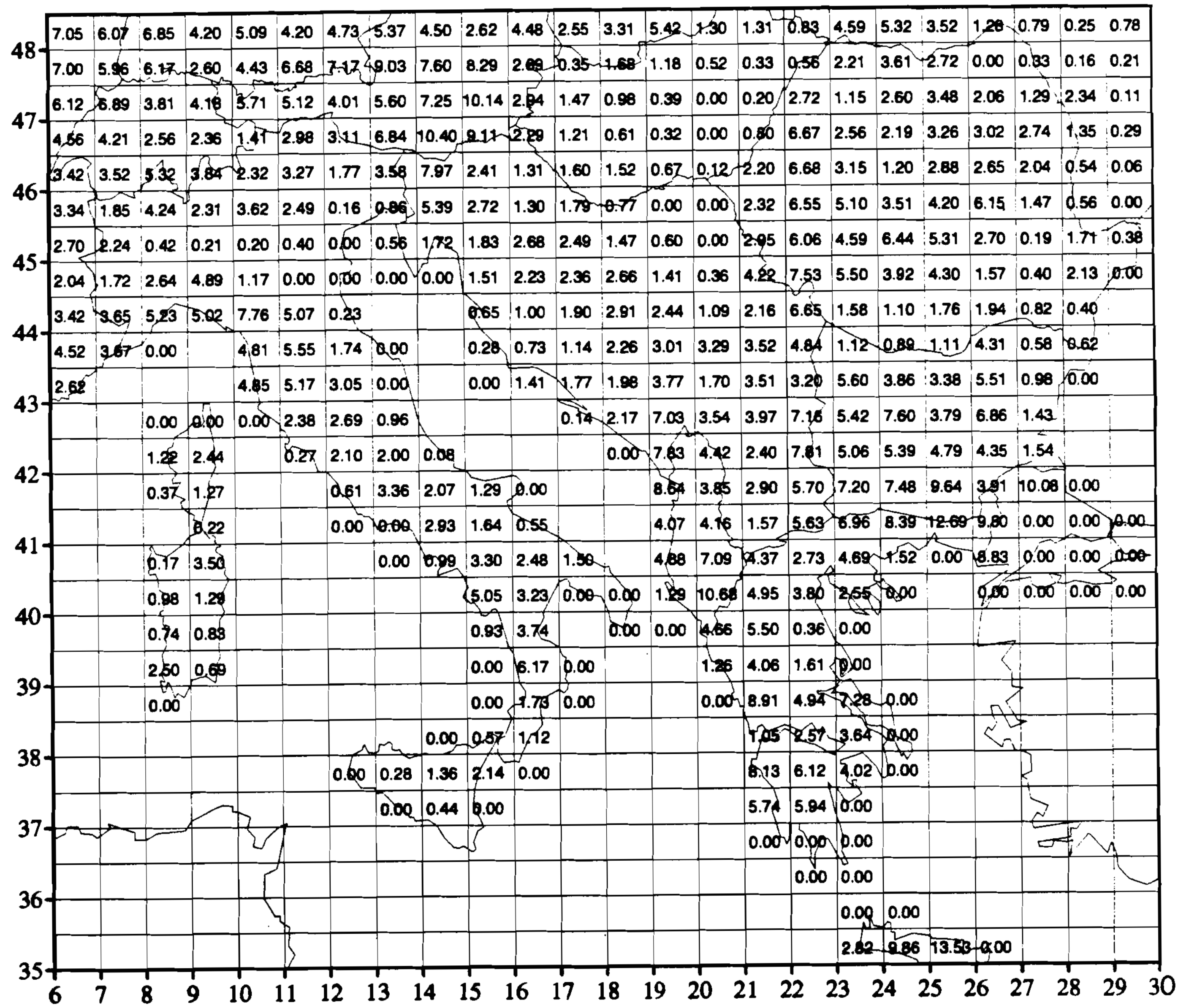

Figure A5.5. Gridded VOC Emissions from Forests in Southeast Europe [ktonnes].

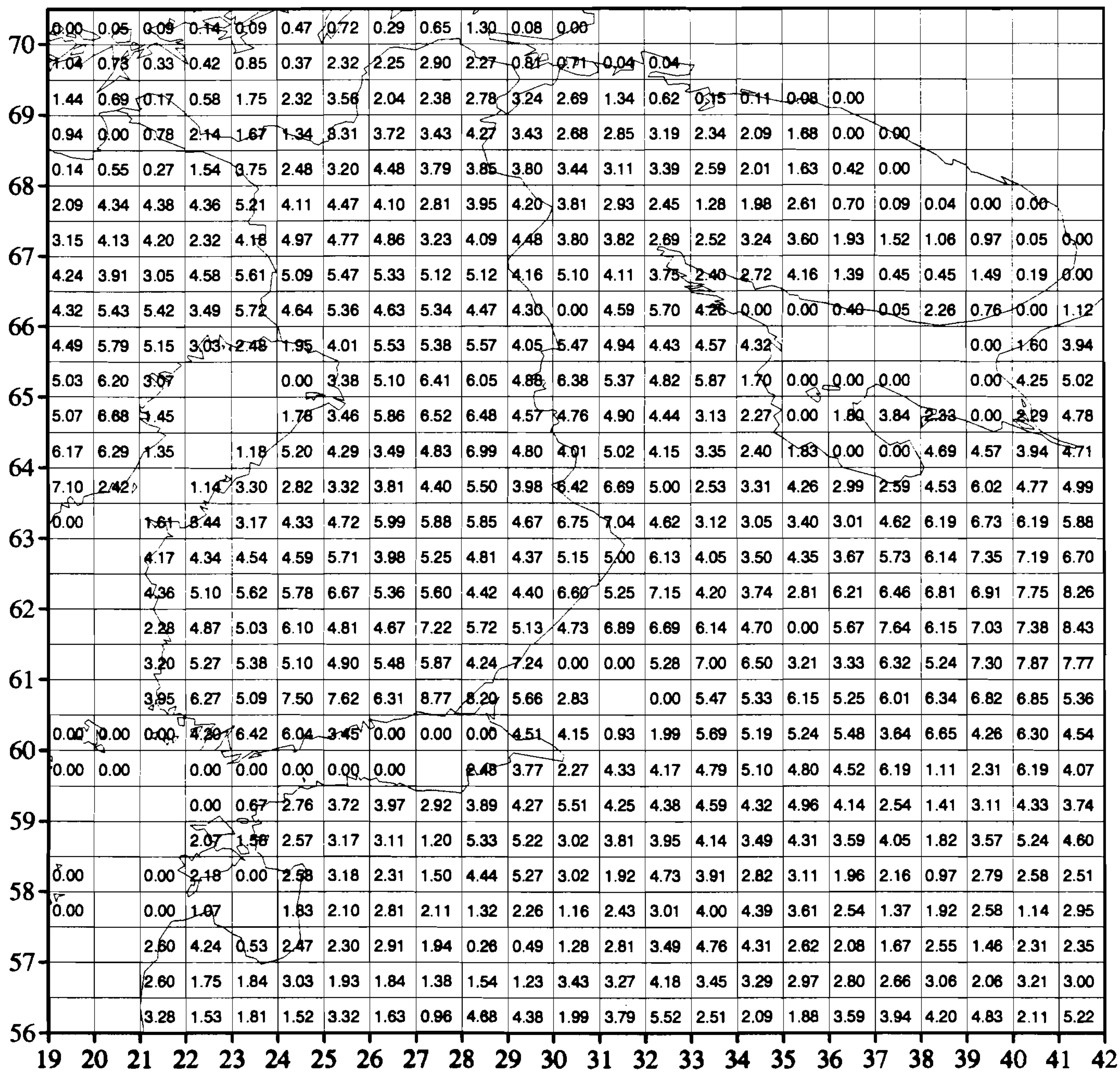

Figure A5.6. Gridded VOC Emissions from Forests in Northern USSR [ktonnes].

Lat \ Lon	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
56			2.79	1.00	1.40	1.70	1.59	1.97	1.71	4.05	4.37	3.02	3.81	3.80	2.81	1.77	3.18	4.47	2.23	3.12	3.04	5.22	4.84
			1.17	2.82	1.42	2.07	2.50	2.01	2.62	2.66	2.11	4.54	2.97	1.99	2.06	2.43	2.93	4.24	4.26	2.70	3.53	3.69	3.75
55	0.00	0.70	2.05	0.54	2.74	2.40	2.39	3.67	4.27	6.17	1.17	5.46	3.34	2.38	1.09	4.66	2.47	2.47	1.33	1.21	1.28	5.26	3.11
	0.96	1.69	1.32	2.68	1.64	3.23	1.62	2.92	3.37	5.33	0.41	6.54	4.85	2.56	1.48	2.18	0.69	1.29	0.73	0.14	0.17	1.08	1.67
54	1.66	3.26	4.07	2.79	5.60	4.83	3.54	6.00	2.48	5.54	4.96	2.18	1.90	3.02	2.93	2.96	2.34	0.51	0.11	0.22	0.30	0.61	1.19
	1.89	2.50	5.16	3.48	4.51	2.59	4.45	1.84	4.85	5.69	4.19	2.50	3.40	2.40	2.46	3.62	1.31	0.32	0.17	0.12	0.28	0.82	1.54
53	1.64	0.82	4.27	2.62	6.40	4.47	5.21	7.13	5.17	7.06	4.78	1.75	1.96	1.90	2.05	3.06	0.24	0.13	0.07	0.14	0.81	0.52	2.03
	0.53	1.81	3.56	2.44	2.38	2.07	3.64	5.80	6.83	7.71	5.37	1.86	3.05	2.07	2.46	1.26	0.41	0.13	0.06	0.22	1.04	0.00	0.89
52	0.99	2.20	3.61	3.43	4.21	3.89	5.90	6.41	5.68	8.47	6.69	3.17	2.82	2.82	1.70	0.48	0.35	0.09	0.00	0.21	1.30	0.09	0.18
	3.90	6.06	4.73	2.21	2.63	3.23	6.22	8.76	8.52	5.11	6.05	4.01	1.74	1.07	0.33	0.53	0.44	0.14	0.09	0.25	0.24	0.75	0.79
51	5.18	4.62	3.75	6.42	3.31	1.66	3.31	3.83	4.56	1.45	5.22	4.32	1.21	0.44	0.42	1.31	0.98	0.29	0.47	0.45	0.17	0.70	0.37
	3.93	1.54	4.38	4.97	6.10	4.78	3.06	3.16	1.38	1.67	2.29	2.24	0.83	0.20	0.26	1.28	0.77	1.31	0.37	0.51	0.18	0.58	0.25
50	2.73	2.19	2.83	2.76	2.99	1.97	0.95	0.05	0.16	0.21	0.28	1.01	0.92	0.11	0.09	0.27	0.59	1.50	0.10	0.00	0.11	0.21	0.39
	2.88	2.44	5.69	5.21	4.12	2.30	0.92	0.40	0.42	0.45	0.29	0.68	2.41	0.92	0.10	0.20	0.00	0.41	1.15	0.25	0.13	0.08	0.00
49	6.05	3.54	6.15	6.07	5.09	5.49	1.03	0.54	0.37	0.42	0.59	0.70	0.28	1.27	0.19	0.05	0.29	0.00	0.66	1.72	0.26	0.00	0.00
	5.42	1.30	1.31	0.83	4.59	5.32	3.52	1.28	0.79	0.25	0.78	0.61	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.30	0.14	0.08	0.00
48	1.18	0.52	0.33	0.56	2.21	3.61	2.72	0.00	0.83	0.16	0.21	0.00	0.00	0.00	0.00	0.00	0.07	0.08	0.29	0.13	0.00	0.18	0.19
	0.39	0.00	0.20	2.72	1.15	2.60	3.48	2.06	1.29	2.34	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00	0.09
47	0.32	0.00	0.60	6.67	2.56	2.19	3.26	3.02	2.74	1.35	0.29	0.00	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.09	0.1	0.1
	0.67	0.12	2.20	6.68	3.15	1.20	2.88	2.65	2.04	0.54	0.06	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.20
46	0.00	0.00	2.32	6.55	5.10	3.51	4.20	6.15	1.47	0.56	0.00	0.00			0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
	0.60	0.00	2.95	6.06	4.59	6.44	5.31	2.70	0.19	1.71	0.38				0.00	0.05	0.00	0.00	0.19	0.1	0.19	0.29	0.16
45	1.41	0.36	4.22	7.53	5.50	3.92	4.30	1.57	0.40	2.13	0.00				0.56	1.30	0.00		2.19	4.57	3.56	0.85	0.22
	2.44	1.09	2.16	6.65	1.58	1.10	1.76	1.94	0.82	0.40					0.00	0.00				0.00	6.35	4.01	0.58
44																							

Figure A5.7. Gridded VOC Emissions from Forests in Southern USSR [ktonnes].