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Density of foliage mass and area in the boreal forest cover in Finland, with applications to the estimation of monoterpene and isoprene emissions

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Abstract

The distribution of the density of foliage mass and area in forest canopies throughout Finland (60–70°N) were determined on the basis of the permanent sample plots used in the Finnish National Forest Inventory. These parameters were linked to the long-term monthly mean air temperatures for 1961–1990, which had been converted to hourly temperature and radiation values with the help of a weather simulator in order to calculate the spatial distribution of mean yearly emissions of monoterpene and isoprene over Finland. The mean total density of foliage mass in southern Finland ($60° \leqslant$ latitude $< 65°$N) was around 500 g m^{-2}, equivalent to 4–5 m^2 of total foliage area per m^2 of land area. In northern Finland ($65° \leqslant$ latitude $< 70°$N), the maximum values remained below 200–300 g m^{-2}, or 2–3 m^2 m^{-2}. The highest values were achieved in forests dominated by mature Norway spruces. The higher temperatures and longer growing season in southern Finland led to greater emissions than in the rest of the country. Total annual emissions of monoterpene were 1070 kg km^{-2} yr^{-1} in southern Finland and 460 kg km^{-2} yr^{-1} in the north, and those of isoprene from Norway spruce canopies 150 and 40 kg km^{-2} yr^{-1}, respectively.

Keywords: Boreal forests; Foliage; Tree species composition; VOC; Monoterpene; Isoprene

1. Introduction

Forests cover about 80% of the total land area of Finland, and the forest canopies are main source of volatile organic compounds (VOC). These forests are mainly coniferous ones dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), which together account for more than 80% of the total stem wood volume. The rest of the forest resources consist of deciduous species, mainly Pendula birch (*Betula pendula*) and Pubescent birch (*Betula pubescent*). The growing stock of stem wood varies from 115 m^3 ha^{-1} in southern Finland ($60° \leqslant$ latitude $< 65°$N) to 60 m^3 ha^{-1} in the north ($65° \leqslant$ latitude $< 70°$N). The forests throughout the country are utilised commercially and managed regularly, with the consequence that the natural tree species composition is greatly affected by human intervention. Management also substantially affects the growing stock and the age distribution of tree populations. This also applies to foliage density, with the consequence that it shows substantial stand-to-stand variability according to the dominant tree species, growing stock and age of the tree populations.

The spatial variability existing in the forest resources implies that VOC emissions vary throughout the country. Therefore, reliable estimates of these emissions need careful analysis of the spatial distribution and properties of the foliage. Furthermore, the seasonality and duration of the deciduous foliage require special attention unlike the coniferous species, the foliage of which is more or less constant throughout the year. This implies that coniferous species are capable of emitting VOC even at times when the deciduous trees have no foliage. Thus, the

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tree species composition combined with the prevailing weather conditions provides the key to the successful analysis of how single tree populations or larger forest areas with numerous tree populations may emit VOC into the atmosphere (Guenther et al., 1993; Lamb et al., 1993; Simpson, 1995; Simpson et al., 1995).

This study aims at characterising forest canopies throughout Finland in terms of the density of the foliage mass and area for use in calculating the emissions of VOCs. The resulting estimates are combined with data on weather conditions and examples of emissions of monoterpene and isoprene are calculated for selected stands. Finally, the forestry statistics and long-term weather statistics are linked and total emissions of monoterpene and isoprene are calculated over the whole country. The data concern only forests on mineral upland sites, and exclude terrestrial sites subject to any other types of land use and peatlands.

2. Material and methods

2.1. Calculation of foliage mass and area

The permanent sample plots established for the Finnish National Forest Inventory were used to calculate the density of foliage mass and area throughout the country. These plots form clusters located systematically across the country in such a way that the distance between them in a North–South and an East–West direction is 16 km (grid size 16 km × 16 km) in southern Finland ($60^\circ \leqslant$ latitude $< 65^\circ$N) and 32 km (grid size 32 km × 32 km) in northern Finland ($65^\circ \leqslant$ latitude $<$ 70°N) (Fig. 1). The network of sample plots excludes the archipelago of southwestern Finland, which is not considered at all here.

The clusters of plots consist of four permanent plots arranged in a North–South direction and located 400 m apart. The size of a plot depends on the diameter of the trees; i.e. trees of diameter >10.5 cm at breast height (1.3 m above ground level) are considered in plots of 0.03 ha (radius 9.77 m) and trees of diameter <10.5 cm in plots of 0.01ha (radius 5.64 m) (Valtakunnan metsien 8. Inventointi. Kenttätyönohjeet, 1986; Metsäntutkimuslaitos, 1995; Metsätilastollinen vuosikirja, 1998). Each tree within a radius equal to half that of the plot (4.89 and 2.82 m) was measured as a sample tree. Only the plots on upland mineral soils, excluding peatlands, were employed for this purpose, i.e. a total of 1256 plots (1009 in southern Finland and 247 in the north).

Most of the plots (1006 out of 1256) were located on unsorted soils; i.e. coarse and fine tills. The most common textures among the sorted soils were sand and fine sand (177 out of 1256). Consequently, most of the plots (1176 out of 1256) were of medium fertility; i.e. *Oxalis–Myrtillus* type (OMT, 233 sites), *Myrtillus* type (MT, 580 sites) or

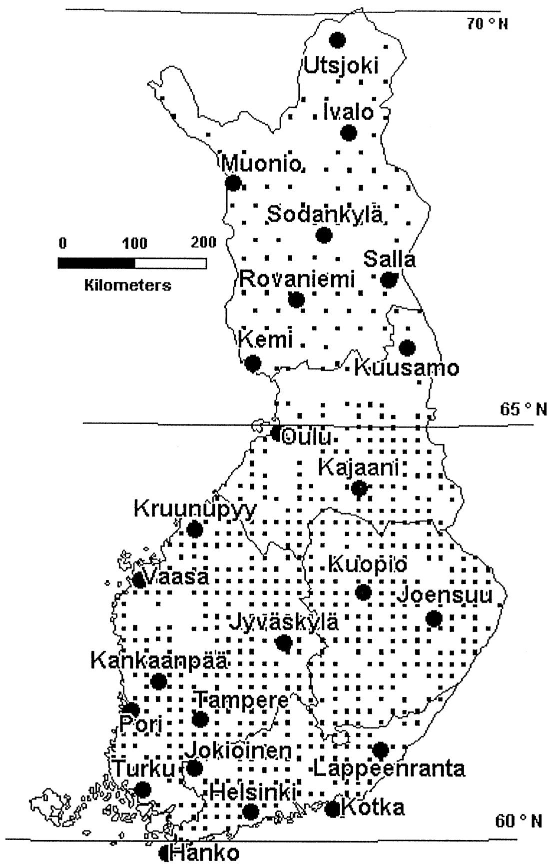

Fig. 1. Locations of the permanent sample plots used in the National Forest Inventory (filled squares) and the weather stations providing data for the present analysis (filled circles).

Vaccinium type (VT, 363 sites). Only 18 plots were on sites of the most fertile type (*Oxalis–Maianthemum* type, OmaT) and only one plot on the least fertile type (*Cladonia* type, ClT). The dominant tree species on OMaT and OMT sites is mainly Norway spruce, with admixtures of the Pendula and Pubescent birches, while on the MT sites varying combinations of Norway spruce, Pendula birch and Scots pine are dominating. The main tree species on the VT, CT, and ClT sites is Scots pine. For details of the site type classification, see Cajander (1909).

The inventory data used in this study was for 1990 and apply 17,999 sample trees which represent six species indigenous to Finland, i.e. 8221 Scots pines, 6259 Norway spruces, 593 Pendula birches, 1991 Pubescent birches, 344 aspens (*Populus tremula*) and 591 grey alders (*Alnus incana*). Aspen and grey alder were excluded from the present calculations due to their marginal importance for forest resources ($<1\%$ of the total volume).

The various parameters making up the descriptions of the sample trees (total height, height of crown bottom,

Table 1
Values for the parameters of Eq. (1) for the principal tree species Marklund (1987, 1988)

Tree species	α_1	β_1	γ_1
Scots pine	− 3.7983	7.7681	7.0000
Norway spruce	− 1.9602	7.8171	12.0000
Birch	− 3.9823	8.0580	8.0000

Table 2
Specific foliage area values for the principal tree species (Kull and Niinemets, 1993; Niinemets and Kull, 1995; Ross et al., 1986)

Species	SLA ($m^2 kg^{-1}$)
Scots pine	5.54
Norway spruce	5.65
Birch	18.46

etc.) include diameter at breast height, values of which were also available for other trees on the sample plots. Based on tree allometry (the regular, species-specific relationship between the dimensions of different organs of a tree), the diameter was used to estimate the mass of foliage in the sample trees. Following Marklund (1987, 1988), the mass of foliage (M, kg) is a function of the diameter:

$$M = e^{\alpha_1 + \beta_1 (d_{1.3}/(d_{1.3} + \gamma_1))} \tag{1}$$

where $d_{1.3}$ is the breast height diameter (cm) and α_1, and β_1 (dimensionless) and γ_1 (cm) are parameters with the species-specific values presented in Table 1. The foliage mass was further converted to total foliage area by means of the values for specific foliage area (two-sided area of foliage per mass (SLA), $m^2 kg^{-1}$) presented by Kull and Niinemets (1993), Niinemets and Kull (1995) and Ross et al. (1986) for the given species (Table 2).

2.2. Calculation of seasonality of deciduous canopies

Eq. (1), which gives maximum values for foliage mass and the derived maximum values for foliage area, gives a sufficient estimate for coniferous trees regardless of the phase of the growing season, but it does not allocate this over the growing season in the case of deciduous trees and provides no indication of the seasonal duration of the foliage. In order to avoid these problems, the effective temperature sum was used to calculate the onset and build-up of the foliage in spring and early summer (Raulo and Leikola, 1974; Hänninen et al., 1990). When the build-up is completed, the mass of foliage will have achieved the value indicated by Eq. (1).

The effective temperature sum (ETS, d.d.) is the sum of daily mean temperatures (T_d, °C) that exceed a given threshold (T_b, °C)

$$\mathrm{ETS} = \sum_{d=1}^{n} (T_d - T_b) \quad \text{if} \quad T_d \geqslant T_b \tag{2}$$

where n is the number of days for which $T_d \geqslant T_b$ and $T_b = 5$°C.

In southern Finland the build-up of foliage is assumed to occur whenever ETS exceeds a value of $a = 36$ d.d. and to be complete when ETS exceeds $b = 865$ d.d. (Raulo and Leikola, 1974). The values for a and b used for northern Finland were $a = 36$ d.d. and $b = 600$ d.d. (Kellomäki and Kolström, 1994). The percentage of the maximum foliage occurring during the build-up phase ($\mathrm{SH_{up}}$, %) is calculated as

$$\mathrm{SH_{up}} = \sum_{d=1}^{n} \left(\left(\frac{(\mathrm{ETS} - a)}{(b - a)/2} \right) \times 100 \right). \tag{3}$$

Senescence of the foliage may be related to the individual effects of temperature and day length (Koski and Selkäinaho, 1982; Hänninen et al., 1990), but these may also interact. In northern Finland in particular, low temperatures in late summer and autumn trigger senescence, and temperature variability is a better indicator of year-to-year variability in the onset of senescence than day length. If only control by day length were assumed, the onset of senescence would be constant for each latitude. Following this assumption, calculation of the senescence of the foliage would be based on ETS as well whereas now it is performed in reverse. The percentage of the foliage present in the canopy is reduced along with the declining ETS ($\mathrm{SH_{down}}$) until no foliage is present, i.e.

$$\mathrm{SH_{down}} = 100 - \sum (T_b - T_d) \quad \text{if} \quad T_d \leqslant T_b \tag{4}$$

where $T_b = 10$°C and n is the number of days from the moment of initiation of senescence to the moment when no foliage is present in the canopy.

2.3. Calculation of monoterpene and isoprene emissions

Emissions of *monoterpene* ($E_{\mathrm{ter}}(T)$, $\mu g\, g^{-1} h^{-1}$) are calculated as a function of air temperature (T, °C), as presented by Guenther et al. (1993), i.e.

$$E_{\mathrm{ter}}(T) = \mathrm{Ef_{ter}} \times e^{(\beta(T - T_s))} \tag{5}$$

where $\mathrm{Ef_{ter}}$ is the emission factor with values of $1.5\, \mu g\, g^{-1} h^{-1}$ for Scots pine and Norway spruce and $1.0\, \mu g\, g^{-1} h^{-1}$ for birches at $T = 30$°C with $\beta = 0.09$°C^{-1}.

Emissions of *isoprene* ($E_{\mathrm{iso}}(T, Q)$, $\mu g\, g^{-1} h^{-1}$) are calculated as a function of air temperature (T) and radiation (Q, $\mu mol\, m^{-2} s^{-1}$):

$$E_{\mathrm{iso}}(T, Q) = \mathrm{Ef_{iso}} \times C_Q \times C_T \tag{6}$$

where Ef_{iso} ($\mu g\, g^{-1} h^{-1}$) is the emission factor with a value of $1.0\, \mu g\, g^{-1} h^{-1}$ at $T = 30°C$ and $Q = 1000\, \mu mol\, m^{-2} s^{-1}$. The correction factor for radiation (C_Q) is given by

$$C_Q = \frac{\alpha C_{Q1} \times Q}{\sqrt{1 + \alpha^2 Q^2}} \tag{7}$$

where $\alpha = 0.0027$ and $C_{Q1} = 1.066$, and Q is radiation. The correction factor for temperature (C_T) is given by

$$C_T = \frac{\exp\left(\dfrac{C_{T1}(T - T_s)}{RT_s T}\right)}{0.961 + \exp\left(\dfrac{C_{T2}(T - T_M)}{RT_s T}\right)} \tag{8}$$

where $R = 8.314\, J\, K^{-1} mol^{-1}$, $C_{T1} = 95{,}000\, J\, mol^{-1}$, $C_{T2} = 230{,}000\, J\, mol^{-1}$, and TM = 314 K.

When calculating monoterpene emissions the foliage in the canopy was treated as a single layer, whereas for isoprene the foliage of the Norway spruces was divided into four layers. The radiation at any height (z) in the canopy was calculated by means of the Beer equation, assuming that the foliage was homogeneously distributed within the canopy space (Oker-Blom, 1986). Consequently, radiation in a layer i is

$$Q(i) = Q(\mathrm{Top})\exp\left(-k \sum_{z=\mathrm{Top}}^{i} \mathrm{LAI}(i)/\sin\theta\right) \tag{9}$$

where LAI(i) is the density of foliage area ($m^2 m^{-2}$) at a distance i from the stem apex, the value Top indicating the height of the surface of the uppermost layer, k the extinction coefficient of radiation, with an assumed value of 0.15 (Oker-Blom, 1986), and θ the angle of solar elevation in degrees. The calculations refer to short wave radiation with no distinction between direct and diffuse radiation.

2.4. Calculation of weather parameters

Emissions of monoterpene and isoprene are calculated on an hourly basis. As only monthly mean temperatures for the period 1961–1990 (Finnish Meteorological Institute, 1991) were systematically available for the 24 airport weather stations used here (locations in Fig. 1), the weather generator developed by Strandman et al. (1993) was employed to convert these to hourly values. Hourly radiation values were also generated for each weather station as described below.

When calculating the hourly temperatures, the monthly mean temperatures were first decomposed into daily mean temperatures by means of the Markov process (Richardson, 1981; Haith et al., 1984)

$$\mathrm{dT}(d) = \mu_{mT} + \rho_{mT}(\mathrm{dT}(d-1) - \mu_{mT}) + \sigma_{mT} n_i (1 - \rho_{mT}^2)^{0.5} \tag{10}$$

where dT(d) is the daily mean temperature, μ_{mT} is the mean temperature for a month, σ_{mT} is the standard deviation of the monthly mean temperature based on daily mean temperatures, ρ_{mT} is the autocorrelation for mean temperature in each month and n_i is a normally distributed random number, $N(0, 1)$. Hourly temperatures (hT(h)) could then be calculated:

$$\mathrm{hT}(h) = \mathrm{dT}(d) + \left(\frac{a_{dT}}{2}\right)\sin((h-6)15) \tag{11}$$

where a_{dT} is the monthly mean amplitude of the daily temperature.

Hourly radiation values were simulated on the basis statistics for temperature and cloudiness. The average daily cloudiness (dcloud(d), expressed as the fraction of the hemisphere covered by clouds (cloud units/8, 0 = no clouds, 8 = full cover) was determined from the mean daily temperature (Haith et al., 1984)

$$\mathrm{dcloud}(d) = \mathrm{tcloud}(d) + \rho_{dc}(\mathrm{dcloud}(d-1) - \mathrm{tcloud}(d)) + \sigma_{dc} n_i (1 - \rho_{md}^2)^{0.5} \tag{12}$$

where tcloud(d) is the expected cloudiness value for the day, σ_{dc} is the standard deviation in daily cloudiness, ρ_{dc} is the autocorrelation for the daily mean cloudiness and n_i is a normally distributed random number, $N(0,1)$. The value of tcloud(d) is calculated as

$$t\mathrm{cloud}(d) = b(m) + m(m)\mathrm{dT}(d) \tag{13}$$

where b (cloud unit) and m (cloud unit $°C^{-1}$) are monthly-specific parameters derived from the weather statistics. The average daily cloudiness was converted to hourly cloudiness by means of a normally distributed random number $N(X_d, \rho_{dc})$.

Hourly values for the short-wave radiation above the plant canopy (wave length 400–2500 nm) were calculated separately for direct (cdirrad(h)) and diffuse radiation (cdifrad(h)) as follows:

$$\mathrm{cdirrad}(h) = \mathrm{RADTOT}(h) \times \mathrm{FDIFF}(h) \tag{14}$$

$$\mathrm{cdifrad} = \mathrm{RADTOT}(h) \times (1 - \mathrm{FDIFF}(h)) \tag{15}$$

where FDIFF(h) = (1 − hcloud(h)) × 0.77 and RADTOT(h) is the total radiation ($W\, m^{-2}$) below the clouds, calculated as (Lumb, 1964)

$$\mathrm{RADTOT}(h) = \mathrm{RADDCLR}(h) \times (1 - 0.71\, \mathrm{hcloud}(h)) \tag{16}$$

where hcloud(h) is the hourly cloud cover (see Finnish Meteorological Institute, 1991) and RADCLR(h) is the total radiation ($W\, m^{-2}$, wave length < 2500 nm) above the clouds, equalling the radiation when the sky is clear (Gates, 1980, pp. 111–117)

$$\mathrm{RADCLR}(h) = S_0 \tau^{th} \sin\theta + S_0(0.271 - 0.294\tau^{th})\sin\theta \tag{17}$$

where S_0 is the solar constant ($1360\,\mathrm{W\,m^{-2}}$), τ is the transmittance of the atmosphere, th is the thickness of the atmosphere (i.e. th $\approx 1/\sin\theta$) and θ is the altitude of the sun. For the calculations of isoprene emissions, the radiation was expressed in terms of $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$.

The parameters were determined and the weather simulator validated using the long-term weather statistics for 1961–1990 (Finnish Meteorological Institute, 1991), by splitting these series systematically into two parts, obtaining the parameter values from the first part and using these to simulate the second part, for validation against the actual statistics. As demonstrated by Strandman et al. (1993), the simulated monthly mean temperatures, monthly mean cloudiness and monthly mean radiation were very close to the data for the second part of the original weather statistics. For further details of the weather simulator and its properties, see Strandman et al. (1993).

2.5. Generalisation over regions

Emissions of monoterpene and isoprene over the whole country were calculated in four phases (Fig. 2). *First*, hourly rates of emission were calculated for each sample plot within a 50 km radius of each weather station, on the assumption that the weather data for a given weather station is valid for all plots within this radius. *Second,* the hourly values were summed separately over the year and the resulting yearly emission rates were taken as being representative of the long-term weather conditions prevailing at each site. *Third*, regressions between the density of foliage mass and annual mean emissions were determined separately for southern Finland and northern Finland on the basis of respective sample plots.

Since VOC emissions are linearly dependent on foliage mass, a first-order polynomial should be used, but temperature conditions and density of foliage mass are correlated (i.e. the trees are larger with a higher density of foliage in the south, where the climate is warmer) with the consequence that higher densities of foliage imply greater emissions of *monoterpene* (E_{ter} (T)) than would be predicted by the linear regression. The same pattern held good for both southern and northern Finland. The best fit for both regions was given by a second-order polynomial

$$E_{\mathrm{Tter}}(i,j) = \beta_1 M(i,j) + \beta_2 M(i,j)^2 \tag{18}$$

where E_{Tter} (i, j) is the amount of monoterpene in mg per m^2 ground area per year ($\mathrm{mg\,m^{-2}\,yr^{-1}}$) emitted from a stand i composed of tree species j, $M(i, j)$ is the respective density of foliage mass ($\mathrm{g\,m^{-2}}$) for a sample plot and β_1 and β_2 are parameters with values as given in Table 3. Emissions of isoprene from the Norway spruce canopies in mg per m^2 ground area per year ($\mathrm{mg\,m^{-2}\,yr^{-1}}$)

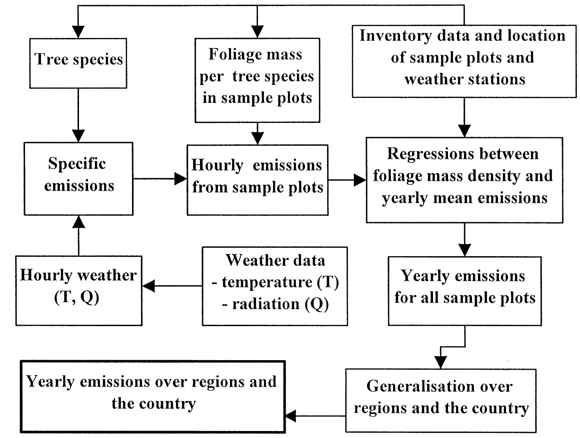

Fig. 2. Outlines of the calculation procedure linking the weather statistics and inventory date to estimate the emissions of monoterpene and isoprene over the regions and the whole country.

Table 3
Parameters for Eq. (18) for monoterpene emissions as a function of tree species and region

Tree species	Southern Finland	Northern Finland
Scots pine		
β_1	1.8327	1.4975
β_2	− 0.0002	− 0.0006
Norway spruce		
β_1	1.7457	1.5442
β_2	0.0006	− 0.0003
Birch		
β_1	1.2671	0.8834
β_2	− 0.0009	0.0010

($E_{\mathrm{Tiso}}(i,j)$, $\mathrm{mg\,m^{-2}\,yr^{-1}}$) were calculated from the function

$$E_{\mathrm{Tiso}}(i,j) = \beta M(i,j)^2 \tag{19}$$

where β is a parameter with values estimated separately for each layer, as presented in Table 4.

Fourth, the density of foliage mass for each plot including plots beyond the 50 km from a weather station, was inserted into the regression equations to yield yearly emissions for all the stands throughout the country. The calculations were performed separately for southern and northern Finland using the respective regressions and weather statistics. The yearly emissions for the stands were generalised over the whole country on the basis of how representative a sample plot is with regard to the areal distribution of the forest land among the classes of site types and of total forest land, excluding peatlands.

Table 4
Values of the parameter β in Eq. (18) for isoprene emissions from spruce canopies as a function of region and canopy layer

Crown layer (from the top)	Southern Finland	Northern Finland
Layer 1	0.8281	0.7385
Layer 2	0.8105	0.7255
Layer 3	0.7918	0.7122
Layer 4	0.7716	0.6981

2.6. Output from the calculations

The calculations were performed separately for the whole country, southern Finland and northern Finland. *First*, the forest canopies were characterised in terms of the mean density of foliage mass and area. This gave the spatial distribution of the density of foliage mass and area, and the seasonality of the deciduous canopies. *Second*, the seasonal variation in the rates of monoterpene and isoprene emissions as regulated by weather conditions were obtained. *Finally*, annual emissions of monoterpene and isoprene and their spatial distributions over the whole country were calculated.

3. Results

3.1. Density of foliage mass

The density of total foliage mass over the whole country (i.e. all tree species) increased with stand age, from 60 g m^{-2} at <20 yr to 500 g m^{-2} at 81–100 yr (Table 5), beyond which it decreased again to 300 g m^{-2}. The same pattern was observed in both northern and southern Finland, expect that the highest values in southern Finland (500 g m^{-2}) represented stands older than 140 yr. The density in northern Finland was only a half of that in the south at any given age.

The density of foliage in the pure (i.e. one species $\geqslant 90\%$ of the total stand volume) young stands (age <20 yr) over the whole country was fairly similar for Scots pine and Norway spruce (70–80 g m^{-2}), but substantially less for birch (20 g m^{-2}) (Table 6). For Scots pine, the values levelled off at 200–290 g m^{-2} in the age class 81–100 yr. The same pattern applied to Norway spruce, but the density in this age class varied over a wide range, 350–950 g m^{-2}. For birches, the density of foliage mass in mature stands varied from 60 to 90 g m^{-2}, the highest value being found in the age class 101–120 yr. In general, the density of foliage in Scots pine in northern Finland was 80–90% of that in southern Finland, whereas that for Norway spruce was only 40–50% of that in southern Finland. For birch, the density in northern Finland was 80–90% of that in the south.

3.2. Seasonality of foliage mass

The build-up and senescence of birch canopies is shown in Fig. 3 in relation to the long-term weather statistics. The build-up began in the southernmost part of the country (Helsinki, 60°N) nearly two months earlier than in the northernmost part (Utsjoki, 70°N), while senescence set in a month later in the Helsinki area than in Utsjoki. The period with a canopy cover was, thus three months longer around Helsinki than in Utsjoki. The earlier onset of build-up in southern Finland indicates an earlier and faster accumulation of the temperature sum than in northern Finland, while the later onset of foliage senescence in the south indicates later commencement of autumn frosts.

3.3. Spatial distribution of the density of foliage mass and area

The density of foliage mass in Scots pine seldom exceeded 600 gm^{-2} even in southern Finland (Fig. 4). More characteristically, it fell within the range 200–400 g m^{-2}, but no special geographical pattern was recognisable. The lowest values were mainly indicative of dominance by Norway spruce. In northern Finland values below 200 g m^{-2} indicated a low growing stock and dominance of young Scots pines. Under these conditions the density of foliage mass for Norway spruce exceeded 500 g m^{-2} locally, indicating the existence of old-growth forests. Generally, the density of foliage in Norway spruce

Table 5
Density of total foliage mass (g m^{-2}) by age class of stand

Region	Age class (yr)								
	<21	21–40	41–60	61–80	81–100	101–120	121–140	>140	Mean
Whole country	60	220	454	427	503	433	307	372	347
Southern Finland	68	230	482	463	545	460	381	571	400
Northern Finland	29	105	186	215	218	262	236	302	194

Table 6
Density of foliage mass ($g\,m^{-2}$) by tree species and age class

Region	Age class (yr)								
	< 21	21–40	41—60	61–80	81–100	101–120	121–140	> 140	Mean
Pine									
Whole country	71	261	233	285	290	289	276	250	244
Southern Finland	85	272	230	289	297	286	274	298	254
Northern Finland	21	141	247	272	260	304	277	235	220
Spruce									
Whole country	80	342	943	833	956	807	719	804	686
Southern Finland	87	360	968	861	982	849	887	1018	752
Northern Finland	44	113	271	312	470	400	500	686	350
Birch									
Whole country	19	61	67	69	67	93	46	55	59
Southern Finland	18	62	69	70	72	91	29	64	59
Northern Finland	26	53	46	64	44	104	57	53	56

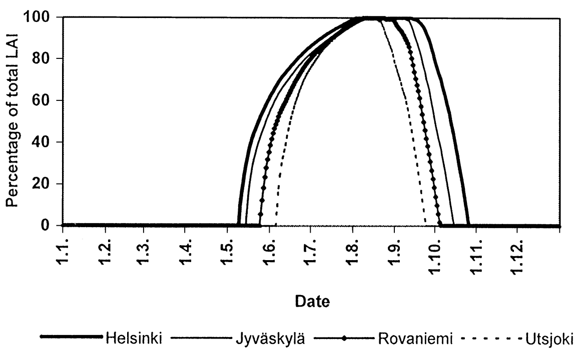

Fig. 3. Seasonal course of the modelled build-up and senescence of deciduous canopies at selected sites.

remained below $200\,g\,m^{-2}$. The density of foliage mass for birches was generally less than $200\,g\,m^{-2}$ throughout the country.

The density of foliage area, or leaf area index, for Scots pine seldom exceeded $1–2\,m^2\,m^{-2}$ (Fig. 5), with higher values representing high dominance of this species on sandy soils in south-eastern Finland. The density of foliage area for Norway spruce mainly fell within the range $4–6\,m^2\,m^{-2}$, the highest values occurring in central Finland and indicating the dominance of Norway spruce on fertile sites. For birches, the density of foliage area was mainly within the range $2–4\,m^2\,m^{-2}$. The distribution of foliage area for birch followed that for Norway spruce to some extent, i.e. birch mainly occurs on fertile sites, as is Norway spruce. The combined density of foliage area for all the tree species was within the range $2–4\,m^2\,m^{-2}$ over the whole country, except for an area across northern Finland, where it was less than $2\,m^2\,m^{-2}$.

3.4. Influence of weather on emissions

The influence of seasonal weather patterns on the rate of monoterpene emission is shown in Fig. 6, with a comparison between a cold year (1962) and a warm year (1988). In both cases the monoterpene emissions were initiated rapidly in the spring, but in 1962 the cold weather substantially limited them later in the summer, so that total monoterpene accumulation in 1962 remained at only 60–80% of that in 1988 (Table 7). The difference was especially pronounced for birch, because of the slow build-up and early senescence of the foliage in 1962 and 1988, giving a substantially shorter duration of the maximum foliage.

3.5. Emissions over the whole country

Annual mean emissions of monoterpene from Scots pine canopies in southern Finland were up to $400\,kg\,km^{-2}\,yr^{-1}$ (Fig. 7), which was substantially less than those from Norway spruce canopies, with emissions frequently more than $1000\,kg\,km^{-2}\,yr^{-1}$. For birches, the mean annual emissions were seldom more than $200\,kg\,km^{-2}\,yr^{-1}$. Emissions from birch canopies in northern Finland were even less (rarely $>100\,kg\,km^{-2}\,yr^{-1}$), and those from Scots pine and Norway spruce canopies were also small (mainly less than $200\,kg\,km^{-2}\,yr^{-1}$).

The overall mean emissions of monoterpene over the whole country were about $250\,kg\,km^{-2}\,yr^{-1}$ for Scots pine canopies, about $660\,kg\,km^{-2}\,yr^{-1}$ for Norway spruce canopies and about $35\,kg\,km^{-2}\,yr^{-1}$ for birch canopies (Table 8), so that total mean emissions for three species were $1070\,kg\,km^{-2}\,yr^{-1}$ in southern Finland, $450\,kg\,km^{-2}\,yr^{-1}$ in northern Finland and $950\,kg\,km^{-2}\,yr^{-1}$ over the whole country.

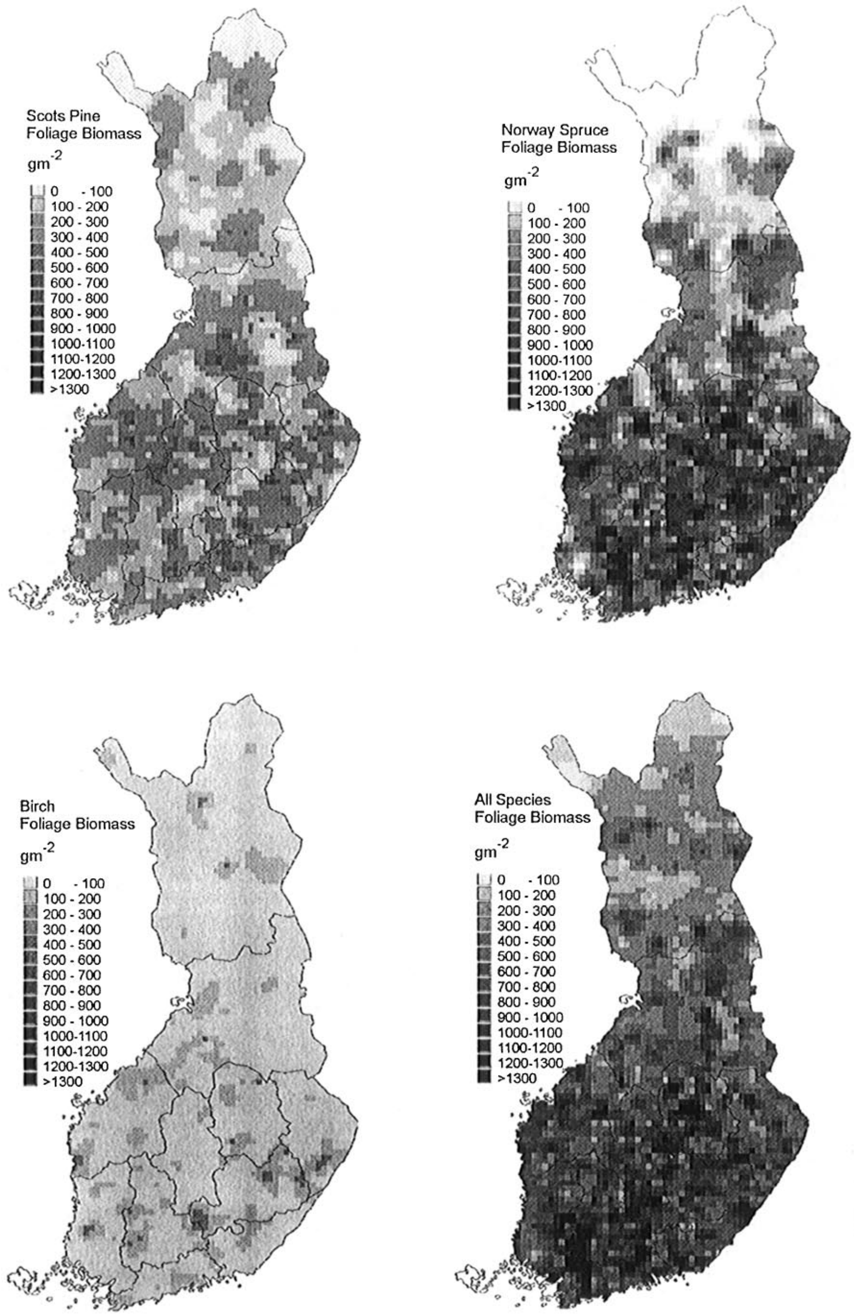

Fig. 4. Spatial distribution of the density of foliage mass by tree species. The network of sample plots excludes the archipelago of southwestern Finland.

Annual mean emissions of isoprene were up to $240\,\mathrm{kg\,km^{-2}\,yr^{-1}}$ in southern Finland (Fig. 8), but only one-fourth of this in the north. The overall annual mean figure for southern Finland was $150\,\mathrm{kg\,km^{-2}\,yr^{-1}}$ and that for northern Finland $40\,\mathrm{kg\,km^{-2}\,yr^{-1}}$ (Table 8). The annual mean emission rate over the whole country was about $130\,\mathrm{kg\,km^{-2}\,yr^{-1}}$.

4. Discussion

The aim of this work was to calculate the spatial distribution of the density of foliage mass and area over Finland in order to determine the respective emissions of monoterpene and isoprene. The calculations for forest canopies were based on the permanent sample plots used

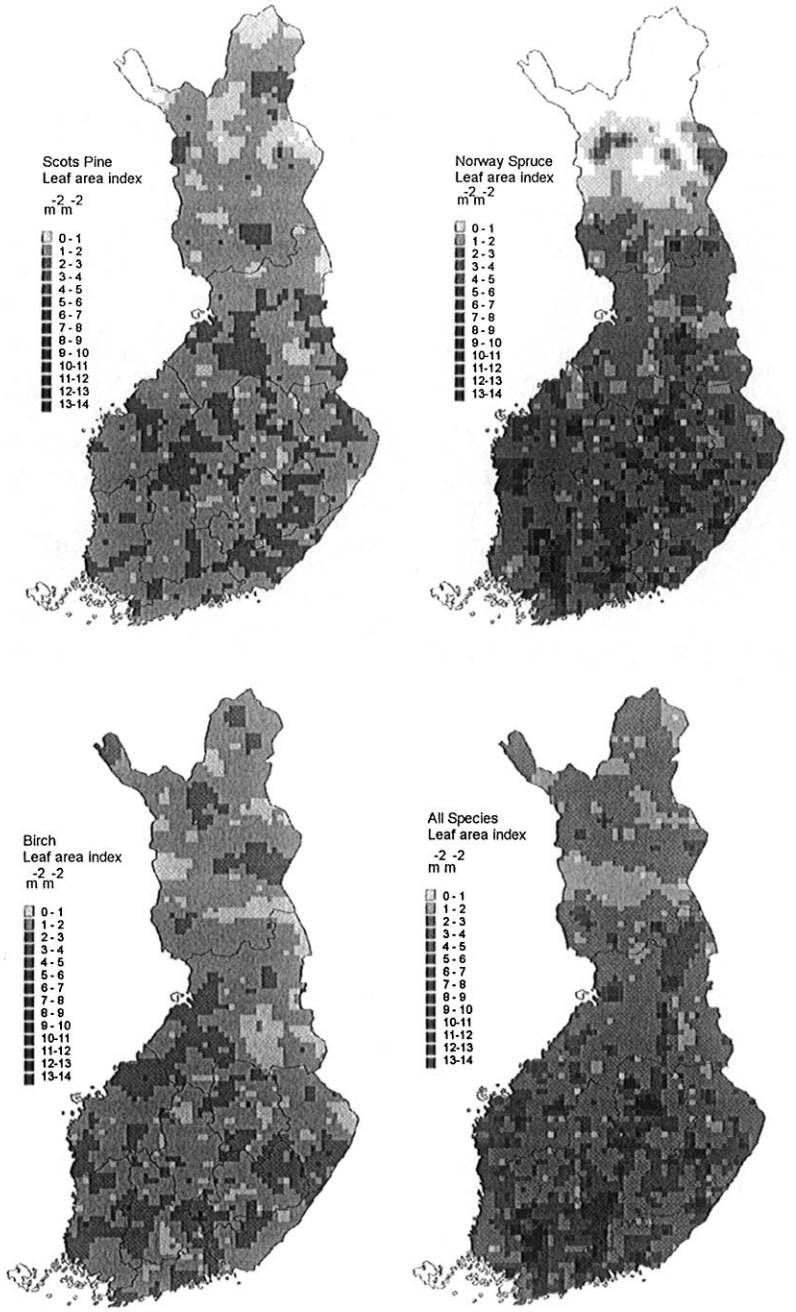

Fig. 5. Spatial distribution of the foliage area index by tree species. The network of sample plots excludes the archipelago of southwestern Finland.

in the Finnish National Forest Inventory and on allometric regressions for the relationship between stem dimensions and foliage mass as complied by Marklund (1986, 1988) for Sweden, since no corresponding equations representative of a wide area exist for Finland. The allometric equation implies that there is a regular species-specific relationship between the dimensions of different organs of trees. This allows simple measurements such as stem diameter to be used to estimate the mass of foliage, branches, stem and roots. For details on the theoretical background to tree allometry, see Kittredge (1944) and Oikawa and Kira (1977).

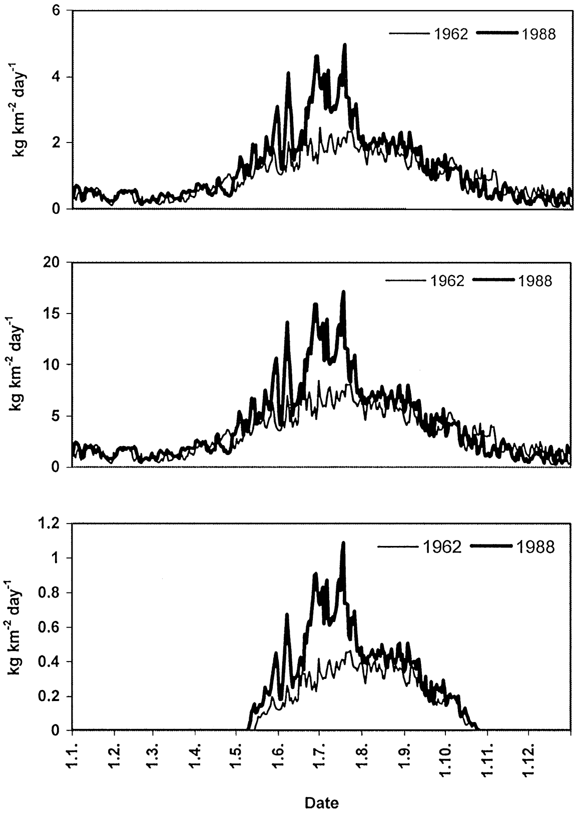

Fig. 6. Effect of the seasonal weather pattern on monoterpene emissions from stands of Scots pine (upper), Norway spruce (middle) and birch (lower) in a year with low summer temperatures (1962) and one with high summer temperatures (1988). The foliage area was the same in each set of calculations.

Table 7
Emissions of monoterpene (mg m^{-2} yr^{-1}) from Scots pine, Norway spruce and birch stands in 1962 (a cold summer) and 1988 (a warm summer)

Tree species	Emissions (mg m^{-2} yr^{-1})		
	1962	1988	1962/1988 (%)
Pine	350	450	78
Spruce	1210	1540	79
Birch	40	70	57

The equations were derived from the data on 493 Scots pines, 551 Norway spruces and 242 birches collected by uniform methods. The diameter distribution of the sample trees covered the range 1–50 cm with a wide representation of trees of varying ages. The comparisons made by Marklund (1987, 1988) between estimates for different compartments of tree biomass based on these equations and others for the volume or mass of the stem available in Sweden (Näslund, 1940) and in Finland (Hakkila, 1971) show that his equations are widely applicable to boreal forests. They nevertheless seem to overestimate the foliage mass of birch in the far north of Finland, where tree height, and thus crown length, is much less than would be expected on the basis of Eq. (1). The same also holds for Scots pine and Norway spruce, but not to the same extent as for birches. As Marklund (1987, 1988) observes, this means that care should be taken in coastal area, at high altitudes, in forests subject to extreme management measures and when seriously damaged trees are involved.

The density of foliage mass for Scots pine obtained in this study is about a half of the figure 500 g m^{-2}, which Veldt (1988) proposes for use in VOC inventories under the boreal conditions beyond 60°N. For Norway spruce our results are slightly higher than that the suggested value of 800 g m^{-2} (Veldt, 1988). The present results for Scots pine and Norway spruce are nevertheless well in line with those obtained by another method used in the BIPHOREP project (1999), but for birches the value of 59 g m^{-2} was substantially lower than that obtained by the alternative method (400 g m^{-2}). Low values for birches may be expected, since these occur mainly in varying proportions among Scots pines and Norway spruces and represent only 18% of the total stem wood volume of forest resources in Finland. On the other hand, calculations based on ground-true date for single trees, as used here may be expected to give different results from a method which sets out from the land use classification derived from Landsat satellite data.

A widely applied procedure was adopted for calculating emissions of monoterpene and isoprene (Guenther et al., 1993; Lamb et al., 1993), in which the species-specific emission rates standardised to a given temperature and radiation value were scaled by reference to the respective temperature data obtained from the weather statistics. The use of air temperatures may result in underestimation of monoterpene and isoprene emissions during sunny periods, but the total effects of these periods are probably small, since even in southern Finland sunny hours accounted for only about 36% of total daytime hours during the period from April 1 to September 30 in 1961–1990. On the other hand, the long-term weather statistics show that wind velocities higher than 2 m s^{-2} occur frequently during the daytime throughout Finland, with the implication that seldom there is probably any clear difference between air temperature and foliage temperature.

The method for calculating emissions of isoprene from spruce canopies was the same as that used by Lamb et al. (1993). The canopy was divided into four layers of equal thickness, and the foliage in each layer was assumed to be distributed in a homogeneous manner. The tree crown

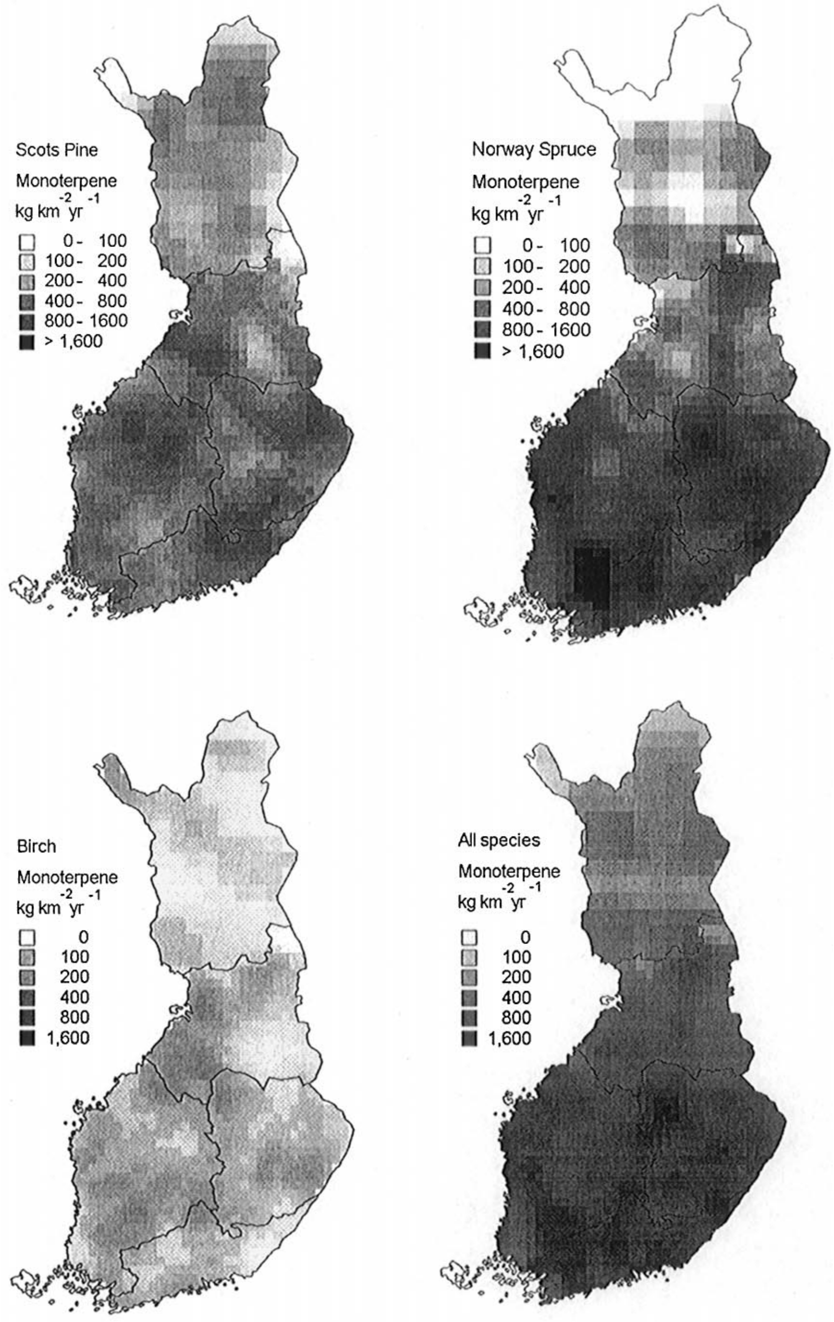

Fig. 7. Spatial distribution of total annual mean emissions of monoterpene throughout the country, calculated on the basis of the density of foliage mass and area as presented in Figs. 3 and 4 and the mean temperatures for 1961–1990. The network of sample plots excludes the archipelago of southwestern Finland.

was assumed to be cylindrical in shape, which may overestimate the foliage area or mass in the upper and lower parts. The extinction coefficient of 0.15 used here is typical of Norway spruce stands if hourly radiation values are to be calculated (Oker-Blom, 1986).

The regional calculations represent integration of the forestry statistics with weather statistics. Since relatively few meteorological stations were available compared with the number of forest sample plots, which cover the whole country in a systematic manner, a procedure was

Table 8
Total annual monoterpene and isoprene emissions (kg km^{-2} yr^{-1}) by region and for the whole country, calculated assuming the foliage area distribution presented in Figs. 3–6 and the mean temperature and radiation values for 1961–1990

Region	Scots pine	Norway spruce	Birch	Total
Monoterpene				
Southern Finland	263	772	36	1071
Northern Finland	209	215	32	456
Whole Finland	253	662	35	950
Isoprene				
Southern Finland		154		154
Northern Finland		42		42
Whole Finland		132		132

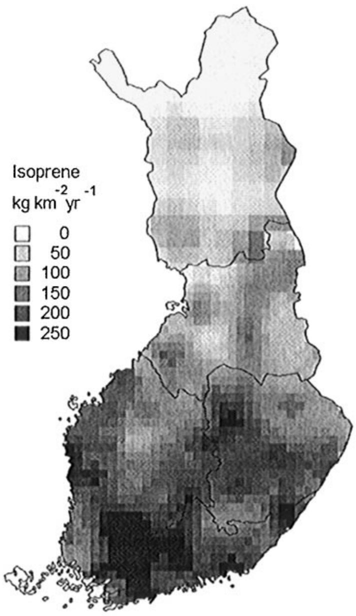

Fig. 8. Spatial distribution of total annual mean emissions of isoprene throughout the country, calculated on the basis of the density of foliage mass and area presented in Figs. 3 and 4 and the mean temperatures for 1961–1990. The network of sample plots excludes the archipelago of southwestern Finland.

adopted in which calculations were performed for the stands located close to the weather stations, yielding estimates for emissions of monoterpene and isoprene per unit foliage mass. It was thus assumed that the weather conditions for the plots around a given weather station are the same and they are determined by the weather records of this station. The output of the calculations was generalised over the regions and the whole country by reference to the foliage mass estimates for the sample plots (stands) in the National Forest Inventory in order to assess how representative a sample plot was with regard to the areal distribution of the forest land between different site type classes and that of total forest land, excluding peatlands.

Annual emissions of monoterpene over the whole country were about 950 kg km^{-2} yr^{-1}, which is higher than the figure of 600–800 kg km^{-2} yr^{-1} obtained for the years 1996 and 1997 by another method in the BIPHOREP project (1999). These estimates are not fully comparable, because they are based on different methods of estimating the density of foliage mass and area and for generalising the model calculations over regions. Furthermore, the calculations presented here are based on monthly mean temperatures over the period of 1961–1990 and not on weather records of single years. The same factors also affect the figures for isoprene, which was estimated to be emitted at a rate of 130 kg km^{-2} yr^{-1}, although this is close to the 100–120 kg km^{-2} yr^{-1} obtained in BIPHOREP (1999).

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