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Is forest management a significant source of monoterpenes into the boreal atmosphere?

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Abstract

Volatile organic compounds (VOCs) including terpenoids are emitted into the atmosphere from various natural sources. Damaging the plant tissue is known to strongly increase their monoterpene release. We measured the terpenoid emissions caused by timber felling, i.e. those from stumps and logging residue. The emissions from stumps were studied using enclosures and those from the whole felling area using an ecosystem scale micrometeorological method, disjunct eddy accumulation (DEA). The compounds analyzed were isoprene, monoterpenes and sesquiterpenes. Strong emissions of monoterpenes were measured from both the stumps and from the whole felling area. The emission rate fell down rapidly within few months after the logging. In addition to fresh logging residue, the results suggest also other strong monoterpene sources to be present at the felling area. Those could include pre-existing litter, increased microbial activity and remaining undergrowth. To evaluate the possible importance of monoterpenes emitted from cut Scots pine forests in Finland annually, we conducted a rough upscaling. The resulting monoterpene release was about 15 kilotonnes per year which is more than 10 % of the monoterpene release from intact forests in Finland.

1 Introduction

Biogenic volatile organic compounds (VOC) have many important effects on the atmosphere and climate. Although the emissions of biogenic VOCs in boreal areas have been studied quite intensively, there are still large gaps remaining in our knowledge. In particular, the seasonality of the emission rates is poorly known (Rinne et al., 2009). The emission rates from Scots pine (*Pinus sylvestris*) have been measured throughout the growing season (Tarvainen et al., 2005) and there are few measurements from Norway spruce (*Picea abies*) also during dormant periods (Hakola et al., 2003). These studies show that few biogenic VOCs are emitted during the winter, and the emission rates are quite low due to low temperatures (Tarvainen et al., 2005).

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Mechanical damage on trees is known to enhance the VOC emissions from e.g. coniferous trees (Juuti et al., 1990; Litvak and Monson, 1998; Loreto at al., 2000) and birch species (Hakola et al., 2001). For coniferous trees this is expected to be particularly important as they store significant amounts of monoterpenes within their resin ducts. Lots of forestry work is conducted during winter and spring in boreal forests. Cut stumps and logging residue can provide a source of VOCs into the atmosphere, possibly also in biologically inactive periods. In winter, the lifetimes of VOCs are also longer and are thus transported to larger area. The spring period is of great interest because the maximum of aerosol particle formation events are observed at that time (Dal Maso et al., 2005), and it is expected to be strongly affected by VOCs in the atmosphere (Kulmala et al., 2004).

In boreal coniferous forests some measurements of monoterpene concentrations in air close to forestry work areas have been reported (Strömvall and Petersson, 1991; Räisänen et al., 2008a). In these studies a clear increase in the monoterpene concentrations were observed. Strömvall and Petersson (1991) measured up to 500 fold monoterpene concentration in air above fresh branch wood of Scots pine and Norway spruce as compared to the background level. Räisänen et al. (2008a) reported 2–3 fold concentration in air on a Scots pine clear cut area for 7 weeks after the felling. During thinning of a ponderosa pine (*Pinus ponderosa*) plantation, tenfold monoterpene fluxes have been measured in California, USA (Schade and Goldstein, 2003). However, no long-term measurements of emissions from cut forests have been reported to our knowledge.

The aim of the present study was to measure the VOC emission rates and composition from tree stumps and forest felling area, and to study their temporal evolution and dependence on environmental parameters. From the results we can evaluate the possible importance of the VOC emissions from forestry work in comparison to intact ecosystems.

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2 Materials and methods

2.1 Experimental sites and times

The measurements took place in the southern Finland, close to the SMEAR II measurement station in Hyytiälä (61°51′ N, 24°17′ E, 180 m a.s.l.). The area belongs to the southern boreal vegetation zone, with mean annual temperature of about 3 °C and mean annual precipitation of about 700 mm. The emission rates and composition were measured on two stands after harvesting of the merchantable stem wood. The slash, consisting of the branches and tree tops, was left at the sites without any treatment.

In 2007 the measurements were conducted on a clear cut area of about 4.3 ha, felled in November 2006. The forest biomass was dominated by Norway spruce. The emissions from single stumps of Norway spruce, Scots pine and birch (*Betula* spp.) were measured using enclosures. The same spruce stump was measured on four days in May, June and August 2007. The emissions from a birch and a pine stump were measured only on one day in June.

In 2008 we conducted more extensive measurement campaign on a seed tree felling area of about 4.0 ha, felled in the end of April. In that area only Scots pine was abundant. In the seed tree method, 50–100 trees per hectare are left standing to advance the natural regeneration. Between May and September, the emissions of two Scots pine stumps were measured using enclosures. In addition to the stump emissions, the ecosystem scale emission was studied using a micrometeorological flux measurement method, disjunct eddy accumulation (Rinne at el., 2000) on six days between June and September.

2.2 Enclosure measurements

The enclosure measurements were carried out by placing a transparent Teflon bag around a tree stump. The bag was secured on the stump sides using tape. Air was pumped through the bag with a flow rate of about 4 l min^{-1}. The inlet air was passed

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through a MnO_2 ozone scrubber. Most of the air pumped to the enclosure exited through the hemline of the bag. The chemical samples were taken from the inlet and the outlet ports to Tenax-TA/Carbopack-B adsorbent tubes with a constant flow rate of about 0.1 l min^{-1}. The closure times varied between 30 min and 3 h. The emission rate from the stump was calculated from the concentration difference between the outlet- and inlet airflow and the flow rate through the enclosure. The emission rates were normalized to the cross sectional area of the stump (m^2_{SA}). Temperature inside the enclosure and photosynthetic photon flux density (PPFD) outside the enclosure were recorded at the same time.

2.3 Disjunct eddy accumulator

The ecosystem scale emission flux was measured using disjunct eddy accumulation (DEA) method (Rinne et al., 2000; Turnipseed et al., 2009). During the operation, a large primary sampling valve was opened once a minute for 200 ms. That allowed the pre-evacuated intermediate storage reservoir (V = 1 l), made of electro-polished stainless steel, to fill with the sample air. Before sampling, the remaining pressure inside intermediate storage reservoir was verified to be below 2 kPa. The vertical wind speed, measured by a sonic anemometer (Metek USA-1), placed above the accumulator at about 2 m height from the ground level, was recorded simultaneously. After the sampling, air was drawn through one of the adsorbent tubes reserved for updraft and downdraft samples. The decision on which tube should be used was based on the direction of the vertical flow at the time of sampling. The volume of the adsorbent flow was proportional to the vertical wind velocity resulting in linearly proportional sample volume, and hence true eddy accumulation. The lines and valves downstream of the intermediate storage reservoirs were heated slightly above ambient temperature to lessen sticking of the VOCs on the instrument surfaces. Two similar samplers were operated simultaneously in turns resulting in 30 s sample interval and altogether 110 samples during 55 min sampling period. The flux calculation was conducted following the method derived for non-ideal conditions by Turnipseed et al. (2009). Continuous

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fetch extended to about 300 m upwind from the instrument location at the times of the measurements.

2.4 Chemical analysis

All adsorbent samples were later analyzed for isoprene, monoterpenes and sesquiterpenes using an automatic thermodesorption device (PerkinElmer TurboMatrix 650) connected to a gas chromatograph (PerkinElmer Clarus 600) with an Elite-1 column (60 m, i.d. 0.25 mm) and a mass-selective detector (PerkinElmer Clarus 600T). Detection limits for isoprene, monoterpenes and sesquiterpenes were 10 ng m^{-3}, 10–20 ng m^{-3} and 20–50 ng m^{-3}, respectively. Of the monoterpenes α-pinene, camphene, β-pinene, Δ^3-carene, limonene, 1,8-cineol and terpinolene and of the sesquiterpenes copaene, longicyclene, iso-longifolene, longifolene, β-caryophyllene, aromadendrene, α-humulene and alloaromdendrene were measured. No breakthrough was detected for any of the compounds from Tenax-TA/Carbopack-B tubes when sampling for 3 h with the flow rate of about 0.1 l min^{-1}. The overall uncertainties of sampling and analysis, calculated from parallel samples, were 12 %, 10–40 % and 33–52 % for isoprene, monoterpenes and sesquiterpenes, respectively.

3 Results and discussion

3.1 Emissions from stumps

Both spruce and pine stumps measured in 2007 emitted large amounts of monoterpenes and some sesquiterpenes. The average monoterpene emission from spruce and pine stumps were 5100 µg m_{SA}^{-2} h^{-1} and 52 000 µg m_{SA}^{-2} h^{-1}, respectively. For the spruce stump, the monoterpene emission rate remained almost constant for the whole summer and it was weakly dependent on temperature. The sesquiterpene emission rate increased in August compared to the measurements earlier in summer. In August

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the sesquiterpene contribution was about 4 % of the monoterpene emission. Earlier, in May and in June it was only less than 1 %. Hakola et al. (2003) measured the emission rates from living Norwegian spruce and they found out that the contribution of the sesquiterpenes was quite small in comparison with monoterpene emission rates early summer, but in July the emission rates of sesquiterpenes increased contributing more than monoterpenes to the total VOC emission.

In 2008 we measured the emission from a pine stump several times, beginning 3 weeks after logging. The average mono- and sesquiterpene emissions from the pine stumps were 25000 $\mu g\, m_{SA}^{-2}\, h^{-1}$ and 600 $\mu g\, m_{SA}^{-2}\, h^{-1}$, respectively. The emission rates of both mono- and sesquiterpenes were weakly dependent on temperature. The monoterpene emission spectra of the two pine stumps studied in 2008 are plotted in Figure 1. There is a clear difference between the two studied stumps: one emits mainly α-pinene (77 %) and the other mainly Δ^3-carene (79 %). There are different Scots pine genotypes growing in Finland, known to have difference in the monoterpene composition (e.g. Tarvainen et al., 2005 and the references therein). The stumps studied in our campaign were clearly of different genotypes which explain the observed difference in their VOC blend.

The monoterpene emission from a birch stump was orders of magnitude lower than from the studied conifers, the average monoterpene emission being 40 $\mu g\, m_{SA}^{-2}\, h^{-1}$. It emitted mainly α-pinene, β-pinene, limonene and camphene. Sesquiterpene emission of the birch stump was negligible. It was not possible to indentify whether the stump was silver or downy birch. Both of these birch species are known have variable mono- and sesquiterpene emissions from their leaves (Hakola et al., 2001; Vuorinen et al., 2005). The emissions from the wooden parts (stem, bark) have not been reported. However, as birches do not have resin ducts or other large storage structures for terpenoids and the emission is entirely of de novo origin (Klika et al., 2004; Baser and Bemirci 2007; Ghirardo et al., 2010), the emission from woody part is likely to be very small. Thus it is easy to understand that the emission was very small after the trees were cut down.

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3.2 Ecosystem scale emission

The ecosystem scale emissions were measured on 6 days between 13 June 2008 and 17 September 2008. Altogether 30 one hour periods were measured. The measured monoterpene fluxes are shown in Fig. 2. The wind data from the first measurement day, 13 June 2008, were probably contaminated from horizontal wind components due to tilted mast. This was indicated by the large positive values of the mean vertical wind velocity (up to $1.8\,\mathrm{m\,s^{-1}}$). Since air sampling is controlled on-line by the wind measurement, no post-processing corrections are possible and all data from that day were discarded from further analyses. However, we show the discarded data in the Figs. 2 and 3 as an order of magnitude estimate. Relative uncertainty of the flux was estimated using analytical uncertainties of the samples and uncertainty estimate of wind measurement. For monoterpene sum, the uncertainty of single flux value was about 21 %. Additional statistical uncertainty in the fluxes due to disjunct sampling was estimated to be $\sigma_m = 9.55\ (1000\ \frac{\Delta t}{T_{avg}})^{0.5} = 29$ % as given by the expression derived by Turnipsseed et al. (2009).

Significant emission of monoterpenes was detected in the beginning of the campaign, the highest measured value being about $5200\,\mu\mathrm{g\,m^{-2}\,h^{-1}}$. Schade and Goldstein (2003) measured up to about $3800\,\mu\mathrm{g\,m^{-2}\,h^{-1}}$ monoterpene fluxes during and after ponderosa pine thinning, which is in line with our results. The measured fluxes exhibit large hour to hour variations. This may be explicable not only by random error but also by great patchiness of the source area. As the footprint area changes with wind and stability, the amount of emission hot spots captured by the measurement changes. Therefore, the further analyses are based only on daily averages. The emission was dominated by monoterpenes α-pinene and Δ^3-carene with minor contributions from ß-pinene and camphene. Although some emission of sesquiterpenes was measured from the stumps using enclosures, in the ecosystem scale these were not detected. Concentrations and fluxes of sesquiterpenes are difficult to measure above ecosystem because they react rapidly in air, already below the measurement height, and the

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sesquiterpenes reaching the measurement equipment are easily destroyed inside the system, e.g. by rapid reactions with ozone (e.g. Helmig et al., 2004 and the references therein).

In Fig. 3 we show the temporal evolution of the daily average fluxes together with corresponding air temperatures. From the figure it is apparent that the monoterpene flux from the cut area does not follow only the temperature but also rapidly decays in time. It is impossible to find out the temperature dependence of the emission from present dataset because the temperature differences during one measurement day were very small and the basal emission rate changed significantly between the measurement days.

In addition to the logging residue, also ground vegetation and soil may emit monoterpenes. Hellén et al. (2006) reported monoterpene emissions up to 373 $\mu g\, m^{-2}\, h^{-1}$ from natural forest floor at nearby SMEAR II measurement station. Their plot included mosses, shrubs, and some litter originating mainly from Scots pine and undergrowth. Hayward et al. (2001) measured somewhat lower monoterpene emission from undisturbed soil in a Sitka spruce (*Picea sitchensis*) forest in UK. However, they reported a significant increase in the emissions when the topmost layers (~3 cm) were removed to expose some fine roots. Isidorov et al. (2010) reported significant monoterpene emissions from needle litter of Scots pine (up to 7.5 $\mu g\, g_{dw}^{-1}\, h^{-1}$) and Norway spruce (up to 1.5 $\mu g\, g_{dw}^{-1}\, h^{-1}$) for about six months after beginning of the decay. Asensio et al. (2008) found significant amounts of monoterpenes and sesquiterpenes in the litter, soil and roots close to Aleppo pine (*Pinus halepensis*) trees. The ground vegetation and root systems remaining suffer heavy mechanical damage during the felling operation, which may increase their monoterpene emissions.

After the forest felling, the remaining ground vegetation and soil encounter several stress factors due to changed environment: solar radiation increases heavily, temperature rises while its diurnal variability becomes larger, water balance changes, and more nutrients becomes available. Besides, damaged soil surface exposes fine roots and partially decayed litter to atmospheric conditions. Increased terpenoid emissions are a

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fundamental response of plants to environmental stresses (e.g. Loreto and Schnitzler, 2010; Niinemets, 2010). Therefore, it can be considered likely that the monoterpene emissions from ground vegetation and pre-existing decaying litter rises substantially as a consequence of forest felling.

3.3 Temporal evolution of the emission rates

In order to get comparable emission rates for temporal evolution estimation and upscaling, we normalized the emissions to +15 °C using the temperature dependence of monoterpene saturation vapor pressure. Figure 4 (a and b) show the temperature compensated emissions of both of the stumps and the whole ecosystem, calculated from the daily average emissions. Note that the stump emission is given per stump cross sectional area (m^2_{SA}) and the ecosystem emission per land area (m^2). For the upscaling, the measured emission potentials were interpolated and extrapolated to yield a continuous emission rate estimate over the whole growing season. We extrapolated the emission potentials two to seven weeks backward and 6 weeks forward as compared to the period covered by the measurement data.

The Scots pine stump emission E_S is modeled as an exponential decay of the form $E_S = 1821.7\,\mathrm{mg\,m^{-2}_{SA}\,h^{-1}} \times e^{-0.031\,D}$, where D is the day of the year. The ecosystem scale emission E is modeled piecewice by three lines: (i) a constant part $E = 3.88\,\mathrm{mg\,m^{-2}_{SA}\,h^{-1}}$ (covering days 122–177); (ii) decaying regression of the form $E = -0.0551\,\frac{\mathrm{mg\,m^{-2}\,h^{-1}}}{d}D + 13.64\,\mathrm{mg\,m^{-2}\,h^{-1}}$ (covering days 178–247) and (iii) a constant part $E = 0\,\mathrm{mg\,m^{-2}_{SA}\,h^{-1}}$ (covering days 248–305). The extrapolations done here are rough order of magnitude estimates.

Both stump and ecosystem emissions show a clear decaying trend in the emission rate. During the first months the emission rate fell down rapidly and continued a slow decrease towards zero about four months after the logging. For the first month after logging there was some fresh resin on the stump surface, probably causing the high emission.

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3.4 Gapfilling and upscaling

To estimate the total monoterpene release from cut forest, the Scots pine stump emissions and ecosystem scale emissions were calculated using the normalized emission curves (Fig. 4) derived in the present study. For comparison, we calculated the monoterpene emission from intact Scots pine forest using temperature dependent emission algorithm (Guenther et al., 1993) and a constant emission potential $E_0 = 1.24\,\mathrm{mg\,m^{-2}\,h^{-1}}$ derived from the measurement data from the SMEAR II station (Rinne et al., 2007). The estimate was done for period May–October 2008 which roughly corresponds to growing season in southern Finland. As a temperature data we used the air temperature measured at the height of 8.4 m (within the forest trunk space) at SMEAR II station in Hyytiälä in 2008. To give an overview of the weather conditions during the studied period we plotted daily minima and maxima temperatures in Fig. 5a. The growing season of 2008 was characterized by a warm spell in the beginning of May followed by a short cold period. The mean temperature during the high emission season was close to +15 °C which was used as a normal temperature throughout this study.

Using the data introduced above, the emissions were calculated for every half-hour period. Daily sums of monoterpene emission were calculated from the half-hourly emission data and plotted as cumulative monoterpene release in Fig. 5b. Over the whole six month period, the resulting ecosystem scale monoterpene releases from the cut and intact forests were about $8.5\,\mathrm{g\,m^{-2}}$ and $1.0\,\mathrm{g\,m^{-2}}$, respectively. The emission from the stumps alone was $33\,\mathrm{g\,m_{SA}^{-2}}$, corresponding to about $0.1\,\mathrm{g\,m^{-2}}$ in the stand scale.

To evaluate the validity of our results we compared the total monoterpene release calculated above to the monoterpene content of logging debris. Table 1 show the estimated mass of each debris fraction in our study site, the range of monoterpene content of each fraction found in the literature (Manninen et al., 2002; Lin et al., 2007; Räisänen et al., 2008b; Isidorov et al., 2010) and the resulting range of monoterpene

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release given that all the monoterpenes were evaporated. The total monoterpene content of the logging debris falls within the range of 2.4–6.7 g m^{-2} which is somewhat lower than the total monoterpene release of 8.5 g m^{-2} obtained in the present study. Moreover, it can be considered unlikely that all of the stored monoterpenes, including those from the roots, evaporated during the first couple of months after the logging.

A discrepancy of the same kind can be found in the data of Isidorov et al. (2010) and it is briefly discussed by the authors (Interactive comment on Biogeosciences Discuss., 7, 1727, 2010). They explain the theoretical cumulative monoterpene emission exceeding the monoterpene content of the needles by the temperature conditions during the experiment: the emission measurements were conducted at the temperature of +20 °C and between them the samples were stored in ground where the temperature supposedly varied around 0 °C. Furthermore, they speculate that decomposing fungi may maintain the terpene emission. However, this discrepancy is not fully explained assuming the temperature dependency of monoterpene release from litter to be even close to that observed before for living plants (Guenther et al., 1993) or that obtained from monoterpene saturation vapor pressure. Therefore, it can be assumed that microorganisms may have an important role in the production of monoterpenes from litter. This assumption is supported by literature demonstrating growth condition dependent (Nilsson et al., 1996) and species dependent (Bäck et al., 2010) monoterpene emissions from isolated fungi. Furthermore, real litter samples are known to emit monoterpenes (e.g. Leff and Fierer, 2008), also from deciduous leaves litter that did not contain monoterpenes originally (Isidorov and Jdanova, 2002).

In order to estimate the significance of forest management to the total monoterpene emission in Finland we conducted simple upscaling. To estimate the total amount of monoterpenes emitted annually due to forestry operations from Scots pine forests in Finland we upscaled this to cover all cutting methods. Instead of area, we used harvested volume as a scaling factor because the emissions are expected to be dependent on the amount of felling waste rather than on the treated area. Besides, the statistics on the harvested volume are very precise and easily available. In the seed tree felling area

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where our measurements were conducted, the drain of the merchantable wood was 135 m^3 ha^{-1}. Since the monoterpene emission for the six month period was calculated to be about 8.5 g m^{-2}, this yields to monoterpene release of about 630 g m^{-3}. According to the cutting statistics from 1998–2007 (Finnish Forest Research Institute, 2008), the total annual drain of Scots pine trees from the Finnish forests is about 24 000 000 m^3 which leads to monoterpene release of about 15 kilotonnes per year. The total annual emissions of monoterpenes from intact forests in Finland are estimated to be about 114 kilotonnes (Tarvainen et al., 2007). Surprisingly, the monoterpene emission caused by forestry operations in Scots pine forests seem to be as high as one tenth of the natural emission. Somewhat lower figure may be assumed for Norway spruce forests in Finland, since their drain is similar to Scots pines but monoterpene content smaller.

We calculated the annual cross sectional area of the new Scots pine stumps separately for different logging methods. The calculation is based on the drain (Finnish Forest Research Institute, 2008) and estimated average tree forms for each method. The emissions from stumps alone looks to be of minor importance since the total cross sectional area of new stumps of Scots pines are about 500 ha per year. Using the above derived release of 33 g m^{-2}_{SA}, the total monoterpene release would be 0.2 kilotonnes per year which is only about 1 % of the total ecosystem emission.

Our results suggests as high as 10 % increase to the total monoterpene release into the atmosphere as compared to the previous inventories. There is some evidence that the observed concentrations of monoterpenes in air are not fully explained by the known biogenic emissions (Lappalainen et al., 2009). Although our measurement data is very limited, it provides evidence that forestry induced emissions of monoterpenes may be of great importance for the air chemistry at certain areas. Obviously more measurement data and model development will be needed to more reliably quantify the VOC emissions due to forest management.

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4 Conclusions

Large monoterpene emissions were measured from both single stumps and from the whole felling area. The emissions of sesquiterpenes were small and the emissions of isoprene were negligible. In the present study only a very limited dataset was collected. Small dataset leads to large uncertainty, particularly in the upscaling. The exact result depends heavily on extrapolation and interpolation of the normalized emission. We chose rather conservative way in the extrapolation. Despite of the uncertainties we believe that the order of magnitude of the upscaled result presented is correct and our conclusion on the importance of the forest management to the aerial concentration of monoterpenes is justified.

The present study gives some evidence that increased microbial processes in litter or soil may significantly increase the monoterpene emissions from forest felling area. This effect may be so large that the total monoterpene release during six months exceeds the original monoterpene content of the logging residue left onsite. Some support for this finding can be found in the literature. However, specific studies with carefully designed experiments are needed to verify and properly quantify this effect.

In any case, the amount of the monoterpenes emitted by the area under forestry operations is significant. In addition to changing the amount of monoterpenes emitted into the atmosphere, forestry work may also alter the timing of the emissions over the year. Forestry work conducted in the wintertime could provide a strong source of VOCs into the atmosphere also during biologically inactive winter period. Although the emissions from logging waste should be smaller in the wintertime due to low temperatures and snow cover, the longer lifetime in the atmosphere may increase the importance of those emissions.

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Table 1. The amount, estimated monoterpene content and the resulting monoterpene mass per land area of each of the debris fraction found in the seed tree felling area.

Fraction of the debris	Amount of the fraction in the area	Estimated monoterpene content in the fraction	Mass of monoterpenes in the fraction
needles	280 $g_{dw}\ m^{-2}$	2.5–8.0 $mg\ g_{dw}^{-1}$	700–2240 $mg\ m^{-2}$
brushwood	1000 $g_{dw}\ m^{-2}$	1.0–1.6 $mg\ g_{dw}^{-1}$	1000–1600 $mg\ m^{-2}$
roots	1800 $g_{dw}\ m^{-2}$	0.4–1.6 $mg\ g_{dw}^{-1}$	720–2880 $mg\ m^{-2}$

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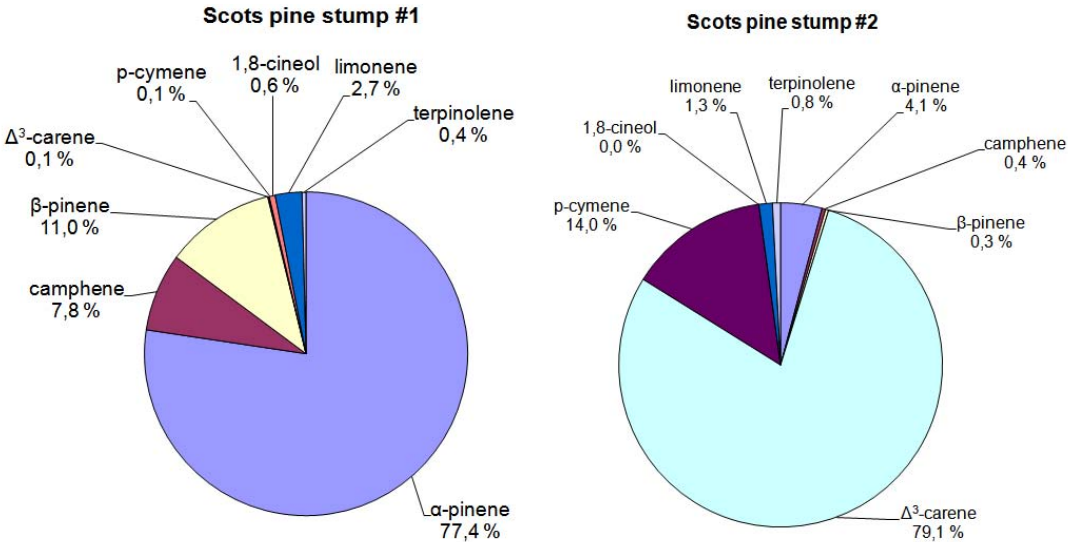

Fig. 1. The monoterpene emission spectra of the two individual Scots pine stumps.

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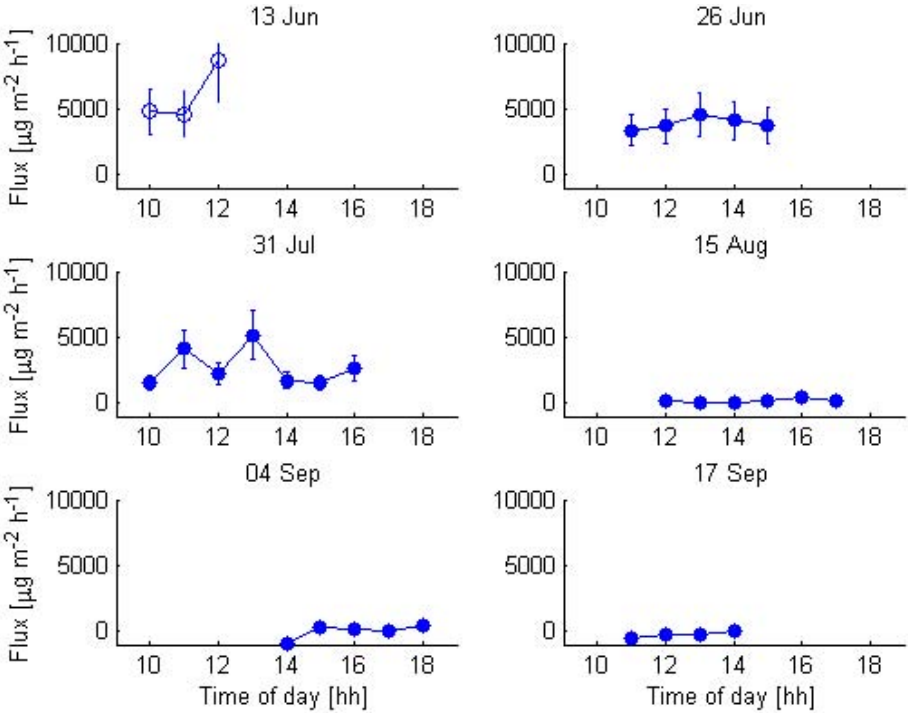

Fig. 2. Ecosystem scale monoterpene fluxes measured using disjunct eddy accumulation (DEA) between 13 June and 17 September, 2008. The data of 13 June was discarded from further analyses due to corrupted wind measurement and is shown here by open circles.

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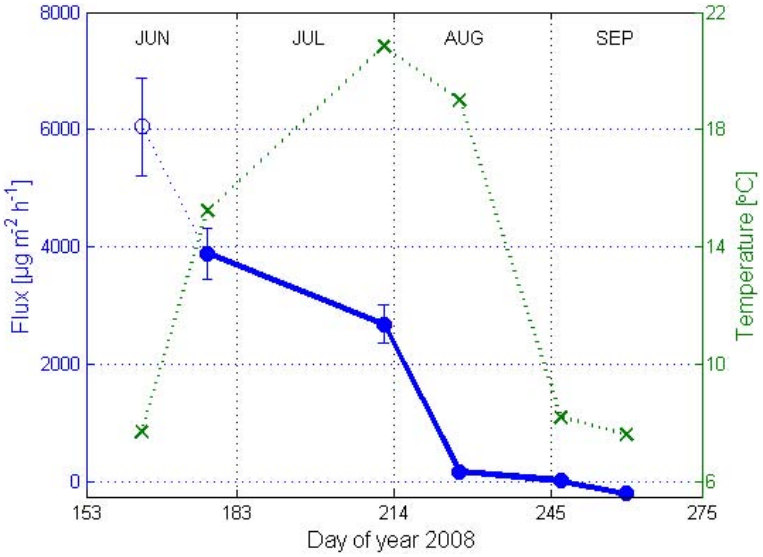

Fig. 3. Daily mean fluxes of monoterpenes (blue solid line) and corresponding air temperatures (dotted green line). Error bars of the fluxes are the standard errors of the means. The data of 13 June was discarded from further analyses due to corrupted wind measurement and is shown here by open circle.

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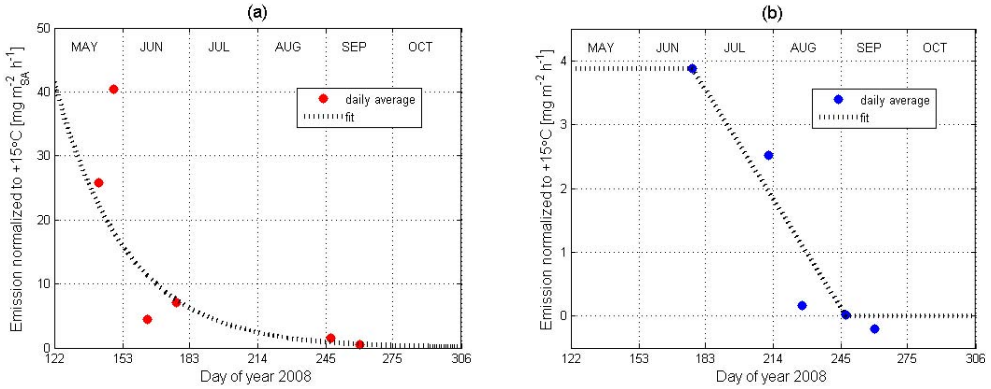

Fig. 4. The monoterpene emissions normalized to +15 °C calculated from the daily averaged emission measurements. **(a)** Red dots are the emissions from the Scots pine stump and the dotted black line the fit used in the upscaling. **(b)** Blue dots are the ecosystem scale emissions and the dotted black line is the fit used in the upscaling. See text for details of the fitted lines.

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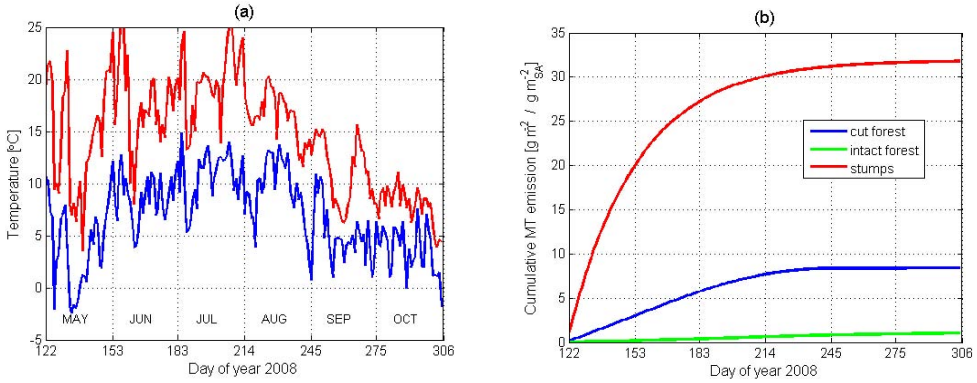

Fig. 5. (a) Daily minima (blue) and maxima (red) of the temperature data used in the upscaling. **(b)** Cumulative monoterpene emission from cut Scots pine forest (blue), intact Scots pine forest (green), and from the Scots pine stumps alone (red). Note that the last one is given per stump area instead of land area.

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