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Biogenic volatile organic compound (BVOC) emissions from boreal forest floors during the first years after wildfire: effects of stand age and management

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Abstract. Boreal forests emit a wide range of biogenic volatile organic compounds (BVOCs) that influence atmospheric chemistry and climate through oxidation reactions and the formation of secondary organic aerosols. These emissions originate from plant metabolism, microbial activity, and storage pools such as litter, and vary in response to environmental conditions and disturbances. Wildfires, the dominant natural disturbance in boreal ecosystems, substantially alter ecosystem structure and carbon cycling, yet their effects on BVOC emissions during the early post-fire years remain poorly understood.

Here, we quantified BVOC emissions during the first years after wildfire across gradients of stand age, fire severity, and post-fire management. BVOC emissions were strongly controlled by tree mortality and management practices. High-severity fire in young stands resulted in persistently low emission rates and a shift away from monoterpene dominance, likely reflecting limited biomass and substrate availability. In contrast, sites with surviving mature trees exhibited elevated emissions dominated by monoterpenes, driven by litter-derived storage pools. Salvage logging caused a transient increase in emissions in the first year after fire due to accumulated needle debris, followed by a rapid decline as litter inputs were depleted. Conversely, reforestation led to increasing emissions over time.

These results demonstrate that early post-fire BVOC dynamics are regulated by the interaction between disturbance severity, stand age and management strategies, leading to distinct emission trajectories in the early recovery phase. Such shifts in BVOC emission magnitude and composition may have important implications for post-disturbance atmospheric chemistry and climate feedbacks. Our findings highlight the need to account for disturbance legacy effects and management practices when representing BVOC emissions in large-scale models.

1 Introduction

The boreal forest floor emit a number of biogenic volatile organic compounds (BVOCs) originating from plant metabolism, microbial activity and storage pools in plant litter (Mäki et al., 2017; Mochizuki et al., 2021; Niinemets and Monson, 2013; Peñuelas et al., 2014). Forest floor BVOC emissions can be affected by multiple factors such as diurnal and seasonal variation, temperature, soil properties, nutrient availability, microbial activity and various disturbances (Hayward et al., 2001; Jiao et al.,

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2023; Mäki et al., 2019a; Mochizuki et al., 2021; Rasheed et al., 2021). Boreal forest soils are typically podzols with distinct organic and mineral layers, which differ in both substrate availability and microbial processes (Lundström et al., 2000). As a result, BVOC composition varies with soil depth. For example, in a Scots pine (*Pinus sylvestris*) forest, the organic layer was generally dominated by monoterpenes whereas the mineral layer had higher sesquiterpene emissions and oxygenated compounds (Mäki et al., 2019). These vertical and environmental controls on BVOC emission magnitude and composition are important for understanding their impacts beyond the ecosystem. Once emitted into the atmosphere, BVOCs are highly reactive and influence atmospheric chemistry through interactions with oxidants such as OH, ozone and NO_x, leading to direct scattering of sunlight and the formation of secondary organic aerosols and changes in greenhouse gas lifetimes (Acosta Navarro et al., 2014; Monson and Baldocchi, 2014; Paasonen et al., 2013; Scott et al., 2018; Weber et al., 2022). Through these processes, BVOCs can exert both warming and cooling effects on climate, linking terrestrial ecosystem processes to atmospheric composition and radiative forcing.

Emissions from the organic layer are primarily driven by litter storage pools, as reflected in the seasonality of forest floor BVOC fluxes, with peak emissions coinciding with periods of fresh litter input in autumn (Aaltonen et al., 2011, 2013; Hayward et al., 2001; Isidorov et al., 2005; Mäki et al., 2017). Elevated monoterpene emissions are also observed in spring from the decomposing litter after snowmelt and forest floor growth processes (Aaltonen et al., 2011; Hellén et al., 2006). In addition to these sources, understory vegetation can act as a sink for BVOCs emitted from the mineral layer; both (Hayward et al., 2001) and (Mäki et al., 2017) found higher emission rates from bare soil compared to vegetated soil. This emission reduction may be explained by adsorption to organic matter or by microbial consumption, both of which can remove BVOCs within the soil profile (Jiao et al., 2023; Joensuu et al., 2016). Consequently, disturbances that remove or alter the organic layer and understory vegetation, exposing mineral soil or redistributing litter pools, can substantially modify BVOC emissions to the atmosphere.

Wildfire is the main natural disturbance in boreal forests, with approximately 1% of the global boreal forest burning annually (Köster et al., 2021a). Wildfire alters ecosystem structure and carbon dynamics by consuming vegetation and organic matter from both above- and belowground pools (Bond-Lamberty et al., 2007). Post-fire recovery of boreal forest is typically slow and can require decades for carbon stocks and soil microbial communities to re-establish (Kelly et al., 2024, 2025; Köster et al., 2014, 2021b; Soares et al., 2026). The impact of wildfire depends on the fire intensity and severity. Fire severity have been defined as the consumption of above and belowground organic vegetation where low-severity fires result in scorched but surviving trees whereas high-severity fires kill the trees (Keeley, 2009). Fluxes of CO_2 were also found to be higher up to four years after a low-severity fire compared to a high-severity fire, indicating that the higher vegetation mortality in the high-severity fire had a larger impact on carbon emissions (Kelly et al., 2021, 2025).

BVOC emissions are expected to be strongly impacted by wildfires disturbances. Because forest floor BVOC fluxes are closely linked to vegetation cover, litter inputs and microbial activity, their recovery following fire may take decades (Mäki et al., 2019b; Zhang-Turpeinen et al., 2025). In boreal Scots pine forests, emissions are typically dominated by monoterpenes, particularly α-pinene and 3-carene (Aaltonen et al., 2011; Mäki et al., 2019a; Petersen et al., 2025; Zhang-Turpeinen et al.,

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2021). Previous studies have explored BVOC dynamics across post-fire chronosequences spanning from 1 to >100 years since fire (Zhang-Turpeinen et al., 2025), providing valuable insights into long-term recovery patterns. However, short-term temporal dynamics of BVOC emissions during the earliest post-fire years, and how they are shaped by fire severity and management strategies, remain poorly constrained. In particular, consecutive measurements from the same sites during the initial years after fire are missing, limiting our understanding of how BVOC emissions respond immediately following disturbance and during early ecosystem recovery.

As ecosystems recover after wildfire and biomass increases over time, BVOC emissions are expected to increase in the long-term. However, recovery trajectories depend strongly on fire severity, which determines vegetation survival, litter inputs and soil exposure. Because forest floor BVOC emissions are largely driven by litter storage pools (Aaltonen et al., 2011, 2013; Mäki et al., 2017), high-severity fires that remove canopy needles may reduce emissions over time due to loss of litter input. Although canopy needles are not always fully removed by fire, trees that remain standing after high-severity events often die, resulting in an initial pulse of emissions from needle litterfall, followed by a decline as litter inputs are no longer replenished. As vegetation re-establishes, BVOC emissions may increase again (Zhang-Turpeinen et al., 2025).

In contrast, low-severity fires with high tree survival can sustain a more continuous BVOC emission pattern. Surviving trees may initially shed significant amount of needles, leading to elevated emissions, while continued growth and litter production support longer-term emission fluxes. Post-fire management is also expected to influence these trajectories. For example salvage-logging can create a short-term increase in emissions due to residual litter and woody debris left on site, which will lead to high emissions that decrease quickly over time because the needle litter is not replenished.

Because of the climate change induced higher air temperatures and heat spells, an increase in wildfire frequencies is expected in the future and is already observed in Fennoscandia (IPCC, 2023; Köster et al., 2021a; Pechony and Shindell, 2010). The severe drought in Sweden during the summer of 2018 led to widespread wildfires across the country (SOU, 2019), including the Ljusdal fire, which burnt the largest area that year.

Here, we assess how wildfire affects BVOC emissions during ecosystem recovery using the Ljusdal fire as a natural experiment. The fire hit the Ljusdal area with varying intensity, providing a unique opportunity to compare the recovery trajectories across fire severities. The study area also included forest stands of different ages and post-fire management strategies (salvage-logged and unlogged), allowing us to evaluate how these factors interact to shape BVOC emissions. Notably, the fire primarily affected the organic soil layer while leaving the mineral layer largely intact.

We formulated the following hypotheses: (1) BVOC emissions from burnt organic layers are lower than from unburnt organic layers due to the loss of understory vegetation and litter input. (2) The organic layer acts as a sink for BVOCs emitted from the underlying mineral soil, even after fire disturbance. (3) BVOC emissions increase over time as the ecosystem recovers from the fires, with increasing vegetation cover. (4) Short-term recovery trajectories differ depending on fire severity, stand age and management strategy, resulting in distinct BVOC emission patterns across sites.

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2 Materials and Methods

2.1 Study area

The measurements were conducted within the area affected by the Ljusdal wildfire in central Sweden (61°56'N, 15°28'E). The fire was ignited by lightning strikes in July 2018 and spread due to prolonged hot and dry conditions. Fire severity varied across the landscape: in some areas, all trees were killed (hereafter 'high-severity fire'), whereas in others the fire primarily consumed ground vegetation and most trees survived (hereafter 'low-severity fire'). The area is dominated by Scots pine (*Pinus sylvestris*) forests growing on nutrient-poor sandy soils and glacial till, with an understory consisting mainly of lichens and dwarf shrubs (*Vaccinium* spp.). The climate conditions in the area were described using the 1991-2020 climate normal period from the Ytterhogdal national weather station, 40 km from the site (SMHI, 2024), during which the mean annual air temperature was 2.7 °C and mean annual precipitation was 648 mm. During the study period (2019-2022), meteorological measurements were measured continuously. In July and August, ambient air temperature during the measurement weeks ranged from 3 °C to 26 °C, with the warmest conditions in 2021 and the coolest in 2020 (Figure 1a). Precipiration during the measurement weeks varied substantially among years, from 6 mm in 2019 to 15 mm in 2020, recorded by the Ytterhogdal station (SMHI, 2024; Figure 1b). Temperature and precipitation anomalies relative to the previous 20-year period are shown in Figure 1c.

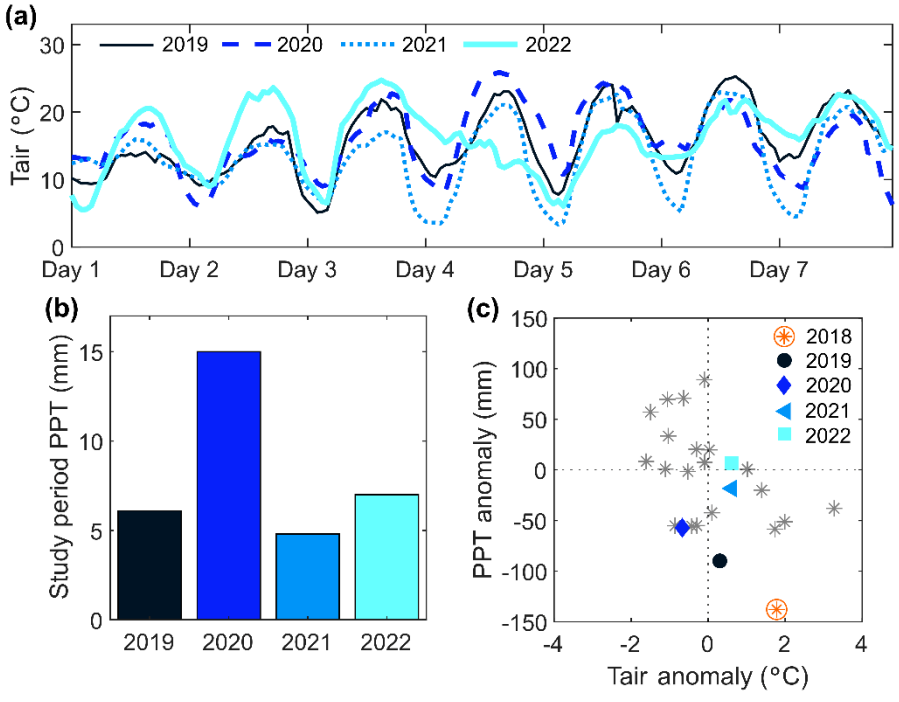

Figure 1. Air temperature and precipitation at the Ljusdal study area. (a) Air temperature during the measurement week in July and August for each study year (2019–2022). (b) Precipitation sum for the measurement week for each study year. (c) Temperature and precipitation anomalies for July and August relative to the 20-year reference period (1999–2018) from the national weather

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station Ytterhogdal (SMHI, 2024). Grey stars represent individual years before the fire (1999–2017), and the orange circled star indicates 2018, the year of the wildfire.

Within the study area, measurements were performed at six sites (Table 1), including one unburnt reference site (UM) and five burnt sites that differed in fire severity, stand age at the time of the fire and post-fire management. All sites were Scots-pine dominated stands prior to the fire and are located within 3 km of each other. All the understory vegetation died during the fire. Over the following years, understory vegetation cover slowly increased but was still less than 30 % total cover by 2022 at all the burnt sites. LM and SLM had the highest total understory vegetation cover (26 % and 24 %, respectively), which was dominated by vascular plants ad LM and bryophytes at SLM. SHM had the slowest recovery of understory vegetation of all the burnt sites with only 8 % total coverage by 2022 comprising entirely of vascular plants. For further details on site characteristics and fire conditions, see Kelly et al. (2021; 2024; 2025) and Dukat et al. (2024).

Table 1. Characteristics of the study sites and BVOC measurements. Tree maturity refers to stand age at the time of the fire in 2018. Forest floor (FF) depth represents the thickness of the organic soil layer, including litter, mosses and lichens. Total FF depth included both charred and uncharred material (data from Kelly et al., 2021). The table also reports the number of measurement collars with and without the FF layer and the years during which BVOC measurements were conducted at each site. Values are reported as mean ± SE.

Site	Fire severity	Post-fire management	Tree maturity	Charred FF depth (mm)	Total FF depth (mm)	BVOC measurement years	Collars with FF	Collars no FF
UM	No fire	None	Mature	NA	149±4	2020-2022	2	2
LM	Low	Standing burnt trees (living), natural regeneration	Mature	8±1	37±2	2020-2022	2	2
HM	High	Standing burnt trees (dead), natural regeneration	Mature	10±0	25±1	2019-2022	2	2
SLM	Low	Salvage-logging of living burnt trees, soil scarification, manual seed spreading of *Pinus sylvestris* in 2019	Mature	0.11±1	23	2020-2022	1	1
SHM	High	Salvage-logging of dead burnt trees, replanted with *Pinus sylvestris* seedlings in 2020	Mature	9±1	23±2	2019-2022	2	2
HY	High	Standing burnt trees, replanted with *Pinus sylvestris* seedlings in 2020	Young	8±1	12±1	2019-2022	2	2

2.2 Experimental design

At each study site, ten collars were installed in May 2019 (Table 1; see Kelly et al. (2021) for details). Two collars per site were selected for BVOC measurements of the organic (forest floor) layer, representing either burnt or unburnt conditions (UM). To assess emissions from the mineral soil, two additional collars were established at each site (except SLM) in close proximity to the original collars (≤ 3 m). In these collars, the organic layer was removed prior to measurements. At the SLM site, soil scarification had already exposed the mineral soil in part of the area. Therefore, one pre-existing collar with an exposed mineral layer was used for mineral soil measurements instead of installing new collars. Measurements were

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consistently conducted at the same collars each year and any newly accumulated litter was removed prior to measurements of the mineral layer.

BVOC emissions were measured using a dynamic chamber system consisting of a custom-built chamber connected to a portable pump unit (Figure 2). The system was similar to that described in Jaakkola et al. (2023), with the exception of the chamber design. Ambient air was drawn through a hydrocarbon trap (Alltech, Chicago, USA) and an ozone filter (MnO_2-coated copper nets) before entering the chamber via a battery-driven pump (Gardner Denver Thomas GmbH, Memmingen, Germany). The purge flow was regulated using a mass flow meter (Aalborg Instruments, Orangeburg, USA) and ranged between 4 L min^{-1} and 6 L min^{-1}, depending on whether blank samples were collected.

The chamber was made of extruded acrylic plastic (PMMA; Evonik Industries, Darmstadt, Germany) and equipped with three ports (Swagelok connectors, Swagelok, Solon, USA) for purge flow, sample collection and temperature measurement. Chamber air temperature was monitored using a stainless steel probe inserted through the chamber wall. The chamber had a height of 0.25 m and an outer (inner) diameter of 180 mm (172 mm). All materials in contact with the air stream, including tubing (1/4 inch PFA), connectors (stainless steel) and valves (PTFE) were selected for their suitability for BVOC sampling.

After placing the chamber on a collar, it was flushed for at least 30 min prior to sampling. BVOC samples were then collected sequentially onto three adsorbent tubes before moving the chamber to the next collar.

Figure 2. In-situ BVOC measurement setup. A transparent chamber was placed on the forest floor and connected to a pump box supplying purified purge air free of BVOCs and ozone. Air from the chamber was drawn through adsorbent tubes using portable pumps to collect BVOCs emitted from the forest floor.

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2.3 BVOC sampling and analysis

BVOC emissions were sampled during field campaigns conducted in July 2019, July-August 2020, August 2021 and July-August 2022. At each site, three replicate samples were collected per sampling occasion. In total, 2014 samples were collected across all years (2019: 26; 2020: 51; 2021: 67; 2022: 70), of which 127 originated from the organic layer and 87 from the mineral layer.

BVOCs were collected from the chamber air by drawing sample air through stainless steel adsorbent tubes (Tenax TA, Carbograph 1TD, Markes International Limited, Llantrisant, UK) using flow-controlled portable pumps (Pocket Pump, SKC Ltd., Dorset, UK). Sampling was conducted at a flow rate of 200 mL min^{-1} for approximately 30 min, resulting in a total sampled volume of 5-6 L per sample.

From 2020 onwards, two parallel chamber-pump systems were operated simultaneously on adjacent collars, whereas in 2019 only one system was used. At least one blank sample per system was collected each day by sampling purge air upstream of the chamber. After sampling, adsorbent tubes were sealed with storage caps and kept cool until laboratory analysis.

BVOC samples were analyzed using thermal desorption coupled to gas chromatography-mass spectrometry (TC-GC-MS). Samples from 2019 were analyzed at Lund university (TD: Turbomatrix ATD 650, PerkinElmer; GC-MS: Shimadzu QP2010 Plus with a BPX5 column, 50 m x 0.32 mm x 1.0 µm), whereas samples from 2020-2022 were analyzed at the University of Copenhagen (TD: TD100-xr, Markes International; GC-MS: Agilent 7890A GC-5975C MSD with a HP-5MS column, 50 m x 0.2 mm x 0.33 µm).

All samples were thermally desorbed at 280 °C for 10 min, cryo-focused at -30 °C, and subsequently flash-heated (40 °C sec^{-1}) to 300 °C for 6 min before injection to the GC column. Helium was used as carrier gas. The oven program started at 40 °C (held for 1 min for 2019 samples and 3 min for 2020-2022 samples), followed by a ramp to 210 °C at 5 °C min^{-1} and to 250 °C at 20 °C min^{-1}, with a final hold of 2 min (2019) or 8 min (2020-2022).

Chromatograms were processed using PARADISe software (v6.0.0.16 (2019) & v.6.0.0-dev6 (2020-2022), (Johnsen et al., 2017; The Copenhagen Chemometrics Group, 2022). Compounds were identified using pure standards (see Supplementary Table S1) and confirmed against the NIST11 library. Quantification was based on calibration with standards of known concentration.

BVOC concentrations were converted to emission rates (µg m^{-2} h^{-1}) according to Ortega and Helmig, (2008) and standardized to a reference temperature of 30 °C and photosynthetically active radiation (PAR) of 1000 µmol m^{-2} s^{-1} following (Guenther et al., 1995, 1993).

2.4 Environmental variables

During sampling, PAR was measured using two LI-190 Quantum sensors (LI-COR, Lincoln, USA) placed adjacent to the chambers and recorded with a data logger (CR100, Campbell, Sci., Logan, USA). In addition to measurements of ambient air temperature and relative humidity (HygroVUE10, Campbell Scientific, Inc., installed at 2 m height), these variables were also

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monitored using a probe (CS215 in a radiation shield, Campbell Sci., Logan, USA) positioned approximately 20 cm above ground between the chambers.

Soil temperature and soil moisture were measured manually outside the chamber frame (<10 cm from the collar) during sampling. Soil temperature was recorded at depths of 3 cm and 10 cm using a handheld temperature probe (model 549, Viking AB, Eskilstuna, Sweden) and soil water content (SWC) was measured using a handheld probe (Delta-T ML3 Theta Probe; Delta-T, Cambridge, UK) with 6 cm stainless steel rods. To account for spatial variability, SWC was measured at three positions around each chamber, whereas soil temperature was measured at a single location to allow for sufficient time for probe equilibrium.

2.5 Data analysis

All data processing and statistical analyses were conducted using R version 4.3.1 (R Core Team, 2022) and MATLAB version R2022b (The Mathworks Inc., 2022). Samples were screened for outliers based on abnormally high concentrations across multiple compounds. Specifically, samples with concentrations exceeding a defined threshold for at least six out of seven selected compounds (Figure S1) were classified as outliers and removed (n = 24). An additional sample was excluded due to unrealistically high concentrations in multiple other compounds (Figure S2), resulting in a total removal of 25 out of 214 samples (~12%) following quality control.

A total of 96 BVOC compounds were identified from the chromatograms. Of these, 10 compounds were consistently detected across all years and were selected as core compounds for analysis. Two additional compounds that were consistently observed from 2020-2022 were also included (Table S2).

To evaluate changed in BVOC composition across years, sites and soil layers, fractional emission profiles were calculated. Mean emission rates for each compound were computed for each combination of year, site and soil layer. These values were then summed to obtain total emission rates and normalized to derive the relative contribution (fraction) of each compound. Only compounds consistently detected across all years were included in these analyses (Table S2).

Temporal trends in BVOC emissions were assessed using regression models of log-transformed concentrations as a function of year. Log transformation was applied to account for the heavy tailed distributions of the raw concentrations. Concentrations below detection limits were replaced with compound-specific limits of detection (LOD; Table S2). These values were treated as the upper bound on the possible log-concentrations in a linear Tobit regression (Amemiya, 1984; Therneau and Grambsch, 2000). The resulting model was fitted as left-censored observations using the ***survival (vesion. 3.5-7)*** package in R (A Package for Survival Analysis in R; (Therneau, 2023).

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3 Results

3.1 BVOC emissions from unburnt forest floor organic and mineral layers

BVOC emission rates were measured from both the organic and mineral soil layers at the unburnt site (UM) between 2020 and 2022. Overall, emissions increased over time, with a strong dominance of monoterpenes across all years.

In the organic layer, emission rates ranged from 14 to 92 µg m^{-2} h^{-1} and increased annually. Monoterpenes consistently dominated, contributing between 88% to 94% of total emissions (Table S3), with relatively minor contributions from other compound classes. In contrast, the emissions from the mineral layer were higher than those of the organic layer in 2020 and 2022 (32 and 228 µg m^{-2} h^{-1}, respectively), but lower in 2021 (19 µg m^{-2} h^{-1}; Table S3). As in the organic layer, monoterpenes were the dominant compounds (83% to 99%) in the mineral layer.

Despite this overall similarity, notable interannual variation in composition was observed. In 2021, the mineral layer showed an increased relative contribution of oxygenated monoterpenes (~3%) and sesquiterpenes (~11%) compared to other years, when these groups typically contributed <1% and <5%, respectively (Table S3). This shift coincided with reduced total emissions in that year. In contrast, the organic layer maintained a relatively stable composition between 2020 and 2021. In 2022, both emission rates and compound composition changed in the organic layer, with an increases contribution of sesquiterpenes (10% compared to <7% in previous years; Table S3). The mineral layer in 2022 exhibited both the highest emission rates and the strongest monoterpene dominance (~99%; Table S3).

Averaged across all years, total BVOC emission rates were lower from the organic layer (45 ± 41 µg m^{-2} h^{-1} mean ± standard deviation) than from the mineral layer (93 ± 117 µg m^{-2} h^{-1}), indicating a generally larger contribution from mineral soils. Despite these differences in magnitude, the dominant compounds were similar in both layers, with α-pinene accounting for the largest share of emissions (22 ± 20 µg m^{-2} h^{-1} and 53 ± 73 µg m^{-2} h^{-1} for the organic and mineral layers, respectively) followed by 3-carene (11 ± 8 µg m^{-2} h^{-1} and 16 ± 16 µg m^{-2} h^{-1}). Among the sesquiterpenes, β-caryophyllene was the only compound with higher emissions from the organic layer (3.3 ± 4 µg m^{-2} h^{-1}) compared to the mineral layer (0.8 ± 0.8 µg m^{-2} h^{-1}), whereas α-humulene was emitted at similar rates for both layers (~0.6 µg m^{-2} h^{-1}). Together, these results show a consistent dominance of monoterpenes across soil layers, with higher emission rates from the mineral layer than from the organic layer, indicating that the organic layer reduces BVOC fluxes to the atmosphere.

3.2 Effects of fire severity, forest management and stand age on BVOC emissions

Wildfire severity strongly influenced BVOC emission rates, with the most pronounced reductions observed at high-severity fire sites (HM, HY, SHM). In 2020-2022, emission rates at high-severity fire sites were consistently lower (<12 µg m^{-2} h^{-1}) than at the unburnt reference site (UM, Figure 3). Although no measurements were available from UM in 2019, emissions at the salvage-logged high-severity fire site (SHM) reached 50 µg m^{-2} h^{-1} in the organic layer, exceeding the average emission rates observed at UM in subsequent years.

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Clear differences were observed between managed and unmanaged high-severity fire sites. At the unlogged site (HM), emission rates increased from 2019 to 2020 (10 to 13 µg m^{-2} h^{-1}) before declining sharply in 2021 (~1.5 µg m^{-2} h^{-1}; Figure 3b). In contrast, at SHM, emissions were initially high in 2019 but decreased rapidly by 2020 (<1 µg m^{-2} h^{-1}; Figure 3d). A similar pattern was observed in the mineral layer, where SHM showed higher initial emissions than HM in 2019 (85 vs 24 µg m^{-2} h^{-1}), followed by a much stronger decline in 2020 (Figures 3f, 3h).

The young high-severity fire site (HY) exhibited a distinct emission trajectory compared to all other sites. Emission rates were initially low in 2019 (~3 µg m^{-2} h^{-1}) and decreased further in the following years before increasing again in 2022 (~11 µg m^{-2} h^{-1}; Figure 3c). In contrast to other sites, mineral layer emissions at HY were lower than organic layer emissions in 2019 (2 vs 3 µg m^{-2} h^{-1}; Figures 3c, 3g). In 2020, however, HY was the only site where mineral layer emissions exceeded those from the organic layer. Both layers showed a similar overall recovery pattern, with low emissions in 2020-2021 followed by a pronounced increase in 2022 (~12-13 µg m^{-2} h^{-1}; Figures 3c, 3g). This recovery trajectory differed from that of mature high-severity fire sites (HM and SHM), where emission rates declined or remained low over time without a comparable increase (Figure 3b, 3d, 3f, 3h), highlighting distinct recovery dynamics at the young site compared to mature high-severity stands.

Low-severity fire sites exhibited substantially higher emission rates than high-severity fire sites. At the mature low-severity fire site (LM), emissions from the organic layer in 2020 and 2021 (64 and 53 µg m^{-2} h^{-1}) exceeded those at both the unburnt and high-severity fire sites (Table S3; Figure S3). The mineral layer at LM showed the highest emission rates observed in the study, with a strong peak in 2020 (~480 µg m^{-2} h^{-1}). Followed by a sharp decline in 2021 (~2 µg m^{-2} h^{-1}). In contrast, the salvage-logged low-severity fire site (SLM) exhibited much lower emission rates and greater variability over time (Figure S3).

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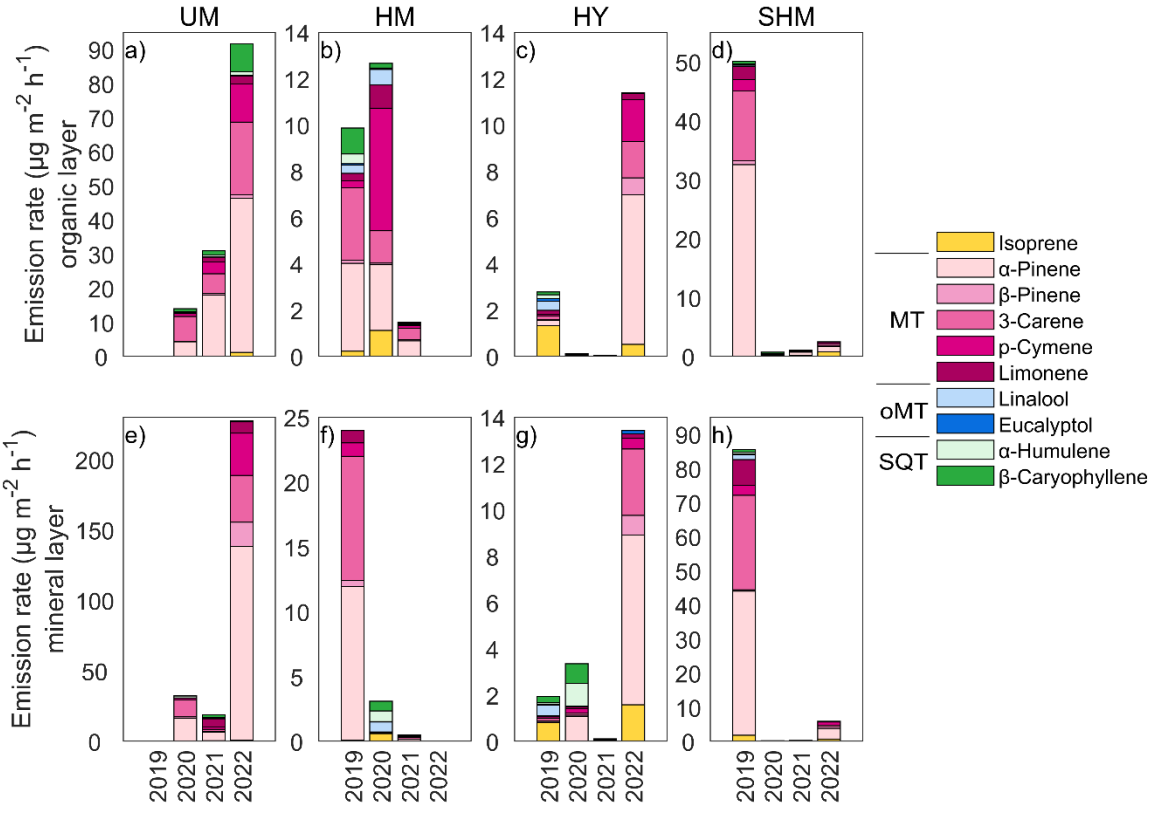

Figure 3. The emission rates (µg m^{-2} h^{-1}) from the organic layer of the a) unburnt mature site (UM), b) high-severity fire mature site (HM), c) high-severity fire young site (HY) and d) salvage-logged high-severity fire mature site (SHM). The emission rates from the mineral layers of e) UM, f) HM, g) HY and h) SHM. The measured BVOC compounds are color-coded with monoterpenes (MT) in red-pink, oxygenated monoterpenes (oMT) in blues and sesquiterpenes (SQT) in greens. Isoprene is ungrouped and colored yellow.

BVOC composition varied substantially across sites and years (Figure 4; Figure S4). Emissions at the unburnt and low-severity fire sites were consistently dominated by monoterpenes, particularly α-pinene and 3-carene. For example, at the low-severity fire site (LM), emission profiles in 2020 were similar to the unburnt site (UM), with comparable contributions of α-pinene (~30%) and 3-carene (LM: 59%, UM: 52%; Figures 31, S4a).

In contrast, high-severity fire sites showed greater variability in composition. At the salvage-logged site (SHM), emissions in 2019 were dominated by α-pinene (65%), whereas the unlogged site (HM) displayed a more diverse composition with lower α-pinene contribution (39%) and relatively higher contributions from 3-carene (32%) as well as sesquiterpenes such as β-caryophyllene (11%) and α-humulene (4%; Figures 4b, 4d).

The young high-severity fire site (HY) exhibited the most distinct emission profile. In 2019, emissions were dominated by isoprene (~48%) in 2019, in contrast to all other sites that were dominated by monoterpenes. In 2020, composition shifted to

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a more even distribution between groups (monoterpenes ~31%, oxygenated monoterpenes ~33% and sesquiterpenes ~35%), before transitioning toward monoterpene dominance in 2021 (~65%) and especially in 2022 (~95%; Figure 4c).

Differences between soil layers were also evident. In 2019, mineral layer profiles were broadly similar to those of the organic layer across burnt sites. However, in 2020, the mineral layer at HM and HY shifted toward sesquiterpene dominance (>50%; Figures 4b, 4c), a pattern not observed in the corresponding organic layers (Figures 4f, 4g). At SHM, β-caryophyllene dominated emissions from both the organic (40%) and mineral layers (65%) in 2020 (Figures 4d, 4h). Additionally in 2021, the mineral layer at UM, HY and SHM showed a pronounced increase in limonene contributions (32%, 34% and 39%, respectively), not observed at the other sites or in other years (Figures 4e, 4g, 4h).

Overall, while monoterpenes dominated emissions at unburnt and low-severity fire sites, high-severity fire sites, particularly HY and SHM, exhibited pronounced temporal variability and shifts in dominant compound classes, with additional divergence between organic and mineral layer composition.

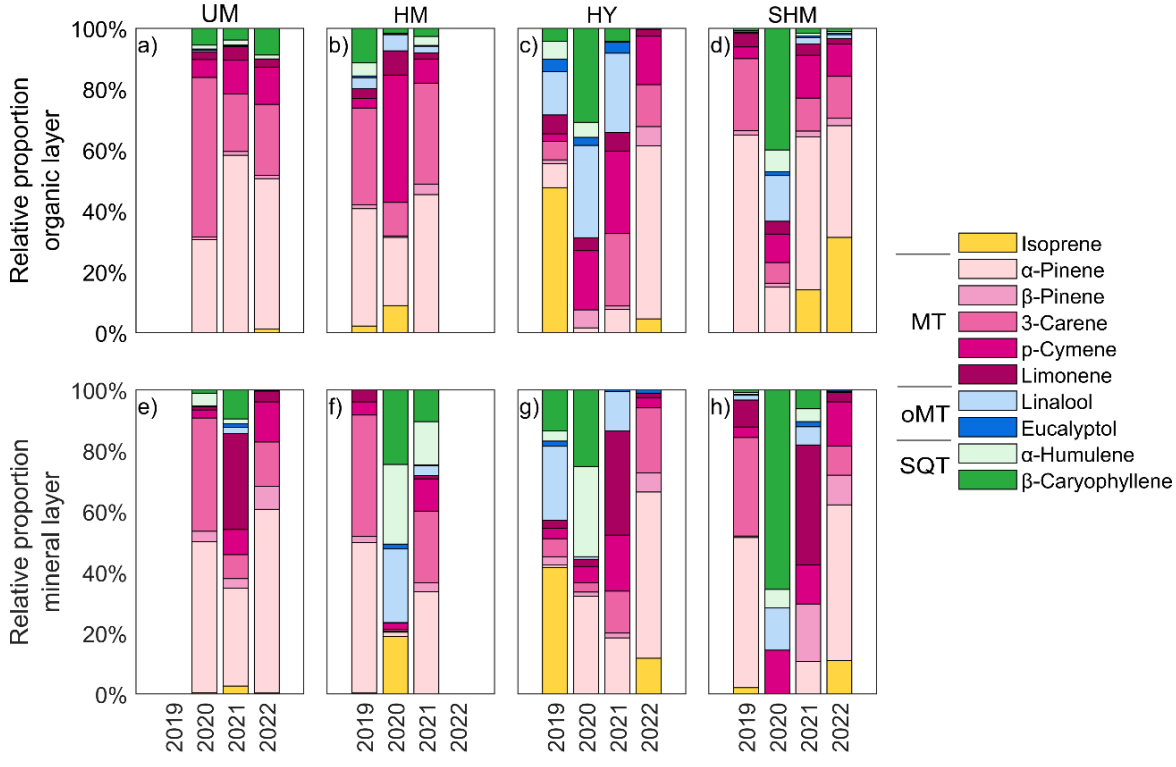

Figure 4. The relative proportion (%) of the emitted BVOC compounds from the organic layers of the a) unburnt mature site (UM), b) high-severity fire mature site (HM), c) high-severity fire young site (HY) and d) salvage-logged high-severity fire mature site (SHM). The relative proportion of the compounds from the mineral layers of e) UM, f) HM, g) HY and h) SHM. The measured BVOC compounds are color-coded with monoterpenes (MT) in red-pink, oxygenated monoterpenes (oMT) in blues and sesquiterpenes (SQT) in greens. Isoprene is ungrouped and colored yellow.

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3.3 BVOC emission rate trends from unburnt and recovering burnt forest floor

Temporal trends in BVOC emission rates were assessed using Tobit regression applied to total emission rates across measurement years (Figure 5). At the unburnt site (UM), emission rates from the organic layer increased significantly over time ($P < 0.001$), whereas no significant trend was observed for the mineral layer (Figure 5a, Table S4). At compound level, several compounds contributed to this increase, including α-humulene, α-tricyclene, 3-carene and β-caryophyllene (Table S4). In contrast, the high-severity fire mature site (HM) showed significant declines in total emission rates from both organic and mineral layers over time ($P < 0.01$; Figure 5b, Table S4). These declines were driven by decreases in dominant monoterpenes such as α-pinene and 3-carene in both layers. Additional compound-specific decreases were observed, including α-tricyclene in the organic layer and β-pinene, d-limonene and p-cymene in the mineral layer (Table S4).

No significant trends in total emission rates were detected at the young high-severity fire site (HY) or the salvage-logged site (SHM) for either soil layer (Figures 5c, 5d). However, compound-level analyses revealed substantial changes. At HY, several compounds decreased significantly over time in both layers, including β-caryophyllene, bornyl acetate and linalool, with an additional decrease in α-humulene in the mineral layer. In contrast, α-pinene in the mineral layer showed a significant increase ($P = 0.04$; Table S4).

At SHM, no significant trends were observed at the compound level in the mineral layer, however, the organic layer exhibited significant decreases in several compounds, including α-pinene, β-caryophyllene, bornyl acetate and β-pinene (Table S4). The only compound showing a significant increase at SHM was isoprene in the organic layer ($P = 0.001$), which increased markedly in 2022 after being close to or below the detection limit in previous years (Figure 3d).

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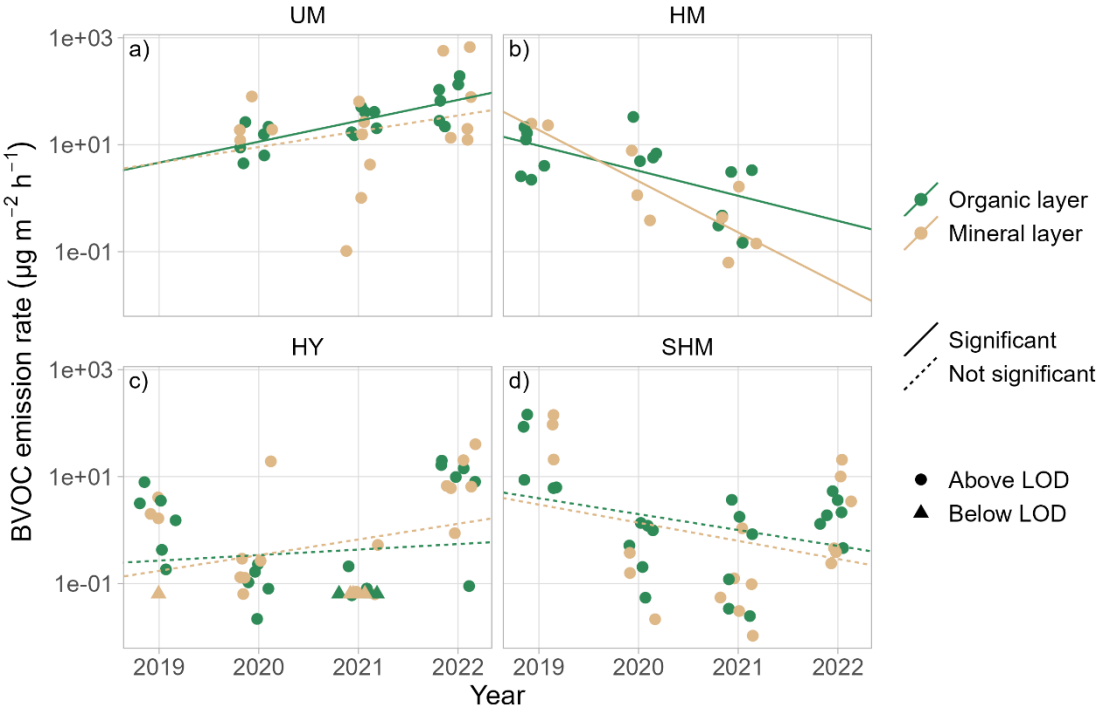

Figure 5. The total BVOC emission rates for each soil layer and the change over the measurement years 2019 to 2022 for the a) unburnt mature site (UM), b) high severity fire mature site (HM), c) high severity fire young site (HY) and d) salvage-logged high severity fire mature site (SHM). The tobit regression lines are plotted for each soil layer. The trends are significant (P<0.05) if the lines are solid and not significant if they are dashed. The BVOC emission rates are presented in log scale. Emission rates measured above the limit of detection (LOD) are indicated by a circle and the measurement points below the LOD by a triangle. Some valid observations can be below the LOD value of other observations depending on which compound of the total BVOC that fell below its specific LOD value before summing to total emissions.

4 Discussion

4.1 Annual variation in BVOC emissions from unburnt forest floor

Measurements from the unburnt reference site (UM) revealed pronounced interannual variability in BVOC emission rates, with the lowest emissions observed in 2020 and the highest in 2022. Variability in BVOC emissions is expected as they are driven by plant metabolism and microbial activity and are therefore sensitive to environmental conditions (Monson et al., 1992; Staudt et al., 2017). Interannual differences in air temperature and precipitation, both preceding and during sampling, are known to influence emission rates (Gulden et al., 2007).

In this study, the lower emissions observed in 2020 coincided with below-average air temperatures and precipitation, whereas the higher emissions in 2022 occurred under conditions closer to the long-term mean (Figure 1c), suggesting a climatic control on BVOC production. However, such variability falls within the expected range for boreal forest floor emissions. Previous studies from Scots pine-dominated forests have reported substantial interannual variation, with monoterpene emissions ranging

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from a few µg m^{-2} h^{-1} to tens of µg m^{-2} h^{-1} with bursts of BVOC emissions to 300 µg m^{-2} h^{-1} during spring (Aaltonen et al., 2011; Hellén et al., 2006; Mäki et al., 2019b).

4.2 BVOC emissions from unburnt and burnt forest floor

We hypothesized that BVOC emissions from burnt forest floors would be lower than those from unburnt forests due to the combustion of BVOC-emitting vegetation. This hypothesis was supported at the high-severity fire young site (HY), which exhibited the lowest emission rates during the first years after fire (2019-2021), both relative to the unburnt site and to other burnt sites.

However, this pattern did not hold for mature high-severity fire sites (HM and SHM). In 2019, emissions at these sites were four to ten times higher than at HY and were comparable to, or in some cases exceeded, emission levels observed at the unburnt site in subsequent years. In particular, emissions at SHM in 2019 exceeded the mean emission rates measured at the unburnt site by approximately 5 µg m^{-2} h^{-1}.

These results indicate that fire does not universally suppress BVOC emissions in the short term and that post-fire emission responses depend strongly on forest stand characteristics and management. This highlights the importance of considering disturbance legacy effects when assessing post-fire BVOC emissions.

4.3 The organic layer as a sink of mineral layer BVOC emissions

Our second hypothesis proposed that the organic layer of boreal forest soils acts as a sink for BVOCs emitted from the underlying mineral layer, through processes such as microbial consumption and adsorption. At the unburnt reference site (UM), this hypothesis was generally supported, as emission rates from the mineral layer exceeded those from the organic layer in 2020 and 2022. This is consistent with previous studies demonstrating that the organic layer can attenuate BVOC fluxes from deeper soil layers (Hayward et al., 2001; Mäki et al., 2017).

However, this pattern was not consistent across all years. In 2021, emissions from the organic layer exceeded those from the mineral layer at the unburnt site. Field observations indicated increased needle litter within the measurement collars during this year, which likely contributed to elevated BVOC emissions. Scots pine litter is known to emit substantial amounts of monoterpenes, particularly α-pinene (Isidorov et al., 2010) and this compound was the dominant contributor to emissions in 2021. Elevated air temperatures during the sampling period may have further enhanced both litter production and emission rates, as warmer conditions are associated with increased needle fall and temperature-dependent BVOC release (Grote and Niinemets, 2008; Kouki and Hokkanen, 1992). Thus, increased litter inputs and favorable climatic conditions likely overrode the sink effect of the organic layer in this year.

Following wildfire, the organic layer may still act as a sink due to remaining surfaces capable of BVOC adsorption. At the high-severity fire mature sites (HM and SHM), this was supported in 2019, when mineral layer emissions exceeded those from the organic layer. However, in subsequent years, emissions from the organic layer were similar to, or higher than, those from the mineral layer. This shift coincided with post-fire inputs of litter and woody debris, including needle shedding and bark

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from standing dead trees and in the case of SHM, additional inputs from salvage logging. These inputs likely increased BVOC emissions from the organic layer through storage pools.

At the same time, reduced emissions from the mineral layer may reflect a decline in root-associated BVOC production following vegetation mortality. Root emissions, including those mediated by mycorrhizal fungi, can contribute substantially to total soil BVOC fluxes (Tang et al., 2019) and their reduction after fire could limit mineral layer emissions. As a result, the apparent weakening of the sink effect in burnt sites may arise from both increased organic layer emissions and decreased mineral layer contributions. This interpretation is supported by observations from the same forest fire area, where fire and post-fire management were associated with lower microbial respiration, reduced bacterial growth and a marked decline in ectomycorrhizal fungal activity (Soares et al., 2026). Although these measurements were not done concurrently with the BVOC campaigns, they suggest that the low mineral layer BVOC emissions observed following high-severity fire occurred alongside documented changes in belowground biological activity.

At the young high-severity fire site (HY), emission rates from both soil layers were low in the first years after fire and differences between layers were small, making inference of a sink effect less clear. However, the pronounced increase in emissions observed in 2022 from both layers may reflect vegetation recovery and the development of root systems following replanting of pine seedlings in 2020. This suggests that the interaction between organic and mineral layer emissions evolves over time as ecosystem recovery progresses.

4.4 Effects of fire severity, forest management and stand age on BVOC emissions

Fire severity, stand age and post-fire management all influenced BVOC emissions through their effects on vegetation mortality, litter inputs and the amount of organic material remaining after the fire. Fire severity appeared particularly important in controlling the availability of post-fire BVOC sources. The low-severity fire site (LM) retained a substantially deeper organic layer than the high-severity fire sites (Table 1) and maintained living trees that continued to supply litter and other plant-derived BVOCs. In contrast, the high-severity fire sites retained only a thin organic layer and depended largely on litter inputs from trees killed in the fire. This difference, together with the continued presence of living trees at LM, may help explain why BVOC emissions remained substantially higher at LM than at the high-severity fire sites during the study period.

At the young high-severity fire site (HY), the complete loss of vegetation resulted in consistently low emission rates during the first years after fire. In contrast, at mature high-severity fire sites (HM and SHM), trees did not burn completely but died gradually, leading to substantial needle shedding in the year following the fire. This resulted in elevated BVOC emissions in 2019, driven by the accumulation of fresh litter. In addition, litter inputs likely differed in quality between fire severities. At the high-severity fire sites, litter originated mainly from heat-killed needles shed from standing dead trees, whereas inputs at LM were primarily derived from surviving trees. Differences in needle condition may have influenced BVOC release from litter, although this was not directly examined in the present study.

The importance of litter inputs as a dominant emission source in the early post-fire phase is further supported by temporal changes at HM and SHM. At both sites, emission rates declined rapidly after 2020, coinciding with the depletion of needle

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litter and, in the case of SHM, the removal of trees through salvage logging. Without continued litter input, emission rates approached near-zero levels. The dominance of α-pinene and 3-carene at these sites further supports a litter-driven origin, as these compounds are characteristic of Scots pine needle emissions and have been shown to dominate forest floor BVOC fluxes in similar systems (Aaltonen et al., 2011; Mäki et al., 2019a; Zhang-Turpeinen et al., 2021).

These results highlight that BVOC emissions measured at the forest floor represent a combination of soil processes and litter-derived emissions. In disturbed systems, particularly shortly after fire, litter inputs can dominate the emission signal, complicating the attribution of emissions to underlying soil processes alone.

4.5 BVOC emission rate trends from recovering burnt forest floor

We hypothesized that BVOC emissions would increase as the ecosystem recovers following fire. However, no consistent increase in total emission rates was observed during the four-year study period. In contrast, the high-severity fire mature site (HM) showed a significant decline in emissions over time, indicating that short-term post-fire dynamics are not characterized by a linear recovery trajectory.

This apparent lack of recovery is consistent with previous studies suggesting that BVOC emissions from boreal forest floors may take decades to return to pre-fire levels (Mäki et al., 2019b; Zhang-Turpeinen et al., 2020). The relatively short observation period in this study likely captures an early post-disturbance phase dominated by legacy effects rather than true ecosystem recovery.

During the first years after fire, BVOC emissions appear to be strongly influenced by the presence and subsequent depletion of litter and woody debris. As discussed above, needle litter can continue to emit BVOCs for more than a year after deposition (Isidorov et al., 2010) and the observed decreases in α-pinene and 3-carene at HM and SHM over time likely reflect the gradual reduction of these litter-derived emission sources. This suggests that emissions measured within two to three years after fire may largely represent transient litter-driven fluxes rather than emissions from the underlying soil system.

However, site-specific trends indicate that recovery trajectories vary depending on stand characteristics and management. Small increases in emission rates at HY and SHM after 2020, which were not observed at HM, support the hypothesis that fire severity, stand age and management influence BVOC dynamics. In particular, increasing α-pinene emissions from the mineral layer at HY may be associated with the establishment of planted pine seedlings, as young pine root systems are known to emit α-pinene (Rasheed et al., 2017, 2021; Tiiva et al., 2019).

Similarly, the significant increase in isoprene emissions at SHM in 2022 may indicate the development of understory vegetation. Pioneer species are often strong isoprene emitters and their establishment following disturbance could contribute to the observed changes in BVOC composition and emission trends (Artaxo et al., 2022; Hanson et al., 1999; Holopainen, 2013).

The contrasting recovery trajectories observed across sites are also consistent with observations from the same forest fire area, where fire severity and post-fire management altered microbial guild structure, microbial respiration and soil carbon dynamics (Soares et al., 2026), indicating that ecosystem recovery diverges not only aboveground but also belowground.

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Changes in BVOC composition observed across sites may have important consequences for atmospheric chemistry. For example, shifts from monoterpene- to isoprene-dominated emissions, as seen following disturbance and during vegetation recovery (Niinemets et al., 2010; Sharkey et al., 2008), can alter oxidation pathways and secondary organic aerosol (SOA) formation potential (Guenther et al., 2012; Hallquist et al., 2009). Similarly, episodic increases in sesquiterpenes may enhance SOA yields due to their high reactivity (Lee et al., 2006). These shifts in BVOC composition and magnitude may therefore influence post-fire atmospheric reactivity and aerosol formation at landscape scales.

Overall, our results show that BVOC emission recovery following wildfire is non-linear and controlled by shifting dominant sources. Emissions are initially driven by litter-derived storage pools, followed by a decline as these pools are depleted, and finally a recovery phase associated with vegetation re-establishment. The timing and magnitude of these phases depend strongly on stand age and management practices, resulting in distinct recovery trajectories across sites.

5 Conclusion

Fire severity, stand age and post-fire management strongly influence the short-term recovery of BVOC emissions from the forest floor following a boreal forest fire. High-severity fires in young stands resulted in persistently low emission rates during the first years after disturbance, whereas mature stands exhibited elevated emissions shortly after fire due to the accumulation of needle litter and woody debris. These emissions declined rapidly as litter inputs were depleted, particularly at salvage-logged sites where the removal of trees eliminated continued inputs. In contrast, unlogged mature stands showed a more gradual decline, reflecting delayed litter fall from standing dead trees.

Post-fire management further altered emission trajectories. Salvage logging caused a transient increase in emissions followed by a rapid decrease to near-zero levels, whereas reforestation through planting led to increased emissions within a few years, with emission profiles converging toward those of unburnt forests.

Overall, BVOC emissions during early post-fire recovery are not solely determined by fire disturbance itself, but by the interaction between disturbance severity, stand structure and management practices. These factors shape both the magnitude and composition of emissions, leading to distinct recovery pathways.

Our study provides new insights into BVOC dynamics during the critical early years following forest fire. The results highlight the importance of accounting for disturbance legacy effects, stand age and management interventions when predicting BVOC emissions. As fire frequency and intensity are expected to increase under climate change, shifts in forest structure and management practices may alter BVOC emissions in ways that influence atmospheric chemistry and climate feedbacks. Long-term observations are needed to capture the full trajectory of BVOC emission recovery and its role in boreal ecosystem-atmosphere interactions.

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Code and data availability

The data that support the findings of this study can be found in Zenodo at https://doi.org/10.5281/zenodo.21835735.

Author contributions

TH conceived and designed the study with NK. TH conducted the data collection. EJ and JL performed the data analysis. Data interpretation was done by EJ with contributions from JL, NK and TH. JK contributed to data curation and visualization. EJ wrote the paper with contributions from all co-authors.

Competing interests

The authors declare no competing interests.

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References

Aaltonen, H., Pumpanen, J., Pihlatie, M., Hakola, H., Hellén, H., Kulmala, L., Vesala, T., and Bäck, J.: Boreal pine forest floor biogenic volatile organic compound emissions peak in early summer and autumn, Agric. For. Meteorol., 151, 682–691, https://doi.org/10.1016/j.agrformet.2010.12.010, 2011.

Aaltonen, H., Aalto, J., Kolari, P., Pihlatie, M., Pumpanen, J., Kulmala, M., Nikinmaa, E., Vesala, T., and Bäck, J.: Continuous VOC flux measurements on boreal forest floor, Plant Soil, 369, 241–256, https://doi.org/10.1007/s11104-012-1553-4, 2013.

Acosta Navarro, J. C., Smolander, S., Struthers, H., Zorita, E., Ekman, A. M. L., Kaplan, J. O., Guenther, A., Arneth, A., and Riipinen, I.: Global emissions of terpenoid VOCs from terrestrial vegetation in the last millennium, J. Geophys. Res., 119, 6867–6885, https://doi.org/10.1002/2013JD021238, 2014.

https://doi.org/10.5194/egusphere-2026-5083
Preprint. Discussion started: 2 September 2026

Amemiya, T.: Tobit models: A survey, J. Econom., 24, 3–61, https://doi.org/10.1016/0304-4076(84)90074-5, 1984.

Artaxo, P., Hansson, H. C., Andreae, M. O., Bäck, J., Alves, E. G., Barbosa, H. M. J., Bender, F., Bourtsoukidis, E., Carbone, S., Chi, J., Decesari, S., Després, V. R., Ditas, F., Ezhova, E., Fuzzi, S., Hasselquist, N. J., Heintzenberg, J., Holanda, B. A., Guenther, A., Hakola, H., Heikkinen, L., Kerminen, V. M., Kontkanen, J., Krejci, R., Kulmala, M., Lavric, J. V., De Leeuw, G., Lehtipalo, K., Machado, L. A. T., McFiggans, G., Franco, M. A. M., Meller, B. B., Morais, F. G., Mohr, C., Morgan, W., Nilsson, M. B., Peichl, M., Petäjä, T., Praß, M., Pöhlker, C., Pöhlker, M. L., Pöschl, U., Von Randow, C., Riipinen, I., Rinne, J., Rizzo, L. V., Rosenfeld, D., Dias, M. A. F. S., Sogacheva, L., Stier, P., Swietlicki, E., Sörgel, M., Tunved, P., Virkkula, A., Wang, J., Weber, B., Yáñez-Serrano, A. M., Zieger, P., Mikhailov, E., Smith, J. N., and Kesselmeier, J.: Tropical and Boreal Forest - Atmosphere Interactions: A Review, Tellus B Chem. Phys. Meteorol., 74, 24–163, https://doi.org/10.16993/tellusb.34, 2022.

Bond-Lamberty, B., Peckham, S. D., Ahl, D. E., and Gower, S. T.: Fire as the dominant driver of central Canadian boreal forest carbon balance, Nature 2007 450:7166, 450, 89–92, https://doi.org/10.1038/nature06272, 2007.

Dukat, P., Kelly, J., Doerr, S. H., Edvardsson, J., Hölttä, T. S., Lehner, I., Lindroth, A., Santín, C., and Kljun, N.: Boreal forest tree growth and sap flow after a low-severity wildfire, Agric. For. Meteorol., 347, 109899, https://doi.org/10.1016/J.AGRFORMET.2024.109899, 2024.

Grote, R. and Niinemets, Ü.: Modeling volatile isoprenoid emissions - A story with split ends, Plant Biol., 10, 8–28, https://doi.org/10.1055/s-2007-964975, 2008.

Guenther, A., Nicholas, C., Fall, R., Klinger, L., Mckay, W. A., and Scholes, B.: A global model of natural volatile organic compound emissions s Raja the balance Triangle changes in the atmospheric accumulation rates of greenhouse Triangle Several inventories of natural and Exposure Assessment global scales have been two classes Fores, J. Geophys. Res., 100, 8873–8892, 1995.

Guenther, A. B., Zimmerman, P. R., Harley, P. C., Monson, R. K., and Fall, R.: Isoprene and monoterpene emission rate variability: model evaluations and sensitivity analyses, J. Geophys. Res., 98, https://doi.org/10.1029/93jd00527, 1993.

Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The model of emissions of gases and aerosols from nature version 2.1 (MEGAN2.1): An extended and updated framework for modeling biogenic emissions, Geosci. Model Dev., 5, 1471–1492, https://doi.org/10.5194/gmd-5-1471-2012, 2012.

Gulden, L. E., Yang, Z. L., and Niu, G. Y.: Interannual variation in biogenic emissions on a regional scale, Journal of Geophysical Research: Atmospheres, 112, 14103, https://doi.org/10.1029/2006JD008231, 2007.

Hallquist, M., Wenger, J. C., Baltensperger, U., Rudich, Y., Simpson, D., Claeys, M., Dommen, J., Donahue, N. M., George, C., Goldstein, A. H., Hamilton, J. F., Herrmann, H., Hoffmann, T., Iinuma, Y., Jang, M., Jenkin, M. E., Jimenez, J. L., Kiendler-Scharr, A., Maenhaut, W., McFiggans, G., Mentel, T. F., Monod, A., Prévôt, A. S. H., Seinfeld, J. H., Surratt, J. D., Szmigielski, R., and Wildt, J.: The formation, properties and impact of secondary organic aerosol: Current and emerging issues, Atmos. Chem. Phys., 9, 5155–5236, https://doi.org/10.5194/acp-9-5155-2009, 2009.

https://doi.org/10.5194/egusphere-2026-5083
Preprint. Discussion started: 2 September 2026

Hanson, D. T., Swanson, S., Graham, L. E., and Sharkey, T. D.: Evolutionary significance of isoprene emission from mosses, Am. J. Bot., 86, 634–639, https://doi.org/10.2307/2656571, 1999.

Hayward, S., Muncey, R. J., James, A. E., Halsall, C. J., and Hewitt, C. N.: Monoterpene emissions from soil in a Sitka spruce forest, Atmos. Environ., 35, 4081–4087, 2001.

Hellén, H., Hakola, H., Pystynen, K.-H., Rinne, J., and Haapanala, S.: C_2-C_{10} hydrocarbon emissions from a boreal wetland and forest floor, Biogeosciences, 3, 167–174, https://doi.org/10.5194/bg-3-167-2006, 2006.

Holopainen, J. K.: Loss of isoprene-emitting capacity: Deleterious for trees?, Tree Physiol., 33, 559–561, https://doi.org/10.1093/treephys/tpt036, 2013.

IPCC: Summary for Policymakers. In: Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)], Geneva, Switzerland, 1–34 pp., https://doi.org/10.59327/IPCC/AR6-9789291691647.001, 2023.

Isidorov, V., Vinogorova, V., and Rafałowski, K.: Gas chromatographic determination of extractable compounds composition and emission rate of volatile terpenes from larch needle litter, J. Atmos. Chem., 50, 263–278, https://doi.org/10.1007/s10874-005-5078-6, 2005.

Isidorov, V. A., Smolewska, M., Purzyåska-Pugacewicz, A., and Tyszkiewicz, Z.: Chemical composition of volatile and extractive compounds of pine and spruce leaf litter in the initial stages of decomposition, Biogeosciences, 7, 2785–2794, https://doi.org/10.5194/bg-7-2785-2010, 2010.

Jaakkola, E., Gärtner, A., Jönsson, A. M., Ljung, K., Olsson, O., and Holst, T.: Spruce bark beetles (Ips typographus) cause up to 700 times higher bark BVOC emission rates compared to healthy Norway spruce (Picea abies), Biogeosciences, 20, 803–826, https://doi.org/10.5194/bg-20-803-2023, 2023.

Jiao, Y., Kramshøj, M., Davie-Martin, C. L., Albers, C. N., and Rinnan, R.: Soil uptake of VOCs exceeds production when VOCs are readily available, Soil Biol. Biochem., 185, https://doi.org/10.1016/j.soilbio.2023.109153, 2023.

Joensuu, J., Altimir, N., Hakola, H., Rostás, M., Raivonen, M., Vestenius, M., Aaltonen, H., Riederer, M., and Bäck, J.: Role of needle surface waxes in dynamic exchange of mono-and sesquiterpenes, Atmos. Chem. Phys., 16, 7813–7823, https://doi.org/10.5194/acp-16-7813-2016, 2016.

Johnsen, L. G., Skou, P. B., Khakimov, B., and Bro, R.: Gas chromatography – mass spectrometry data processing made easy, J. Chromatogr. A, 1503, 57–64, https://doi.org/10.1016/J.CHROMA.2017.04.052, 2017.

Keeley, J. E.: Fire intensity, fire severity and burn severity: A brief review and suggested usage, Int. J. Wildland Fire, 18, 116–126, https://doi.org/10.1071/WF07049, 2009.

Kelly, J., Ibáñez, T. S., Santín, C., Doerr, S. H., Nilsson, M. C., Holst, T., Lindroth, A., and Kljun, N.: Boreal forest soil carbon fluxes one year after a wildfire: Effects of burn severity and management, Glob. Chang. Biol., 27, 4181–4195, https://doi.org/10.1111/gcb.15721, 2021.

https://doi.org/10.5194/egusphere-2026-5083
Preprint. Discussion started: 2 September 2026

Kelly, J., Kljun, N., Cai, Z., Doerr, S. H., D'Onofrio, C., Holst, T., Lehner, I., Lindroth, A., Thapa, S., Vestin, P., and Santín, C.: Wildfire impacts on the carbon budget of a managed Nordic boreal forest, Agric. For. Meteorol., 351, 110016, https://doi.org/10.1016/j.agrformet.2024.110016, 2024.

Kelly, J., Doerr, S. H., Ekroos, J., Ibáñez, T. S., Islam, M. R., Santín, C., Soares, M., and Kljun, N.: No recovery of soil respiration four years after fire and post-fire management in a Nordic boreal forest, Agric. For. Meteorol., 364, 110454, https://doi.org/10.1016/J.AGRFORMET.2025.110454, 2025.

Köster, K., Berninger, F., Lindén, A., Köster, E., and Pumpanen, J.: Recovery in fungal biomass is related to decrease in soil organic matter turnover time in a boreal fire chronosequence, Geoderma, 235–236, 74–82, https://doi.org/10.1016/j.geoderma.2014.07.001, 2014.

Köster, K., Aaltonen, H., Berninger, F., Heinonsalo, J., Köster, E., Ribeiro-Kumara, C., Sun, H., Tedersoo, L., Zhou, X., and Pumpanen, J.: Impacts of wildfire on soil microbiome in Boreal environments, Curr. Opin. Environ. Sci. Health, 22, 100258, https://doi.org/10.1016/j.coesh.2021.100258, 2021a.

Köster, K., Aaltonen, H., Berninger, F., Heinonsalo, J., Köster, E., Ribeiro-Kumara, C., Sun, H., Tedersoo, L., Zhou, X., and Pumpanen, J.: Impacts of wildfire on soil microbiome in Boreal environments, Curr. Opin. Environ. Sci. Health, 22, 100258, https://doi.org/10.1016/j.coesh.2021.100258, 2021b.

Kouki, J. and Hokkanen, T.: Long-term needle litterfall of a Scots pine Pinus sylvestris stand: relation to temperature factors, Oecologia, 89, 176–181, https://doi.org/10.1007/BF00317216, 1992.

Lee, A., Goldstein, A. H., Kroll, J. H., Ng, N. L., Varutbangkul, V., Flagan, R. C., and Seinfeld, J. H.: Gas-phase products and secondary aerosol yields from the photooxidation of 16 different terpenes, Journal of Geophysical Research Atmospheres, 111, D17305, https://doi.org/10.1029/2006JD007050, 2006.

Lundström, U. S., Van Breemen, N., and Bain, D.: The podzolization process. A review, Geoderma, 94, 91–107, https://doi.org/10.1016/S0016-7061(99)00036-1, 2000.

Mäki, M., Heinonsalo, J., Hellén, H., and Bäck, J.: Contribution of understorey vegetation and soil processes to boreal forest isoprenoid exchange, Biogeosciences, 14, 1055–1073, https://doi.org/10.5194/bg-14-1055-2017, 2017.

Mäki, M., Aaltonen, H., Heinonsalo, J., Hellén, H., Pumpanen, J., and Bäck, J.: Boreal forest soil is a significant and diverse source of volatile organic compounds, Plant Soil, 441, 89–110, https://doi.org/10.1007/s11104-019-04092-z, 2019a.

Mäki, M., Krasnov, D., Hellén, H., Noe, S. M., and Bäck, J.: Stand type affects fluxes of volatile organic compounds from the forest floor in hemiboreal and boreal climates, Plant Soil, 441, 363–381, https://doi.org/10.1007/s11104-019-04129-3, 2019b.

Mochizuki, T., Ujihara, M., Takahashi, Y., Kobayashi, H., and Tani, A.: Seasonal variation of monoterpene emissions from forest floor and its contribution to whole canopy flux in a Larix kaempferi forest, Geochem. J., 55, 313–324, https://doi.org/10.2343/geochemj.2.0640, 2021.

Monson, R. and Baldocchi, D.: Fluxes of biogenic volatile compounds between plants and the atmosphere, in: Terrestrial Biosphere-Atmosphere Fluxes, Cambridge University Press, 395–414, 2014.

https://doi.org/10.5194/egusphere-2026-5083
Preprint. Discussion started: 2 September 2026

Monson, R. K., Jaeger, C. H., Adams, W. W., Driggers, E. M., Silver, G. M., and Fall, R.: Relationships among isoprene emission rate, photosynthesis, and isoprene synthase activity as influenced by temperature, Plant Physiol., 98, 1175–1180, https://doi.org/10.1104/pp.98.3.1175, 1992.

Niinemets, Ü. and Monson, R. K.: Biology, controls and models of tree volatile organic compound emissions, edited by: Niinemets, Ü. and Monson, R. K., 253–284 pp., https://doi.org/10.1007/978-94-007-6606-8, 2013.

Niinemets, Ü., Arneth, A., Kuhn, U., Monson, R. K., Peñuelas, J., and Staudt, M.: The emission factor of volatile isoprenoids: Stress, acclimation, and developmental responses, Biogeosciences, 7, 2203–2223, https://doi.org/10.5194/BG-7-2203-2010, 2010.

Ortega, J. and Helmig, D.: Approaches for quantifying reactive and low-volatility biogenic organic compound emissions by vegetation enclosure techniques - Part A, Chemosphere, 72, 343–364, https://doi.org/10.1016/j.chemosphere.2007.11.020, 2008.

Paasonen, P., Asmi, A., Petäjä, T., Kajos, M. K., Äijälä, M., Junninen, H., Holst, T., Abbatt, J. P. D., Arneth, A., Birmili, W., Van Der Gon, H. D., Hamed, A., Hoffer, A., Laakso, L., Laaksonen, A., Richard Leaitch, W., Plass-Dülmer, C., Pryor, S. C., Räisänen, P., Swietlicki, E., Wiedensohler, A., Worsnop, D. R., Kerminen, V. M., and Kulmala, M.: Warming-induced increase in aerosol number concentration likely to moderate climate change, Nat. Geosci., 6, 438–442, https://doi.org/10.1038/ngeo1800, 2013.

Pechony, O. and Shindell, D. T.: Driving forces of global wildfires over the past millennium and the forthcoming century, Proc. Natl. Acad. Sci. U. S. A., 107, 19167–19170, https://doi.org/10.1073/pnas.1003669107, 2010.

Peñuelas, J., Asensio, D., Tholl, D., Wenke, K., Rosenkranz, M., Piechulla, B., and Schnitzler, J. P.: Biogenic volatile emissions from the soil, Plant Cell Environ., 37, 1866–1891, https://doi.org/10.1111/pce.12340, 2014.

Petersen, R. C., Holst, T., Wu, C., Krejci, R., Chan, J. K., Mohr, C., and Rinne, J.: BVOC and speciated monoterpene concentrations and fluxes at a Scandinavian boreal forest, Atmos. Chem. Phys., 25, 17205–17236, https://doi.org/10.5194/ACP-25-17205-2025, 2025.

Rasheed, M. U., Kasurinen, A., Kivimäenpää, M., Ghimire, R., Häikiö, E., Mpmah, P., Holopainen, J. K., and Holopainen, T.: The responses of shoot-root-rhizosphere continuum to simultaneous fertilizer addition, warming, ozone and herbivory in young Scots pine seedlings in a high latitude field experiment, Soil Biol. Biochem., 114, 279–294, https://doi.org/10.1016/j.soilbio.2017.07.024, 2017.

Rasheed, M. U., Kivimäenpää, M., and Kasurinen, A.: Emissions of biogenic volatile organic compounds (BVOCs) from the rhizosphere of Scots pine (Pinus sylvestris) seedlings exposed to warming, moderate N addition and bark herbivory by large pine weevil (Hylobius abietis), Plant Soil, 463, 379–394, https://doi.org/10.1007/s11104-021-04888-y, 2021.

R Core Team: R: A language and environment for statistical computing, 2022., 2022.

Scott, C. E., Monks, S. A., Spracklen, D. V., Arnold, S. R., Forster, P. M., Rap, A., Äijälä, M., Artaxo, P., Carslaw, K. S., Chipperfield, M. P., Ehn, M., Gilardoni, S., Heikkinen, L., Kulmala, M., Petäjä, T., Reddington, C. L. S., Rizzo, L. V.,

https://doi.org/10.5194/egusphere-2026-5083
Preprint. Discussion started: 2 September 2026

Swietlicki, E., Vignati, E., and Wilson, C.: Impact on short-lived climate forcers increases projected warming due to deforestation, Nat. Commun., 9, 1–9, https://doi.org/10.1038/s41467-017-02412-4, 2018.

Sharkey, T. D., Wiberley, A. E., and Donohue, A. R.: Isoprene emission from plants: Why and how, Ann. Bot., 101, 5–18, https://doi.org/10.1093/aob/mcm240, 2008.

SMHI: Meteorological observations from Ytterhogdal weather station, https://www.smhi.se/data/hitta-data-for-en-plats/ladda-ner-vaderobservationer/airtemperatureMean24h/124110, 2024.

Soares, M., Kelly, J., Rousk, J., and Kljun, N.: Wildfire and post-fire management reshape soil microbial guilds and carbon dynamics at a boreal forest site in Sweden, Biogeochemistry 2026 169:3, 169, 28-, https://doi.org/10.1007/S10533-026-01344-W, 2026.

SOU: Skogsbränderna sommaren 2018, Stockholm, 2019.

Staudt, M., Bourgeois, I., Al Halabi, R., Song, W., and Williams, J.: New insights into the parametrization of temperature and light responses of mono - and sesquiterpene emissions from Aleppo pine and rosemary, Atmos. Environ., 152, 212–221, https://doi.org/10.1016/j.atmosenv.2016.12.033, 2017.

Tang, J., Schurgers, G., and Rinnan, R.: Process Understanding of Soil BVOC Fluxes in Natural Ecosystems: A Review, Reviews of Geophysics, 57, 966–986, https://doi.org/10.1029/2018RG000634, 2019.

The Copenhagen Chemometrics Group: PARADISe, https://ucphchemometrics.com/paradise/, last access: 3 November 2022., 2022.

The Mathworks Inc.: MATLAB, 2022., 2022.

Therneau, T.: A Package for Survival Analysis in R, https://CRAN.R-project.org/package=survival, 2023.

Therneau, T. M. and Grambsch, P. M.: Modeling Survival Data: Extending the Cox Model, Springer Science & Business Media, 2000.

Tiiva, P., Julkunen-Tiitto, R., Häikiö, E., and Kasurinen, A.: Belowground responses of scots pine (Pinus sylvestris) seedlings to experimental warming, moderate nitrogen addition, and bark herbivory, Canadian Journal of Forest Research, 49, 647–660, https://doi.org/10.1139/cjfr-2018-0099, 2019.

Weber, J., Archer-Nicholls, S., Abraham, N. L., Shin, Y. M., Griffiths, P., Grosvenor, D. P., Scott, C. E., and Archibald, A. T.: Chemistry-driven changes strongly influence climate forcing from vegetation emissions, Nat. Commun., 13, https://doi.org/10.1038/s41467-022-34944-9, 2022.

Zhang-Turpeinen, H., Kivimäenpää, M., Aaltonen, H., Berninger, F., Köster, E., Köster, K., Menyailo, O., Prokushkin, A., and Pumpanen, J.: Wildfire effects on BVOC emissions from boreal forest floor on permafrost soil in Siberia, Science of The Total Environment, 711, 134851, https://doi.org/10.1016/j.scitotenv.2019.134851, 2020.

Zhang-Turpeinen, H., Kivimäenpää, M., Berninger, F., Köster, K., Zhao, P., Zhou, X., and Pumpanen, J.: Age-related response of forest floor biogenic volatile organic compound fluxes to boreal forest succession after wildfires, Agric. For. Meteorol., 308–309, 108584, https://doi.org/10.1016/J.AGRFORMET.2021.108584, 2021.

https://doi.org/10.5194/egusphere-2026-5083
Preprint. Discussion started: 2 September 2026

Zhang-Turpeinen, H., Aaltonen, H., Tang, J., Kou, D., Kivimäenpää, M., Rinnan, R., and Pumpanen, J.: Changes in the Factors Influencing Forest Floor Terpenoid Emissions During Post-Fire Forest Succession, J. Geophys. Res. Biogeosci., 130, https://doi.org/10.1029/2024JG008113, 2025.