

Review

Soil Biogenic Volatile Organic Compounds: Sources, Sinks, Emission Controls, and Ecological Functions

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Abstract

Biogenic volatile organic compounds released from soil (SBVOCs) are an important component of the material exchange and information transmission between terrestrial ecosystems and the atmosphere. Soil ecosystems act as both critical sources and frequently overlooked sinks of BVOCs. SBVOC emissions are mainly regulated by the temperature, moisture, and pH of the soil. Climate warming may enhance volatilization and microbial production in the short term. However, its long-term effects depend on drought, vegetation composition, substrate availability, permafrost thaw, and microbial acclimation. SBVOCs also influence microbial activity, nutrient cycling, plant–microbe interactions, plant defence, and below ground trophic interactions, although the strength of evidence differs among these functions. Ecologically, SBVOCs promote carbon cycling, modulate plant-microbe interactions, and influence atmospheric chemistry. This review further synthesizes SBVOC emission and uptake patterns across different climatic zones. Several challenges remain, particularly the scarcity of long-term quantitative measurements and difficulties in distinguishing multiple emission sources. Our understanding of rhizosphere interactions and climate-change feedback is also limited. It is essential to enhance long-term observational studies and optimize models to deepen our understanding of the role of SBVOCs in the global carbon cycle and air quality.

Keywords: BVOCs; soil ecosystems; emission; absorption; environmental controls

1. Introduction

Biogenic volatile organic compounds (BVOCs) are primarily low-molecular-weight and are produced by biological entities including plants and microorganisms through metabolic processes [1]. They encompass terpenoids (including isoprene, monoterpenes, and sesquiterpenes), aldehydes, ketones, alcohols, and volatile fatty acids [2]. The total BVOC emissions are estimated to be 700~1100 Tg C·yr^{−1} [3,4], among which soil-emitted BVOCs (SBVOCs) account for approximately 1~15% [5–7]. SBVOCs originate from plant root exudates [8], metabolic products of soil microorganisms, soil organic matter (SOM) [6], and litter decomposition [9], which constitute an important supplement to BVOC emissions from terrestrial ecosystems.

In varied ecosystems SBVOCs (from bare soil and litter) account for 1~20% of total BVOC emissions [10–12]. Ignoring SBVOCs may result in a substantial underestimation of total BVOC emissions [13,14]. When litter is included, the contribution can be much



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larger because decomposing plant residues act both as direct sources of volatiles and as substrates for microbial BVOC production. For instances, Staudt et al. [15] found that the soil in a coastal pine forest is an important source of pinene. In a temperate coniferous forest in the United States, soil (with litter) monoterpene emission can account for 12~136% of the canopy emission during the nongrowing season [16]. Root-associated emissions represent another source compartment, reflecting rhizosphere microbial activity and direct root release. During the growing season, soil including root contributions accounted for approximately 24% of canopy monoterpene emissions [17]. Bourtsoukidis et al. [14] found that sesquiterpene emission fluxes from Amazon forest soil were comparable to those from the forest canopy during the dry season.

Importantly, soil also acts as a sink for BVOCs [12]. Mu et al. [18] reported that litter-free soil in Guangdong, China, showed net uptake of isoprene, monoterpenes, and sesquiterpenes, with fluxes of -71.84 , -6.20 , and $-6.19 \mu\text{g m}^{-2} \text{h}^{-1}$, respectively. Yang et al. [19] observed significant net uptake of BVOCs by soils in Northeast Spain during the dry season, while Llusà et al. [20] found sesquiterpene uptake rates up to $282 \mu\text{g m}^{-2} \text{h}^{-1}$ in tropical rainforest soils during the wet season. This bidirectional flux mechanism highlights soil's dual role in the global BVOC cycle, its carbon balance, and its ecological importance. Some studies have shown that SBVOCs may be used as an energy source by microorganisms, which may promote the degradation and conversion of organic matter, and then affect carbon cycling in soil [21–24]. Albers et al. [25] demonstrated that soil microorganisms can rapidly mineralize atmospheric BVOCs taken up by the soil, thereby contributing to their removal from the atmosphere.

Although the net emission flux of SBVOCs is generally low, due to their high reactivity they play a key role in atmospheric chemistry and climate [26]. Research indicates that neglecting soil emissions can lead to an underestimation of ozone concentrations [27]. Additionally, SBVOCs can regulate the interaction between bacteria/fungi and plants. Root-derived BVOCs can recruit beneficial microorganisms, promote the formation of mycorrhizal symbionts, and enhance plant nutrient absorption capacity [28]. Bidirectionally, fungal volatile substances can stimulate plant root growth and activate defense [29].

Research on SBVOCs has gradually expanded from the initial quantitative observation of single-point fluxes to a comprehensive ecosystem covering spatial and temporal scales and multiple influence factors. However, there are significant gaps and uncertainties in understanding the process mechanisms for the source–sink transformation of SBVOCs, the quantitative attribution of dominant functional microbial communities, and their metabolic pathways. Therefore, this review examines how interacting production, transport, retention, and removal processes determine whether soils function as net sources or sinks of BVOCs under different environmental conditions. Compared with the previous description, we integrate source–sink mechanisms, compound-specific flux evidence, methodological uncertainty, and climate-driven controls within a unified framework.

2. Sources and Sinks of BVOCs

Soil is a complex ecosystem. It emits BVOCs primarily from plant roots, soil microorganisms, litter, and soil organic matter (SOM) decomposition. At the same time, it can also act as a sink, absorbing VOCs through physical and chemical processes. The exchange of BVOCs between the atmosphere and soil is described in Figure 1.

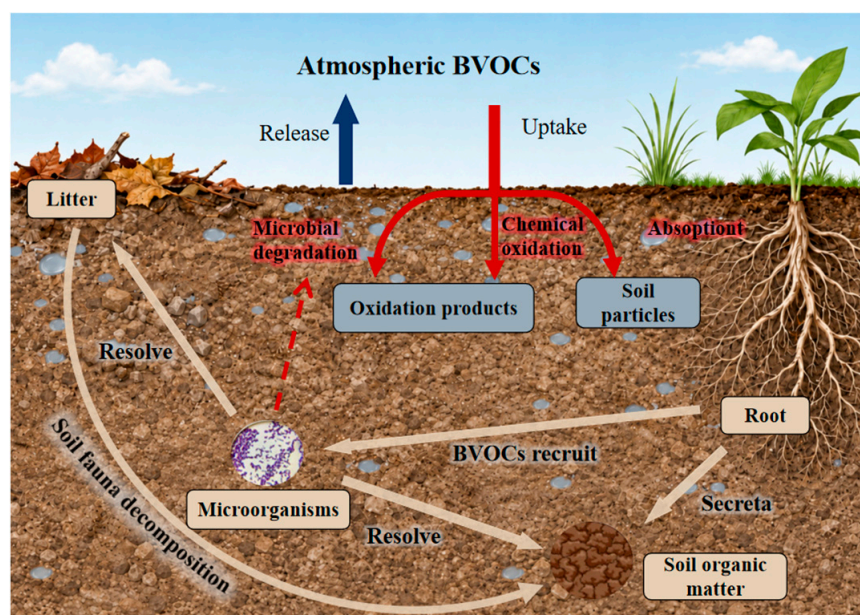


Figure 1. The exchange of BVOCs between the atmosphere and soil ecosystems, as well as the connections between emission sources. The faint yellow arrows indicate the production of BVOCs from the sources of soil (roots, microorganisms, litter, and soil organic matter). The red arrows represent the process of soil uptake of BVOCs.

2.1. Potential Production Compartments

2.1.1. Plant Root System

Plant roots constitute an important biological source of SBVOCs and can directly synthesize and release a wide range of compounds, including monoterpenes, sesquiterpenes, and other VOCs. Lin et al. [30] found that the root systems of pine trees can emit α -pinene, β -pinene, and various sesquiterpenes, of which concentrations in the rhizosphere soil are significantly higher than those in non-rhizosphere soil. BVOC quantity and composition emitted by the root systems can differ significantly among plant species. For example, pine roots emit mainly monoterpenes, while oak roots emit more sesquiterpenes [31]. Dehimeche et al. [32] conducted a study on eight tomato genotypes and found that the root system's BVOC emissions exhibited significant genotype specificity.

Soil temperature, moisture, and nutrient availability are the key environmental factors affecting root system BVOC emissions. Gray et al. [17] discovered that in the subalpine forest, the emission of certain BVOCs from soils with active root systems was positively correlated with temperature. Under drought, plants may increase the emission of specific BVOCs by roots as a stress response signal [4,33].

Root-derived BVOCs can shape the structure of the rhizosphere microbial community. Certain specific BVOCs can attract beneficial microorganisms or inhibit pathogenic microorganisms. Root-released methyl salicylate induces chemotaxis and colonization of beneficial rhizobacteria (e.g., *Bacillus subtilis*), promoting biofilm formation and defense gene expression [34]. Consequently, it enhances their antagonistic ability against soil-borne fungal diseases, constructing a "protective microbial barrier" centered around beneficial bacteria in the rhizosphere [35,36]. Root exudates can also reshape the soil microbial network structure on a larger spatial scale by finely regulating the resource allocation and signal exchange among different nutritional and functional types of microorganisms. Evidence from microcosm experiments and high-throughput sequencing has shown that root-emitted BVOCs can drive the changes in composition and interaction of complex soil biofilm communities [37,38]. Furthermore, by influencing the rhizosphere microbial community, BVOCs from microorganisms may also change.

2.1.2. Microorganisms

The main SBVOCs released by microorganisms include some intermediate metabolites and by-products generated during organic matter decomposition, including methanol, ethanol, acetone, and volatile fatty acids (including acetic acid and propionic acid) [39,40]. They also include some secondary metabolites including terpenoids and volatile signaling substances (including α -pinene, β -caryophyllene, 2-phenylethanol, geosmin, and 2-methylisoborneol) [41–47]. These compounds are common for actinomycetes and fungi, which can participate in chemical communication and antagonism between microorganisms and plants.

Taxon-specific BVOC profiles have primarily been characterized using isolated strains, genomic analyses, or controlled culture systems. In bacteria, *Streptomyces* and related actinomycetes possess diverse terpene synthases and can produce terpenoids, geosmin, and 2-methylisoborneol under laboratory conditions [23,48], and are involved in signal transduction and diffusion [46]. The Proteobacteria phylum includes several important categories as main producers of BVOCs and their relative abundances are positively correlated with BVOC emissions. *Pseudomonas* can produce not only sulfur-containing BVOCs to participate in chemical communication between species, but also ketones and alkynes [49]. *Burkholderia phytofirmans* PsJN releases metabolites including 1-hexanol, 3-methyl-1-butanol, and dimethyl disulfide to participate in the regulation of interspecies interactions in the soil microenvironment [50,51]. Obligate anaerobic bacteria release short-chain volatile fatty acids including butyric acid and propionic acid and sulfurous compounds through fermentation pathways under anaerobic conditions [52]. Culture-based studies show that soil fungi release diverse alcohols, benzenoids, aldehydes, ketones, furans, and terpenoids, with emission profiles varying among genera, species, strains, substrates, and growth conditions. For example, *Aspergillus* and *Penicillium* cultures produce characteristic blends dominated by alcohols, ketones, and furans [4]. However, most taxon-specific evidence has been obtained from isolated cultures or controlled interaction experiments, whereas rhizosphere and mycorrhizal studies generally reflect combined fungi–plant effects [53,54].

SBVOC emission from microorganisms exhibit a strong dependence on environment and ecology. A two- to threefold increase in emission rates per 10 °C rise in temperature corresponds to a Q_{10} value of approximately 2–3, indicating a high temperature sensitivity that is consistent with substantial biological control [12]. The peak emissions in the summer in high-latitude regions also reflect the sensitivity of microbial metabolism to temperature [5]. The pulse effect of precipitation can trigger a sharp increase in emissions by rapidly activating microorganisms and increasing substrate availability [19]. Furthermore, regulating microbial diversity systematically alters the “quantity and quality” of SBVOCs. A study showed that under similar microbial biomass, a decrease in diversity increases the total flux by 0.5 to 3 times, but reduces the variety of compounds. The relative abundances of the Proteobacteria phylum, Bacteroidetes phylum, and fungi are positively correlated with the flux, while some prokaryotic groups show a weak or negative correlation [55].

2.1.3. Litter

The BVOCs released from litter originate primarily from two sources: the gradual release of volatile compounds retained in plant tissues after senescence or death [56], and metabolites produced by microorganisms during litter decomposition [57,58]. BVOC emission and composition from litter can differ significantly among plant species, but plants with similar structures and microbial communities often exhibit similar BVOC emission patterns [17].

The decomposition stage of dead branches and fallen leaves also affects their BVOC emission. Multiple indoor microcosm and field experiments have shown that in the initial stage of decomposition, there is usually an emission peak dominated by terpenoids and other secondary metabolites that are synthesized and stored in the tissues before branches and leaves fall. During this stage, the proportion of monoterpenes, sesquiterpenes, and some aromatic compounds in the total flux is much higher. Subsequently, as the cell structure is destroyed and the easily decomposable substrates are exhausted, the total flux of BVOCs gradually decreases, and its chemical composition evolves towards a “microbial-driven” spectrum dominated by oxygen-containing volatile compounds including aldehydes, ketones, and low-molecular-weight organic acids [59–61]. The 99-day microcosm experiment using ^{13}C -labeled litter further confirmed that as decomposition progresses, more and more BVOCs can be attributed to the decomposition and re-synthesis of litter carbon by microorganisms [62]. A study reported that BVOC emissions from fallen Aleppo pine needles reach a peak approximately 3 months after decomposition begins, mainly consisting of terpenes including α -pinene, terpinenes, and β -caryophyllene; then, the fluxes of terpenes significantly decrease while the oxygen-containing BVOCs including methanol, acetone, and acetic acid increase. Different tree species can exhibit significant species-specificity along this succession [61,63].

In the vertical profile, the SBVOCs released by the litter layer are typically much higher than those in the mineral soil layer, with difference often reaching up to an order of magnitude in various systems [62,64]. The vertical variation is closely related to microbial biomass, CO_2 production rate, and substrate characteristics [24].

2.1.4. SOM

SOM is largely formed through the decomposition of plant and animal residues mediated by microbial activity, becoming another important source of SBVOCs. Although the emission flux of SBVOCs from SOM sources is usually lower than that from plant litter and roots, the vast microbial community in the soil can directly produce and release various BVOCs through the decomposition of SOM [65]. This process is closely related to soil respiration and the release of CO_2 , which both often occur simultaneously. Through microbial metabolism, SOM is converted into BVOCs and released into the atmosphere. Therefore, the composition and function of the soil microbial community play a crucial role in regulating the production quantity and emission rate of BVOCs from SOM sources [66]. However, it remains challenging to accurately distinguish and verify whether these VOCs are directly derived from SOM itself or the metabolic activities of soil microorganisms. Moreover, the emission intensity of SBVOCs is regulated by multiple environmental factors, further increasing the complexity of source tracing [67,68].

2.2. Soil as a BVOC Sink

The exchange of BVOCs between the soil and atmosphere is essentially bidirectional and maintains a dynamic balance. As a sink, soil removes BVOCs through physical adsorption, chemical transformation, and biological degradation. During the process of physical adsorption, BVOCs are fixed on the surface of soil particles through van der Waals forces or electrostatic interactions. This process is strongly time dependent: rapid uptake often occurs initially when adsorption sites are available, but sink strength declines as these sites become occupied and may partially reverse through desorption when temperature rises, moisture conditions change, or ambient BVOC concentrations decrease [69]. Therefore, physical sorption should be regarded as a reversible buffering mechanism rather than a permanent removal pathway. In particular, soils rich in organic matter and clay exhibit stronger adsorption capabilities [70,71]. There are significant

differences in adsorption efficiency among soil types [72]. Isoprenoids are more easily adsorbed in soils with high clay content [19,73]. Dissolution into soil water is a separate reversible partitioning process [69]. Soil moisture is a crucial influencing factor. The water phase formed by high humidity can facilitate the absorption of water-soluble or hydrophilic VOCs [69,72], and this pathway becomes increasingly important for polar compounds with high aqueous solubility [12]. Compounds with low Henry's law constants preferentially partition into soil water, whereas less soluble and more volatile compounds tend to remain in the gas phase.

Following sorption or dissolution, a fraction of BVOCs may undergo compound- and mineral-specific chemical transformations at soil interfaces. Adsorbed formaldehyde may undergo hydration and reversible oligomerization, while reactions on mineral oxides can convert it to formate through surface-bound dioxymethylene [71]. Chemical oxidation may ultimately mineralize a fraction of soil-retained BVOCs to CO₂ and H₂O [74]. However, direct evidence for complete abiotic mineralization of BVOCs on natural soil surfaces remains limited, because most soil uptake studies have not quantified CO₂ production or established a complete carbon balance [12,25]. Chemical transformation may also occur concurrently with microbial degradation. Microbial nitrification and denitrification, together with nitrite-related surface reactions, can release nitric oxide (NO) and nitrous acid (HONO) from soils [75]. Photolysis of HONO provides an important near-surface source of OH radicals, thereby accelerating the atmospheric oxidation of soil-emitted BVOCs [74,76].

Biological degradation is the most important mechanism for soil acting as a sink for BVOCs. A large number of microorganisms can utilize BVOCs as a carbon source and energy for metabolic activities. For example, methylotrophic bacteria can efficiently degrade methanol, while isoprenoid-degrading bacteria specifically decompose isoprene. These microorganisms gradually decompose BVOCs through enzymatic reactions, ultimately converting them into cellular substances or completely mineralizing [66,77]. Microbial degradation operates over a broad timescale ranging from several hours to multiple days. For example, BVOCs such as methanol, benzaldehyde, acetophenone, and geraniol can be rapidly mineralized by soil microorganisms within hours. In contrast, p-cymene is mineralized more slowly in some soils, with substantial differences among soil types, whereas chloroform exhibits consistently slow mineralization across all tested soils, extending over several days or longer [25].

The absorption capacity of different ecosystem types of soil also varies. Generally, forest soil with high organic matter content has a stronger absorption capacity than barren desert soil [19,66,77]. On the spatial scale, there is a vertical gradient in the absorption of BVOCs [12,77]. The surface soil (0–10 cm in depth) usually exhibits the strongest absorption capacity due to its high microbial biomass and abundant organic matter. On the time scale, the absorption rate shows seasonal variations, typically reaching its peak during the plant growing season, which is consistent with the seasonal pattern of microbial activity [12,19,20].

The source–sink status of soil is defined by the direction of the net BVOC flux across the soil–atmosphere interface, reflecting the balance between gross production and release and concurrent uptake, retention, and degradation. Field studies show strong seasonal reversals between source and sink states. In a Mediterranean forest, soil was an annual net sink for isoprenoids, with the highest summer uptake, but became a source in spring and autumn [19]. Among abiotic controls, soil moisture appears to be the most important switch. In an experimental rainforest soil, prolonged drought progressively reduced sink strength, and the soil became a net source of several BVOCs when soil moisture declined below approximately 19% [43]. But in Mediterranean forest soils, long-term drought reduced

SBVOC emissions by 43% [73]. Warming can enhance volatilization, diffusion, root activity, and microbial production, but it may simultaneously stimulate microbial degradation or indirectly suppress production through soil drying [6,78]. Nutrient availability also affects SBVOC fluxes. Tropical soils have been reported to act as BVOC sinks under ambient conditions, while nitrogen or phosphorus fertilization may shift the system toward emission [20]. Overall, the factors influencing this transformation are mutually influencing, and each is different in each ecosystem.

2.3. Dominant Components

Microorganisms in the soil release isoprene by decomposing litter and themselves produce isoprene (Table 1). However, plant roots produce relatively less isoprene. A study by Tsuruta et al. [79] revealed that the isoprene emissions from the bare roots of 15 different tree species were below the analytical quantification limit. Moreover, most studies have shown that the soil may act as a net sink for isoprene, especially under conditions of high microbial activity [17,20]. The roots and fallen leaves of coniferous trees can release monoterpenes. For example, in the surface of coniferous forests in southern Finland, monoterpenes account for over 90% of the total SBVOC emissions [13]. In subalpine forests, the roots contribute significant monoterpene emissions [17]. Staudt et al. [15] noted that, after the removal of litter, the emission flux of monoterpenes in the soil remained at a relatively high level, which indicates that other SBVOC emission sources are also important sources of monoterpenes [20]. The emission of soil sesquiterpenes is related to microbial activities [80]. Fungal emission of sesquiterpenes is primarily linked to growth phases rather than fungal biomass. Fungi release substantially greater quantities of sesquiterpenes during early growth stages compared to mature phases, even though biomass tends to be higher in the latter [81]. Under certain environmental conditions, the soil emissions of sesquiterpenes can be comparable to those from the tree canopy, which is proved by a study in the Amazon during the dry season [14]. Most studies have shown that the sesquiterpenes in the soil show a trend of emission [12,14].

Table 1. Source and distribution of major compounds.

Category	Compounds	Source			Sink
		Litter	Root	SOM	
Terpenoid	Isoprene	++	+	+	--
	Monoterpene	+	+	+	-
	Sesquiterpene	+	+	+	-
Alcohol	Methanol	+	+	++	-
	Ethanol	+	+	++	-
Aldehydes	Acetaldehyde	+	+	+	-
Organic Acid	Formic acid	++	++	+	--
	Acetic acid	+	++	++	--
Thioethers	Dimethyl sulfide	+	+	+	-

Note: ++ indicates strong emission, + indicates moderate emission, - indicates weak absorption, -- indicates strong absorption.

Oxygenated VOCs constitute another major class of SBVOCs. Methanol is one of the most significant SBVOCs. It can be produced through physical, chemical, and biological processes (such as the decomposition of lignin and pectin). Plant roots are an important source of methanol, especially during plant growth and maintenance [17,82]. At the same time, methylotrophic bacteria in the soil can consume methanol, resulting in the net absorption of methanol by the soil in certain ecosystems [25,83]. Ethanol is a typical product of anaerobic fermentation and is released in large quantities in submerged roots [84].

Smith et al. [85] found ethanol is the main fermentation product of Alders' roots. Short-chain aldehyde compounds formaldehyde and acetaldehyde are also important SBVOCs. Soil could produce formaldehyde through the demethylation reaction of methylotrophic bacteria [71,86]. Acetaldehyde is mainly released by submerged roots and litter, and it may also be an intermediate product of ethanol oxidation [43,87]. It is worth noting that most studies have shown that soil, in general, acts as a sink for these compounds [12,25,71]. Formic acid and acetic acid are the most common soil-emitted organic acid. Researches have shown that tropical savannas soil release formic acid and acetic acid during the dry season, with average daily emission fluxes being 23.2 and 15.1 $\mu\text{g m}^{-2} \text{h}^{-1}$, respectively [88]. Additionally, formic acid and acetic acid can have relatively high absorption rates in the Mediterranean forest [89]. Acetone emissions can result from both biotic litter decomposition and abiotic release processes. Heating and rewetting plant litter can induce substantial acetone emissions through physicochemical processes. It is notable that the soil moisture will affect the mechanism of acetone production. Acetone in dry soil may come from microbial production in the deep soil, while in wet soil, its source is more likely to change to the surface physical processes [58,59].

Benzenoid compounds constitute another important category of SBVOCs. Studies have shown that both soil organic carbon (SOC) and fallen leaves can release various benzene compounds [9,12]. In addition, soil microorganisms can rapidly decompose compounds such as benzaldehyde and convert them into CO_2 through enzymatic reactions. This indicates that soil also has a certain absorption for benzenoid compounds [77].

Dimethyl sulfide (DMS) has relatively low concentrations in SBVOCs but are not to be ignored. DMS can be produced through the aerobic metabolism of sulfur-containing amino acids. Research has shown that tropical rainforest soil can significantly accumulate DMS concentrations at night [12].

3. Measurement Methods for SBVOC Fluxes

3.1. Chambers

Dynamic chambers are generally preferred for BVOC flux measurements because continuous airflow and controlled inlet air help maintain more stable enclosure conditions and reduce concentration-gradient artifacts compared with closed static chambers [90,91]. Even so, dynamic systems are not artefact-free: field testing showed underestimation of artificially generated BVOC fluxes by roughly 5–30% for isoprene, monoterpenes, and many oxygenated BVOCs [92]. Static chambers remain useful when fluxes are small and instrumentation is less sensitive, because longer accumulation can improve detectability and in some settings static GC-based approaches can outperform low-precision dynamic systems for individual-measurement uncertainty [93].

3.2. Analytical Method

PTR-MS provides high sensitivity and fast response for online flux work, which is why it underpins many long-term or ecosystem-scale BVOC studies [94,95]. Its main weaknesses are humidity dependence, fragmentation, compound ambiguity, and background drift, all of which require frequent calibration [96,97]. Fragmentation can contribute up to 50% of signal at masses commonly assigned to isoprene in some settings, and GC pre-separation improves interpretation and correction of those interferences [98]. GC-MS and TD-GC methods trade time resolution for speciation confidence and lower ambiguity. TD-GC-MS on soil and forest-floor samples has been widely used to resolve monoterpenes and sesquiterpenes that online bulk signals cannot separate cleanly [90,99].

3.3. Isotopic Tracing

Stable isotopes can bound or estimate contributions from multiple sources, but identifiability depends on the number of tracers, source separation in isotopic space, and explicit reporting of uncertainty rather than single-point estimates [100]. Their limitation is that physical and biochemical processing can enrich or deplete signatures over space and time, weakening simple source to sink assumptions [101]. Rhizosphere microcosms and microscale imaging offer process resolution that field chambers lack. Microdialysis and microsensors can measure concentration and flux at submillimeter scales with less invasion than coring, while intact rhizosphere imaging combined with ^{13}C or ^{15}N tracing reveals where plant-derived carbon moves among roots, microbes, fungi, and minerals [102].

3.4. Disturbance

The biggest biological artefacts arise when source-partitioning manipulations alter the system they are supposed to isolate. Understory vegetation removal can help separate aboveground and belowground exchange, but it also changes root emissions and microbial community composition [12]. Litter removal, root exclusion, and trenching similarly change soil temperature, moisture, dissolved carbon, microbial activity, and nutrient dynamics, so flux differences after treatment reflect both source removal and treatment-induced ecological change [91,103]. Long-term detritus manipulations show that litter removal can warm and dry soils, while root exclusion can alter persistent organic carbon pools and respiration [104,105]. Some studies intentionally reconstruct simplified systems to isolate components, those designs are useful for mechanism, but they are not direct estimates of intact in situ net exchange, which is why gradient or ecosystem-scale flux methods remain important complements [95,106].

4. Abiotic Factors Affecting SBVOC Emission

The emission process of SBVOCs is subject to complex regulation by various abiotic factors, including the soil temperature, moisture, and physical and chemical properties, as well as atmospheric environment. These factors interact with each other and still exhibit variations among different compounds, ecosystems, and source-sink processes. They can influence the generation and consumption of BVOCs by altering the activity and metabolic pathways of microbial communities, and regulate the BVOC emission fluxes by affecting their diffusion within soil pores and distribution at the gas–liquid–solid interface.

4.1. Soil Temperature

Soil temperature is a key factor in regulating the emissions of SBVOCs. An increase in soil temperature generally enhances the metabolism of microorganisms and enzyme reactions, thereby accelerating the decomposition of organic matter and the generation of SBVOCs [90]. In studies of Mediterranean shrubland and subalpine forest soils, the total emissions of SBVOCs are positively correlated with soil temperature [17]. However, there are nonlinear relationships between soil temperature and BVOC emission. When the temperature exceeds a threshold, the emission may stabilize and even decrease, which is related to the limitation of microbial activity and substrate consumption [30,91].

4.2. Soil Moisture

Soil moisture can alter the environment matrix of microorganisms and the efficiency of gas transmission. Appropriate moisture conditions generally promote the activity of aerobic microorganisms, thereby increasing the production of BVOCs [107,108]. Water saturation may induce anaerobic metabolic pathways, resulting in the production of fermentation products including ethanol and butyric acid [12,109]. Meanwhile, the adsorption

capacity for BVOCs by soil also weakens under drought stress, leading to the increase on net emission. In research on the Amazon tropical rainforest, soil sesquiterpene emissions are higher during the dry season, comparable to that from the plant canopy [14]. Alternating dry and wet conditions often trigger intense pulse-like emissions. When the soil is re-moistened after drought, the microbial activity will instantly increase, causing the soluble organic carbon accumulated during the previous drought to be rapidly mineralized, resulting in enhancement of BVOC emissions [110,111].

4.3. Soil pH

Soil pH alters the generation and transformation of BVOCs by influencing the structure of microbial communities, enzyme activity, chemical reaction environment, and adsorption-desorption equilibria. Acidic soils tend to promote the dominance of fungi, and neutral and slightly alkaline soils are more conducive to the diversity and metabolic activity of bacteria [12,112]. Soil pH regulates key enzyme activities and shifts aromatic degradation pathways, thereby directing metabolic flux toward either complete mineralization or transient intermediate formation [113]. In addition, pH also affects the solubility, adsorption capacity, and volatility of organic compounds in the soil by altering their ionization state. A higher pH can significantly reduce the emission of carboxylic acid-based BVOCs [114]. For non-polar terpenoid emission, pH has impacts mainly through influencing structure of the microbial community and regulation of enzyme function [115].

4.4. Chemistry and Physics of the Atmosphere

Atmospheric physical processes regulate soil-atmosphere BVOC exchange mainly by modifying transport conditions. Wind and turbulence reduce aerodynamic resistance and promote the transfer of BVOCs across the soil surface, while pressure fluctuations may drive soil-air pumping and short-term emission pulses [116]. Under stable conditions, soil-derived BVOCs can accumulate near the forest floor, whereas turbulent mixing enhances their upward transport and dilution [117]. Rainfall and snowmelt may also displace VOC-rich pore air [94].

Atmospheric OH radicals, O₃, and NO₃ radicals can oxidize BVOCs in the near-surface atmosphere, thereby reducing the concentrations of their parent compounds and altering the concentration gradient across the soil-atmosphere interface [118]. For bidirectionally exchanged compounds such as methanol, a decrease in ambient concentration may enhance soil emissions or weaken soil uptake, whereas an increase in ambient concentration may promote deposition and uptake by soils [70]. In addition to altering gas-phase concentration gradients, atmospheric oxidants, including O₃, OH radicals, NO₂, and peroxides, may deposit onto soil surfaces and promote heterogeneous reactions on soil mineral surfaces. Using sterilized soils, Li et al. [69] observed that most ambient VOCs were taken up by the soil, whereas formic acid was released. They therefore proposed that deposited VOCs may undergo further oxidation on mineral surfaces, leading to the formation and subsequent emission of formic acid.

4.5. Other Factors

4.5.1. Fire Effects on SBVOC Emissions

The impact of fires on the emission of BVOCs by soil-dwelling organisms shows a distinct spatiotemporal non-steady state. In the short term, it is mainly characterized by strong pulse releases [119–121], while in the long term, it is more manifested as changes in emission capacity and the establishment of a new steady state [122,123]. Fires affect SBVOC emissions through three main pathways. First, high temperatures cause existing volatile components to escape and generate new low-molecular-weight substances [124]. Second, burning removes surface organic matter, reducing the carbon sources and precursors for

microbial synthesis of BVOCs over a long period. Third, fires change soil temperature, moisture, redox conditions, and microbial community structure, thereby influencing the production pathways of microbial metabolites [123].

The impact of wildfires on the fluxes of SBVOCs may be temporary, since fires cannot completely eliminate all microorganisms [125]. Low-intensity fires have minimal impact on soil microorganisms, while extremely intense fires may lead to complete sterilization of the soil surface layer [126]. However, a study conducted by Köster et al. [127] in Valiol showed that the impact of wildfires on soil carbon can persist for decades. Zhang-Turpeinen et al. [122] indicate that the forest floor (including surface vegetation, soil organic matter, and soil microbial communities) in the 48-year-old area has recovered from the wildfire, resulting in an increase in BVOC fluxes. These findings highlight the complexity of post-fire BVOC dynamics, where recovery trajectories are shaped by multiple interacting factors.

4.5.2. Climate Effects on SBVOC Emissions

Climate change reshapes the emission patterns of SBVOCs through temperature increase, water redistribution, precipitation pattern changes, and nitrogen deposition increase [128]. A direct increase in temperature can directly enhance the volatilization and diffusion of VOCs stored in soil and litter and may also stimulate their biological production by increasing microbial and enzymatic activity [73]. Warming can indirectly affect the SBVOC exchange by altering soil moisture. Moderate drying may increase gas diffusivity within soil pores and thereby facilitate BVOC release. In contrast, severe drought can suppress microbial activity, reduce root exudation, limit litter decomposition, and decrease substrate turnover [129].

In the long term, climate change can alter the capacity of ecosystems to produce and consume BVOCs by plant community replacement and soil microbial community reorganization. Climate warming and recurrent drought can alter ecosystem vegetation composition by selecting for heat- and drought-tolerant plant species. Such vegetation succession can systematically modify the chemical composition of root exudates and litter, thereby changing the composition and availability of substrates used by soil microorganisms for SBVOC production [130]. In parallel, warming may shift the taxonomic and functional composition of soil microbial communities. Changes in the relative abundance of microbial taxa or functional guilds with different capacities for SBVOC production and consumption can consequently alter the composition, magnitude, and even direction of net soil SBVOC fluxes [131]. Notably, these biological reconstructions show significant differences in different habitats, such as alpine, Mediterranean-type arid, and mixed coniferous-leaved forests [132]. In the high northern region, long-term warming can change the microbial metabolic window through thawing and soil melting, inducing new seasonal BVOC emissions. In the Mediterranean-warm dry scenario, net BVOC emissions overall decrease and are accompanied by changes in the relative abundance of aromatic/terpenoid compounds [133]. A study also shows that mycorrhizal associations have an important regulatory effect on SBVOCs—changes in mycorrhizal communities significantly affect the net fluxes of BVOCs in the rhizosphere and soil layer, suggesting that plant-microbe interactions are key amplifiers or buffers in climate-driven responses [132].

5. Ecological Functions of SBVOCs

SBVOCs play a crucial ecological regulatory role in the soil-plant-microbe system. Due to the enclosed and heterogeneous soil pores, SBVOCs have higher locality and stronger signal accuracy than the aboveground BVOCs, making them an important “chemical language” of ecological processes underground.

The best-supported functions involve microbial VOC uptake and short-term changes in soil carbon and nitrogen transformations. In laboratory soil incubations, low-molecular-weight VOCs such as methanol and acetone caused transient increases in microbial respiration, contributed to the labile soil carbon pool, and inhibited nitrification [134]. However, most evidence has been obtained from short-term or enclosed experimental systems and does not establish that SBVOCs regulate long-term soil organic carbon storage or whole-ecosystem carbon budgets [25]. Microbial BVOCs can act not only as antagonistic compounds that suppress soil-borne pathogens, but also as signaling molecules in plant-microbe communication. After diffusing through soil pore spaces, these compounds can be perceived by plant roots and modulate hormone- and defense-related signaling pathways, thereby altering root architecture, nutrient acquisition, and systemic resistance [135].

Root-derived SBVOCs can mediate in plant-to-plant and plant-to-microbe interactions, and regulate plant community structure, below ground competition, disease suppression, and nutrient utilization efficiency. Current evidence is derived primarily from soil odor detectors, pot experiments, and microbial systems simulating soil [136,137]. For example, they can be in stable chemical gradient in the rhizosphere and be sensed by the root systems of adjacent plants, thereby regulating their growth and root morphology and inducing their defense [4,138]. In addition, SBVOCs will change the foraging and egg-laying preferences of insects to attract or deter their feeding in the rhizosphere [139]. In the underground ecosystem, SBVOCs can reshape the community functional profile by selectively stimulating or inhibiting specific communities (such as cellulose-degrading bacteria, ammonia-oxidizing bacteria, or denitrifying bacteria), thereby altering the carbon and nitrogen cycling rates and the spatiotemporal patterns of greenhouse gases (CO_2 and N_2O) emissions. In terms of biological control and multi-nutrient-level interactions, volatile mixtures from soil microorganisms or plants have been proven to have various attracting, repelling, and lethal effects on soil animals (such as parasitic nematodes) and soil-root-associated insects. This demonstrates the potential pathways for regulating pest populations and attracting natural enemies through VOCs.

6. Spatial Variations of SBVOC Emission

The observations compiled in Table S1 reveal substantial spatial and temporal variability in soil-atmosphere BVOC exchange. To provide a clearer overview of these patterns, Figure 2 summarizes the predominant net flux direction and relative magnitude of major VOC classes across climatic zones. Variability within the same climatic zone is often greater than that among climatic zones. Negative net fluxes represent atmospheric uptake, whereas positive values indicate net emission.

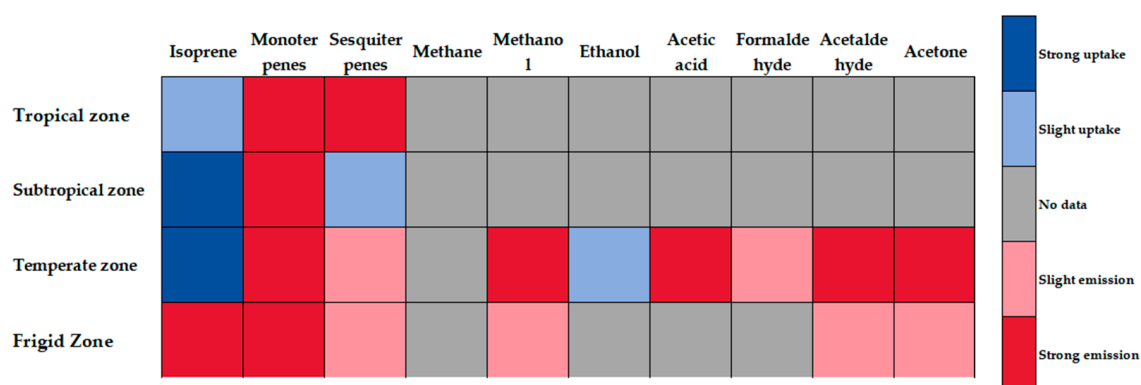


Figure 2. The distribution of main SBVOC fluxes in each climate zone. The data used to construct this figure were compiled from Table S1.

In tropical and subtropical ecosystems, soils frequently act as sinks for isoprene, whereas monoterpene and sesquiterpene fluxes are more variable. In the Amazon rainforest, net isoprene fluxes ranged from -2.41 to $-0.10 \mu\text{g m}^{-2} \text{h}^{-1}$ across seasons and litter treatments, while monoterpenes and sesquiterpenes shifted between weak uptake and emission. In French Guiana, monoterpene exchange changed from uptake during the dry season to emission during the wet season, whereas strong sesquiterpene uptake occurred under wet conditions. Nutrient addition substantially altered these patterns, with nitrogen and phosphorus treatments producing monoterpene and sesquiterpene emissions of up to 406 and $210 \mu\text{g m}^{-2} \text{h}^{-1}$, respectively. In a subtropical *Eucalyptus urophylla* plantation, isoprene, monoterpenes, and sesquiterpenes all showed net uptake. Removing litter strengthened isoprene and monoterpene uptake but reduced sesquiterpene uptake, indicating that litter can function simultaneously as a volatile source and as a regulator of soil sink strength. By contrast, subtropical pine and evergreen broadleaf forests at Dinghushan exhibited substantial monoterpene emissions, ranging from approximately 36 to $137 \mu\text{g m}^{-2} \text{h}^{-1}$.

Temperate ecosystems display particularly pronounced seasonal and compound-specific variability. In Mediterranean soils, monoterpene fluxes ranged from strong uptake to moderate emission, including seasonal values from -27.96 to $5.48 \mu\text{g m}^{-2} \text{h}^{-1}$. Experimental drought in a French deciduous forest increased isoprene uptake and changed monoterpenes from a net emission of $0.91 \mu\text{g m}^{-2} \text{h}^{-1}$ to near-neutral or weak uptake. Root and litter treatments further produced large differences among source compartments. For example, root-associated measurements in a subalpine forest showed substantially stronger isoprene uptake than measurements dominated by soil and litter alone. Temperate agricultural soils were generally weak sources of terpenoids, but methanol fluxes ranged from uptake to emissions exceeding $500 \mu\text{g m}^{-2} \text{h}^{-1}$, suggesting that crop phenology, soil management, and short-term environmental conditions can dominate oxygenated-VOC exchange.

Boreal, subarctic, and frigid ecosystems should not be characterized uniformly as weak SBVOC sources. Swedish boreal forest soils emitted approximately $3.18\text{--}10.17 \mu\text{g m}^{-2} \text{h}^{-1}$ of monoterpenes across summer and autumn measurements, while a subarctic heath emitted $9.38 \mu\text{g m}^{-2} \text{h}^{-1}$ of isoprene during the growing season. Finnish boreal soils commonly emitted monoterpenes at rates of approximately $5\text{--}49 \mu\text{g m}^{-2} \text{h}^{-1}$, while measurements from different soil-profile depths reached $61.9 \mu\text{g m}^{-2} \text{h}^{-1}$.

7. SBVOC Exchange Modeling

Modeling studies of SBVOC exchange remain relatively limited and are dominated by empirical or site-specific statistical approaches. Most existing models relate measured fluxes to environmental variables such as soil or chamber temperature, soil moisture, relative humidity, photosynthetically active radiation, and litter properties [58,80,106]. For example, Mäki et al. [94] developed a mixed-effects linear model based on an eight-year forest-floor data set. After accounting for chamber-specific variability, temperature, relative humidity, and above-canopy radiation, the model explained 79–88% of the variation in monoterpene, methanol, acetone, and acetaldehyde fluxes. However, the model underestimated high flux events and was not directly transferable to other ecosystems.

Because soil can simultaneously produce and consume BVOCs, bidirectional exchange models are more appropriate than emission-only parameterizations. Bachy et al. [70] modeled soil–atmosphere methanol exchange as the balance between internal production and adsorption–desorption, reproducing emission under warm, dry conditions and uptake under cool, wet conditions. Their results indicate that net flux is jointly controlled by

temperature, moisture, ambient VOC concentrations, surface resistance, sorption capacity, and biological consumption.

Tang et al. [12] proposed a process-oriented framework that integrates SBVOCs into ecosystem models through coupled vegetation, soil-climate, and soil-biogeochemical modules. In this framework, BVOCs are produced from litter decomposition, soil organic carbon, and roots, while microbial uptake regulates their consumption. Temperature, water-filled pore space, substrate availability, litter quality, and root biomass are used to parameterize these biological processes. More detailed implementations may additionally distinguish gaseous, dissolved, and particle-adsorbed BVOC pools and simulate diffusion, dissolution, and adsorption–desorption within different soil layers.

8. Conclusions

SBVOCs play a vital role in linking terrestrial ecosystems and the atmosphere by exchanging material and transferring information. They are released through plant root exudates, microbial metabolic products, decomposition of SOM, and litter degradation. They also act as a sink by adsorbing atmospheric VOCs through physical adsorption, chemical oxidation, and biological degradation, thus forming a “source–sink” dynamic balance. Their emissions are co-regulated by abiotic and biotic factors, driving the transition between source and sink roles, and playing a crucial role in the soil–plant–microbe system. Future research should therefore prioritize coordinated, long-term measurements that distinguish net exchange from gross production and uptake across intact field systems and controlled experiments.

Current process-based models are limited by sparse field observations and incomplete representation of bidirectional source–sink processes. Uncertainty in compound-specific production, uptake, and environmental responses further reduces their predictive accuracy. Addressing these gaps through improved field measurements and process characterization would provide essential soil parameters for more comprehensive BVOC emission and land–atmosphere exchange models. Distinguishing the contributions of different sources is crucial for understanding the biological processes and ecological functions underlying SBVOC production. However, SBVOCs have diverse sources and complex pathways of formation and consumption dynamics in soil being strictly regulated by environmental conditions. This makes the quantification of contributions from different biological sources challenging.

Moreover, our understanding of the diversity of biological interactions occurring in the rhizosphere among plants, microorganisms, and arthropods within the soil system remains limited. Integrating microbial metagenomic analysis may help explore the role of different compounds in selectively influencing the microbial communities in the rhizosphere.

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