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Ubiquitous and Underestimated?
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Published in:
Journal of Geophysical Research: Biogeosciences

DOI:
10.1029/2020JG005773

Publication date:
2020

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Soil Uptake of Volatile Organic Compounds: Ubiquitous and Underestimated?

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Abstract Volatile organic compound (VOC) emissions from ecosystems to the atmosphere have been widely studied, and the importance of soil contributions to VOC fluxes has received increasing attention. We suggest that while soil VOC emissions may be important in some situations, soil uptake of VOCs by microbial degradation is likely an omnipresent process, as also recently suggested by Trowbridge et al. (2020, https://doi.org/10.1029/2019JG005479). To be able to model net VOC fluxes, we need to be able to estimate both soil release and uptake processes and their drivers.

Plain Language Summary Plants are a well-known source of short-lived trace gases other than methane—so-called volatile organic compounds (VOCs)—to the atmosphere. Much less is known about the role of soil. Here, we discuss the importance of soils and their microbial communities in the release and uptake of VOCs between ecosystems and the atmosphere, inspired by the findings of a recent study by Trowbridge et al. (2020, https://doi.org/10.1029/2019JG005479). We highlight that microorganisms living in soil can degrade VOCs and speculate on the potential importance of soils as a sink of VOCs.

1. From Emissions to Uptake

Ecosystems release about 1,000 Tg of carbon to the atmosphere annually as volatile organic compounds (VOCs) (Guenther et al., 2012), a diverse group of chemicals, mostly with short atmospheric lifetimes. Until recently, attention has focused on the quantification of VOC emissions, which influence local air quality, as a result of ozone and particle formation, and climate, via complex contributions to climate-aerosol feedbacks (Arneth et al., 2010). Vegetation is the primary source of biogenic VOCs to the atmosphere, but soils also contribute significant emissions, at least in specific situations, like the dry season in the Amazonas (Boursoukidis et al., 2018), permafrost thaw in the Arctic (Kramshøj et al., 2018), or shoulder seasons in boreal forest (Miiki et al., 2019). More recently, advances in instrumentation that have allowed for continuous measurements in situ have led to observations of bidirectional ecosystem VOC fluxes (Millet et al., 2018; Park et al., 2013) that have highlighted the importance of both emissions and deposition.

But what does the deposition actually mean? Atmospheric deposition can be “dry,” where free or particle-bound atmospheric trace gases deposit directly onto the surface, or “wet,” when dissolved in or scavenged by precipitation. From a biogeochemical perspective, this definition is not satisfactory; we want to know what happens to the VOCs showing negative (“deposition”) fluxes, that is, uptake from the atmosphere to the ecosystem, and how the compounds participate in biogeochemical cycles. A recent paper by Trowbridge et al. (2020) provides new information on the ecosystem uptake of VOCs, whereby soils and their microbial communities play a central role.

2. Battle of Processes in a Complex Environment

VOC uptake in soil can be divided into transfer processes from the atmosphere to soil and sink processes within the soil (Figure 1). The transfer processes are primarily driven by advection and concentration gradients. The higher the atmospheric concentration and the smaller the stagnant boundary layer above the soil, the more VOCs will be transported from the atmosphere to the soil. Sink processes are numerous, but may overall be divided into adsorption, dissolution, and degradation (see also Tang et al., 2019). VOCs may
Trowbridge et al. (2020) report net flux of VOCs from the forest atmosphere to soil (red arrow) and its dependence on tree types and soil temperature. The question mark indicates the uncertainty of the magnitude of soil VOC uptake.

The study does not suggest that ECM fungi were responsible for VOC uptake but that the higher uptake in ECM soil relative to arbuscular mycorrhizal soil was related to differences in activity of the soil microbial communities present (Trowbridge et al., 2020). In fact, we have limited understanding of the organisms responsible for VOC consumption in soil. One reason for this is the simple fact that the vast majority of soil microorganisms cannot be cultured with current cultivation techniques (Chaudhary et al., 2019; Vartoukian et al., 2010). Soil microbial communities readily mineralize VOCs and mineralization rates, and capacity seem to be optimized to follow the VOC blends in their particular environment (Albers et al., 2018). For example, the microbial uptake of isoprene (Cleveland & Yavitt, 1997; Cleveland & Yavitt, 1998; Gray et al., 2015) could be highest in soils from ecosystems with strong isoprene emitters. Such an adaptation is well known for many other organic compounds. For example, trichloroacetic acid is degraded rapidly and without a lag phase in forest soil, where it is formed naturally, but degraded slowly and with a lag phase in agricultural soil, where this compound only occurs when it is applied as a herbicide (Albers et al., 2010). The continuous, or regular, availability of an organic compound in soil leads to the growth of microorganisms capable of degrading the compound or to activation of the enzyme systems required for degradation. Such increases in degradation potential have been shown for many herbicides and other pesticides (Arbeli & Fuentes, 2007). The same phenomenon likely also applies to VOCs: Increasing inputs stimulate degradation.

Isoprene is the VOC emitted at the highest rates from vegetation, with a global annual net emission of 500 Tg (Guenther et al., 2012). But actually, we do not know the gross ecosystem emission of isoprene because we have only rough estimates of the soil uptake capacity. All types of living organisms, including microbes, release isoprene (McGenity et al., 2018), but significant isoprene emission is rarely reported for soils. This is likely simply due to isoprene consumption exceeding its production. Could soil consumption by microorganisms be responsible for reducing ecosystem emissions by 20.4 Tg per year, as earlier suggested (Cleveland & Yavitt, 1997)? During daytime, isoprene has a lifetime of 1–2 hr in the atmosphere, where it reacts with hydroxyl radicals, nitrogen oxides, and ozone (Pacifico et al., 2009). Is that long enough for the molecules to reach the soil and be consumed by soil microbes prior to atmospheric oxidation? This is dependent not only on the atmospheric reactivity but also on wind characteristics, atmospheric segregation, and the distance of the isoprene source from soil. Therefore, isoprene consumption might be most important for emissions arising from litter and low-statured vegetation.
Soil uptake is likely more important for compounds with lower reactivity in the atmosphere, like methanol, which has an atmospheric lifetime of about 10 days (Jacob et al., 2005). Methanol is released from plant leaves upon growth, when the cell walls are expanding (Hu¨ve et al., 2007), showing clear seasonal and diel patterns in ecosystem emissions (Wohlfahrt et al., 2015). It is also released from decomposing leaves when cell walls are broken down by decomposing microbes (Gray et al., 2010; Schink & Zeikus, 1980). Soil emissions of methanol originate both from abiotic and biotic sources (Asensio et al., 2008; Jiang et al., 2010; Kramshøj et al., 2018). The same soil can also switch between releasing methanol when dry and consuming methanol when wet (Bourtsoukidis et al., 2018). In ecosystem measurements, methanol deposition has been reported in the early morning and suggested to be related to dissolution of the water-soluble methanol to the surfaces moist with morning dew (Schallhart et al., 2016). Trowbridge et al. (2020) report soil methanol uptake during the daytime and suggest that the uptake was due to microbial activity. Indeed, it is well known that methanol-oxidizing bacteria, from a range of phylogenetic groups, are widely present in soils (Kolb, 2009; Stacheter et al., 2013). Recently, it was shown that complete methanol degradation to CO2 in soil may be very fast at environmental methanol concentrations (Albers et al., 2018). What actually influences methanol degradation capacity in soil is, on the other hand, not well known. It has been suggested that the community structure of methanol-oxidizing bacteria in forest soils is influenced by plant diversity and soil pH (Stacheter et al., 2013), but so far the evidence has been limited. The new study by Trowbridge et al. (2020) supports this view and demonstrates that soil parameters related to different mycorrhizal communities may be important.

For compounds like methanol, microbial uptake is likely comparable to what we know of methane uptake. Methane oxidation in soil is the most important biogenic sink for this important greenhouse gas and is performed by distinct groups of bacteria adapted to methane oxidation, either in atmospheric concentrations or at the elevated concentrations present in soils with methane production in their waterlogged anoxic layers (Ho et al., 2013). Perhaps the same is true for some VOCs. Methanol and ethanol, released in high concentrations from thawing permafrost especially when the frozen soil had a high water and organic matter content, were microbially consumed in the well-aerated surface soil (Kramshøj et al., 2018). Actually, it may be a common phenomenon that soil VOC emissions consist of just a minor fraction of the gross VOC production in soil due to simultaneous microbial degradation. In a completely different setting, this process is used to our advantage for mitigating emissions of harmful cocktails of VOCs from waste disposal landfills: Covering landfills with soil layers reduces VOC release to the atmosphere, thanks to the microbial biodegradation of VOCs (Bogner et al., 2003; Schueit & Kjeldsen, 2005).

3. Relevance and Future Directions

How large is the soil sink of VOCs? If VOCs are released from soil in the same way as gases from thawing permafrost or methane produced in deeper, anoxic soil layers, they are likely largely taken up by microorganisms, while diffusing toward the atmosphere through the oxic soil layers (Kramshøj et al., 2018). However, it is uncertain how important microbial VOC uptake in soil is for compounds originating from aboveground sources, such as tree canopies, which are the major biogenic VOC source. Experiments using isotope-labeled compounds in situ could be a starting point for assessing the relevance of atmospheric-soil fluxes of VOCs, with focus on top soils, which typically harbor higher microbial biomass and activity than deeper soil layers. For example, VOCs labeled with stable isotopes, like 13C, may allow for simultaneous determination of production and consumption fluxes, as has previously been shown for methane and methyl halides, both in the laboratory and in the field (Rhew et al., 2003; von Fischer & Hedin, 2002). Soil uptake might be especially relevant regionally, the same way as methane oxidation. For example, although the Arctic is a considerable methane source as a whole, ice-free Greenland has been shown to provide a net sink for atmospheric methane, due to the importance of soil methane oxidation in this area dominated by upland oxic soils (Jørgensen et al., 2015; St Pierre et al., 2019).

In general, quantifying net VOC emissions from ecosystems to the atmosphere is relevant for the sake of their atmospheric impacts. However, for the complete picture of how changing climate impacts net VOC emissions, we need to understand how both production and consumption of different VOCs respond to alterations in the environment. Total vegetation VOC emissions are expected to increase with climatic warming, despite the reduction of VOC biosynthesis in plant leaves under elevated CO2 concentration.
(Peñuelas & Staudt, 2010). Although we know that soil microbial processes, often measured as soil respiration, increase with temperature (Conant et al., 2011), the temperature relationships are different for different organisms and functions. We should aim at disentangling how VOC consumption in soil responds to alterations in temperature, as well as changes in soil moisture resulting from altered precipitation patterns.

Acknowledgments
We thank the Independent Research Fund Denmark/Natural Sciences and the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (Grant Agreement 771012). We also thank Cleo Davie-Martin for comments on the manuscript.

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