How do rainforest scents drive climate and air quality?

Forests have distinctive scents because they emit reactive organic gases. Recent observations from the ATTO project show that Amazon forests emit more of these molecules than expected. These molecules influence the climate by reacting with atmospheric gases to form small particles (aerosols) that are needed for clouds to form and rain to fall.

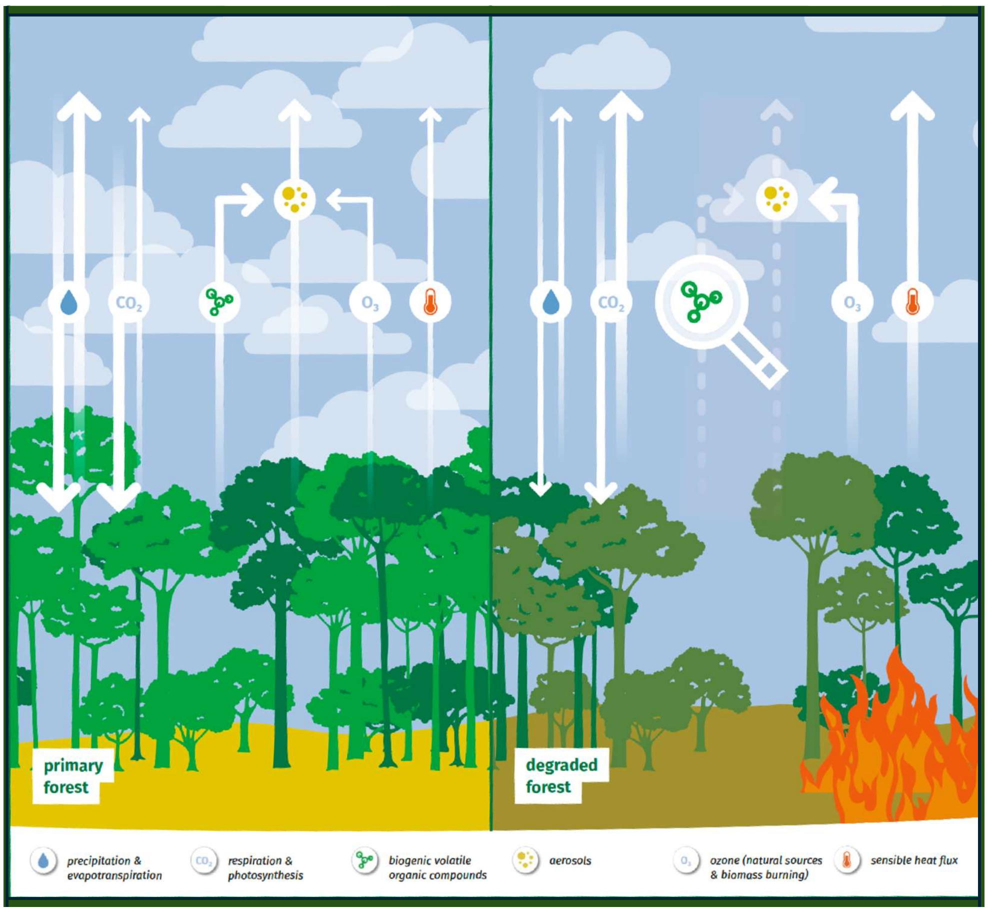

Figure 1. The impact of biogenic volatile organic compounds (BVOCs) emitted by forests on biosphere-atmosphere interactions and climate is significant in both natural and disturbed ecosystems. Forests directly affect the climate by exchanging water, heat, and CO_2 with the atmosphere, and indirectly by emitting BVOCs. After primary forests emit BVOCs, these compounds react with atmospheric oxidants, such as ozone, which can result in the formation of particles (aerosols) on which water can condense to create clouds and rain. The formation of aerosols from BVOCs is a necessary part of how primary forests produce their own rain and thereby impact the climate. However, forest degradation affects these processes by increasing emissions and altering the composition of BVOCs, as a result of hotter temperatures and longer, more intense droughts caused by degradation. Additionally, fires in degraded forests contribute to increased ozone concentrations in the atmosphere, which further influences atmospheric reactivity and air quality. These processes, in turn, alter cloud formation and rainfall patterns, impacting forests and climate in ways that we are only beginning to understand. Note: The width of the arrows indicates the intensity of a process. Thicker arrows represent larger fluxes, and dashed arrows represent processes that we are beginning to understand.

Preface

Forest scents result from a variety of biogenic volatile organic compounds (BVOCs) emitted by plants and soils. They play a crucial role in Earth's atmospheric processes and ecological functions. Some of these organic gases — including isoprene (C_5H_8), monoterpenes ($C_{10}H_{16}$), and sesquiterpenes ($C_{15}H_{24}$)—play multiple roles in plant physiology and atmospheric chemistry. Within plants, BVOCs promote thermotolerance, defend against herbivores and pathogens, and mediate communication between organisms[1]. In the atmosphere, BVOCs significantly influence the formation of secondary organic aerosols (SOAs), affect cloud formation, and alter the oxidative capacity of the air by reacting with atmospheric oxidants like hydroxyl radicals (OH)[2]. These reactions ultimately impact air quality and climate, highlighting the importance of BVOC emissions in linking biological activity with atmospheric composition and environmental change[3].

The Amazon Rainforest, the world's largest tropical forest and a major global source of BVOCs, is a vital hotspot for these interactions. Its dense and diverse vegetation emits vast quantities of BVOCs, shaping local and regional air quality, weather patterns, and even the global climate system[4]. Understanding the dynamics of BVOC emissions in the Amazon is essential for accurately modeling climate feedbacks and assessing the forest's role in Earth's changing atmosphere[5].

For over four decades, research on BVOC emissions in the Amazon has highlighted the region's immense biodiversity as a key driver of its high BVOC emissions[3]. Studies have shown that the chemical composition of these emissions varies among ecosystems and can shift significantly during extreme events such as El Niño years[6,7].

In this context, intensifying pressures from extreme droughts, forest degradation, deforestation, and climate change exert compounded effects on BVOC emissions, thereby influencing key atmospheric processes with significant implications for air quality and climate regulation[3]. These changes pose a particular threat to the southeastern Amazon, where BVOC dynamics have been altered by land use change, forest degradation, and fires[8] (Figure 1).

Recognizing the critical role of BVOCs for air quality and climate regulation, the IPCC AR6 report has identified BVOC-climate interactions as among the most uncertain biogeochemical feedbacks in the climate system. This underscores the urgent need for integrated research that combines long-term observations with advanced modeling to improve our understanding of BVOC dynamics across ecosystems and regions, particularly at the biosphere–atmosphere interface.

The Amazon Tall Tower Observatory (ATTO), along with collaborative efforts from other research initiatives across the Amazon basin, is already making significant progress in addressing these knowledge gaps. Together, these efforts are laying the foundation for informed policies and actions aimed at managing climate and environmental change, both within the Amazon and at the global scale.

Relevance of ATTO observations

The Amazon Tall Tower Observatory (ATTO) provides continuous, high-precision measurements with a particular focus on BVOCs, primary and secondary aerosols, and trace gases relevant to air quality, such as ozone and NOx. Complementing these atmospheric observations, ecological studies conducted across diverse forest types and throughout different seasons are exploring how ecosystems and plant species respond to environmental variability, including extreme events like the El Niño-Southern Oscillation.

These integrated measurements are critical for advancing our understanding of the complex soil–plant–atmosphere interactions that drive BVOC emissions and feedbacks. This includes responses to environmental stressors such as heat, drought, and elevated ozone levels[9] from biomass burning, as well as their influence on atmospheric oxidative capacity, aerosol, and cloud formation.

BVOC dynamics differ by forest type

Different plant species emit distinct blends of BVOCs, leading to considerable variation in emissions across natural ecosystems. At the ATTO site, this variability is captured along a rich gradient of ecosystems, including wetlands (such as igapós and small forested swamps), ancient river terrace forests (paleoigapós), white-sand forests (campina and campinarana), and upland forests (*terra firme*)[4]. These ecosystems, commonly found throughout the Amazon basin, differ in soil properties, plant species composition, and water availability—factors that shape their unique responses to environmental conditions and extreme events.

These responses are reflected in shifts in BVOC emissions, particularly in the form of increased release of heavier and more reactive compounds—such as monoterpenes and sesquiterpenes, which play a key role in aerosol formation—during the dry season, El Niño years, and notably in upland forests

(Figure 2)[6,7] where plants tend to store high amounts and a wide diversity of these compounds[10,11].

When accounting for a broader range of plant types (from bryophytes to canopy trees), indicators of herbivory, and diverse soil types, the contribution of these heavier and more reactive compounds to the overall BVOC budget becomes even more pronounced[12–14]. Additionally, soil-litter BVOC fluxes, including both emissions and uptake, varied across forest types, with white-sand forests emerging as hotspots for specific compounds[15]. These findings deepen our understanding of how biodiversity influences BVOC emission dynamics, and the long-term, ecosystem-specific measurements at ATTO provide a critical reference for monitoring BVOC-related atmospheric processes across regions of the Amazon with similar ecological characteristics.

Effects of land use change and forest degradation on BVOC emissions and air quality

Land use change and forest degradation have increased significantly across the Amazon, with the southeastern region experiencing some of the most intense pressures [16]. These disturbances are driving shifts in plant species composition and altering ecosystem responses to heat stress and prolonged droughts[17,18]. Our recent findings indicate that degraded forests in southeastern Amazonia are emitting substantially higher levels of monoterpenes and sesquiterpenes—highly reactive BVOCs that play a major role in aerosol formation and air quality. The interaction of these compounds with pollutants from biomass burning, such as ozone, may further degrade air quality in the region[8].

In this context, the collaboration between the ATTO project and other research initiatives in the Amazon's Arc of Deforestation is proving essential for advancing our understanding of how BVOC-mediated biosphere–atmosphere interactions are being altered by environmental and climate change. These joint efforts are providing critical insights into the shifting BVOC dynamics of one of the most vulnerable and rapidly changing regions of the Amazon, helping to inform both regional and global strategies for monitoring and mitigating the impacts of changes in use and climate.

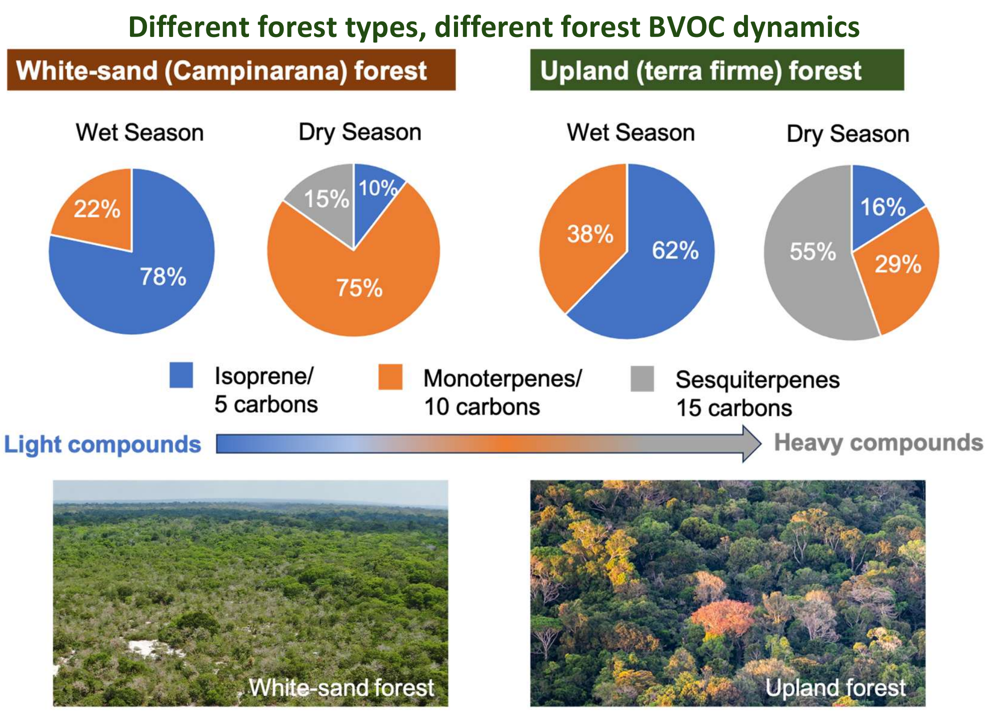

Figure 2. During the dry season, BVOC emissions tend to shift toward heavier and more reactive compounds, transitioning from predominantly isoprene (a five-carbon molecule) to larger molecules such as monoterpenes (10 carbons) and sesquiterpenes (15 carbons). This shift is particularly pronounced in upland forests, where vegetation stores and emits a greater diversity and quantity of these complex compounds in response to environmental stressors like heat and drought[6].

Recommendations

Recent observations from the ATTO project have revealed that emissions of highly reactive BVOCs—such as monoterpenes and sesquiterpenes—are significantly higher than previously estimated. Further, their emissions are strongly influenced by heat stress, drought, and forest degradation. Our findings also show a clear link between BVOC emissions and biodiversity across different ecosystems, underscoring the complex interplay between ecological composition and atmospheric chemistry. To enhance our understanding and improve predictions of biosphere–atmosphere interactions in both intact and disturbed Amazonian ecosystems under future climate scenarios, we recommend the following:

1. Continuous monitoring of a broad spectrum of BVOC chemical species across diverse ecosystems is essential for identifying indicators of forest vulnerability and climate stress. Such monitoring serves as a critical tool to detect shifts in emission patterns linked to environmental changes, particularly during extreme events. Moreover, it provides valuable insights into how atmospheric chemical composition may evolve under these conditions, thereby supporting more accurate predictions of future climate scenarios and informing strategies for ecosystem resilience and climate change mitigation.
2. Integrative approaches that combine in-situ observations, remote sensing, and modeling are essential for capturing the full complexity of processes operating across the soil–plant–atmosphere continuum and for scaling findings to the entire Amazon basin. These methods can effectively leverage existing long-term datasets to enhance our understanding of ecosystem dynamics and their influence on regional and global climate.

Scientific insights gained from such integrative efforts must be translated into comprehensive policies focused on ecosystem conservation and air quality improvement in Amazonia and beyond. Future research should be closely aligned with actions across political, economic, social, and environmental sectors, supporting forest conservation, reducing deforestation and degradation, and ultimately improving the quality of life for Amazonian communities—benefiting not only the region but the health of the entire planet.

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Contact

Eliane Gomes Alves
Max Planck Institute for Biogeochemistry,
Dept. Biogeochemical Processes
Hans-Knöll-Str. 10, 07745 Jena, Germany
egomes@bgc-jena.mpg.de