

Role of the Terrestrial Biosphere in Atmospheric Chemistry and Climate

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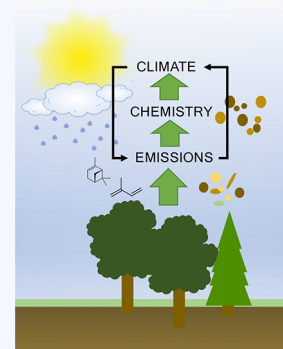


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CONSPECTUS: The terrestrial biosphere–atmosphere interface provides a key chemical, biological, and physical lower boundary for the atmosphere. The presence of vegetation itself modifies the physical boundary, or the biogeophysical aspects of the system, by controlling important climate drivers such as soil moisture, light environment, and temperature. The leaf surface area of the terrestrial biosphere provides additional surface area for emissions, and it can be up to 55% of the total Earth's surface area during the boreal summer. Vegetation also influences the biogeochemical aspects of the system by emitting a broad suite of reactive trace gases such as biogenic volatile organic compound (BVOC) emissions and climate-relevant primary biological aerosol particles (PBAP). Many of these emissions are a function of meteorological and climatological conditions at the surface, including temperature, light environment, soil moisture, and winds. Once emitted, they can be processed in the troposphere through a suite of chemical reactions. BVOC can contribute to the formation of ozone and secondary organic aerosols (SOA), and PBAP can rupture to form smaller particles with climatic relevance. These emissions and subsequent aerosol products can influence atmospheric processes that affect the surface climate, such as the attenuation of radiation, the formation of greenhouse gases such as ozone that can feedback to surface air temperature, and the alteration of clouds and subsequent precipitation. These atmospheric changes can then feedback to the land surface and emissions themselves, creating positive or negative feedback loops that can dampen or amplify the emission response. For the dominant BVOC isoprene, the feedback response to temperature can be positive or negative depending on ambient temperatures that drive isoprene emissions. The feedback response to soil moisture and precipitation can be positive, negative, or uncoupled depending on the moisture content of the soil and the total atmospheric aerosol loading. For light, the isoprene response can be positive or negative depending on the role of diffuse light. Overall, these feedbacks highlight the dynamical response of the biosphere to changing atmospheric conditions across a range of time scales, from minutes for trace gases and aerosols, to months for phenological changes, to years for land cover and land use change. The dynamic aspect of this system requires us to understand, simulate, and predict the complex feedbacks between the biosphere and atmosphere and understand their role in the simulation and understanding of climate and global change. From the observational perspective, these feedbacks are challenging to identify in observations, and predictive modeling tools provide a crucial link for understanding how these feedbacks will change under warming climate scenarios.



■ TERRESTRIAL BIOSPHERE–ATMOSPHERE INTERACTIONS

The terrestrial biosphere represents the portion of the Earth's land surface that supports living organisms. From the atmospheric science perspective, the terrestrial biosphere–atmosphere interface represents the lower boundary condition for the atmosphere and exchanges mass, energy, and momentum. Because the terrestrial biosphere is a living and therefore dynamic entity, processes at this interface are subject to broad variations in temporal (e.g., diurnal, seasonal, interannual, and decadal) and spatial (organism, ecosystem, regional to global) scales. From the perspective of atmospheric chemistry, this interface can be a source and sink for trace gases

and aerosol particles that can drive chemistry in the troposphere, or roughly the lowest 10 km of the Earth's atmosphere.

Earth scientists frequently partition the Earth's surface as approximately 30% terrestrial and 70% ocean. Yet from the perspective of atmospheric chemistry, an important driver of the interface is not only the surface area that covers the Earth, but

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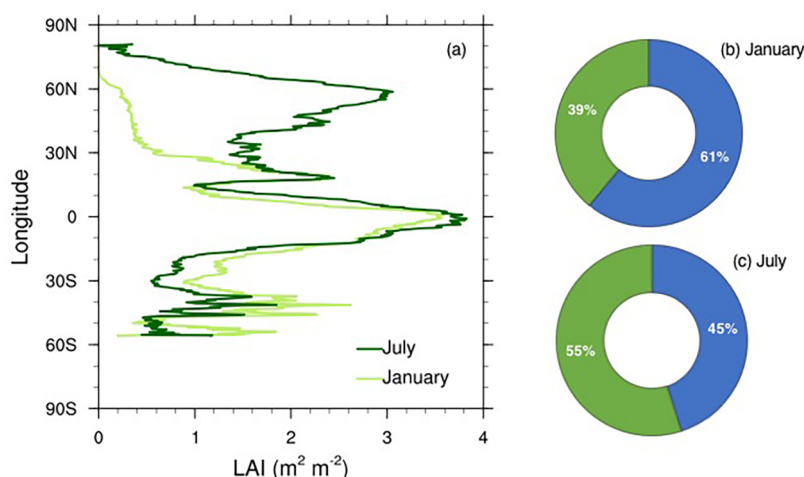


Figure 1. Global leaf area index and influence on total surface area. (a) Longitudinal average of leaf area index (LAI; m^2 leaf area m^{-2} ground area) based on a climatological average of MODIS LAIs from 1981 to 2015¹ for July and January. (b) January and (c) July percent land (green) and ocean (blue) when leaf surface area is included in the total estimate.

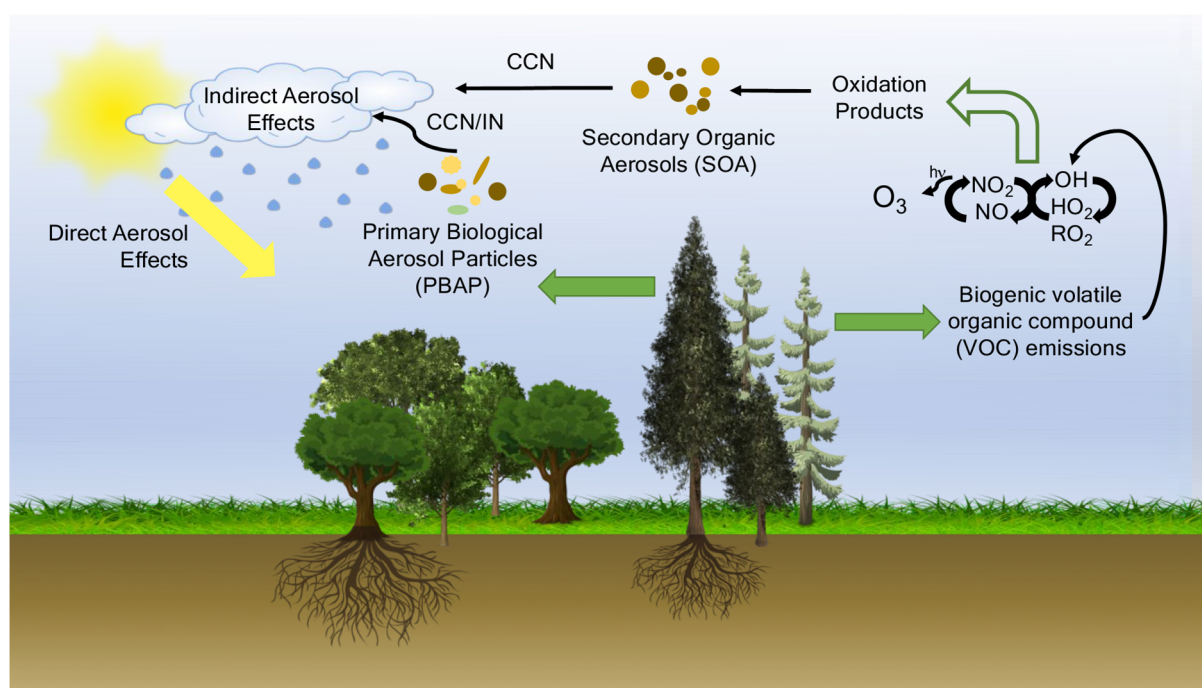


Figure 2. Terrestrial biosphere–atmosphere interactions. Processes at the surface drive emissions, which then react and interact in the atmosphere to influence climate.

the biological surface area presented by vegetation that can emit and take up trace compounds. This biologically available surface area is described as the leaf area index (LAI) and represents the ratio of the available leaf surface area to the footprint of ground area, with units of m^2 leaf area per m^2 ground area. For example, a vegetated forest with a LAI of $5 \text{ m}^2 \text{m}^{-2}$ represents a total surface area 5 times greater than the area of the forest itself. Using climatological LAIs derived from NASA's MODIS satellite,¹ inclusion of this surface area increases the fraction of the Earth's surface that can act as a lower boundary condition up to 55% in July and up to 39% in January (Figure 1). This seasonal difference is driven by the larger land mass in the Northern Hemisphere, where the greater greening area during the boreal summer translates to a greater increase in biologically available leaf surface area. This suggests that the terrestrial

biosphere can increase the potential surface area by up to 1.5 times its actual surface area when accounting for vegetation on the Earth's surface, and this vegetation surface area can provide an important and substantial exchange point for tropospheric chemistry.

From the biogeophysical perspective, atmospheric scientists quantify the role of the land surface in the exchange of energy, mass and momentum with the atmosphere² (Figure 2). Of crucial importance in the land–atmosphere exchange is the surface energy budget, as the land surface returns about 90% of the energy absorbed by the Sun back to the atmosphere as either sensible or latent heat. This ratio (known as the Bowen ratio, or sensible divided by latent heat) can influence convection, the moisture content of the atmosphere, and the formation of clouds.³ From the biogeochemical perspective, the biologically

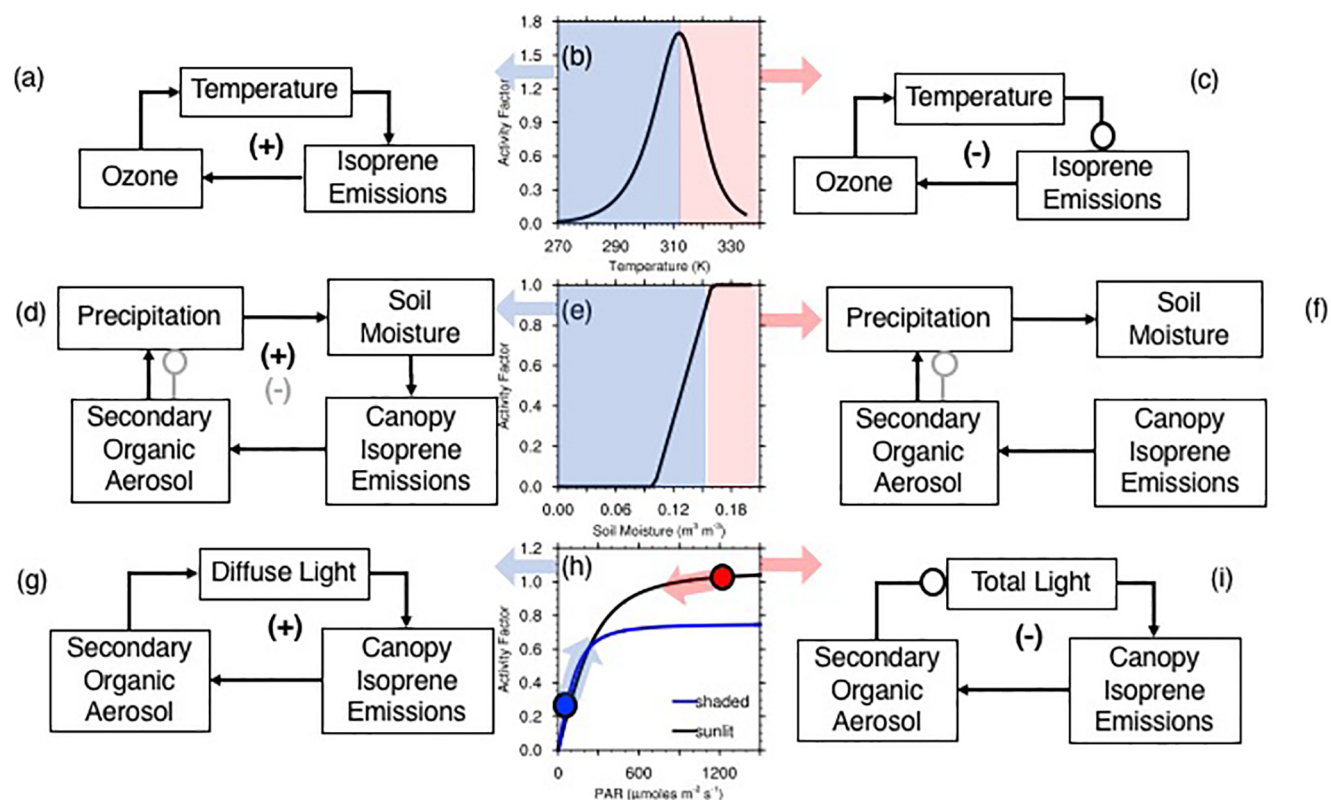


Figure 3. Terrestrial biosphere–atmosphere feedbacks. A generalized biogenic emission “activity factor” induced by changes in (b) temperature, (e) soil moisture (implicitly driven by changes in precipitation), and (h) light in a forest canopy. For temperature (a–c), biosphere–atmosphere feedbacks can be (a) positive at temperatures below the isoprene optimum (blue shaded region) or (c) negative at temperatures above the isoprene optimum (red shaded region). For soil moisture (d–f), the feedbacks between isoprene emissions, secondary organic aerosols, and precipitation can be (d) positive under low aerosol loading (black arrow, +) or negative under high aerosol loading (gray arrow, –). (f) When soil moisture is sufficient, the link between isoprene and soil moisture is absent and there is no feedback. For the light environment (g–i), (g) an increase in diffuse light is expected to promote a positive feedback with emissions, yet (i) if aerosol and clouds significantly reduce the total light environment, then the feedback could be negative. Feedbacks are represented as systems diagrams showing a positive relationship (arrows) or a negative relationship (open circles), with the overall feedback cycle denoted as positive (+) or negative (–).

available land surface area can act as a source or a sink of reactive trace gases that can influence chemistry in the troposphere. These sources include the emissions of biogenic volatile organic compounds (BVOCs) from vegetation or nitrogen oxides from soil biogeochemistry, and sinks can include the uptake of trace gases such as ozone directly to plant surfaces or through stomata.⁴ Stomata, or the openings in leaf surfaces that enable the exchange of water and carbon dioxide with the atmosphere, can also act as a sink for trace gases depending on their solubility.

One of the complexities at the biosphere–atmosphere interface is that the emissions of trace gases and aerosol particles can influence atmospheric processes that directly feedback on emissions and sink processes themselves, creating a feedback loop between the biosphere and the atmosphere (Figure 2). Because the terrestrial biosphere is a dynamic component of the Earth system, it is challenging to quantify these feedback loops in the Earth system from observations. Earth system models have the ability to capture these processes, if they are properly parametrized. This Account will describe the processes in the terrestrial biosphere that emit trace gases and aerosols, and subsequently influence gas-phase tropospheric chemistry and the formation of ozone and aerosols. Examples of three environmental drivers (temperature, soil moisture, and light) that affect emissions from the terrestrial biosphere and atmospheric feedbacks are presented, along how these feedbacks

may change in a warming world. Opportunities to improve their representation in Earth system models for the predictive capability of future climate are discussed.

EMISSIONS OF BIOGENIC VOLATILE ORGANIC COMPOUNDS AND INFLUENCE ON TROPOSPHERIC CHEMISTRY

The discovery of biogenic volatile organic compound (BVOC) emissions from vegetation was first noted in the early 1950s by the Georgian scientist Sanadze, although much of the early data was published in the Russian literature and not appreciated broadly by scientists across the globe.⁵ Around the same time, the first studies of biogenic emissions emerged in the United States ecological community, including Rasmussen⁶ quantifying emissions from individual plants and Went⁷ hypothesizing on the role of biogenic VOCs in the formation of the blue haze observed in the southeastern U.S. Blue Ridge mountains. The first regional-scale BVOC emissions model⁸ allowed these emissions to be connected with the atmospheric community and models of tropospheric chemistry, allowing an understanding of the role of BVOCs on the formation of ozone and secondary organic aerosol (SOA).

The dominant BVOC emission from vegetation is isoprene (C_5H_8), and current emission estimates suggest annual emissions of approximately 500 Tg year^{-1} , which is about an

order of magnitude greater than all anthropogenic VOC emissions.⁹ In addition to the large quantity emitted, its lifetime with the hydroxyl (OH) radical in the atmosphere is about 1–2 h.¹⁰ Other biogenic VOCs are emitted from vegetation, with monoterpenes (C₁₀H₁₆) following isoprene as the second largest emission. The diversity of monoterpene structures is broad, and they are emitted in a lesser magnitude than isoprene (approximately 30–130 Tg year⁻¹), yet with greater uncertainty.¹¹ Other biogenic VOC emissions include sesquiterpenes, alcohols, and other oxygenated VOCs,⁹ which can also react in the atmosphere to influence tropospheric chemistry.

Environmental chamber studies demonstrate that BVOC emissions are strongly dependent on climatic conditions, with isoprene dominantly controlled by temperature (Figure 3b) and light (Figure 3h). Models of biogenic isoprene emissions are typically estimated empirically as a function of light and temperature (as in Figure 3b),¹² with more recent inclusions of longer time scale temperature variations, soil moisture, and leaf age.¹³ The current understanding of isoprene synthesis is that it occurs via the methyl erythritol 1-phosphate (MEP) biochemical pathway within the plant, with carbon being sourced from metabolic byproducts.¹⁴ Yet uncertainties in the biosynthesis mechanism still exist and need to be rectified to understand the connections of emissions to other ecological processes. For example, diurnal cycles of observed isoprene emissions suggest a close link with between photosynthesis, yet they are not always correlated. Isoprene emission is uncoupled from photosynthesis under high temperatures, which reduces photosynthesis when plants close their stomates to conserve water. Experimentally, isoprene does not exhibit this behavior, and emissions can continue throughout the midday decrease in photosynthesis.¹⁵ Additionally, the influence of drought on isoprene emissions on both short (e.g., diurnal) and long (e.g., seasonal) time scales is still uncertain. Soil moisture stress is included in more recent isoprene models, with isoprene emissions reduced with decreasing soil moisture¹³ (e.g., Figure 3e), although studies to support this parametrization are extremely limited. Identification of the soil moisture response in field observations is challenging to obtain and is difficult to uncouple from temperature.¹⁶ Overall, isoprene emissions are clearly correlated with the land surface environment, and prior frameworks have tied these emissions and influence on ozone to a surface coupling mechanism.¹⁷

The effort to define and constrain isoprene emissions is linked to their relevance for tropospheric chemistry, and the oxidation of isoprene became the first BVOC reaction to be included in tropospheric chemistry mechanisms. Studies by Trainer et al.¹⁸ and Chameides et al.¹⁹ showed that the oxidation of isoprene could be important for ozone formation in both rural and urban regions, respectively, and highlighted the role of understanding the influence of these natural compounds in relation to anthropogenic emissions of VOCs for ozone control. Isoprene's role in ozone formation is due to the formation of peroxy radicals, which can rapidly convert NO to NO₂ when sufficient NO_x are available (Figure 2). The subsequent photolysis of NO₂ produces an oxygen atom, which can then react with the oxygen molecule to produce ozone in the troposphere. The importance of VOCs in the ozone production mechanism depends on the molecule's reactivity with OH, the dominant oxidant in the troposphere. Isoprene is important for ozone formation because of (1) the ubiquity of isoprene emissions and (2) their relatively fast reaction rate with OH.

■ AEROSOLS FROM THE TERRESTRIAL BIOSPHERE

In addition to gas-phase emissions of BVOCs from vegetation, the emission and formation of organic aerosol particles from the terrestrial biosphere also can drive changes in atmospheric chemistry and climate. Vegetation emits primary organic particles (POA, or often referred to primary biological aerosol particles: PBAPs) in the form of bacteria, fungal spores, and pollen, with large spatial and temporal gradients.²⁰ Also, the oxidation of gas-phase BVOC emissions leads to lower volatility products that can partition to the particle phase and form SOAs. Together both primary and secondary aerosols from vegetation have the potential to alter the energy balance of the Earth system, both directly by scattering and/or absorbing incoming radiation and indirectly by influencing the properties of warm or cold phase clouds. These particles can also influence gas-phase chemistry, as many PBAPs and SOAs undergo chemical processing in the atmosphere and in clouds.

Sources of PBAPs depend on the ecosystem and its location within different climate regimes. Terrestrial emissions of bacteria and fungal spores frequently originate from soil environments, where fungi and bacteria have symbiotic relationships with plants such as those that assist in nitrogen acquisition in nitrogen-limited soils;²¹ however, they can also be coemitted with other biological material from the soils or plant canopy. Bacterial emissions ($\ll 1 \mu\text{m}$) exhibit a wide diversity in composition, making it challenging to determine direct origin. Emissions are typically estimated as a function of temperature and wind speed, and little information about spatial variability is known. Fungal spore emissions have been estimated globally as they can constitute large number concentrations in the atmosphere. Fungal spore PBAPs range from 5 to 15 μm , and emissions can be simulated as a function of LAI and specific humidity.²² Pollen emissions have also been estimated in a number of studies, although most published emissions estimates focus on regional studies and specific taxa that are known to be allergenic. Wozniak and Steiner²³ developed an emissions model for the dominant anemophilous (or wind-driven) taxa within the United States. While pollen represents a much larger PBAP (e.g., 20–100 μm depending on the taxa), epidemiological studies first noted that pollen can rupture under moist conditions²⁴ and create a large number of smaller, submicrometer particles. A chamber study suggests the rupture particles are less than 1 μm with the largest number in the 100–200 nm range,²⁵ and a recent field study noted fragments in the 0.25–1 μm range following precipitation,²⁶ though both studies may be subject to instrument limitations for smaller size particles. Studies of fungal spores note that these particles can rupture as well,²⁷ and recent work shows that these can lead to fluxes of submicrometer particles in the range of 30 nm to the atmosphere.²⁸ Understanding the primary emissions of PBAPs and their generation of smaller particles in the atmosphere requires further attention, particularly due to the allergenic properties of both fungal spore and pollen particles.

In contrast to PBAPs, the mechanisms of biogenic SOA formation have received much greater attention from the atmospheric chemistry community. The reactions of monoterpenes with ozone were long known to lead to low volatility products and formation of SOA.²⁹ Initially, isoprene was not thought to contribute to SOA, yet new oxidation pathways of isoprene suggest that isoprene can be a greater contributor to SOA than previously thought.^{30,31} Recently, the fate of isoprene under low-NO_x conditions and improved understanding of

autoxidation reactions of isoprene peroxy radicals³² suggest that isoprene can produce low volatility compounds such as hydroperoxides, leading to the formation of SOA in the troposphere. One of the challenges in understanding the role of SOA in the global aerosol budget is the complexity of BVOC emissions and its fate in the troposphere. There is a broad suite of VOCs emitted from vegetation, with many of the higher reactivity compounds such as sesquiterpenes being challenging to measure *in situ*; therefore, many BVOC emissions may not be adequately quantified. Additionally, the confounding effects of other trace gases in the atmosphere such as nitrogen oxides,³³ and sulfate and its influence on acidity,^{34,35} make understanding and simulating organic aerosol challenging. Traditional methods to simulate the formation of SOAs from BVOC emissions used a simple two-product model, based on an empirical yield from chamber studies to constrain the formation of oxidation products.³⁶ More detailed mechanisms have evolved based on volatility (e.g., the Volatility Basis Set or VBS³⁷), yet despite adding chemical complexity evaluation with observations suggests that simple yield models may be similar to more complex models at the global scale.³⁸

Biologically derived aerosols also have an impact on Earth's climate. There is the direct effect of aerosols, which can reduce the amount of incoming radiation from the Sun. Biogenically derived aerosols (either primary or secondary) are understood to be effective scatterers, with some potential for absorption depending on the SOA formation pathway.³¹ Additionally, many biogenically derived organics are hygroscopic, leading to the influence on cloud formation. Bacterial and fungal spore emissions from terrestrial ecosystems are known to influence the formation of clouds and also contribute to the total organic content of the atmospheric aerosol population. Pollen, which is frequently emitted from higher latitude ecosystems in lower quantities, can act as both a cloud condensation nuclei (CCN) and an ice nucleating particle (INP), which can influence the formation of precipitation in both warm and cold clouds. While these effects on the global system have been estimated to be small,³⁹ they may have a greater impact at the regional scale.⁴⁰ One important aspect is that many biological particles are known to be effective INPs.⁴¹ If PBAP is lofted to higher heights in the atmosphere through deep convection, this can influence an important and uncertain aspect of the global climate forcing.⁴² Over most continental areas with substantial BVOC emissions, anthropogenic aerosols are present in sufficient quantities to provide sufficient CCN for cloud formation, suggesting that the addition of more biogenically derived aerosols would further act to suppress precipitation. However, a solid constraint on the preindustrial aerosol loading is still lacking,⁴³ and assessing aerosols from the terrestrial biosphere (either PBAP or SOA) will be important for assessing the pre- and postindustrial aerosol differences that drive radiative forcing calculations in global models.

IDENTIFYING TERRESTRIAL BIOSPHERE–ATMOSPHERE FEEDBACKS

Because the terrestrial biosphere is a dynamic system, the emissions described above (BVOC, subsequent SOA, and PBAP) will vary as the meteorological and climatological conditions on the Earth change. Unlike anthropogenic emissions of greenhouse gases and aerosols, controlling biogenic gas and aerosol emission sources is difficult at the regional and global scale, making understanding their feedbacks increasingly important. As the Earth continues to warm, a range of potential

changes in vegetation are anticipated, including an increase in the growing season length and the phenology of vegetation, species range expansions or shifts as temperatures increase, and changes in meteorological drivers such as temperature and winds that will alter emissions.

Feedbacks between the biosphere and the atmosphere can occur when gases and particles are emitted from the terrestrial biosphere to the atmosphere, where they undergo chemical reactions, interact with radiation, and affect the formation of clouds and precipitation (Figure 2). The interaction of these short-lived gases and aerosols in the atmosphere with radiation and clouds then influences the meteorological drivers at the Earth's surface (e.g., temperature, precipitation, light), thereby altering emissions and closing the feedback loop. The following discussion provides several examples of these terrestrial biosphere–atmosphere feedbacks. Specific examples include how changes in environmental conditions influence biogenic VOC emissions and drive tropospheric ozone formation (a short-lived greenhouse gas), the alteration of clouds and precipitation from biogenically derived aerosols (the indirect effect), and the direct interaction of biogenically derived aerosols with incoming shortwave radiation (the direct effect) (Figure 3). Quantification of these feedbacks remains challenging because the magnitude is model-dependent and difficult to quantify with observations; therefore, this discussion focuses on the relationship between processes of emissions, chemistry, and climate.

Because biogenic VOC emissions are a function of temperature, they are susceptible to feedbacks with the atmosphere. Laboratory studies indicate that isoprene emissions increase with increasing temperature until a temperature optimum (approximately 314 K), after which emissions start to decrease (Figure 3b) due to the denaturing of proteins at higher temperatures.¹² Because of this behavior, it can be difficult to predict how isoprene, and subsequently ozone, will respond under a warming climate. At temperatures below the optimum temperature, an increase in temperature will increase isoprene emissions and if sufficient nitrogen oxides (NO_x) are present, this could increase ozone concentrations, contribute to further warming, and lead to a positive feedback (Figure 3a). However, at ambient air temperatures above the temperature optimum, isoprene emissions may decrease with further warming, which could slow ozone production and dampen the feedback (Figure 3c). Generally, ozone is observed to increase with increasing temperatures, although there may be a limit to this behavior.⁴⁴ Using long-term measurements in California, we found that the increase in ozone with temperature may be limited by emissions of isoprene and subsequent peroxyacetyl nitrate (PAN) chemistry,⁴⁴ suggesting observational evidence of the high temperature feedback in Figure 3c. This isoprene–ozone feedback can be confounded by other meteorological factors such as stagnation events, which may drive the observed saturation of ozone with temperature in other locations,⁴⁵ and the decrease of ozone deposition as drought drives the closure of stomata.⁴

Soil moisture is the second environmental driver that could initiate terrestrial biosphere–atmosphere interactions. Laboratory studies have suggested that isoprene is suppressed by drought,⁴⁶ and modeling studies have incorporated parametrizations to reduce isoprene emissions as a function of soil moisture and the localized wilting point (θ_w)⁹ (Figure 3e). Modeling studies such as those by Tawfik et al.¹⁶ highlight the challenges of decoupling soil moisture and temperature

influences on isoprene emissions and note that much of the variability in isoprene emissions was driven by the coupled soil-moisture temperature parametrizations. Recent studies suggest that the long-term effects of drought can be observed in ambient isoprene concentrations, but the drought must be severe and sustained to have feedbacks with ozone.⁴⁷ The isoprene emissions–soil moisture coupling can then drive feedbacks through the influence of SOAs on clouds and precipitation. In a water-limited system, a decrease in soil moisture could drive a decrease in canopy emissions and resulting SOAs (Figure 3d). If conditions are clean (with few CCN), this decrease in SOAs could drive a decrease in precipitation, further strengthening the soil moisture decline and creating a positive feedback cycle. Note that if, under polluted conditions, biogenically derived particles would compete for water with hygroscopic anthropogenic aerosols and under present-day anthropogenic loadings, the addition of more CCN-active biological particles will act to suppress precipitation, which would change the overall sign of the feedback cycle. When soil water is not limited, the link between soil moisture and isoprene is removed, as isoprene emissions are no longer influenced by soil water (Figure 3f). This thereby eliminates the feedback cycle between isoprene and soil moisture.

Similarly, if increased precipitation were to reduce the emissions of PBAPs through wet removal, the overall feedback response would depend on the CCN loading in the atmosphere (Figure 4). If CCN are low and the addition of PBAPs increases

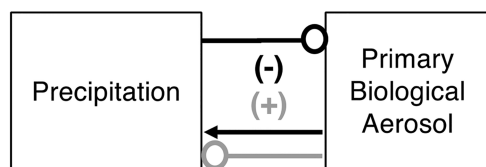


Figure 4. PBAP–precipitation feedbacks. Feedback model between PBAPs and precipitation. Precipitation feedbacks are dependent on the total aerosol loading, represented as clean conditions (black, low CCN) or polluted conditions (gray, high CCN).

the total CCN with sufficient atmospheric moisture, then an increase in PBAP emissions could increase precipitation, thereby creating a negative feedback cycle. However, it is important to note the feedback effect is sensitive to the presence of anthropogenic pollution, where we have simulated that the addition of hygroscopic PBAPs such as subpollen particles will serve to suppress precipitation.⁴⁰ If aerosol loading is high (or even under typical clean continental conditions), then additional CCN from biological sources would then suppress precipitation, creating a positive feedback cycle that would overall reduce precipitation and soil moisture conditions. For PBAPs under clean, nonanthropogenic conditions, a “bio-precipitation” hypothesis has been proposed, where the presence of PBAPs can enhance precipitation to further sustain vegetation.⁴⁸

These biosphere–cloud feedbacks are important to accurately constrain the pre- to postindustrial radiative forcing of aerosols. Emerging results from the Coupled Model Intercomparison Project (CMIP6) suggest that the aerosol–cloud forcing can greatly alter the equilibrium climate sensitivity of the future model projections⁴⁹ and there is wide variability in how biogenically driven aerosols are included in Earth system models. Most models typically assign a certain amount of

“background aerosol” or CCN to represent the preindustrial, and many of the CMIP simulations do not account explicitly for the contribution of biogenic SOAs or PBAPs to the total aerosol burden. From the feedback perspective, this can be important as CCN number concentrations can control the amount and placement of precipitation, which can then feedback to both PBAP emissions (rain initially suppresses these emissions, but can later enhance them for fungal spores) and BVOC emissions (where rain can enable continued photosynthetic production and potentially emission).

The third feedback is driven by changes in light that reaches the total surface area of the vegetation. The direct effect of aerosols is defined by the scattering or absorption of incoming solar radiation by aerosol particles, producing more diffuse light while reducing the total amount of light reaching the surface. As noted from the carbon community, this increase in diffuse light may increase the light penetration into the canopy and increase the light use efficiency (LUE) of the total forest canopy.^{50,51} Sunlit portions of the canopy receive direct sunlight and tend to be on the saturated portion of the emissions curve, while the shaded part of the canopy receives less light and most of it as diffuse light (Figure 3h). Therefore, if aerosols in the atmosphere scatter more incoming solar radiation and create more diffuse light, we could expect to see an increase in emissions from the shaded canopy and a small decrease in emissions from the sunlit canopy (Figure 3h). Overall, this increase in diffuse light may be greater than the effect of the total radiation reduction and may lead to an overall increase in emissions. Increased light in the shaded portion of the canopy is likely to increase the lower-canopy production of biogenic VOCs, which can then feedback to influence the production of additional SOAs in the atmosphere which can further enhance the emissions of BVOCs⁵² (Figure 3g). However, if the atmospheric aerosol loading is sufficient to drive a total light reduction that outweighs the increase in diffuse light, this could create a negative feedback cycle (Figure 3i).

These feedbacks between biogenic aerosols and radiation remain difficult to quantify in observations, and the current understanding is largely based on model simulations and some eddy covariance studies of carbon exchange. One challenge in the representation of canopy light processes is that most models used to assess the diffuse effect implement a forest canopy that may not accurately capture the distribution of light within the canopy. Using a multilayer canopy model that provides a detailed description of light penetration, we found that the in-canopy radiative transfer models like those used in many Earth system models overestimate the diffuse effect on photosynthesis,⁵³ and this would likely influence the simulation of BVOC emissions. Therefore, models may be overestimating the impact of the diffuse radiation in the lower canopy, and thus, these results need to be interpreted with caution until we have improved observations to quantify the bounds of this feedback between aerosols and the canopy light environment.

FUTURE DIRECTIONS

Over the past 30 years, our understanding of how emissions from the terrestrial biosphere has expanded and many processes are now included within Earth system models. From the perspective of global change, these biosphere–atmosphere exchanges and feedback processes represent an important component of our understanding of how the atmosphere will evolve over time. While many challenges for representing these feedbacks still exist, there are a number of current opportunities

to improve and advance our understanding of the role of reactive gas and aerosol emissions from the terrestrial biosphere.

The first opportunity to develop a better understanding of terrestrial biosphere–atmosphere feedbacks is to leverage the new suite of satellites launched that will provide an unprecedented understanding of the terrestrial biosphere. For example, new retrievals from the Cross-track Infrared Sounder (CrIS) instrument suggest the potential to develop satellite-derived global spatial maps of isoprene.⁵⁴ Other new satellites are focused on the terrestrial carbon and water balances, although they hold many promising features for BVOC and PBAP research. For example, the new instrument suite on the International Space Station including the Ecosystem Spaceborne Thermal Radiometer Experiment (ECO-STRESS; evaporation), the Global Ecosystems Dynamics Investigation (GEDI; canopy structure), the Orbiting Carbon Observatory (OCO-3; carbon), and the Hyperspectral Imager Suite (HISUI; vegetation composition) could provide useful information about the vegetation framework that drives emissions of BVOCs and aerosols.⁵⁵ There will be limitations with these satellite products for understanding trace gases, as information about vegetation composition may not be sufficient to explain the intraspecies and interspecies differences in BVOC emissions, yet leveraging these products into the atmospheric chemistry community may provide some advances in the representation of vegetation and emissions.

Second, the increase in global temperatures driven by anthropogenic greenhouse gas emissions is projected to increase the number of extreme temperature events. These extreme events will increase near surface temperatures and alter meteorology and the number of frequency of stagnation events linked to poor air quality.⁵⁶ One next generation challenge will be to understand how emissions from the terrestrial biosphere and subsequent feedbacks in the atmosphere will change under these extreme events. In many cases, vegetation will emit different VOCs under stress, which can drive changes in the constituency of future emissions. Expanding our Earth system models beyond isoprene and monoterpenes to include more complex species and PBAPs will be necessary to accurately quantify these feedbacks.

A final outstanding challenge is to include sufficient biological process-level information within models such that they can accurately capture feedbacks between atmospheric chemistry and climate. To understand how these compounds will play a role in the future climate, it is essential to have predictive models that can accurately capture emissions and their feedbacks in the atmosphere. Continued model development within the BVOC community that moves from empirical-based emissions models to ones that capture the response of BVOCs to different stressors is still needed in order to understand the response of vegetation under future climate regimes, especially as we move to new climatic regimes.

Observations provide key constraints for the model development required to include these processes and feedbacks. Two time scales of ground-based observations are needed, including both short-term directed experiments targeted to capture extreme events and long-term observational frameworks to examine BVOC and PBAP emissions over multiple seasons and years. While the measurements to understand BVOC emissions and their oxidation products have substantially improved in the past decades, there are still limited observations to understand and quantify PBAP emissions. Expanded chemical characterization have recently been shown to capture rupture events,^{26,28}

yet more observations are needed to quantify primary PBAP emissions and rupture events for process-based characterization. Methods such as single-particle fluorescence spectroscopy and polymerase chain reaction (PCR) methods to identify DNA and RNA fragments of biological particles could be more frequently deployed to probe the processes and frequency of these events. Developing new observational studies that capture the spatial and temporal heterogeneity of emissions from the terrestrial biosphere will be key toward making these process level improvements for future Earth system modeling development and improving our quantification of terrestrial biosphere–atmosphere feedbacks.

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Notes

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Biography

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ABBREVIATIONS

BVOC, biogenic volatile organic compounds; CCN, cloud condensation nuclei; LAI, leaf area index; PBAP, primary biological aerosol particle; SOA, secondary organic aerosol

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