The Global Woody Surface: A Planetary Interface for Biodiversity, Ecosystem Function, and Climate

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Recent quantification reveals that global aboveground woody surface area of forests spans approximately 143 (±59) million km²—a magnitude equivalent to Earth's entire terrestrial surface area of 149 million km² (Gauci et al. 2024). This complex network of bark, stems, and branches represents a "third dimension" of Earth's ecosystems, a dynamic planetary interface that expands and contracts with forest cover and disturbance. These woody surfaces add a vertical dimension to ecological surface area that scales with vegetation structure rather than geographic extent, and unlike the terrestrial land surface, woody surface area responds actively to human activity and management decisions.

Emerging evidence reveals the substantial biogeochemical significance of this interface. Woody surfaces mediate massive fluxes of climatically important compounds. Stem respiration transfers 27.4 ± 5.9 PgC annually to the atmosphere (Zhang et al. 2025), a carbon flux nearly three times larger than global fossil fuel emissions, and nine times larger than the land carbon sink (Friedlingstein et al. 2025). Simultaneously, tree stems can function as atmospheric methane sinks, potentially removing 24.6–49.9 Tg of methane yearly through specialized bark-dwelling microbial communities (Gauci et al. 2024), a flux comparable to the global soil methane sink (~30 $TgCH_4\ yr^{-1}$) and approaching the magnitude of methane emissions from the entire natural gas sector (Saunois et al. 2025). These processes operate at magnitudes that rival major components of Earth's carbon cycle, yet remain poorly integrated into current modeling frameworks.

This oversight reflects both historical research priorities and methodological constraints. Forest science emphasized timber volume over surface area (Boyce 1975; Gregoire and Valentine 1996), climate research focused on photosynthetic surfaces and soil carbon, and most woody surface area exists in forest canopies beyond the reach of ground-based measurement approaches. However, advances in remote sensing technologies—including terrestrial laser scanning, airborne LiDAR, and the spaceborne GEDI mission—are revealing the importance of forest structural complexity for ecosystem dynamics and enabling unprecedented analysis of three-dimensional surfaces at multiple scales (de Conto, Armston, and Dubayah 2024; Atkins et al. 2023). Accumulating evidence indicates that woody surfaces perform ecological functions with considerable implications for understanding forest contributions to forest structure and health, global biogeochemical cycles, and planetary climate.

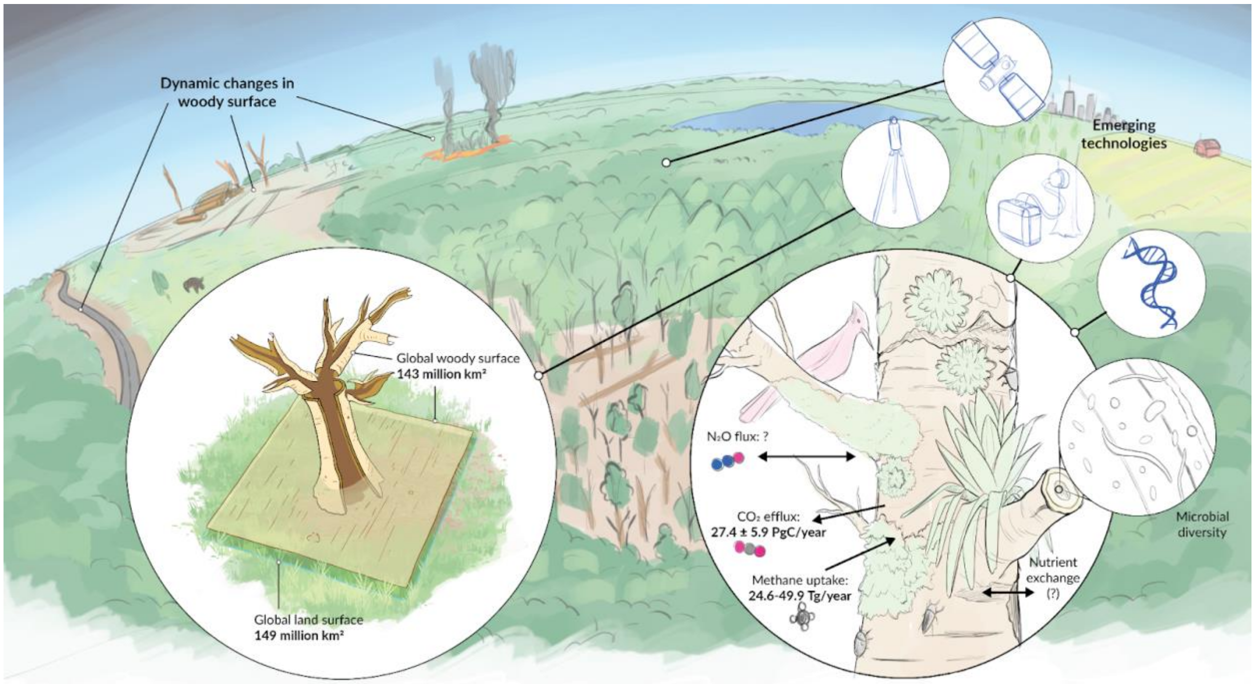

Figure 1. Woody surfaces constitute a massive, dynamic planetary interface with unexplored ecological and environmental significance. Global aboveground woody surface area (143 ± 59 million km²) nearly equals Earth's terrestrial land surface (149 million km², left inset), yet remains largely unaccounted for in Earth system models. This three-dimensional interface mediates substantial atmospheric exchanges including CO_2 efflux (27.4 ± 5.9 PgC year^{-1}) and methane uptake (24.6–49.9 Tg year^{-1}), while supporting diverse microbial communities and numerous unquantified biogeochemical processes (right inset) as well as hosting biodiversity across the domains of life. The interface scales dynamically with forest cover, expanding and contracting with deforestation and restoration. Emerging technologies (circular insets) enable systematic investigation of this previously inaccessible interface across scales from microbial communities to global monitoring.

Environmental and Ecological Functions of Woody Surfaces

Tree stems and branches serve as active sites for the exchange of climatically important gases. While trees have increasingly been recognized as methane sources in wetland and some upland environments, recent studies demonstrate that stems in upland tropical, temperate, and boreal forests may also act as net atmospheric methane sinks (Gauci et al. 2024; Pangala et al. 2017; Gauci 2025). This uptake occurs primarily above two meters from the forest floor, mediated by methanotrophic bacteria that can constitute up to 25% of microbial communities on certain tree species (Jeffrey et al. 2021; Leung et al. 2024). Given methane's 20-year global warming potential of 84 times that of CO_2, this process represents a previously unquantified climate service that could substantially alter forest climate valuations.

Woody surfaces also contribute substantially to forest carbon budgets through stem respiration. This flux involves complex internal dynamics of production, transport, refixation, and consumption that vary spatially across tree structures—including specialized exchange sites such as lenticels—and temporally with growth, environmental conditions, and tissue damage (Teskey et al. 2008). These exchanges are neither static nor uniform, but rather spatially and temporally dynamic, with exchanges varying across plant structures (e.g. lenticels; (Zhong et al. 2024) and heights (Gauci et al. 2024) and affected by growth, development, and wounding (Gorgolewski et al. 2022) and environmental conditions.

In addition to carbon and methane, woody surfaces facilitate exchange of hydrogen, carbon monoxide, volatile organic compounds, and other trace gases (Leung et al. 2024; Niinemets, Loreto, and Reichstein 2004), while potentially serving as sites for water and nutrient uptake and various biogeochemical transformations (Berry et al. 2019; Sparks 2009). The structure and biology of tree woody surfaces also make them interceptors of air pollutants, a trait that can be exploited for air quality management in certain settings (Barrett et al. 2019).

The microbial communities inhabiting woody surfaces—termed the "caulosphere"—constitute biogeochemical hotspots with distinct taxonomic and functional characteristics. Recent work has identified specialized bacterial groups including hydrogen metabolizers and facultative fermenters that actively mediate cycling of hydrogen and carbon monoxide under aerobic conditions (Leung et al. 2024). These surface-associated communities complement the diverse endophytic microbiomes within woody tissues, where an average tree harbors approximately one trillion prokaryotic cells in its aboveground woody components alone (Arnold et al. 2025). This vast microbial ecosystem transforms trees into holobionts—integrated biological units composed of the plant and its microbiota—with caulosphere communities showing sensitivity to environmental change that makes documenting this biodiversity urgent.

Beyond microbes, woody surfaces support diverse epiphytic plant communities and provide critical habitat for arboreal animals for nesting and foraging (Jackson 1979). Surface properties—including bark texture, chemistry, and shedding patterns—strongly influence community assembly and the diversity and abundance of trunk-associated biota across all domains of life. While research has traditionally examined the ecology of some lichens, mosses, higher plants, animals, and microbes in isolation, understanding the cross-kingdom community and ecosystem ecology of these surfaces—and their function as integrated ecological units in their own right—represents a major frontier for biodiversity science (Spicer and Woods 2022).

The Scale and Measurement Challenge

Woody surfaces have received disproportionately limited attention compared to leaf surfaces. Leaf area index (LAI)—the total one-sided area of leaf tissue per unit ground surface area—is one of the most widely measured vegetation parameters, capturing leaves' roles in photosynthesis, transpiration, gas exchange regulation, foliar uptake of water and nitrogen, volatile organic compound emissions, and pollutant interception. While LAI is a core parameter in Earth system models (Mahowald et al. 2016), woody surface area remains largely unaccounted for, despite providing complementary but distinct ecological functions as persistent exchange surfaces that remain active even when leaves are absent seasonally in deciduous systems.

A foundational study by Whittaker and Woodwell (1968) found several square meters of plant surface occur above each square meter of ground surface in temperate forests, including 0.3–0.6 m^2 of stem bark, 1.2–2.2 m^2 of branch bark, and 3.0–6.0 m^2 of leaves. Importantly, they found branch bark surface increases more rapidly than leaf surface with increasing tree size, indicating shifts in surface proportions with forest development. Surface area remains poorly understood as a forest property; while self-thinning laws govern stand development, it remains unknown how surface area varies through succession, given surface area does not directly scale with volume (Gavrikov 2017; Inoue and Nishizono 2015). Different tree architectures and assemblages likely lead to differing surface area magnitudes for different forest types and stand histories.

The spatial distribution and accessibility of woody surfaces present fundamental measurement challenges. Traditional ground-based studies typically sample only the lower two meters of tree stems, creating severe sampling bias (Table 1).

Table 1: *Impact of sampling height on tree surface area measurements for a 26-meter tall tree with average DBH, assuming conical trunk geometry and including branch surface area, showing the proportion of total tree surface area captured at different measurement heights and the corresponding correction factors needed to estimate complete tree surface area.*

Sampling Height	Surface Area Captured	Surface Area Missed	Correction Factor
2 meters (standard)	4%	**96%**	7.1x
10 meters	19%	81%	1.6x
Entire tree	100%	0%	1x

This sampling limitation potentially misrepresents forest-scale biogeochemical processes and limits our understanding of canopy-atmosphere interactions, particularly given that methane uptake occurs primarily above two meters from the forest floor.

Surface area quantification itself presents conceptual challenges analogous to the coastline paradox—measured area increases substantially with measurement resolution due to bark texture, crevices, and three-dimensional complexity. While simple geometric projections may suffice for scaling many ecosystem-atmosphere exchanges, finer-scale fractal surface features may be critical for stemflow regulation, habitat provision for animals and fungi, and pathogen ingress sites.

Advances in remote sensing technologies are transforming measurement capabilities. Terrestrial laser scanning provides millimeter-level structural detail enabling rapid surface area quantification across forest stands. Airborne and spaceborne LiDAR systems, including the GEDI mission, offer unprecedented ability to assess three-dimensional forest structure at landscape to global scales (Atkins et al. 2023; Calders et al. 2020). These technologies enable systematic investigation of woody surface ecology across the full vertical profile of forest canopies, and its importance for forest processes and productivity (Liu et al. 2024).

Climate Policy Implications

The woody surface interface scales dynamically with forest cover, creating feedbacks between forest structure and biogeochemical function that current policy frameworks do not capture. Forest carbon markets focus primarily on biomass and soil carbon, missing complementary services like atmospheric methane removal that may add 10% to forest climate benefits (Gauci et al. 2024; Gauci 2025). With 453 million hectares of potential tropical forest expansion projected (Griscom et al. 2017), strategic species selection could optimize multiple trace gas exchanges rather than carbon storage alone.

This represents a fundamental shift in climate accounting, where forest structure and processes—not just area or volume—determines atmospheric services. As woody surfaces respond to management practices, disturbance regimes, and environmental change, forest climate contributions will vary in ways not predicted by current models or valuation systems.

Research Priorities

Advancing woody surface science requires targeted research investments across multiple scales. Laboratory studies must characterize the environmental controls on microbial community assembly and gas exchange rates, including moisture thresholds, nutrient limitations, and succession dynamics that determine surface biogeochemical activity. Field research should prioritize developing or utilizing canopy-access methods for direct flux measurements, given that traditional ground-based approaches may capture less than 5% of total tree woody surface area.

At ecosystem scales, remote sensing integration with process models represents the path forward for global quantification and monitoring. The cross-kingdom ecology of woody surfaces—linking microbial, plant, and animal communities—remains unexplored despite representing a major component of forest biodiversity that could inform management strategies. Documenting this diversity is particularly urgent in the face of global change that could alter or eliminate countless yet unknown species (Zhu et al. 2022).

The integration of woody surface processes into Earth system models represents a key challenge requiring new parameterizations and measurement approaches. Model development should focus on parameterizing woody surface area as a dynamic vegetation property, analogous to leaf area index, enabling predictions of how changing forest structure affects atmospheric chemistry under future climate scenarios.

Key research priorities include developing standardized protocols for woody surface area quantification across species and ecosystems, including clear definitions of surface area compartments; clarifying linkages between surface structure, microbial communities, and biogeochemical processes; leveraging remote sensing technologies to estimate global woody surface area and monitor spatiotemporal dynamics; improving field measurement techniques for quantifying gas exchange within upper canopies; and expanding vegetation models to incorporate woody surface exchanges alongside existing leaf- and soil-based frameworks.

Realizing this potential requires rapid advancement in woody surface science, from fundamental understanding of microbial processes to landscape-scale modeling of gas exchange. Integration of woody surface processes into climate science, forest management, and conservation planning represents both a scientific imperative and a practical necessity for effective climate policy.

Acknowledgements: Figure 1 by Elena Hartley [© Elena Hartley www.elabarts.com].

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