



Integrating scales and disciplines to promote climate-resilient forests

Integración de escalas y disciplinas para promover bosques resilientes al clima

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ABSTRACT

Trees are long-lived organisms that have shaped landscapes for hundreds of millions of years. Today, forests cover roughly 30% of the Earth's land area and provide essential environmental, social, and economic services. While increasingly frequent and severe disturbances pose challenges, forests can remain resilient. A holistic, cross-scale approach—integrating ecological, social, and governance dimensions from local to global levels—is key to supporting climate-resilient forests and informing effective policies. In this opinion paper, I highlight how multidisciplinary science, combined with inclusive, community-based decision-making, can help forests withstand extreme events while continuing to provide vital ecosystem services and support human well-being.

Keywords: ecosystem services; extreme weather events; human health; multidisciplinary approaches; social–ecological systems; trees.

RESUMEN

Los árboles son organismos longevos que han moldeado los paisajes durante cientos de millones de años. Hoy en día, los bosques cubren aproximadamente el 30 % de la superficie terrestre y proporcionan servicios ambientales, sociales y económicos esenciales. Aunque las perturbaciones cada vez más frecuentes y graves representan desafíos, los bosques pueden mantenerse resilientes. Un enfoque holístico y multiescalar —que integre las dimensiones ecológicas, sociales y de gobernanza desde el ámbito local hasta el global— resulta fundamental para apoyar bosques resilientes al clima y orientar políticas eficaces. En este artículo de opinión, destaco cómo la ciencia multidisciplinaria, combinada con la toma de decisiones inclusiva y basada en la comunidad, puede ayudar a los bosques a resistir eventos extremos y, al mismo tiempo, seguir proporcionando servicios ecosistémicos vitales y respaldando el bienestar humano.

Palabras clave: servicios ecosistémicos; eventos meteorológicos extremos; salud humana; enfoques multidisciplinarios; sistemas socioecológicos; árboles

Forests are unique ecosystems that play a vital role in human life. We evolved alongside them, relying on their resources in sustainable and adaptive ways (Berkes et al., 2000). Many indigenous and traditional communities embody a deep sense of belonging and integration with their forest environments, illustrating our long-standing connection and coevolution with these landscapes (Brondízio et al., 2021). Their homes are built within the forest, and people see themselves as part of a living system. Children grow up climbing trees and interacting with the animals around them, naturally engaging with the forest as an extension of their home.

Although urban life often distances people from natural landscapes, human societies remain fundamentally dependent on the resources and ecosystem services provided by forests. In addition to supplying food, water, and timber, forest ecosystems contribute to social well-being and mental health through regulation of climate, air quality, and restorative experiences (United Nations, 2023). Safeguarding these functions has become an urgent scientific and social priority. Addressing this challenge requires an interdisciplinary, multiscale approach that integrates the earth, physical, and life

sciences with social sciences and policy. Such integration is essential for promoting climate-resilient forest systems—and, in turn, resilient human societies—capable of mitigating contemporary climate change and minimizing its impacts on current and future generations.

Trees constitute a major fraction of the living biomass in forests and can function as small ecosystems, supporting hundreds of associated species such as insects, fungi, other plants, and microorganisms (Ricklefs, 2008). They vary strongly in form, with some reaching over 80 meters in height and surviving for centuries (Gorgens et al., 2019, Vieira et al., 2005). The trunk provides structural support and contains vascular tissues that transport water and nutrients. Growth is driven by meristems—specialized tissues that produce leaves, wood, flowers, and other organs. Leaves are highly efficient structures that convert sunlight, water, and nutrients into sugars through photosynthesis (Esau, 1977). Trees also have diverse reproductive organs and dispersal strategies, each adapted to the environmental conditions of their habitat.

What makes trees especially important in an era of climate change and increasing disturbances is their central role in key biogeochemical cycles, particularly those of water and carbon. Through photosynthesis, trees convert sunlight, water, and soil nutrients into sugars, sustaining their growth and the forest ecosystem. Remarkably, water and carbon can account for roughly 70% of the biomass of a tree (IPCC, 2006; Magnabosco Marra et al., 2016)—meaning a 100-kg tree contains about 70 kg of these elements—, highlighting their critical role in storing and cycling the fundamental resources that support both forests and human societies.

Forests are composed of tree-dominated vegetation, which the Food and Agriculture Organization of the United Nations (FAO, 2025) defines as areas larger than half a hectare, with trees at least 5 meters tall covering at least 10% of the area. This scientifically grounded definition emphasizes that even relatively small forests can provide essential ecological functions for humans. Forests typically occur where annual rainfall exceeds 100 mm and average temperatures are above 10°C; in drier or colder conditions, other vegetation types dominate. About half of the world's forests are tropical, a quarter are boreal, roughly 16.5% are temperate, and 11% are subtropical. Globally, five countries—Russia, Brazil, Canada, the United States of America, and China—contain roughly half of all forested areas (Global Forest Watch, 2024). Biodiversity and endemism, however, rely on forests across many countries and climates, underscoring the global importance of conservation across nations.

Forests are not only essential for biodiversity, climate regulation, and hazard mitigation—they also provide vital social benefits (FAO, 2025). Most forests around the world remain public and belong to people. For example, in Brazil, over half of the Amazon biome is protected within conservation units. In Japan, nearly 70% of the land is forested, and about half of these forests are publicly accessible. Finland has over 70% of its forests publicly owned or managed for common use. In Gabon, roughly 50% of forests are also under public protection. Scientific studies also indicate that forests support human health: forest bathing in Japan can reduce stress and blood pressure, and exposure to green spaces—whether in parks or forests—improves mood, attention, and cognitive function (Lee et al., 2025; Li et al., 2011).

The Amazon, the largest contiguous tropical forest on Earth, illustrates the importance of integrating disciplines and scales to understand the interactions between people and forests. Covering a vast, mostly flat region of South America, its formation reflects dramatic geological and climatic changes over millions of years. Initially largely treeless, the region was transformed by the uplift of the Andes, which created a highland barrier that eventually eroded, allowing rivers to flow eastward to the Atlantic (Ribeiro et al., 1999). The Amazon River, at least 11 million years old, carries 15–20% of the world's freshwater, shaping both the landscape and the forest ecosystem (Junk et al., 2011). The most recent stage of forest development occurred under a relatively stable climate, allowing both ecological and cultural systems to co-evolve. The Amazon itself has existed for over 2.4 million years and functions as a climate regulator, with trees fixing carbon and transpiring water, and recycling moisture to sustain rainfall across the region and beyond (Artaxo, 2023; Spracklen et al., 2012).

Amazon forests are extraordinarily diverse in taxa and structure, with over 14,000 plant species recorded. Trees account for over 4,500 species, and a single hectare can contain more than 280 species (Brazil Flora Group, 2015; Cardoso et al., 2017). Human presence predates European arrival by millennia. Pre-Columbian societies have occupied and managed this region for thousands of years, leaving lasting marks on the landscape (Peripato et al., 2023). The relatively high linguistic diversity—180 different languages in Brazil alone—highlights how intimately these societies were connected to their habitat (IBGE, 2023). They cultivated and dispersed plant species, reflecting a long history of sustainable use and deep knowledge of the forest (Clement et al., 2018). Recognizing this long-term, harmonious interaction underscores the need for holistic strategies that effectively promote forest resilience to climate change while mitigating its impacts on human societies. Multidisciplinary approaches can inform strategies that simultaneously conserve biodiversity, maintain hydrological and carbon cycles, and support the economy and well-being of local, regional, and global communities.

Since systematic monitoring began in the 18th century, global temperatures have risen by more than 1.2°C (NOAA, 2025). This warming is uneven, with some regions experiencing much higher increases and more frequent climate extremes.

While natural factors such as glaciation cycles, solar radiation, and oceanic oscillations (El Niño and La Niña) influence climate over long timescales, they cannot explain the rapid changes observed in recent years. Human activities—population growth, rising resource demand, and land-use changes—have amplified these effects, from large-scale agriculture to increased fire frequency, significantly impacting ecosystems and societies (IPCC, 2023).

When forests are cut or degraded, the carbon stored in trees is mainly released as CO₂ and methane (CH₄), adding to greenhouse gases that trap heat in the atmosphere. While fossil fuel combustion is the dominant source of global CO₂ emissions, deforestation and fires contribute to amplify the greenhouse effect (IPCC, 2006; 2023). This intensified heat trapping drives rising temperatures and changes in rainfall regimes, which can alter the frequency and severity of forest disturbances. Climate extremes such as prolonged droughts, heatwaves, and severe storms disrupt fundamental physiological processes in trees, including water transport, carbon assimilation, and nutrient uptake (Allen et al., 2010). As trees become water-stressed or metabolically limited, their defenses—such as resin production, antimicrobial compounds, and wound recovery—are significantly weakened (McDowell et al., 2011). This physiological impairment makes them more vulnerable to biotic disturbances, allowing insects, pathogens, and other pests to colonize and spread more easily (McDowell et al., 2011; Seidl et al., 2017). In many regions, this interaction between climatic stress and biological agents is a key driver of the escalating rates of tree mortality, with profound ecological, social, and economic impacts, including crop failures, loss of life, and financial costs (Hartmann et al., 2025a and 2025b; McDowell et al., 2018).

Worldwide, forests are experiencing higher tree mortality due to the combined pressures of extreme weather events, and invasive species (McDowell et al., 2018). Monitoring over the last 10–15 years shows these impacts are intensifying, highlighting the urgent need for integrated strategies to protect forest health in a changing world. Building on the impacts of contemporary climate change, globalization further threatens forests (Hammond et al., 2022). Shifts in temperature and precipitation affect tree metabolism and resilience, while the rapid spread of pests and pathogens introduces new threats (Hartmann et al., 2025a; Hartmann et al., 2025b).

Catastrophic tree mortality in Germany since 2018, driven by interacting abiotic and biotic disturbances, has severely affected the wood industry, as well as local communities dependent on forest-based tourism and cultural activities (BMEL & Thünen-Institut für Waldökosysteme, 2024; Hartmann et al., 2025b). In the Amazon, recurrent floods and droughts over the past 10–15 years demonstrate these effects. Downbursts—strong wind gusts from towering cumulonimbus clouds—can topple trees, alter species distributions, and reduce forest biomass and carbon storage (Magnabosco Marra et al., 2018). Although forests can recover over decades, the recently reported increase in frequency and intensity of these events means disturbances may occur faster than recovery, risking long-term carbon loss and major ecosystem changes (Urquiza-Munoz et al., 2024). These examples highlight how escalating disturbance regimes threaten the resilience of different forests.

Assessing the effects of disturbances and the short- to long-term responses of forests requires a holistic, process-oriented framework that accounts for the multitude of interacting mechanisms shaping forest dynamics. Achieving this is inherently challenging, as it demands integration across scales and disciplines. Understanding how forests have evolved and how they may respond to shifts in climate and disturbance regimes requires consideration of hierarchical levels (from molecules to organs, individuals, and ecosystems), taxonomic scales (from species to populations and communities), spatial dimensions (from square millimeters to landscapes and regions), and temporal ranges (from fractions of seconds to decades or centuries). Bridging these dimensions requires diverse expertise—from scientists and stakeholders to public agencies and society at large—capable of reliably quantifying processes and responses and translating them into robust projections and effective management strategies.

Meeting these demands also requires specialized technologies, ranging from cost-efficient sensors capable of high-frequency, near-real-time measurements to advanced tools for long-term ecosystem monitoring. Because trees are long-lived organisms and climate assessments shall cover at least 30 years of observation (WMO, 2017), long-term forest monitoring based on standardized protocols is essential for producing harmonized and comparable datasets. Such integration—across disciplines, methods, spatial and temporal scales—can only be achieved through long-term, stable funding and coordinated scientific and social collaboration.

At the Julius Kühn-Institute for Forest Protection (JKI/WS), we develop multidisciplinary and applied research aiming at promoting forest resilience to extreme weather events and biotic disturbances. Our approach integrates ecological, biophysical, and social aspects, beginning with assessing forest conditions and quantifying damage. By understanding the processes driving disturbances—from climate extremes to pests—, these insights are scaled using remote sensing and translated into practical strategies for foresters, stakeholders, and practitioners, enabling the management and restoration of forests that can better cope with current and future challenges. Within this framework, the Forest Laboratory of the JKI/WS focuses on integrating spatial and temporal scales to better understand forest dynamics. We monitor individual trees with custom-built instruments and conduct experiments, such as simulating disturbances and mortality, to assess forest

responses to stress. By integrating these detailed observations with remote sensing and modeling, we can more robustly calculate species responses to disturbances and climate scenarios, providing data-driven guidance for planting and managing forests that maintain ecological functions while attending economical and societal needs in a rapidly changing world.

How can psychologists, psychotherapists, and other professionals who work with individuals and groups help reconnect people to their biological, evolutionary, and ancestral relationships with forests? Consider children who grow up climbing trees and experiencing the forest as an extension of themselves—an early immersion that fosters an almost instinctive sense of care and belonging. Modern societies have largely lost this relational understanding, and this is where your expertise becomes crucial. Beyond the mathematical, biophysical, and ecological work we forest scientists conduct, there is a societal dimension we cannot address alone. You can help cultivate awareness, strengthen emotional and cognitive bonds with forests, and support the cultural and behavioral shifts needed for people to recognize nature as essential to their well-being and long-term survival. When individuals understand how profoundly forests matter—to climate stability, to livelihoods, to identity, and to future generations—, they are far more likely to value and protect them. Without this collective understanding, even the most advanced scientific knowledge will not be enough to secure resilient forests and societies.

Conflicts of interest

Nothing to declare.

Availability of data and material

All dataset were generated or analyzed in the current study.

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