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Assessing forest resilience using multiple indicators: integrating structural, hydrological, ecophysiological, and stakeholder perspectives

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Forests play a key role in mitigating climate change, yet their capacity to do so critically depends on their resilience to increasing climatic stressors such as drought and heat extremes. Here we aim to enhance science-based knowledge on forest resilience by applying a multi-scale research framework that integrates structural, hydrological, ecophysiological, and stakeholder perspectives at European beech (Fagus sylvatica L.) stands in Central Germany.

In a first step, we combine terrestrial, drone-based, and airborne LiDAR technologies to comprehensively characterize three-dimensional forest structure across spatial scales. From these data, we derive indicators of forest resilience related to canopy complexity. A particular focus is placed on evaluating the robustness of LiDAR-derived metrics with respect to phenological variability and spatial resolution, ensuring their applicability for long-term monitoring and cross-site comparisons.

To link forest structure with ecosystem functioning, we investigate forest water, carbon and other biogeochemical fluxes along gradients of water availability and stand structure. In 2025 we carried out intensive measurement campaigns including detailed measurements of soil moisture at multiple depths, allowing us to assess how different stand structures influence soil water dynamics. We also measured mercury (Hg) concentration in the forest canopy for assessing Hg cycling of forests as indicator of biogeochemical resilience. We performed tree-level observations of growth and water consumption via dendrometer and sap flux sensors and combined them with ecosystem-scale measurements of CO□, water, and energy exchange between forests and the atmosphere using the eddy covariance technique for ecophysiological indicators of forest resilience.

Complementing these biophysical assessments, we integrate a socio-ecological dimension through qualitative interviews with forest stakeholders. This allows us to evaluate stakeholder assessments

of the status quo, their visions for resilient forests, and the specific requirements for a successful transformation toward those goals.

By integrating multiple indicators derived from measurements across spatial, temporal, and social scales, we provide a broad assessment of forest resilience. Our results contribute to a mechanistic understanding of how forest structure mediates water and carbon fluxes under climate stress, supporting the development of resilient forest management strategies and improved monitoring approaches for climate change mitigation that are both scientifically robust and stakeholder-informed.