FoResLab

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HAWK HOCHSCHULE FÜR ANGEWANDTE WISSENSCHAFT UND KUNST Hildesheim/Holzminden/Göttingen

Leibniz Universität Hannover

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN IN PUBLICA COMMODA SEIT 1737

ASSESSING FOREST RESILIENCE USING MULTIPLE INDICATORS: INTEGRATING STRUCTURAL, HYDROLOGICAL, ECOPHYSIOLOGICAL, AND STAKEHOLDER PERSPECTIVES

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I. Introduction

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. Given that forests are multifunctional systems and shaped by various actors, assessing resilience requires clarity about "resilience of what, to what, and for whom" (Le Polain de Waroux et al. 2024). In the project FoResLab, we therefore aim to advance science-based knowledge on forest resilience by applying a multifunctional research framework that integrates structural, hydrological, ecophysiological, and stakeholder perspectives in European beech (*Fagus sylvatica* L.) stands in central Germany. Organized into three research platforms and 12 subprojects, FoResLab compares and interrelates forest resilience indicators across six sites, each comprising five study plots along a structural gradient.

Central Question: **How can we asses forest resilience using a multi-functional approach considering structural, hydrological, eco-physiological, and stakeholder perspectives?**

II. Study Sites and Methods

Nr.	Sites
1	Unterlüß
2	Solling
3	Lange Bramke
4	Göttinger Wald
5	Leinefelde
6	Hainich

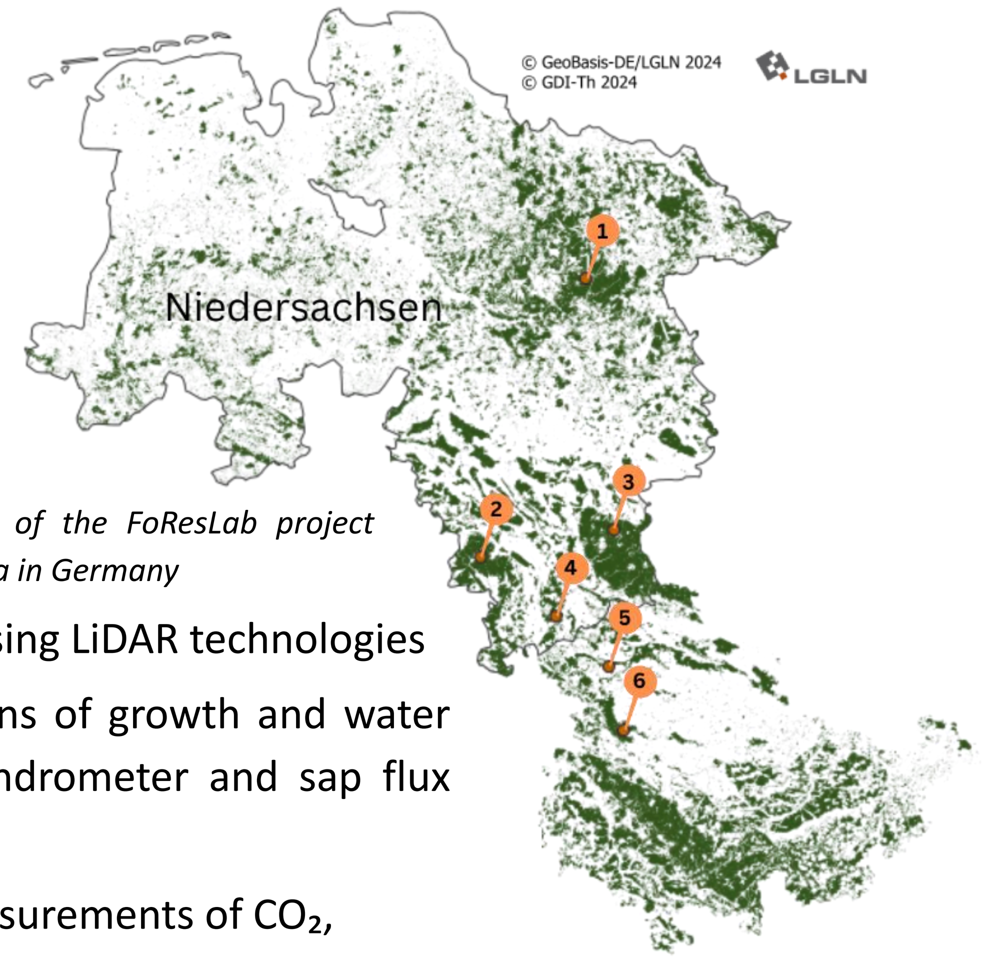


Fig. 1: Study Sites (orange) of the FoResLab project in Lower-Saxony and Thuringia in Germany

- 3d forest structure using LiDAR technologies
- tree-level observations of growth and water consumption via dendrometer and sap flux sensors
- ecosystem-scale measurements of CO_2, water, and energy fluxes using the eddy covariance technique
- soil moisture dynamics and mercury (Hg) concentration in the forest canopy as indicators of hydrological and biogeochemical resilience
- qualitative interviews with forest stakeholders & outreach activities

III. Towards Multi-Functional Forest Resilience Indicators

Ecophysiological indicators

Tree-level responses

- sap flow and high-resolution dendrometers indicate tree water use, tree water deficit, and growth dynamics

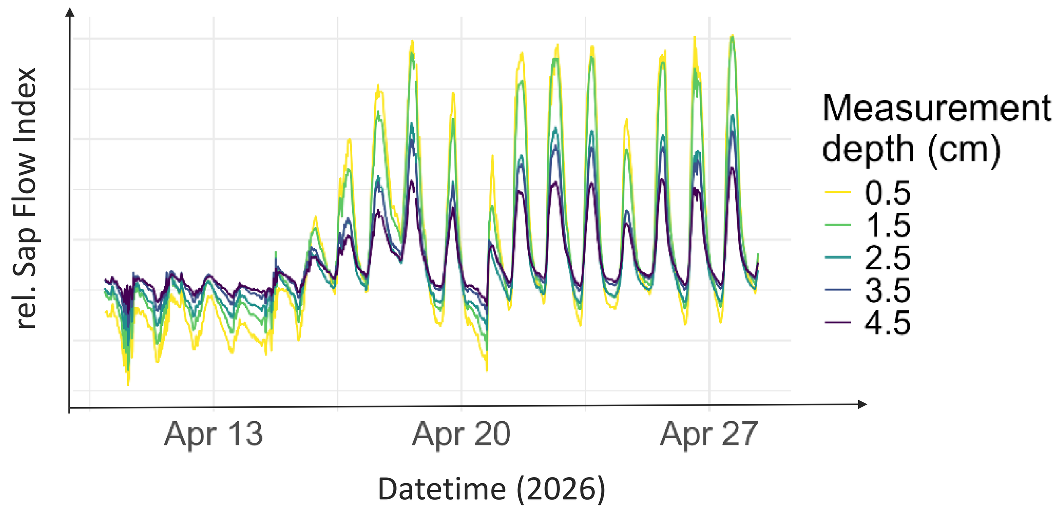


Fig. 2: Sap flow measurements at the Unterlüß site in April 2026.

Ecosystem-level fluxes

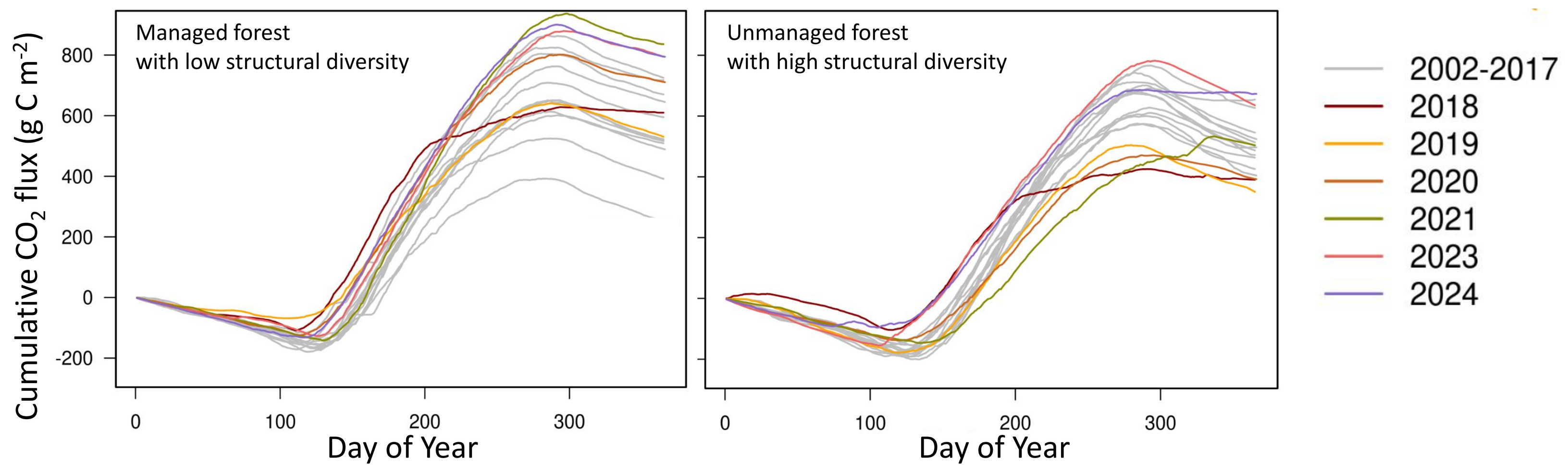


Fig. 3: Multi-annual cumulative CO_2 fluxes (g C m^{-2}) from eddy covariance at a conventionally managed forest site (Leinefelde, left) and an unmanaged forest site (NP Hainich, right), showing differences in stability of carbon uptake.

Structural indicators

- characterization of 3D forest structure from ground to canopy top using mobile (MLS), drone-based (ULS), UAV-borne and airborne (ALS) laser scanning
- high-resolution plot-level metrics as reference for upscaling to landscape and regional scales

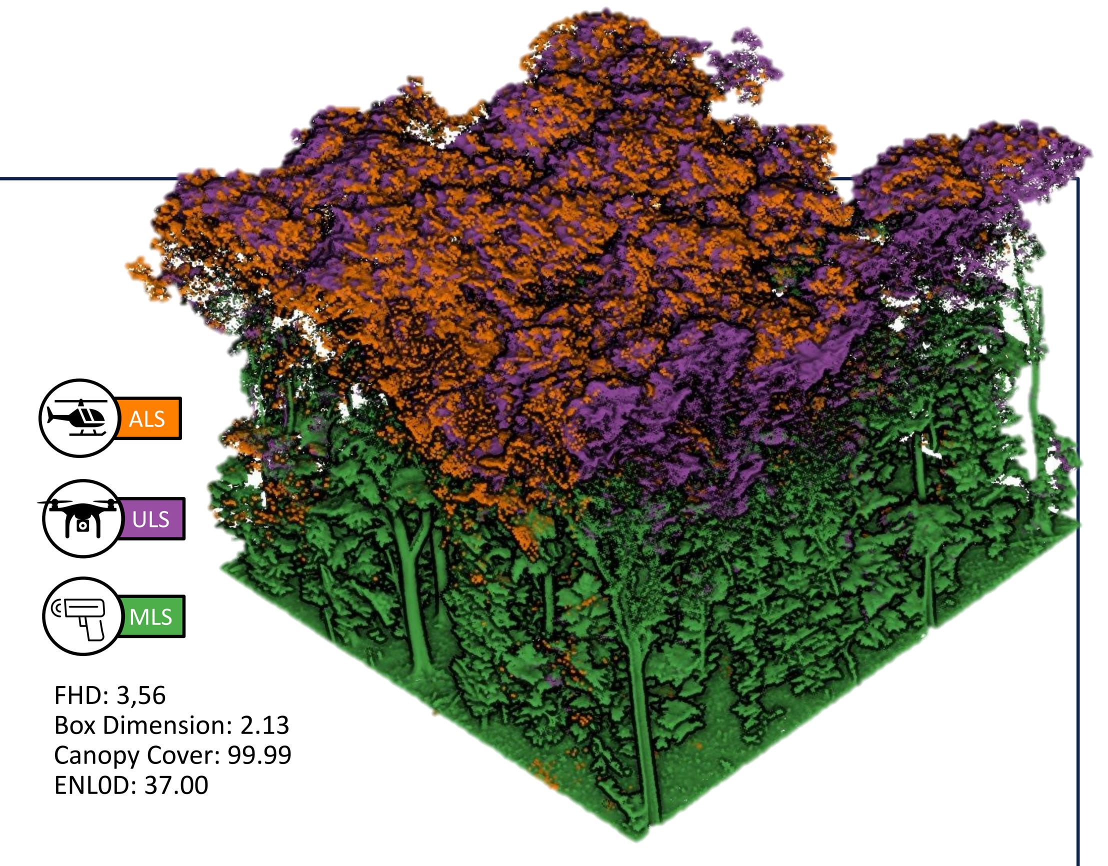


Fig. 4: Multi-platform LiDAR point cloud of a 50 × 50 m forest plot in Hainich Nationalpark.

FOREST RESILIENCE

as the capacity
- to absorb,
- adapt to, and
- transform
after perturbations

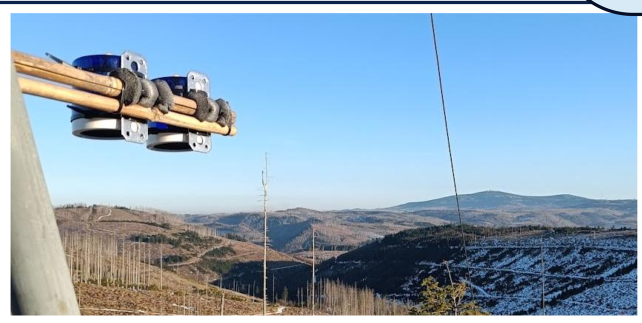
Social indicators

- extensive interviews discussing the status quo, the vision for 2100, and the needs for making forests more resilient
- follow-up questionnaires eliciting the stakeholder network and the most demanded policy changes

Fig. 5: Interview with state owners, private owners, foresters, tourism representatives, national park authorities, conservationists, label representatives, foundations, hunters.

Biogeochemical indicators

- leaf mercury (Hg) as a functional proxy for canopy activity and atmospheric uptake processes
- seasonal Hg accumulation may indicate whether canopy uptake is maintained or reduced under drought or heat stress
- Hg indicates forest filtering capacity but depends on leaf area, litterfall, stand structure, and Hg exposure



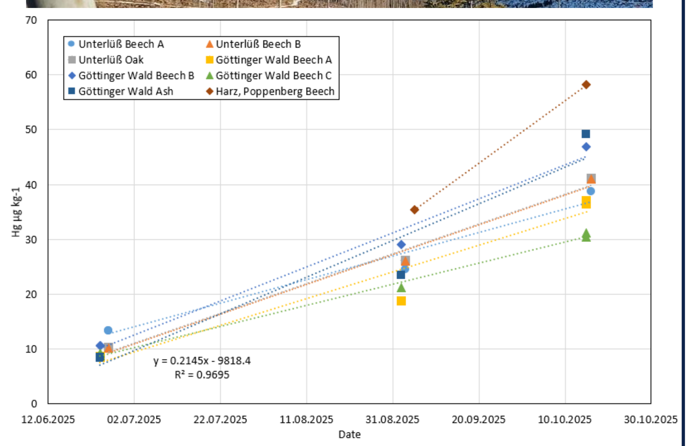


Fig. 6: Hg sampler at the Lange Bramke site in the Harz Mountains & leaf Hg concentrations (µg kg^{-1} DW) in Unterlüß, Göttinger Wald, and Harz, measured in June, September, and October 2025, indicating a 2–3-fold increase within two months.

Hydrological indicators

- volumetric soil water content measured down to 2 m and soil matric potential measured down to 80 cm depth

ULU1: high structural complexity

ULU3: natural regeneration

ULU5: low structural complexity

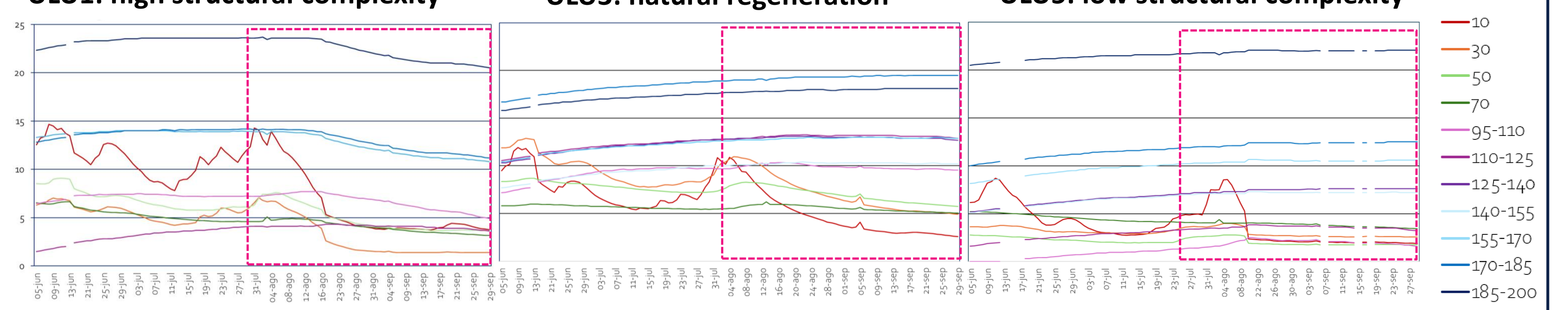


Fig. 7: Volumetric soil water content [vol.%] in the upper 200 cm at Unterlüß, Lower Saxony, across a structural gradient from high (ULU1) to low (ULU5). The pink boxes highlight a dry period in summer 2025, where differences in deep soil water dynamics among the different structure classes are evident.

Acknowledgements and References

We thank the administration of the Hainich National Park and the Forestry office and district management of Leinefelde, Heiligenstadt, Reinhausen, Unterlüss, Solling and Harz. We acknowledge funding from zukunft.niedersachsen by the Ministry of Lower-Saxony for Science and Culture (MWK) and the Volkswagen Foundation through the project FoResLab (ZN4445).

le Polain de Waroux, Yann, et al. "How do we study resilience? A systematic review." *People and Nature* 6.2 (2024): 474-489.