Scaling drought stress monitoring in reforestation: Integrating dendrometers, remote sensing, and modeling

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Droughts, combined with bark beetle attacks and wind throw, have caused extensive damage to forest areas in Central Europe, endangering essential ecosystem services. For Germany, it was estimated that more than 500,000 ha need to be reforested. In some regions, such as the Franconian Forest in northern Bavaria, salvage logging created several hundred clear-cut areas exceeding five hectares, which is unusually large for Central Europe. Particularly during drought phases, extreme microclimatic conditions can occur on these sites, leading to high sapling mortality, which is especially pronounced on soils with low water-holding capacity. Adapted management strategies, such as irrigating the tree saplings, could increase the survival of the saplings under drought conditions. To promote the acclimatization of the saplings to drought conditions, while enhancing their long-term resilience, as well as to conserve scarce water resources, targeted irrigation strategies are required. These strategies must provide sufficient support while avoiding overirrigation. However, precise and practical monitoring tools for assessing the water status of tree saplings are lacking. Therefore, we conducted experimental studies in a greenhouse and on forest sites in the Franconian Forest to develop practical monitoring approaches for determining drought stress in tree saplings, which could inform irrigation scheduling.

First, we elaborate on the application of dendrometer data to derive precise ecophysiological irrigation thresholds based on the tree water deficit (TWD), a common indicator of drought stress. Further, we evaluate the thresholds under practical conditions on a reforestation site. In the next step, we investigated whether early signs of drought stress, as measured by dendrometers, could be detected using low-cost handheld thermal cameras. These could directly be used by forest practitioners on their forest sites to refine existing broad-scale monitoring products derived from remote sensing or modeling, which are currently not specifically targeted at tree saplings. Our approach involves semi-automated tree segmentation with *Segment Anything 2*, a state-of-the-art foundation model. The processed images are used to select pixels in the thermal images required for calculating the Cop Water Stress Index (CWSI). Generalized additive models enabled us to robustly determine early signs of drought stress from CWSI, specifically whether the daily minimum TWD recovered or not. Results from the 5-fold cross-validation revealed a balanced accuracy (BA) of 70.7% and a Cohen's Kappa of κ=0.44. Model performance improved when additional environmental information, such as soil water content and vapor pressure deficit, was included (BA 92.4%, κ=0.85), capturing the compromise between measurement effort and model accuracy. The proposed method is especially valuable for sites with skeletal soils, where soil water measurements are difficult or unreliable.

Finally, we provide a preview of how remote sensing and further machine learning approaches could scale up our current insights. These methodologies would allow the monitoring of larger sites and safeguard successful reforestation while sustainably managing natural resources. In addition to foresters, forest owners, and forest practitioners, forest administrations would also benefit from our findings, as these insights can inform management decisions and the design of funding schemes.