



Drone-based LiDAR reveals dynamic links between forest structure and microclimate during phenological transitions

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Forest microclimates play a critical role in shaping biodiversity, ecosystem functioning, and species responses to climate variability. Within forested environments, near-surface air temperatures often deviate substantially from macroclimatic conditions as a result of canopy structure and seasonal vegetation dynamics. Despite growing interest in forest microclimate buffering, the fine-scale and seasonal links between forest structure and temperature regulation remain poorly quantified, particularly during phenological transitions such as spring leaf onset.

Here we show that high-resolution LiDAR-derived forest structural metrics capture rapid canopy development during leaf emergence and robustly explain spatial and temporal variability in forest temperature offsets relative to macroclimatic conditions. We combined repeated UAV-based LiDAR acquisitions conducted throughout spring 2025 with in situ microclimate measurements across four temperate forests in Wallonia (Belgium). Metrics describing canopy density and structural complexity, such as plant area index, rumple index, and canopy height skewness, characterize complementary aspects of structural development during leaf onset.

Together, these structural indicators explain a substantial fraction of the variability in forest temperature offsets and reveal seasonally evolving relationships between canopy structure and microclimate buffering. These results indicate that microclimate buffering is primarily driven by short-term structural dynamics during leaf onset rather than by static canopy properties.

Our findings advance the mechanistic understanding of how phenological dynamics modulate forest microclimates and emphasize the importance of accounting for seasonal structural variability when assessing forest resilience to climate extremes. Given the strong sensitivity of forest species and ecosystem processes to small microclimatic variations, incorporating temporally explicit canopy structure is essential for improving predictions of ecosystem responses under ongoing climate change.