Temperature-driven onset and light quality-linked senescence in *Fagus sylvatica* phenology

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Understanding phenology is crucial for assessing forest responses to climate change, but research has mostly focused on spring onset, with fewer studies on autumn senescence. This study investigates leaf phenology, cambial activity, xylem/phloem formation, sap flow, and GPP in *Fagus sylvatica* from 2018 to 2022 in the White Carpathians, Czech Republic.

Spring phenology, including budbreak, cambial reactivation, and GPP onset, was mainly driven by air temperature above 10°C, starting around DOY 112. In contrast, autumn phenology was more influenced by light quality, particularly the clearness index, which correlated strongly with leaf coloring and phloem compression ($r = 0.97$), highlighting light's role in regulating senescence.

The study shows an extended growing season due to rising temperatures, with thresholds advancing by 5, 9, and 34 days for 5°C, 10°C, and 15°C, respectively. These shifts were linked to significant changes in physiological processes, including radial growth, xylogenesis, and carbon assimilation, all closely synchronized with phenological events.

Our results show that budbreak and cambial activity align with the growing season onset, while leaf formation correlates with GPP onset and sap flow initiation. Additionally, light quality, especially the clearness index, regulates autumn senescence, emphasizing the complementary roles of thermal and radiative signals in phenological transitions (fig. 1).

This research highlights climatic and physiological factors affecting forest phenology, with implications for productivity, resilience, and carbon cycling under climate change. It emphasizes the need to integrate ecophysiological indicators into phenology models to predict forest dynamics and carbon sequestration, especially in temperate forests dominated by *Fagus sylvatica*.

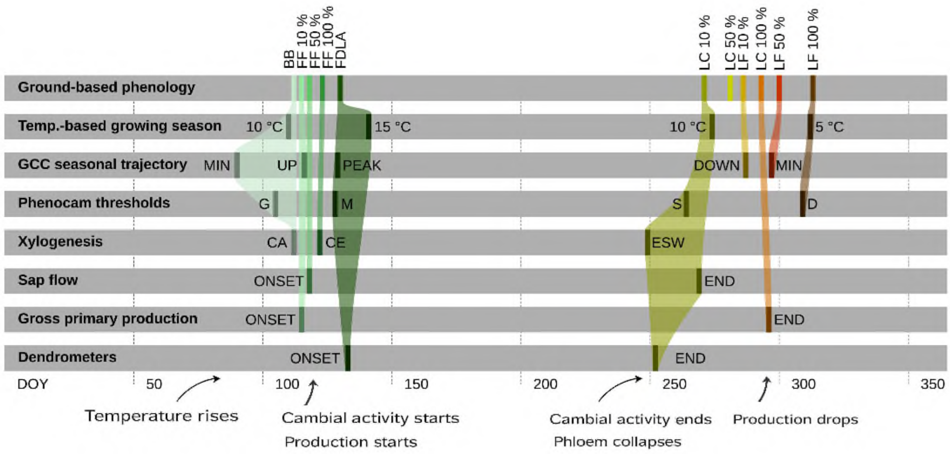

Fig. 1. Temporal alignment of spring and autumn phenophases of *Fagus sylvatica* with other monitored physiological and ecosystem processes between 2018 and 2022. The diagram shows the closest matches among ground-based phenology, temperature-based growing season thresholds, GCC seasonal trajectory metrics, phenocam thresholds, xylogenesis, sap flow, gross primary production, and dendrometer-derived growth dynamics along the day-of-year (DOY) axis. BB, budbreak; FF, foliage formation (10%, 50%, 100%); FDLA, fully developed leaf area; LC, leaf coloring (10%, 50%, 100%); LF, leaf fall (10%, 50%, 100%); G, green-up; M, maturity; S, senescence; D, dormancy; MIN, pre-season minimum canopy greenness; UP, spring increase in canopy greenness during leaf formation; PEAK, maximum canopy greenness corresponding to full leaf development; DOWN, autumn decline in canopy greenness associated with senescence and browning; MIN, post-season minimum canopy greenness; CA, cambial activity; CE, cell enlargement; ESW, end of secondary wall thickening.