Phenological Climate Sensitivity of European Beech Along Elevation Gradients Using Remote Sensing

Introduction

Climate change is reshaping European forests through warming, altered precipitation regimes and more frequent extreme events. The European beech (*Fagus sylvatica* L.) is a keystone temperate tree, forming extensive forests and underpinning biodiversity and ecosystem services across Central and Western Europe. Yet beech is known to be sensitive to drought, heat, and late spring frosts, especially at the southern and eastern range margins. Recent "hot droughts" (e.g. 2003, 2018–2019) led to crown defoliation, growth decline and locally elevated mortality in many beech stands, raising concerns about long-term resilience.

While numerous studies have documented local or regional phenological shifts in beech, we still lack a continent-scale picture of how beech phenology and growing season dynamics respond to climate across distinct climatic zones and elevation belts. In particular, it is unclear to what extent beech forests in different macro-climatic contexts (maritime, transitional, continental) and at different elevations (lowland, montane, high-elevation) share similar climate sensitivities, or whether some combinations of climate zone and altitude are already approaching tipping points.

This study addresses that gap by combining long-term satellite-based phenology with gridded climate data for hundreds of beech locations stratified across European climate zones and elevation classes.

Data and Study Area

Our analysis uses 356 *Fagus sylvatica* locations from the EUFORGEN database, covering the main west–east and north–south gradients of the species' European range. Each site is assigned to one of seven warm-subtropical or warm-temperate climate zones and to one of three elevation belts (0–500 m, 500–1500 m, >1500 m a.s.l.), yielding 21 strata for comparing climate–phenology relationships (Figure 1).

All processing is done with openly available datasets. Climate data come from ERA5-Land, from which we derive mean annual temperature and total annual precipitation (2001–2024), aggregated to zone × elevation means after basic outlier filtering. Land surface phenology is characterised using the MODIS MCD12Q2 product (500 m), providing annual day-of-year (DOY) of green-up, peak greenness and senescence (2001–2024). From these, we compute growing season length (GSL = senescence – green-up) and spring development duration (peak – green-up), retaining realistic DOY ranges (50–330) and averaging per year and stratum.

The analysis has three steps: (i) estimating climate trends by regressing annual temperature and precipitation against year (°C/decade, mm/decade); (ii) estimating phenology and GSL trends in days/decade using the same approach; and (iii) quantifying phenoclimatic sensitivity through correlations and simple regressions between climate and phenology variables in each stratum, followed by hierarchical clustering of standardized trend and sensitivity metrics to identify vulnerability types.

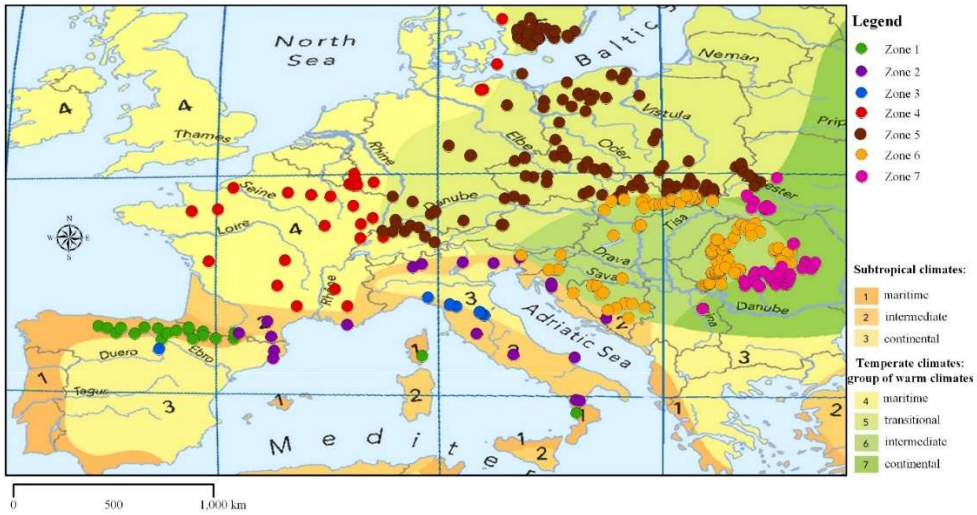

Figure 1. Study area; *Fagus sylvatica* locations from the EUFORGEN database over the main climates in Europe.

Results

Climate trends show a clear, near-universal warming signal across the 21 strata, typically around +0.5 to +0.8 °C per decade, with some of the strongest trends at high elevations in warm-temperate zones, indicating that montane beech forests are among the most rapidly warming environments. Precipitation trends are more mixed: some lowland zones exhibit strong drying while others show modest wetting, resulting in contrasting moisture trajectories across the beech range.

Phenology trends indicate earlier springs everywhere and, in many strata, delayed autumn. Green-up advances in all zones and elevations, strongest at high elevations where spring onset can shift by several days per decade (Figure 2). Senescence trends are generally weaker but often delayed, especially in mid- and high-elevation groups. Consequently, growing season length changes range from modest to substantial: some lowlands gain around a week per decade, whereas certain maritime high-elevation sites show a shortening of roughly half a week per decade. In at least one continental zone, spring development

duration increases, hinting at a local decoupling between early leaf-out and the pace of canopy development.

Phenoclimatic sensitivity patterns reveal that control of beech phenology is strongly elevation-dependent. At high elevations, GSL is mainly temperature-limited: warmer years consistently extend the season, and temperature is the dominant driver of interannual variability. Many low- and mid-elevation forests are clearly precipitation-sensitive: wetter summers and autumns delay senescence and lengthen GSL, while dry years shorten it even when springs are warm. Some strata are co-limited, requiring both favourable temperature and moisture for GSL extension.

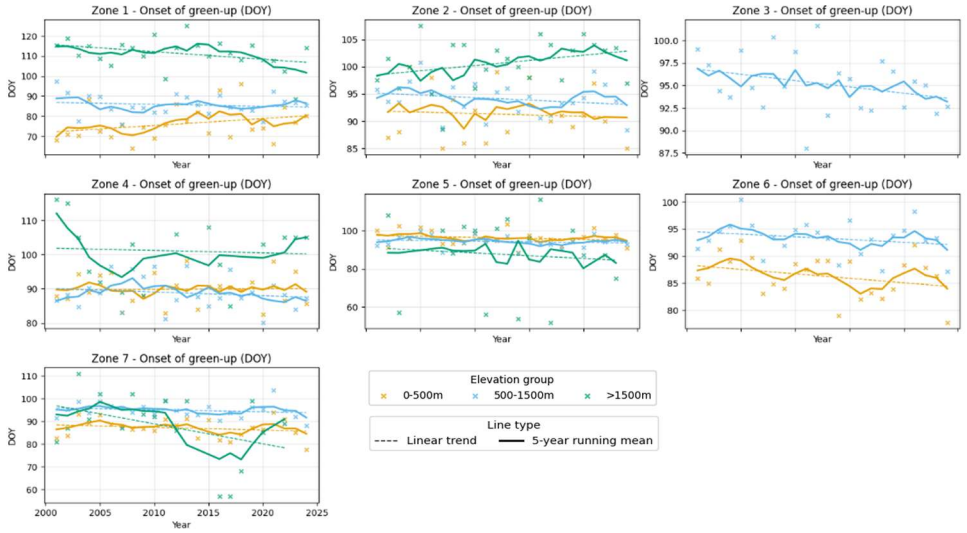

Figure 2. Climate Trends – Onset of green-up for each zone × elevation group.

Discussion and Conclusions

Although methodologically simple, the results are directly relevant for practice. National forest services and regional managers can see which beech regions are warming or drying fastest and where growing seasons are lengthening or shortening, informing silviculture, regeneration planning, species mixtures and provenance choice near climatic limits. Climate adaptation and biodiversity agencies gain a spatially structured picture of beech phenology responses across climate zones and elevation belts, supporting adaptation planning, Natura 2000 and other conservation instruments.

For forest ecologists and modellers, the zone- and elevation-specific sensitivities (e.g. days of green-up change per °C, GSL response per mm) offer empirical constraints for dynamic vegetation and species distribution models. Genetic conservation and provenance networks such as EUFORGEN can use the identification of thermo-limited and water-limited regions to prioritise provenance trials and genetic monitoring.