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Constraints on ever earlier spring leaf-out and its consequences for forest productivity

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Global climate warming is currently advancing the onset of the growing season in temperate trees enhancing global net primary productivity and terrestrial carbon capture. However, it remains unclear whether this trend will continue over the rest of the century because we do not know if warming-induced advances in spring leaf-out will be constrained by reductions in spring day-length and winter chilling. Here, we use the PEP database, containing 727,401 ground-sourced observations of spring leaf-out times in nine dominant European tree species, to test for the interactive effects of spring warming, day length, winter chilling, and autumn temperatures on spring leaf phenology. For all species, we find consistent effects of day length and winter chilling, with reductions of both factors increasing the amount of accumulated warming required for leaf emergence. Models based on these statistical relationships accurately predict observed leaf-out times, outperforming models accounting only for winter chilling. Based on these empirical relationships, we forecast that leaf-out could advance by <1 week under a "CO_2 stabilization scenario" or <2 weeks under a "high CO_2 emission scenario, by the end of the 21st century. This corresponds to a $\sim$60% reduction in the response to climate warming compared to a spring-warming only model. By avoiding model overparameterization our direct empirical relationships can provide unique insights into the phenology of temperate trees under current and future climate conditions. Using a dynamic global vegetation model, we estimate an average future reduction in NPP of 3% compared to previous estimates, which equals a 22 Gt decrease in cumulative net carbon gain of temperate trees until the end of the 21st century.