

Early leafout leads to cooler growing seasons in woody species

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Abstract

Recent results have challenged the assumption that longer growing seasons increase plant growth, but struggled to explain why. Using rarely available plant-scale phenological measurements from a common garden of 18 woody species, we found earlier leafout led to earlier budset and thus lower thermal growing seasons, especially for early-leaving species. These results challenge our fundamental understanding of budset and may help explain why apparently longer seasons do not increase growth.

Terrestrial forests are a major mitigation pathway for climate change, sequestering 20% of greenhouse

gas emissions (2). Most models of climate change assume warming will drive longer seasons, more tree growth and, thus, more carbon storage, following decades of evidence from ecosystem-scale studies (4; 5). However, recent findings from observations of individual trees have questioned this assumption (8; 14). At the same time new experiments on saplings have suggested that plants may adjust their end of season timing dynamically such that longer seasons do not increase total productivity, though the mechanism—and prevalence—of this effect is unclear (6; 7; 9),

These results suggest fundamental gaps in our understanding of how early-season events and the environment of the growing season shape end-of-season events, but addressing these gaps requires working across plant strategies and varying definitions of a growing season. Because the timing of leafout and senescence are critical to plant growth strategies they vary strongly across species (15). Within species, populations also vary (16), especially because end-of-season events are usually locally adapted (e.g. budset 17; 18). Increasing evidence also suggests local climate may define narrow periods of growth for many species, with most significant growth earlier in the growing season (19; 9). These results suggest the calendar growing season (i.e., the number of days between the start and end of the growing season) may be less informative to predicting growth than estimates that directly incorporate environmental conditions (10).

The thermal growing season—a period of favorable meteorological conditions for plant growth (10)—offers an alternative to the calendar growing season. It is also widely used, most commonly in the metric of growing degree days, a temperature derived measure of time that accumulates when temperatures are above a certain minimal threshold (20; 21; 22). Because plant photosynthetic rates increase with temperature (23) the thermal growing season is mechanistically related to primary productivity, and thus may be a better proxy than calendar time for relating growing season length to carbon gain. Yet we generally lack plant-level phenological data for the start and end of season to examine how the calendar and thermal seasons of species and populations compare across years.

Here, we use rarely available plant-scale data from three years of a multi-species, multi-population common garden to test how variation in start and end of season events drive shifts in calendar and thermal growing seasons. Our results leverage phenological observations of leafout and growth cessation (budset) at the individual tree-level to understand how growing seasons scale across populations, species

and communities, and may thus improve our understanding of ecosystem measures to improve forecasting.

1 Results & Discussion

Across three years and 18 co-occurring species from four populations across a 4.5, our common garden captured high variation in the timing of both start (leafout) and end of season (budget) events (Figure 2). Resulting calendar and thermal growing seasons varied almost two-fold across individual trees (2.1x and 1.8x respectively), with earlier leafout leading to longer calendar growing seasons (Fig: 1a,b), as routinely seen with anthropogenic climate change (24; 25).

Longer calendar growing seasons did not lead to higher thermal growing seasons, as generally assumed; instead early calendar growing seasons led to lower (cooler) thermal growing seasons (Figure 1c,d, this and other results were similar when we determined the length the growing season length with leaf coloration instead of budget, Figure ??). This result was driven by an apparent relationship between leafout and budget at the individual level combined with differences in thermal conditions of the early season during leafout and later in the season during budget. When plants leafed out earlier in the spring they stopped growth (budget) earlier, but the additional days of growth in the spring—when temperatures were cool—were rarely offset thermally by the days lost in the later season to earlier budget, which occurred in warmer months (July-August, Figure 3a,b).

Differences between thermal and calendar growing seasons were strongest in the earlier-leafout species, which leaf out during the coolest part of the spring (Figure 1-3). For later leafing species, earlier leafout did not substantially reduce their thermal growing season, likely because their earlier leafout still occurred in thermally favorable times of the season. Species was also the a major predictor of variation in leafout, budget and growing season length ($\sigma_{species}$ days for leafout: : 8.22UI₉₀[5.62,11.7], days for budget: 9.84 UI₉₀[7.01,13.52], days for season length: 14.54, UI₉₀[10.43,19.74] Figure 2a-b).

These results suggest that some of the apparently conflicting recent findings of whether longer seasons increase growth or productivity may be due to different scales of observation, including the different species they integrate over. Our result that individual trees appear to hasten their end of season events with earlier start of season events supports other studies conducted on a small number of species (though using alternative metrics of senescence, 26; 6). Thus, we may expect that studies of individual trees—and

for certain species—could find little relationship between earlier leafout and growth (? 6), which could be driven by currently unstudied shifts in the thermal seasons. Additionally, because differences between thermal and calendar growing seasons were strongly species-dependent, previous findings may depend on the species studied, consistent with other work comparing across smaller sets of species (27; 28). This variation also likely scales up to affect ecosystem-level estimates which generally have one measure of the start of season—for the earliest leafout species—and one for the end of season, likely capturing the later-leafout species given the correlations we found between start and end of season events.

Beyond species-level variation, we found high variation across years in both leafout and budset. We expected large differences across years in leafout (σ_{year} :10.62 days $UI_{90}[4.83,21.22]$, Figure 2), because it varies strongly with local climatic conditions—one of the reasons it is the most consistent biological indicator of anthropogenic climate change (29). In line with this, we also found little variation across populations in leafout ($\sigma_{population}$:0.61, $UI_{95}[0.03,1.86]$, Figure 2b). Yet the finding of strong variation across years in budset was surprising (σ_{year} :15.13 days $UI_{90}[6.24,31.02]$, Figure 2) because budset is generally thought to be strongly locally adapted and controlled by photoperiod, which does not vary year to year (18; 16). We did find evidence of local adaptation ($\sigma_{population}$:2.35 days, $UI_{90}[0.38,6.39]$, Figure 2), with populations from the site with the fewest frost free days (FFD, Figure ??) setting buds approximately two days before the site with next fewest FFD. These differences, however, were weak (Figure 2b) and 6X and spVpopX smaller than the variation due to year and species (respectively).

The shift in budset with earlier leafout suggests a potential pathway to better understand and predict recent findings, given additional research. While most work on budset has stressed the role of photoperiod (18), other studies have found evidence of temperature control (32; 33). Our results suggest an additional potential role of leafout timing, which could be confounded with temperature. Teasing apart these potential cues appears an important next step. Testing these relationships for other end of season events could also help resolve connections between start and end of season events with growth. While we found similar findings using leaf coloring, there are many ways that plants transition from growth to dormancy each year—generally at different times for different events (33), and with different implications for carbon gain (10).

Our multi-species common garden study showed that for early-leaving species, earlier leafout does

not extend their thermal growing season—a proxy for potential carbon uptake period—despite extending the calendar growing season. Given that photosynthesis is limited by cold temperatures in early spring, earlier leafout appears to provide limited opportunity for substantial growth, yet may deprive plants of fully using late-season warmth. This may explain why multiple studies have failed to find correlations between longer seasons and increased plant growth (36; 8; 14). Our results suggest little advantage from a carbon or primary productivity perspective for leafing out too early in the season, as thermal conditions are not favorable for photosynthesis and assimilation. Varying light availability over the early season combined with different plant strategies may alter this equation, and explain why some species leafout early during these thermally unfavorable conditions. Supporting this, we found understory species often showed the strongest relationship, suggesting that leafing out in thermally poor conditions before the upper canopy closes and reduces light may be a successful strategy.

The link between earlier leafout and lower thermal seasons was driven by variation across years at the individual and species levels—scales that are not always studied closely in phenology research (24). While satellite observations can document intriguing trends (e.g., 9), observations that include far more species at a finer scale are likely critical for mechanistic understanding. Sampling across species of different leafout and growth strategies appears especially important as we found later-leafout species did not exhibit a strong trade-off. Whether this is consistent across other communities of species—and other climates—is an important question. Understanding whether the thermal responses are consistent across species with different strategies could also inform how the thermal season varies over time and space, improving our ability to accurately model biological carbon fluxes.

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3 Figures

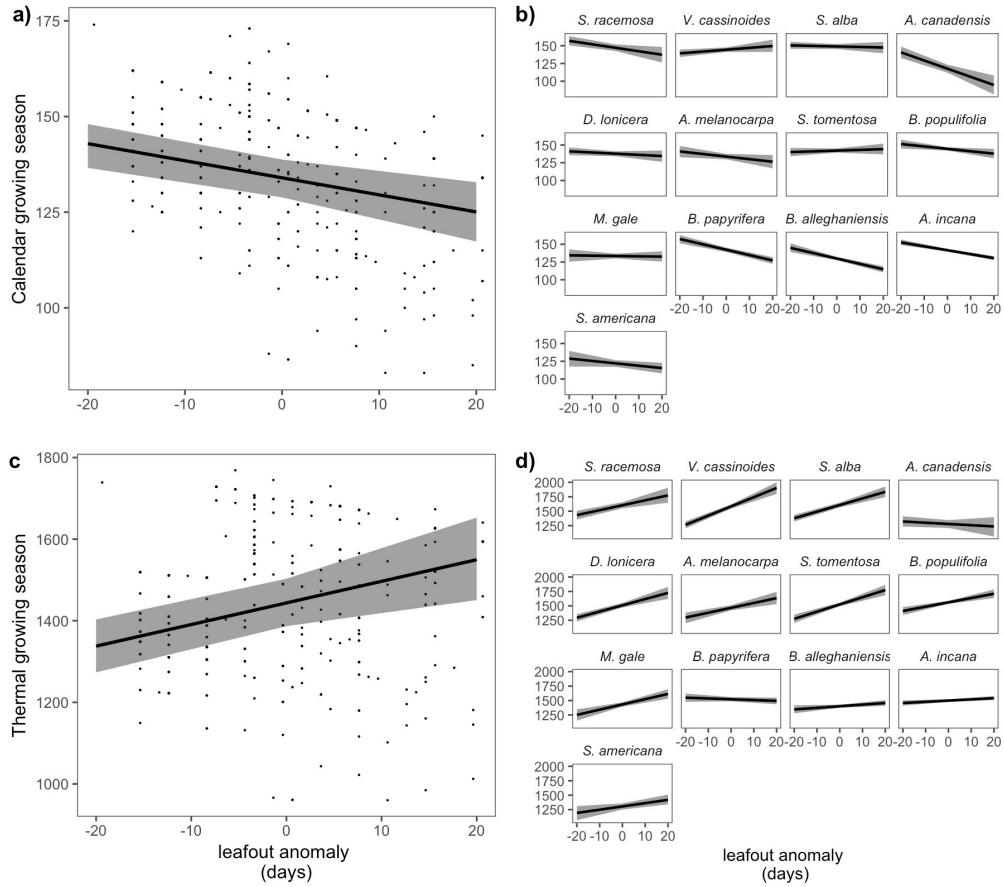


Figure 1: The relationship between Start of Spring (calendar day of leafout) and growing season length differs between the calendar growing season and the thermal growing season. Later leafout resulted in a shorter calendar growing season (median estimated effect: -0.44 days, $UI_{90}[-0.68, -0.21]$) (a) and this pattern was consistent across species in our study (b). In contrast, an increasing later leafout resulted in a longer thermal growing season (median estimates effect: 5.39 growing-degree days, $UI_{90}[2.15, 8.52]$) (c) though this effect was stronger for species that typically leafout earlier in the season—panels in c) display in the typical order of leafout among species. The black trend lines represent the median effect of leafout timing on growing season length and shaded region 90% uncertainty intervals. Points in a), and c) represent the raw data (per individual tree per year).

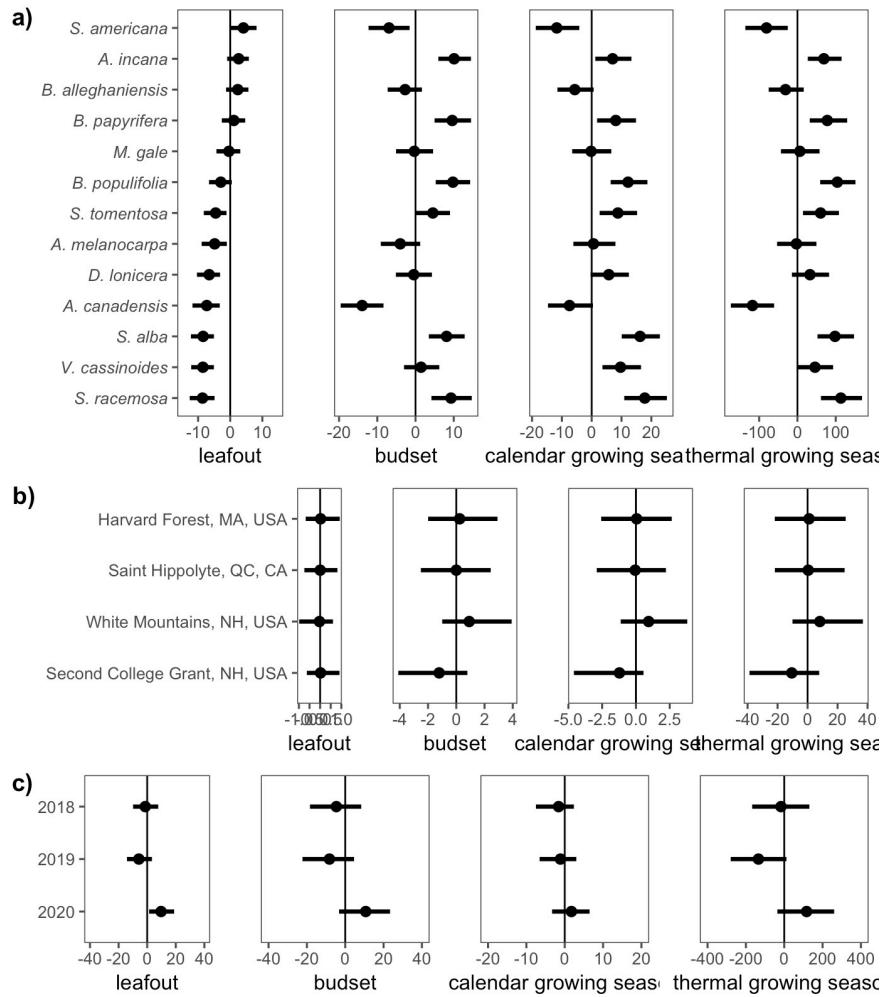


Figure 2: Difference in leafout, budset and growing season length (in days) partitioned between species (a) populations (b) and years (c). Point represent the median effect size estimate, and bars the 90% uncertainty intervals.

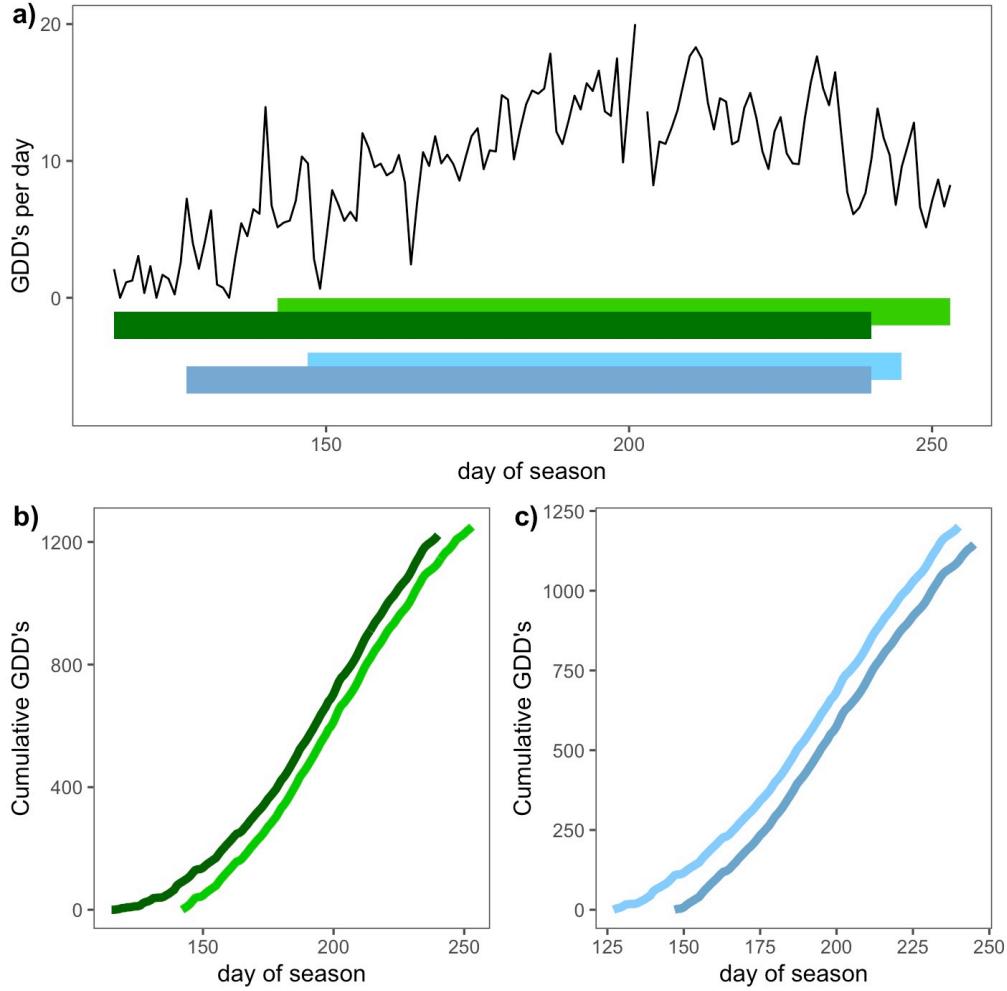


Figure 3: Thermal conditions vary across the calendar growing season, which can generate a complex relationship between the calendar and thermal growing seasons. Panel a) depicts the daily heat sums at the Weld Hill Research Building in 2019 and the calendar growth season of early and late leafing individuals of *Aronia melanocarpa* (green bars) and *Myrica gale* (blue bars). Despite the fact the the early individual of *A. melanocarpa* leafs out 24 days before it's later con-generic and only sets bud 13 days before it (i.e., it has a 14 day longer calendar growing season) it's thermal growing season is shorter (panel b) because most of its growth advantage (explain this better) takes place in the unfavorable early spring. In contrast for *M. gale* where both the early and late individual leaf out later in the spring, the 20 day head start and 5 day earlier finish of the earlier individual (15 day longer calendar growing season) results in a longer thermal growing season for it as well (panel c)

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