

Why longer seasons with climate change may not increase tree growth

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Abstract

A number of recent studies have challenged the fundamental assumption that longer growing seasons lead to increased tree growth, raising concerns that forecasts of future climate change—which include increased carbon storage through this assumption—may be overly optimistic. In a review of recent literature, we found that 58% of studies supported the assumption of increased growth with longer seasons, while 36% of studies did not. Diverging results remained when holding methodology constant, which suggests the current major challenge is to understand what underlies this widespread variation. Studies have proposed a suite of hypotheses for why longer growing seasons may not always increase tree growth, including drought-related constraints and internal limits. These hypotheses and their underlying mechanisms, however, were generally tested in different ways by different fields on different species, making comparisons difficult. We outline how bridging these current divides while simultaneously integrating ecological theory could yield new advances in fundamental biology and build a unified model across species for when longer seasons will—or will not—lead to greater growth, with major forecasting implications.

Introduction

The idea that longer growing seasons lead to increased plant growth is an intuitive tenet across multiple fields of biology, including physiology, dendrochronology and ecosystem ecology (Nobel *et al.*, 1983; Frank *et al.*, 2022). It is also a foundational assumption of many global carbon cycle models (e.g. Ito *et al.*, 2020; Friedlingstein *et al.*, 2022). These models project that continued anthropogenic warming will be partly offset by increased carbon sequestration as warming lengthens growing seasons in many forests (Friedlingstein *et al.*, 2022), an assumption supported by ecosystem-scale studies (Chen *et al.*, 1999; Keenan *et al.*, 2014; Finzi *et al.*, 2020).

Yet recent work has questioned this longstanding assumption (e.g. Dow *et al.*, 2022; Green & Keenan, 2022; Silvestro *et al.*, 2023), with potentially large implications for future climate change. These recent studies challenge decades of research reporting increased growth with longer seasons, from observations along elevational and latitudinal gradients (Myneni *et al.*, 1997; Berdanier & Klein, 2011; King *et al.*, 2013; Cuapio-Hernández *et al.*, 2022), classic experiments in lab settings (Went, 1957), to trends in ecosystem fluxes with warming (Chen *et al.*, 1999; Keenan *et al.*, 2014; Finzi *et al.*, 2020). Proposed mechanisms for the apparent disconnect are diverse (Fig. 1), including the complex nature of climate change (e.g. drought or heat stress, Dow *et al.*, 2022) and internal limits on plant growth (Zohner *et al.*, 2023).

Here we review methods and metrics used in diverse fields to uncover connections between growing season length and tree growth and identify the potential mechanisms that unite—and could disconnect—these processes. Results suggest that predictable—and substantial—variation in growth \times season length relationships across species exist. However, we also find a pervasive disciplinary split between studies, which often test different mechanisms on different species, and overlook insights from community and phylogenetic ecology (e.g. Grime, 1977; Webb *et al.*,

2002; Ávila-Lovera *et al.*, 2023). We therefore argue that increased cross-disciplinary efforts to build a unified model across species would allow the field to rapidly develop a unified theoretical framework to predict when, where and how climate change may increase tree growth.

Evidence that longer seasons increase plant growth, or not

The idea that time limits growth is a fundamental principle across biology. Many biological processes—including photosynthesis and aspects of growth—are rate-limited, making time a crucial commodity (Nobel *et al.*, 1983; Cosgrove, 2005; Hilty *et al.*, 2021). Thus, the hypothesis that longer growing seasons should increase growth is intuitive—and pervasive.

Multiple fields have long assumed that longer seasons yield more growth. Foundational evidence comes from spatial clines across elevation and latitude, with growth decreasing alongside growing season length at higher elevations (Fig. 2) and latitudes. Experimentally, this assumption is supported by small-scale field warming studies that find that phenologically advancing species also grow more with warming (Cleland *et al.*, 2012), while observationally, ecosystem-scale studies have reported a similar positive relationship between season length and carbon fluxes across decades with global warming (Keenan *et al.*, 2014) or in years with warm, early springs (Chen *et al.*, 1999). However, some recent studies do not support these previous findings. These studies, which often focus on inter-annual correlations with metrics of standardized individual tree growth (Dow *et al.*, 2022; Silvestro *et al.*, 2023), have generated debate about whether future carbon storage forecasts are overestimated and which metrics of growth (Green & Keenan, 2022), or growing season length (Körner *et al.*, 2023), are relevant.

Despite this recent debate, we found little support for a wholesale disconnect between growth and growing season length—instead finding split support for when longer seasons lead to increased growth. Papers spanning 25 years have variously found evidence for—or against—the relationship, with no clear pattern by method or year (Fig. 3 and see ‘Literature review methods’ in Supplement). For example, carbon assimilation studies were evenly split in finding evidence for or against the relationship (or simply not testing it, Fig. 3). Diverging results were consistently found within methods, suggesting the drivers of this variation are likely due to biological mechanisms, not solely inconsistent definitions of growth or growing season length (as some have recently suggested, e.g. Green & Keenan, 2022; Körner *et al.*, 2023).

Most studies tested the hypothesis that longer seasons with climate change increase growth via either increased time to grow (10 of 36 papers) or because longer seasons are usually warmer (8 papers), although many also considered hypotheses that could disconnect growth from season length. Studies from dendrochronology (the study of tree rings and their dating) and physiology have readily offered explanations for findings that increased growth may not be a universal outcome of longer seasons (Fig. 1). External climatic drivers that offset the positive growth effects of longer seasons are often reported in tree ring studies (Kolář *et al.*, 2016; de Sauvage

(*et al.*, 2022; Camarero *et al.*, 2022). In particular, the hypothesis that higher temperatures paired with lower precipitation produce negative correlations of season length with growth appeared in 58% of tree ring studies we reviewed (and was only mentioned once outside of these studies, see also Fig. 1). In contrast, 43% of lab experimental and wood phenology (xylogenesis) studies suggested fundamental internal constraints that prevent trees from responding to longer seasons (Fig. ??, Cuny *et al.*, 2012; Michelot *et al.*, 2012; Zohner *et al.*, 2023). Yet we found that these hypotheses have been tested in radically different ways, never together, and all ignore a suite of relevant research from other disciplines.

Controllers on growth × season length relationships

Studies have uncovered a suite of major mechanisms that could limit or disrupt the positive effects of longer growing seasons. These generally fall into two categories: (1) external factors, such as drought, which should impact ecosystem-level trends at regional scales, and (2) internal physiological constraints, which some research suggests are either universal across plants (e.g. Zohner *et al.*, 2023), or species- and population-specific (e.g. Soolanayakanahally *et al.*, 2013). The importance of internal versus external drivers, however, likely vary by species, highlighting the need to integrate perspectives from community and phylogenetic ecology.

External drivers

Fundamentally, temperature limits many biological processes. Temperatures that are too cool (below 5°C for temperate trees) and too warm (an area of active research, but likely between 35-45°C; Martinez-Meier *et al.*, 2008; Cabon *et al.*, 2022) slow down biological processes and eventually can lead to tissue death (see Fig. 4, Larcher, 1980; Kramer, 2012). Between these upper and lower limits, biological processes underpinning growth generally accelerate such that warming can have a direct effect, by accelerating biological time, up until the maximum rate for that particular process. Assuming a common growth response curve to temperature, possible increased growth should be predictable at an ecosystem level based on the current seasonal temperatures and the amount of warming (Fig. 5).

How much or whether growth increases at all depends on the non-linear effect of temperature on biological processes (Fig. 4). At very cool temperatures—such as in early spring—a small increase in temperature may have limited effect (or even increase frost risk through early bud-burst, Fig. 1e, Chamberlain *et al.*, 2021), while an increase at warmer temperatures—such as those more common in the summer (e.g. 16 to 18°C)—could have a larger physiological impact. However, warming that pushes plants beyond their optima, where many biological rates crash, could have large negative impacts (Nobel *et al.*, 1983; Leuning, 2002). Thus, some studies hypothesize that longer seasons effectively only extend the very cool early-season periods and may have no discernible effect on growth, while other studies—based on tree rings—suggest that any increases in growth due to longer seasons are offset by reduced growth due to high summer

temperatures (Fig. 1, Gantois, 2022; Dow *et al.*, 2022). In contrast, other researchers argue that warmer temperatures have not yet pushed trees above their optima (Schaber & Badeck, 2002), and instead have driven increases in growth through accelerated rates, rather than longer seasons (e.g. Ren *et al.*, 2019).

Positive effects of longer—or warmer—seasons on growth predicted from temperature responses alone, however, could be counteracted by other external drivers. Moisture deficits from reduced precipitation or higher evaporative demand (commonly invoked in tree ring studies, Fig. 1) can slow or stall growth. Support for this hypothesis comes from negative correlations between growth and precipitation (or other metrics related to plant access to water in tree ring studies, Kolář *et al.*, 2016; Etzold *et al.*, 2022), and is well supported by physiological observations that tree water status can be a biophysical limit to growth (i.e., cells cannot expand without sufficient turgor, Peters *et al.*, 2021; Cosgrove, 2023), though we found few physiological studies on season length considered this effect (Fig. 3). External biotic factors—including herbivory, disease and competition—can also limit productivity (Sturrock *et al.*, 2011; La Porta *et al.*, 2008; Senf *et al.*, 2017) and are shifting with longer seasons. Extended growing seasons allow for additional generations of pests and pathogens (Mitton & Ferrenberg, 2012; Lange *et al.*, 2006), and may reshape plant competition (Cleland & Wolkovich, 2024), though they are missing from the current debate on the impacts of longer seasons on growth (we found no mention of them, Fig. 1e).

Internal constraints

When and how growth is initiated and ceases is under genetic and developmental control, and thus plants' internal programming could limit growth responses to longer seasons (Marchand *et al.*, 2021; McKown *et al.*, 2016; Soolanayakanahally *et al.*, 2013). Research has repeatedly shown that populations vary in their growth and its responses to extended seasons (Fig. 1d), reflecting differences in genetic and developmental controls that likely evolved to limit tissue loss to rare early or late-season events. Populations often vary predictably in their end-of-season phenology, with more poleward populations tending to stop height growth (budget) earlier using locally adapted photoperiod cues (Soolanayakanahally *et al.*, 2013; Aitken & Bemmels, 2016). This means longer seasons are generally driven by spring phenology, which appears far more flexible, and has advanced more rapidly than fall events (Aitken & Bemmels, 2016). Some recent studies suggest novel roles for the summer solstice (Zohner *et al.*, 2023) in setting a fixed universal developmental switch between when warming temperatures hasten or delay leaf senescence, and in determining when warmer temperatures trigger greater reproduction (Journé *et al.*, 2024).

Trade-offs between vegetative and reproductive investments may produce important growth response differences across years within individuals, as well as between species. Years of high reproductive output can reduce growth (Thomas, 2011; Hacket-Pain *et al.*, 2016a). For species that mast—producing abundant cones or fruits in only some years—high reproduction could

especially impact measures of wood growth. Many hypotheses suggest higher summer temperatures trigger masting in the following year (Hacket-Pain *et al.*, 2016a,b); if true, then reduced growth in years following warm summers may not indicate temperatures too high for growth, as recent studies have suggested (e.g. Gantois, 2022; Dow *et al.*, 2022), but instead shifting investment to reproduction.

Species-level variation

The effects of these external and internal drivers are likely to vary across species, with species identity strongly predicting variation in growth \times season length relationships (e.g. Cuny *et al.*, 2012; Michelot *et al.*, 2012). Though this reality was rarely acknowledged in studies we reviewed (Fig. 1c), research in dendrochronology, physiology and in phenology often mentions important differences between certain species groups that should affect how longer seasons affect growth.

The distinct strategies of deciduous versus evergreen species, including in how and when they invest in leaf and shoot elongation versus cambial growth, can affect how they respond to longer seasons. While evergreen species generally leaf out later than deciduous species they can more immediately photosynthesize with earlier springs, though both types of species generally invest in buds (for new leaves, shoots and flowers) in the preceding year. This means neither species type can rapidly change its leaf area in response to an earlier spring, but both can have multiple flushes of leaves (Day & Greenwood, 2011; Soolanayakanahally *et al.*, 2013). Wood growth in evergreen species is generally thought to come from current season photosynthate, while deciduous species may more often use stored carbon resources (Gordon & Larson, 1968; Monson *et al.*, 2018). These differences would suggest season length by growth relationships may be more apparent in evergreen species, and more apparent via lagged effects in deciduous species (NeedCITES), though to date this has not been consistently reported. Further, evergreen species are thought to grow more slowly and thus differences due to season length may be harder to detect (Waring & Franklin, 1979).

This division between evergreen and deciduous species hints at a larger suite of traits that predict growth by growing season length relationships among species. Species that budburst earlier and more readily produce additional leaves (e.g., lamas growth and other characteristics of ‘indeterminate’ species, Kikuzawa, 1982; Lechowicz, 1984) may respond more to longer seasons (though potentially with a lag) versus those that budburst later and flush new primary growth only once. Similarly, species adapted to cold or dry conditions across their range may have different thresholds for when these external drivers limit or promote growth (NeedCITES). Such differences could easily obscure any overall relationship between growth and growing season length. Supporting this possibility, current studies finding divergent results (Fig. ??) span a wide range of species (we found 57 species from 26 genera across 36 papers). While this diversity may appear to make identifying a common relationship between growth and growing season length more difficult, it may instead offer the path to an improved framework.

Building a new framework for growth × season length relationships

Leveraging the diversity of responses observed across species is possible by integrating ecological advances in how species traits and evolutionary history shape species responses to climate change (Cornwell & Nakagawa, 2017). In particular, ecophylogenetics (Webb *et al.*, 2002) has moved research away from treating species identity as a simple grouping factor where each species is unique (e.g., *Fagus sylvatica* is different from *Quercus robur* and *Pinus sylvestris*) or fits into a limited set of groups (e.g., deciduous versus evergreen) and towards species as suites of correlated observations, separated by their evolutionary distance (*Fagus sylvatica* is much more closely related to *Quercus robur* compared to *Pinus sylvestris*). New models built from these advances can fit data from all species at once while including differences in growth strategies through additionally measured traits (Pearse *et al.*, 2019; Morales-Castilla *et al.*, 2024).

In step with these advances, trait ecology has documented leaf and wood economic spectra that suggest major traits to include in these models (with related databases of these traits often available, Chave *et al.*, 2009; Diaz *et al.*, 2016). These ‘economics’ define a common trade-off along an acquisitive to conservative axis, where some species grow rapidly and more flexibly to take advantage of resources, but are less defended against herbivores and compete poorly at low resource levels, whereas other species compete well at low resource levels, but at the expense of growing slower and conservatively (Grime, 1977; Chave *et al.*, 2009; Diaz *et al.*, 2016). While these traits likely miss critical components for understanding how growing season length shapes growth, such as when different species invest in shoot and leaf versus wood growth, they provide a baseline from which to build, and a powerful approach to combine data usefully across species.

In addition to naturally organizing species differences, a trait-based ecophylogenetic approach can help build a more testable and predictable framework. Because this approach can fit evolutionary history and traits together, it allows clades or species groupings that respond similarly to emerge from the data and models (Davies *et al.*, 2019), versus being a priori grouped or defined. Similarly traits that co-vary with different responses can be more quickly identified (e.g., Willis *et al.*, 2008; Davies *et al.*, 2019). Both of these benefits could help identify which species or traits to focus additional studies on to gain the most insights, while similarly suggesting areas that should be less studied (e.g., traits that may be too confounded with evolutionary history, Cornwell *et al.*, 2014; Westoby *et al.*, 2023) or outlier species that may not represent most species (Morales-Castilla *et al.*, 2024). This approach may thus redefine debates over which metrics of growth or growing season length are relevant into debates over which metrics are most relevant for which clades and/or traits.

This approach aids the search for a universal model of how growing season length influences growth by providing a framework that effectively assumes one model, which is then shaped by evolutionary history and trait differences to produce the divergent responses observed across species today. Combined with data on species abundance across forests (e.g. Forest Service - United States Department of Agriculture; Fischer *et al.*, 2019), it can easily scale up to predict

larger-scale metrics, such as satellite observations of phenology and productivity. This framework also provides an organizing method to re-approach the fundamental question of how external and internal drivers shape growth responses to longer seasons, and a way to tackle what we are argue the three most critical questions in this area.

What is the scale of variation in GSL x growth relationships across space and time?

The idea that growing season length influences plant growth is fundamental to plant biology, but we found it is rarely tested in ways relevant to the current debate (see ‘Growth \times elevation relationships’ in Supplement), providing a major gap that limits progress. For example, while multiple papers report a lack of relationship between growth and growing season length (Figs. 1, 3), we have no fundamental understanding of what the effect size of this relationship should be, and thus no way to know if we have sufficient power in current studies to detect it. Additionally, understanding large-scale patterns often improves models of the underlying processes, by finding unexpected trends or highlighting covarying drivers that must be disentangled.

Identifying the macro-scale pattern of how growth and growing season length relate should be a primary goal, and one that seems broadly tractable. Tree ring studies designed to leverage latitudinal and elevational gradients in climate could quickly provide the raw data. Research will then need to develop models that tease out the effects of warmer temperatures across the season—likely affecting important biological rates (Figs. 4–5)—versus longer seasons. Disentangling these may require focused efforts to understand xylogenesis across species and climates, but doing so across major climatic gradients could make differences more obvious. Research will also then need to integrate beyond wood growth, including methods to better characterize changes across the leaf, shoot and wood architecture of different species (e.g., Puletti *et al.*, 2020; Sillett *et al.*, 2024) and also extending to the complexity of roots (McKown *et al.*, 2016; Radville *et al.*, 2016). Wood growth, however, provides an obvious and tractable baseline from which to set expectations of how much growth can vary across space, and links to existing major datasets (Fig. 6). These data can provide a baseline to compare to the scale of shifts over time, which studies of growth \times growing season length to date have focused (Fig. 3), since the same tree rings measured for understanding spatial variation will also capture inter-annual variation.

How prevalent are internal constraints across species and populations?

New evidence suggests inter-annual variation in growth may be limited because of internal constraints that prevent plants from fully using longer seasons (Zohner *et al.*, 2023). If true, this would have major ramifications for fundamental plant biology and for how much we expect growth to shift with warming, but requires much more study. All plants are limited by internal constraints and how quickly they can build new tissues (Marchand *et al.*, 2021; Luo *et al.*, 2024), but selection towards different growth strategies (e.g., acquisitive versus conservative) should drive variation in these constraints across species, and possibly populations (McKown *et al.*, 2016; Soolanayakanahally *et al.*, 2013). As budset—which indicates the end of height growth—

is strongly locally adapted (Aitken & Bemmels, 2016; Zeng & Wolkovich, 2024), we should expect variation in these constraints across populations, as selection should favor individuals better matches to local environmental optima (Colautti *et al.*, 2010; McKown *et al.*, 2014).

Current results often smear across species and populations (e.g., studies using NDVI, Zohner *et al.*, 2023), but new studies could rapidly test for constraints across species and populations, to work towards a predictive framework using phylogeny and traits to predict these constraints. Studies across space could provide early inferences by studying how growing seasons measured by vegetative versus wood phenology vary—and attributing variation through models that nest species within populations and include traits, while experiments could provide more robust tests. While juvenile stages of trees are often more flexible than their adult forms, they still usually provide predictable inference in differences across species and populations, and so should be integrated far more into studies of how season length affects growth. Using saplings and controlled environments could quickly test how much growth can shift with longer seasons—providing a potentially standardized way to compare constraints across species and populations.

How do external drivers and internal constraints act together?

Most research on how growth impacts growing season length with climate change has been focused on this question, with certain studies documenting potential constraints and others focused on teasing out how temperature, drought and other external forces impact growth. Inherently, however, external and internal factors are interconnected and thus any useful model must include both together. We argue that understanding the pattern across space—and using it benchmark the possible magnitude of inter-annual responses—alongside documenting the scale of internal constraints across species and populations will be critical to help compare responses of external and internal drivers. As these new data come together with trait-mediated ecophylogenetic models, we expect real advances will require more experiments across scales and disciplines.

The complexity of climate change and plant growth in response to longer, warmer seasons makes experiments vital to building useful mechanistic models for forecasting. Observational data—used mainly to date to tackle this question (Figs. 3, ??)—generally confounds multiple external drivers, including season length, temperature and precipitation regimes (Ren *et al.*, 2019; Canadell *et al.*, 2021; Camarero *et al.*, 2022), making it impossible to tease out actual drivers behind observed trends.

In particular, mechanistic models will need to tease out changes in season length from warming that affects rates; a challenge best addressed by new experiments that decouple these two factors. Such experiments could start on juvenile trees to help inform the underlying model, select representative species to focus on, and develop predictions for large-scale studies. Experiments could also inform a better model of lag effects across species, with small-scale studies sampling saplings multiple years after manipulations (versus the common practice of destructive sampling at the end of the treatment growing season) and large-scale studies following existing efforts

to test for ecological ‘memory’ (e.g. Flinker *et al.*, 2021; Schweiger *et al.*, 2022; Chin *et al.*). These efforts should help bridge across the contrasting timescales of current physiological and dendrochronological studies of growing season length: we found most physiological studies of growth \times growing season length relationships studied 1-2 years of dynamics, usually of juvenile trees, while tree ring studies focused on synthesizing across decades of adult tree growth.

Bridging such disciplinary gaps often comes alongside large-scale experiments. While experimenting on adult trees is difficult, previous challenges in climate change research have led to tree or larger-scale experiments to understand other complex drivers (e.g. SPRUCE, Drought-Net, Pfynwald, Norby & Zak, 2011; Hanson *et al.*, 2017; Smith *et al.*, 2016). We expect similar experiments will be critical here. Preparing for these large experiments using trait-mediated phylogenetic models to understand responses across species, however, could advance new experiments well beyond past efforts by informing which species to study and potentially spanning enough phylogenetic or trait diversity to forecast to species beyond the experiment (Morales-Castilla *et al.*, 2024).

Conclusions: Anthropogenic climate change has often been described as an unfortunate and unplanned experiment. Like many experiments, it has highlighted important biology we do not know well, requiring us to rediscover dusty old fundamentals, and also expose their limits. Understanding when, how and why longer seasons lead to increased tree growth requires an interdisciplinary reckoning with how temperature, time and a suite of external and internal drivers affect plant growth across species. A mechanistic understanding of how these drivers integrate over species diverse growth strategies and the imprints of evolutionary history to affect growth today is possible, but will require new approaches. Starting now to leverage data across species to inform and design new large-scale studies and experiments be critical for accurate models of future forest and related carbon dynamics, with implications for projections of carbon sequestration and carbon markets.

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1 Boxes

Box. Standardized measurements

Understanding the diverse drivers and testing underlying hypotheses (Fig. 1) for growth \times season length relationships requires a common language. We found 14 different metrics of start of season, 16 metrics of end of season (25 metrics of growing season length), and 21 different metrics of growth across 59 studies—highlighting just part of the problem (see also *The challenge of metrics: Measuring growth* in the Supplement). Definitions and metrics for external and internal drivers were myriad, with papers reporting dozens of tests of different aspects of climate over different temporal windows. Although this is understandable given the differing goals of these papers, it also slows progress.

A common framework for explanatory and response variables would accelerate research by easing communication between fields and providing a path to comparable quantitative estimates. This should also include expected statistical tests, as we found a number of papers failed to directly test for growth \times growing season length relationships (Fig. 3), often instead testing only certain hypothesized indirect relationships (e.g. spring temperature \times growth in Dow *et al.*, 2022).

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3 Figures

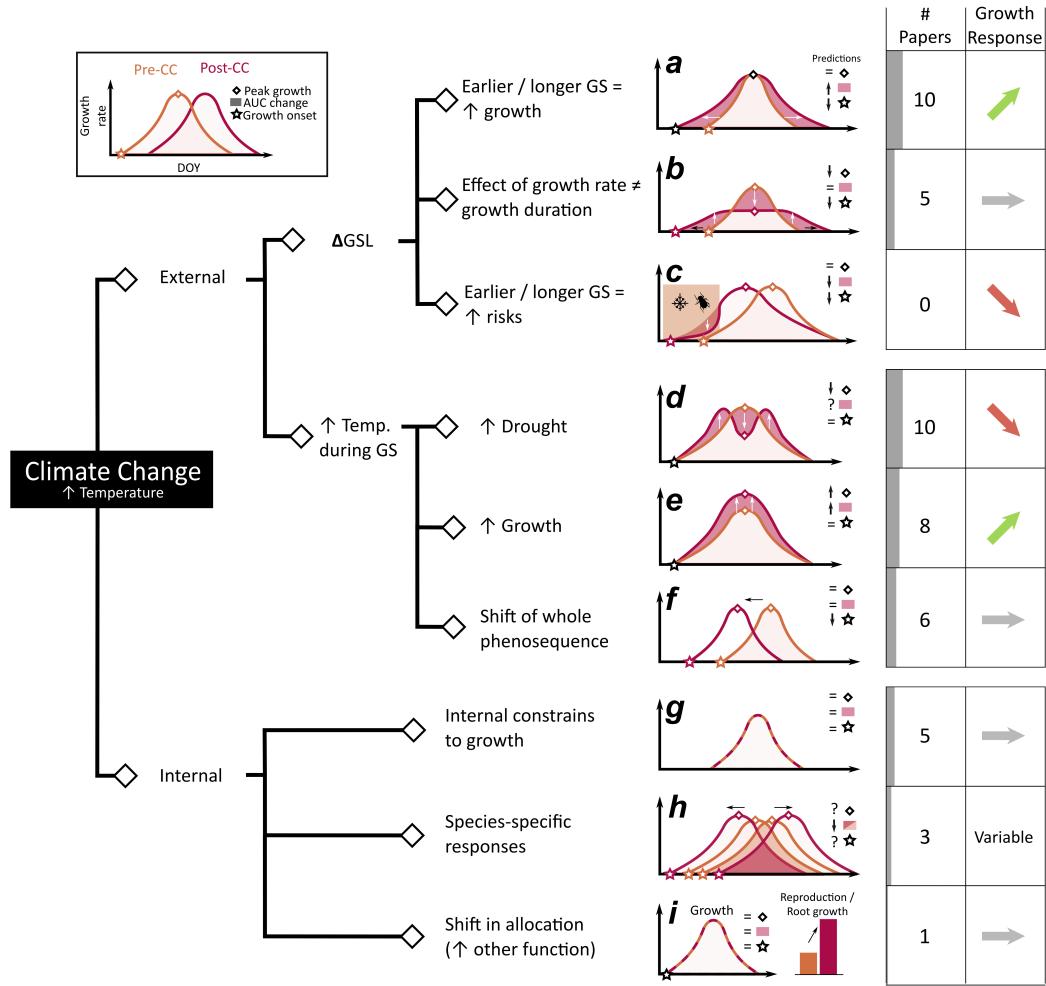


Figure 1: Climate change may alter growing season (GS) length, which can then affect growth through diverse pathways. We review hypotheses for these pathways showing the number of papers (from a review of papers studying growth \times growing season length) that mentioned each hypothesis (width of the shaded areas of left column is proportional to the number of papers with the number also given, right column shows the expected growth response for each hypothesis). We group hypotheses as focused on mechanisms moderated by the environment (“external”) versus those focused on internal physiological constraints, which span both source (photosynthesis-limited) and sink limitation. For more details, see Supplement.

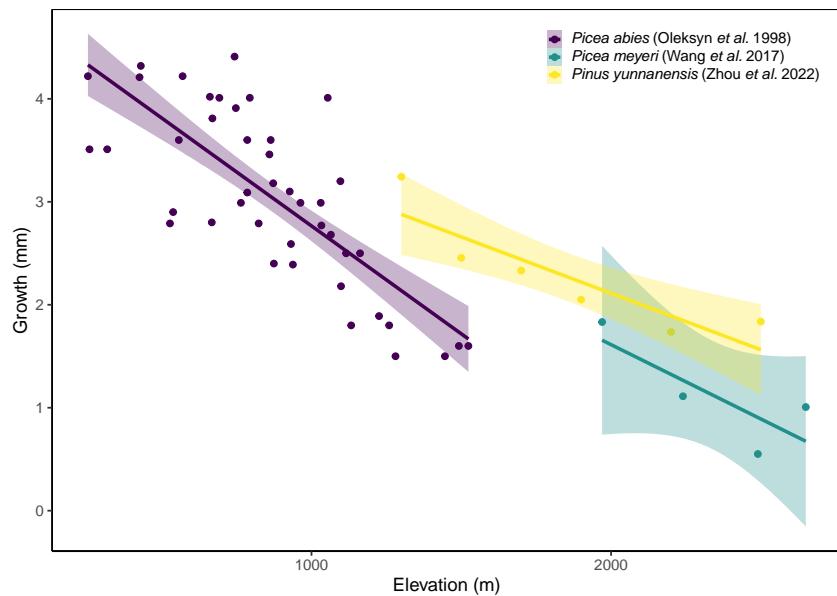


Figure 2: Growth \times elevation relationships from the literature with simple linear regression fits shown with 89% confidence intervals. Oleksyn *et al.* (1998) measured growth (mm) as diameter at breast height increments, while the other studies (Wang *et al.*, 2017; Zhou *et al.*, 2022) measured growth (mm) as ring width. See Supplement for more methods details.

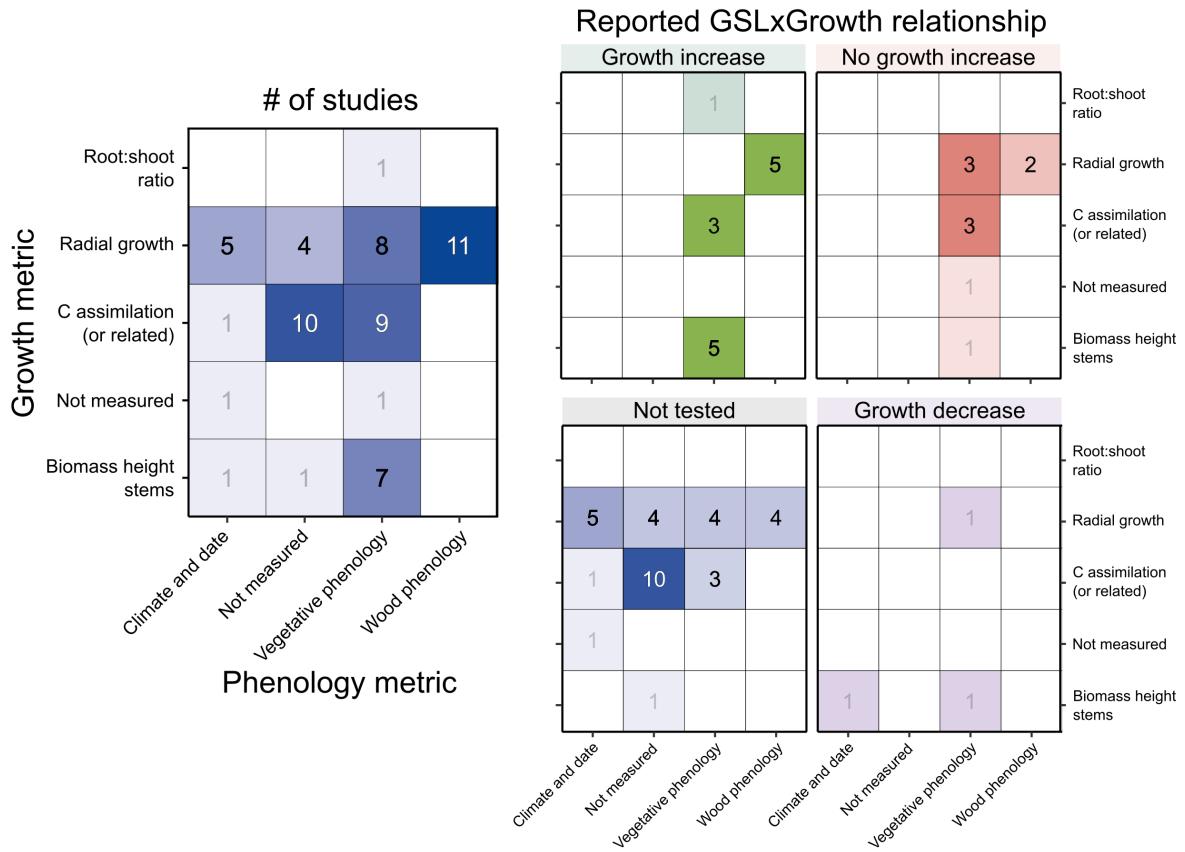


Figure 3: A review of growth \times growing season length relationship studies spanned a diversity of methods, but there was no coherency in which methods did or did not find a positive relationship. A number of studies tested relationships possibly related to growth \times growing season length (e.g., they tested how spring temperatures related to growth) but never directly growth \times growing season length, thus ‘not tested’ was surprisingly common across methods. See Supplement for review details.

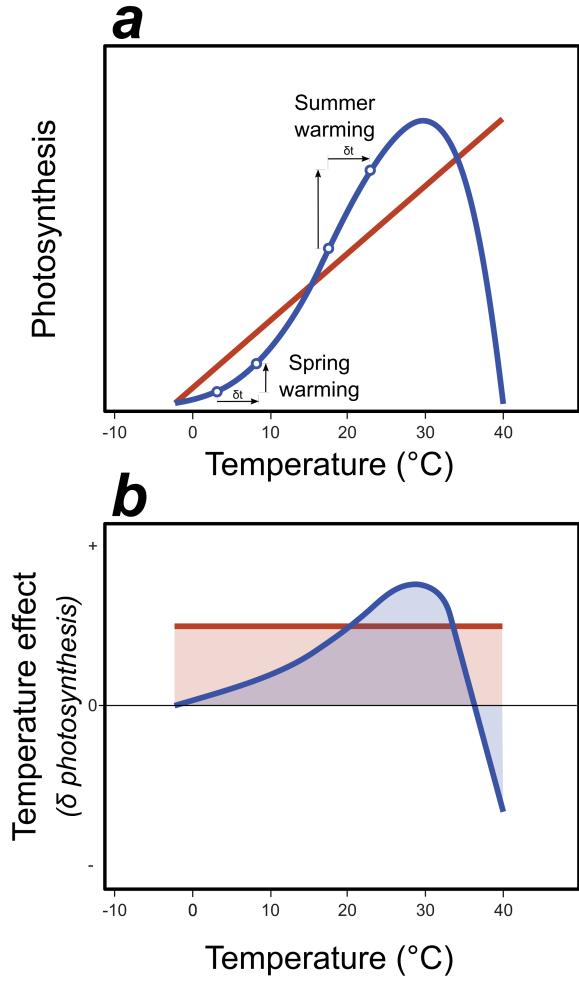


Figure 4: (a) Growth responses to temperature depends on a suite of complex factors and is often represented as net photosynthesis, which has a non-linear response to temperature (blue curve, adapted from meta-analysis of Rezende & Bozinovic, 2019), though it is often modeled as linear (red). (b) This non-linearity means that increases in lower temperatures—such as those in the spring when much of growing season extensions may happen—have lower absolute increases in photosynthesis compared to increases in later-season (e.g., summer) warmer temperatures, while a linear response assumes a constant scale of effect across low to high temperatures.

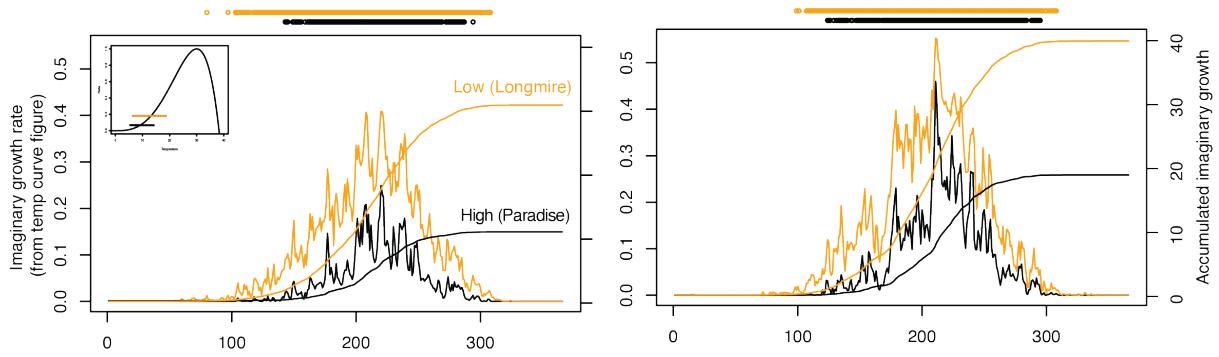


Figure 5: (DRAFT of potential new figure): Testing how growth varies across larger spatial gradients of growing season length could help establish a baseline expectation of the scale of temporal—especially inter-annual variation—and force a greater reckoning with drivers that shift alongside growing season length. This conceptual figure uses data from a cool-weather, temperate site at two elevations (Mount Rainier/Tahoma in USA) with show potential differences in growing season length (dots on top) and biological rates. Other gradients in warmer locations would show much higher rates, but also likely more days where rates are zero due to too high temperatures. Here we estimated growing season length as days above 5°C and used an idealized curve (inset) to calculate daily rates. Left shows based on climatic data from the 1980s, while the right is based on 2014-2023.

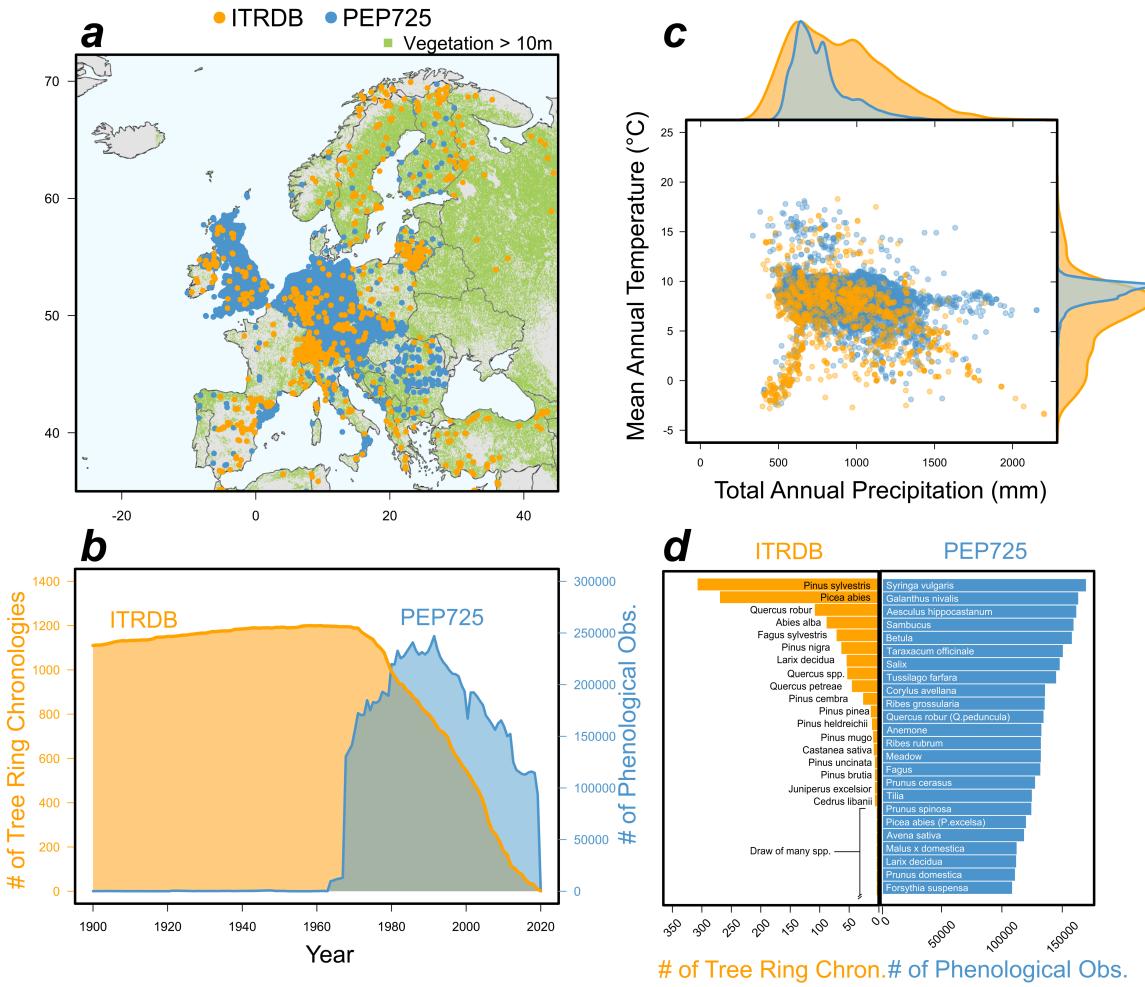


Figure 6: Data overlap between the two major databases of growth (International Tree Ring Data Bank, ITRDB, orange) and plant phenology (Pan European Phenology Project, PEP725, blue). Both databases are compared in terms of their spatial distributions (a), temporal overlaps (b), coverage of environmental conditions in climate space (c) and taxonomical representation (d). Note that the number of tree ring chronologies in (b) are composed by multiple trees per site, typically 10-20. Climatic data from Worldclim database ver. 2.1 at 2.5°grid resolution. PEP725 records in d) show the largest records for any given phenophase per species.