

# Why longer seasons with climate change may not increase tree growth

Team Grephon

March 13, 2024

## Abstract

Recently a number of studies have challenged the fundamental assumption that longer growing seasons lead to increased tree growth. This has generated alarm because it suggests that forecasts of future climate change, which generally include increased carbon storage through this assumption, may be overly optimistic. Using a review of recent literature, however, we found limited support for this new hypothesis: 36% of studies reported longer seasons did not lead to increased growth, while most—58% of studies—supported the assumption that that longer growing seasons lead to increased growth. Results diverged within different methods and species, suggesting the current challenge is not a binary one, but instead understanding and predicting apparent widespread variation. Studies have proposed a suite of hypotheses for why longer growing seasons may not always increase tree growth, including drought-related constraints, internal limits, and methodological differences. Yet we found these hypotheses were generally tested in different ways, but different sub-fields making comparisons across them difficult: studies of tree ring growth tended to focus on external drivers, such as drought, while physiological studies of biomass or carbon allocation, tended to focus on internal limits, such as effects of photoperiod. We argue that bridging this disciplinary divide and better partitioning species-level variation by integrating theory from trait and phylogenetic ecology could rapidly help develop and test a mechanistic framework for when longer seasons will—or will not—lead to greater growth.

## 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 most models of the future global carbon cycle (e.g. Friedlingstein *et al.*, 2022; Ito *et al.*, 2020). Most models project that continued anthropogenic warming will be partly offset by increased carbon sequestration as warming lengthens growing seasons in temperate and boreal forests (Friedlingstein *et al.*, 2022), an assumption supported by a suite of ecosystem-scale studies (Chen *et al.*, 1999; Keenan *et al.*, 2014; Finzi *et al.*, 2020).

Yet recent work has questioned this longstanding assumption and suggested that longer growing seasons do not necessarily lead to greater growth (e.g. Dow *et al.*, 2022; Green & Keenan, 2022; Silvestro *et al.*, 2023), with potentially large implications for future climate change. Such

findings challenge decades of research that report that growth increases with longer seasons, from studies along natural elevational and latitudinal gradients (Myneni *et al.*, 1997; Berdanier & Klein, 2011; King *et al.*, 2013; Cuapio-Hernández *et al.*, 2022), classic studies in lab settings (Went, 1957), to stand-level 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 non-linear effects of climate change itself (e.g., drought or heat stress, Dow *et al.*, 2022), internal limits on plant growth (Zohner *et al.*, 2023), as well as inconsistent use of growth and growing season metrics and definitions (Green & Keenan, 2022; Körner *et al.*, 2023).

Here we review the connections between growing season length and plant growth across fields to identify the potential mechanisms that unite—and could disconnect—these processes. Leveraging a systematic literature review, we examine which methods and metrics suggest that extended seasons appear to lead to increased growth, and the current proposed hypotheses. We find a pervasive disciplinary split between studies, which may limit progress in identifying the underlying processes and mechanisms. Further complicating progress, research has tested different mechanisms on different species, ignoring insights from trait and phylogenetic ecology (e.g., Grime, 1977; Ackerly, 2009; ?) that suggest predictable—and substantial—variation in growth  $\times$  growing season relationships across species. We argue that with increased cross-disciplinary efforts, the field could rapidly develop a framework to predict when, where and how climate change may increase tree growth—with implications both for forecasts of future climate change and for fundamental science.

## Evidence that longer seasons increase plant growth, or not

The idea that time limits growth is a fundamental principle of most biological fields. Many biological processes, including photosynthesis and many 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.

Indeed, the hypothesis that longer seasons yield more time for growth was by far the most common hypothesis for why longer seasons should increase growth across our review of growth  $\times$  growing season length studies, with 19 of 59 total studies including it (Fig. 1). Foundational evidence for this relationship comes primarily from spatial clines across elevation and latitude, with growth decreasing alongside growing season length at higher elevations and latitudes (Fig. 2). Experimentally, this hypothesis is supported by small-scale field warming studies that find that species which advance phenologically with warming also grow more (Cleland *et al.*, 2012), while observationally, ecosystem-scale studies have reported a similar positive relationship between growing 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). These findings, however, have not been supported by recent work that has focused often on inter-annual correlations with metrics of standardized individual tree growth (Dow *et al.*, 2022; Silvestro *et al.*, 2023). This has led to debate about whether future carbon forecasts are overestimated and which metrics of growth (Green & Keenan, 2022), or growing season length (Körner *et al.*, 2023) are relevant.

Despite the recent eruption of this debate, we found little support for a wholesale disconnect

between growth and growing season length. Instead, research has generally found split support—across methods—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 Supplement). For example, studies that measured C assimilation were evenly split in finding evidence for or against the relationship—or simply not testing it (Fig. 3). Diverging results were consistently found within all well-studied methods, suggesting the drivers of this variation are likely due to biological mechanisms, not solely inconsistent definitions or methods (as Green & Keenan, 2022; Körner *et al.*, 2023, recently suggested).

Studies from the disciplines of dendrochronology (the study of tree rings and their dating) and physiology have readily offered mechanisms for the recent results that increased growth may not be a universal outcome of longer seasons. Hypotheses focus on both source (photosynthesis-limited, including  $CO_2$  limitation) and sink limitations (Fig. 4). 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 with growth appeared in 33% of tree ring studies we reviewed (and was only mentioned once outside of studies measuring radial growth, see also Fig. 1). In contrast, 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 ignore a suite of relevant research from other disciplines on this topic. As we outline below, a single mechanism is unlikely to explain all results, requiring a more unified framework—and tests of it—for progress.

## Controllers on growth $\times$ growing season length relationships

A suite of major mechanisms that could limit or disrupt the positive effects of longer growing seasons on growth can be usefully grouped into categories that should operate at different levels. Currently disconnected research has focused on: (1) external factors, such as drought, which should impact ecosystem-level trends at regional scales, and (2) internal physiological limits, such as photoperiod constraints, which contrasting research suggested as either universal across plants (e.g., Zohner *et al.*, 2023), or population-specific (e.g., Soolanayakanahally *et al.*, 2013). The effects of mechanisms in these two groups, however, are highly likely to vary by species, highlighting the importance of integrating perspectives from phylogenetic and trait ecology, as we review below.

### External

Fundamentally, temperature limits many biological processes. Temperatures that are too cool (often considered to be below 5°C for temperate trees) and too warm (an area of active research, Martinez-Meier *et al.*, 2008; Cabon *et al.*, 2022, see also Fig. 4) slow down biological processes and eventually can lead to tissue death (Larcher, 1980; Kramer, 2012). Between the upper and lower limits biological processes underpinning growth generally accelerate such that warming

can have a direct effect, effectively by accelerating biological time, up until the maximum rate for that particular process. Given a common growth response to curve temperature, increased growth should then be predictable at an ecosystem-level given the current seasonal temperatures and the scale of warming.

Positive effects of longer seasons on growth, however, could be counteracted by moisture deficits due to reduced precipitation or higher evaporative demand, which was a common hypothesis in tree ring studies (Fig. 1). Such studies reported support for this through negative correlations between growth and precipitation or other metrics related to plant access to water (George, 2014; Babst *et al.*, 2019). While we found drought limitation was far less studied by more physiological-focused studies, the mechanism is well supported by fundamental physiology. Because cells cannot expand without sufficient turgor (Cosgrove, 1987, 2023) tree water status is an inescapable biophysical limit to growth (Peters *et al.*, 2021), driving diel correlations between vapor pressure deficit and growth (Babst *et al.*, 2019; Zweifel *et al.*, 2021).

Even without the complicating factor of soil moisture temperature’s non-linear effects on growth can also limit growth responses. At very cool temperatures—such as those of early spring—a small increase in warming may have limited effect, while a jump in more common summer-time temperatures, for example from 16 to 18°C, would be physiologically more significant. 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 thus have no discernible effect on growth, while a number of other studies—based on tree rings—suggest that any increases in growth due to longer seasons are offset by reduced growth from high summer temperatures (Fig. 1 Gantois, 2022; Dow *et al.*, 2022). Other studies suggest current summer temperatures have not pushed trees above their optima (Schaber & Badeck, 2002), with some suggesting increased growth is driven mainly by higher growth rates, not longer seasons.

External factors related to biotic interactions—including herbivory, disease and competition—can also limit growth, and may themselves be responsive to an extended growing season. For example, herbivory can have large impacts on forests, leading to declines in satellite measures of greenness often associated with signals of plant senescence. Plant pathogens are also known to respond to warming, and limit productivity (Sturrock *et al.*, 2011; La Porta *et al.*, 2008). These biotic drivers of growth were rarely mentioned in studies examining growing season length (we found no mention of them, Fig. 1e), but could increasingly limit growth as extended growing seasons allow for additional generation cycles in many pest species (Mitton & Ferrenberg, 2012; Lange *et al.*, 2006).

## Internal

When and how growth is initiated and ceases is clearly 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). Some recent studies suggest a novel role for the summer solstice (Zohner *et al.*, 2023) in setting a universal developmental switch between when warming temperatures hasten or delay leaf senescence (thus influencing

growing season length and growth). However, these studies contrast with decades of work showing population-level differences in how and when species grow.

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. For example, populations often vary predictably in their end-of-season phenology, with more poleward populations tending to stop height growth (budset) 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). Within populations, individual trees may also vary in how early or late they are for both spring and fall events. This can be driven by maturity and a shifting investment to growth, survival and/or reproduction. Saplings, for which growth and survival are paramount, tend to both grow more rapidly (Hilty *et al.*, 2021) and have longer seasons relative to adult trees (Augspurger & Bartlett, 2003; Rozendaal *et al.*, 2010; Vitasse *et al.*, 2014), which need to also invest in reproduction.

Trade-offs between vegetative and reproductive investments are a paradigm of life history theory and may also 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 years 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 often 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 on growth are highly likely to vary across species, a reality rarely acknowledged by current studies (Fig. 1c), but with major implications for understanding the widespread observed variation in growth  $\times$  growing season relationships. Biogeographical patterns in climate and assembly within communities both predict species should evolve towards different optima and different strategies. For example, leaf strategies vary strongly between evergreen and deciduous species, but also within each group—where variation in ‘determinacy’ defines the timing and investment of shoot growth and leaf emergence. Determinate species have most of their leaf material prebuilt in overwintering buds, generally unfolding their entire canopy within few weeks each season, while indeterminate species continue to produce new shoots including leaves over the growing season (??). Such differences can clearly influence the extent to which the growth of different species responds to increases in growing season length, even under identical conditions. Given research to date across external and internal drivers has covered over 36 diverse species, it is perhaps then not surprising that research has failed to identify a common relationship.

Yet both trait and phylogenetic ecology make useful predictions for when and where growth  $\times$

growing season should be most apparent. Trait ecology predicts trade-offs 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; Diaz *et al.*, 2016). These ideas would thus predict indeterminate acquisitive species, such as poplar, to grow more with longer seasons, while conservative species, such as beech, may not. Trait ecology further predicts where species fall along the acquisitive versus conservative trade-off through a suite of leaf, wood and reproductive traits, thus providing an axis of important variation that could be used to identify focal species for further study and to test predictions. Species with low leaf mass per area, diffuse vessels and consistent investment in fruit would show stronger shifts in growth with changing growing season length—assuming no other factors (e.g., drought or high temperatures) become limiting.

Phylogenetic ecology layers onto these predictions selection from past periods, producing species differences that do not always reflect optimal strategies today. Imprints of past selection often drive species-level differences, producing phylogenetic patterns that both limit how well species are adapted to current conditions and especially constrain their responses to rapidly changing conditions (Ackerly, 2009). Most studies testing for such historical effects on plant responses find them (e.g., Davies *et al.*, 2013), and even more physiological syntheses find results suggestive of strong phylogenetic relationships (though they are more rarely formally tested, e.g., Way & Oren, 2010).

## **Building a framework for growth $\times$ growing season length relationships**

Predicting when and where longer seasons lead to increased growth may seem overwhelming given the diversity of potential drivers and complexity of species-level differences, but together they offer a set of testable hypotheses that could rapidly advance progress—if tackled with a more organized and cross-disciplinary approach. The high variation we found in observed growth responses to longer seasons across methods and even within species (Figs. 3,??, see Supplement) could be reduced in some part through standardized measurements (see Box) and larger shifts within fields (see Box) that may take time, but major hypotheses may be tractably tested now. Taking advantage of existing data sets and ongoing experiments could provide tests of variation in growth—and potentially controllers on it—across individual to species and ecosystem scales, while new experiments can compare effects of external versus internal drivers on growth. Combining these in models that build up from internal limits to external drivers and include species-level variation would then provide predictions.

## **Using existing data and networks to partition levels of variation across drivers**

Existing freely-available repositories of data could test predictions from trait ecology for species-level variation in responses to external drivers. Combining large-scale databases of tree rings and vegetative phenology (e.g., the International Tree Ring Database, ITRDB, and the Pan European Phenology project, PEP725) would provide major spatially and temporally diverse dataset to compare how external climatic drivers, species and population together explain growth

× growing season length relationships. Depending on the data overlap (see Box: Extending disciplinary focus), these datasets may also allow us to identify where longer growing seasons will increase growth and for which types of species. For example, combined databases could test the prediction that longer growing seasons will increase growth for species with regular reproduction (no masting, see also new masting database in Hackett-Pain *et al.*, 2022), an acquisitive strategy, from clades that are historically (on an evolutionary timescale) plastic, in locations that are warm—but not too warm—and moist.

Existing common garden studies provide an opportunity for more robust tests of population and individual variation could come. Given that many common garden studies have some data on phenology and are designed to tease out population versus inter-annual variation, collecting tree ring data from them seems a rapid way to estimate variation across these two levels. Repeating such measurements for multiple common gardens would also allow for an exploration of species level variation. Common gardens not collecting regular phenology, or annual growth data, could start. Given how old some common gardens are, research may also be able to examine impacts of biotic and abiotic disturbances or effects of climatic variation.

Taking advantage of existing ecological and field global change experiments could help bridge across the two major fields currently studying growth × growing season length relationships—physiology and dendrochronology—and their contrasting timescales. We found most physiological studies of growth × growing season length relationships studied 1-2 years of dynamics, usually of juvenile trees, while tree ring studies focused on synthesizing across decades or longer of adult tree growth. Perhaps because of this dichotomy, tree ring studies often study lag effects, while they are rarely mentioned in physiological studies, but current large-scale experiments on heat (e.g., SPRUCE, Hanson *et al.*, 2017), moisture via drought or irrigation (e.g., DroughtNet, Phynwald Smith *et al.*, 2016) and other factors (e.g.,  $CO_2$  in FACE) have increasingly been used to test ecological ‘memory’ (e.g., Flinker *et al.*, 2021; Schweiger *et al.*, 2022). They thus could help scale up from smaller and shorter-time scale physiological studies, potentially to ecosystem-level dynamics such as carbon cycling (Ding *et al.*, 2021; Jensen *et al.*, 2019). Building on available data and infrastructure could also bridge this gap, for example, adding dendrometers to locations with phenological sampling and vice versa. Such efforts may be especially valuable in sites across elevational and latitudinal gradients (e.g., PSP, Feeley elevation network, Coweeta). These sites in turn could be priority locations for xylogenesis and focused physiological studies.

Understanding the scale of variation across all these levels could both help to refine theory and provide a benchmark when comparing the effect sizes of other drivers of variation. While multiple papers report a lack of relationship between growth and growing season length, we have no fundamental understanding of what the effect size of this relationship should be, and thus no way to know if we have good power in current studies to detect it. Estimates of how growth shifts with elevation likely include responses from both plasticity (within-individual variation) and local adaptation (population-level variation) and thus could be an upper bound on our expectations, yet elevational trends to date appear relatively weak and noisy (Fig. 2)—suggesting this is only part of our missing mechanistic understanding.

## New experiments to tease apart external and internal drivers

Given the complex effects of external drivers and internal constraints on growth  $\times$  growing season length relationships, disentangling them will require new experiments. Teasing out the effects of warmer temperatures versus longer seasons can only be robustly done with experiments, and seems a paramount need, especially if done across multiple species spanning diverse strategies. Similarly, experiments to compare impacts of extended seasons (via early growth or delayed senescence), and differentiating between external abiotic (e.g., heat waves, droughts) and biotic (e.g., pests, competition) drivers could provide comparable estimates and test lag effects, when sampled multiple years after the manipulations. While these are most easily done for juvenile trees, they could also be done on adult trees, given investment in infrastructure.

Efforts to design and launch such large-scale experiments should start now. A long-term experiment on adult trees that manipulates temperature, precipitation and growing season length, would test a suite of drivers at the relevant lifestage. It could robustly compare drivers and become a resource for studies of underlying mechanisms for constraints, if properly measured and designed. This would mean careful measurements of carbon allocation, including to reproductive output, and tissue lost to frost and biotic drivers, and choosing species to maximize divergent strategies and provide the potential for genomic and related studies (e.g., *Populus*, *Quercus*). Given the potential role of evolutionary history, selecting for these varying strategies within a clade, or—if not feasible—correcting for phylogenetic distance would more robustly test how strategies influence the growth  $\times$  growing season length relationship. At a larger spatial scale, distributed experiments to measure growth and phenology (ideally wood and vegetative) of multiple provenances of multiple species across sites could estimate variation—and potential constraints—that operate at different organizing levels.

## One model to rule them all

Efforts to bridge across existing datasets, integrate current experiments, and launch new ones will need models that allow for and test inter-connections between external drivers, internal constraints and species-level differences in growth responses to warmer, longer seasons. Statistical models that include separate effects of temperature, moisture and growing season length while partitioning individual, population and species-level variation could provide broad-scale estimates of the effects of the major external drivers versus potential internal constraints (which may be apparent as population differences). Including species-level effects while also integrating phylogenetic relationships between species could then test for the role of evolutionary history in shaping responses, while adding in site  $\times$  year-level effects of biotic disturbances could begin to compare across abiotic and biotic external drivers. But such models should be built alongside a suite of mechanistic process-focused models that scale up. For example, one model may build from carbohydrate balance and cell division (see Locosselli & Buckeridge, 2017) to predict growth dynamics observed in xylogenesis. As new experiments identify potential internal growth constraints and what level they operate on (universal, population or otherwise), both statistical and physiological process models can be adapted and improved. Together the interplay of statistical and more mechanistic process-focused models would likely provide major insights into the fundamental biology how tree growth  $\times$  shifts with extended seasons, and yield a unified model



for robust predictions of growth responses to warmer, longer seasons across species, species and levels of warming.

*Conclusions:* Anthropogenic climate change has often been described as an unfortunate experiment. It has highlighted important biology we don't know well, requiring us to rediscover dusty old fundamentals, and also expose their limits—and thus our limits of understanding. Understanding when, how and why longer seasons lead to increased tree growth requires an interdisciplinary reckoning with how temperature, growth and a suite of external and internal drivers affect plant growth. The task may seem large, but bridging across theory and data from dendrochronology, phenology research, physiology, evolutionary and life-history theory could rapidly advance fundamental biology in ways that translate directly to improved models of future forest dynamics, and the suite of species and services that depend on them.

*Acknowledgements:* B. Wu for extracting growth  $\times$  elevation data; N. Pederson for discussions and J. Davies for comments that improved the manuscript.

# 1 Boxes!

## Box. Standardized measurements

Tackling the diverse drivers and their underlying hypotheses (Fig. 1) for growth  $\times$  growing season length relationships requires a common language and set of metrics for growing season length (Körner *et al.*, 2023), growth, and the potential drivers. We found 14 different metrics of start, 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. Definitions and metrics for external and internal drivers were myriad, with many papers reporting dozens of tests of different aspects of climate over different temporal windows. This is understandable, given the complexity of environmental variables and our limited understanding of how they trigger phenology and growth, but also slows progress. A common framework where researchers measure and report common 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.

Tree growth, which can be measured in a variety of ways, highlights this issue. Our literature review found that most studies quantified growth by measuring radial growth (e.g., through increment cores or dendrometers,  $n = 28$ ), but a number also looked at metrics related to C assimilation (e.g. net ecosystem productivity or gross primary productivity,  $n = 20$ ), while a smaller number examined biomass, height, or number of stems ( $n = 9$ ), or root:shoot ratio ( $n = 1$ ). Some studies used modeled estimates of photosynthesis (e.g., Smith *et al.* (2014) relied on daily photosynthesis estimates derived from the LPJ-GUESS photosynthesis model, while Chen *et al.* (2000) estimated photosynthesis using the Integrated Terrestrial Ecosystem C-budget model, InTEC). Others measured photosynthesis at the leaf level, through flux towers, or used greenness metrics (NDVI).

Growth measurements vary across disciplines and study types, posing a further challenge to an interdisciplinary approach to understanding how growing season length relates to growth. Greenhouse or growth chamber studies and provenance trials were more likely to measure height or biomass, whereas larger scale syntheses and remote-sensed studies are more likely to use metrics of carbon assimilation.

Aligning across the range and scale of growth metrics will be critical for an integrated understanding of growth-growing season length relationships and implications under continued climate change. There is decoupling among some metrics of growth. For example, vegetation photosynthesis may be poorly correlated with tree radial growth, and this relationship can vary seasonally (Cabon *et al.*, 2022). Further, tree radial growth is not a perfect indicator of whole tree growth, since plants allocate carbon to their roots, leaves, reproductive structures, and stores in addition to aboveground biomass. Relationships among different metrics of growth are not simple, so selecting relevant ones and aligning across the most widely used ones will be necessary, though not easy: the relationship between photosynthesis, radial growth, and carbon uptake has large implications for future carbon sequestration and it remains widely debated (Green & Keenan,

2022). Further, there is a need to understand how to scale up across these varying metrics- from leaf and individual level to populations, communities, and ecosystems- while incorporating the variation that exists within and across levels.

### **Box: Extending disciplinary focus to help bridge the internal-external drivers divide**

Standardized measurements will not yield fully comparable estimates—especially on the relative impacts of external and internal drivers—without larger shifts within fields. We found that dendrochronology considers almost exclusively external climatic drivers, while physiological tests of internal constraints do not usually make predictions that scale up easily beyond the lab or greenhouse. Major fields studying this relationship—dendrochronology, phenology research and physiology—all need to broaden in specific ways to overlap with one another to facilitate interdisciplinary work. At the same time, all fields have missed certain major hypotheses they could test (Fig. 1), highlighting the need to integrate perspectives from other disciplines with relevant theory and methods.

Each field studying growth  $\times$  growing season length (dendrochronology, phenology research and physiology) has its own historical aims, and thus its own biases towards certain species, methods and metrics. Dendrochronology’s original focus on using tree growth to estimate climate has led to certain assumptions and methods that likely obscure the complexity of how growth shifts with growing season length. Fundamentally, the field relies on an assumed relationship that, within individual and populations of trees, growth (measured by annual ring width) is greater when growing conditions are better (Cook & Kairiukstis, 2013, e.g.). Dendrochronologists’ traditional aim to magnify the climate signal has led to standard approaches, including sampling biases (e.g., to ‘climate-sensitive’ individual trees, Klesse *et al.*, 2018; Nehrbass-Ahles *et al.*, 2014) and statistical detrending (Rollinson *et al.*, 2021), that may obscure patterns where the signal longer growing seasons and biotic drivers may be most apparent (such as rapid growth phases, Manzanedo & Pederson, 2019). Further, these approaches mean dendrochronology studies are also fundamentally washing out much of what physiological studies focus on, limiting opportunities for interdisciplinary overlap.

Opportunities for overlap between dendrochronology and phenology research are potentially high, but sampling biases in both fields limit current opportunities. Dendrochronology generally focuses on conifers (gymnosperms Zhao *et al.*, 2019), creating a major split from most studies of leaf phenology, which focus almost entirely on deciduous angiosperm species (see Fig. 1). Phenology research has also been strongly focused on spring events (e.g., budburst, leafout), with limited data on fall events and thus limited data to calculate growing season length. This focus on spring events may have been justified decades ago, when most shifts from anthropogenic warming occurred in the spring, but less justified as increasing research suggests important complexity in fall shifts (Gill *et al.*, 2015; Zohner *et al.*, 2023) and a need to scale up phenological research to understand tree growth.

All fields could benefit from tackling the challenge of understanding the physiological connections between growing season length and growth, and even the genetic and developmental underpinnings of these connections. To date, much work has focused on measures of growth and

phenology without a clear mechanistic understanding of what triggers growth and its cessation, and how these triggers and responses have evolved. Progress in this area is could be particularly important for making projections, as extrapolating can be dangerous when the underlying mechanistic model is wrong. Physiological studies that follow carbohydrate balance and cell division (see Locosselli & Buckeridge, 2017) versus growth dynamics could yield insights, as could additional work on xylogenesis—especially if done with a focus both to extrapolate to long-term tree ring studies and/or in physiological experiments (Fang *et al.*, 2020; Simard *et al.*, 2013). Expanding beyond the current disciplines focused on this topic could also be informative. For example, a clearer physiological understanding of which environmental stimuli trigger leaf expansion, senescence, woody growth, and heartwood formation alongside an evolutionary perspective could contribute towards a clearer understanding of growth constraints (Baas & Wheeler, 2011; Eckert *et al.*, 2019; Ensminger *et al.*, 2015; Juvany *et al.*, 2013).

## 2 Figures

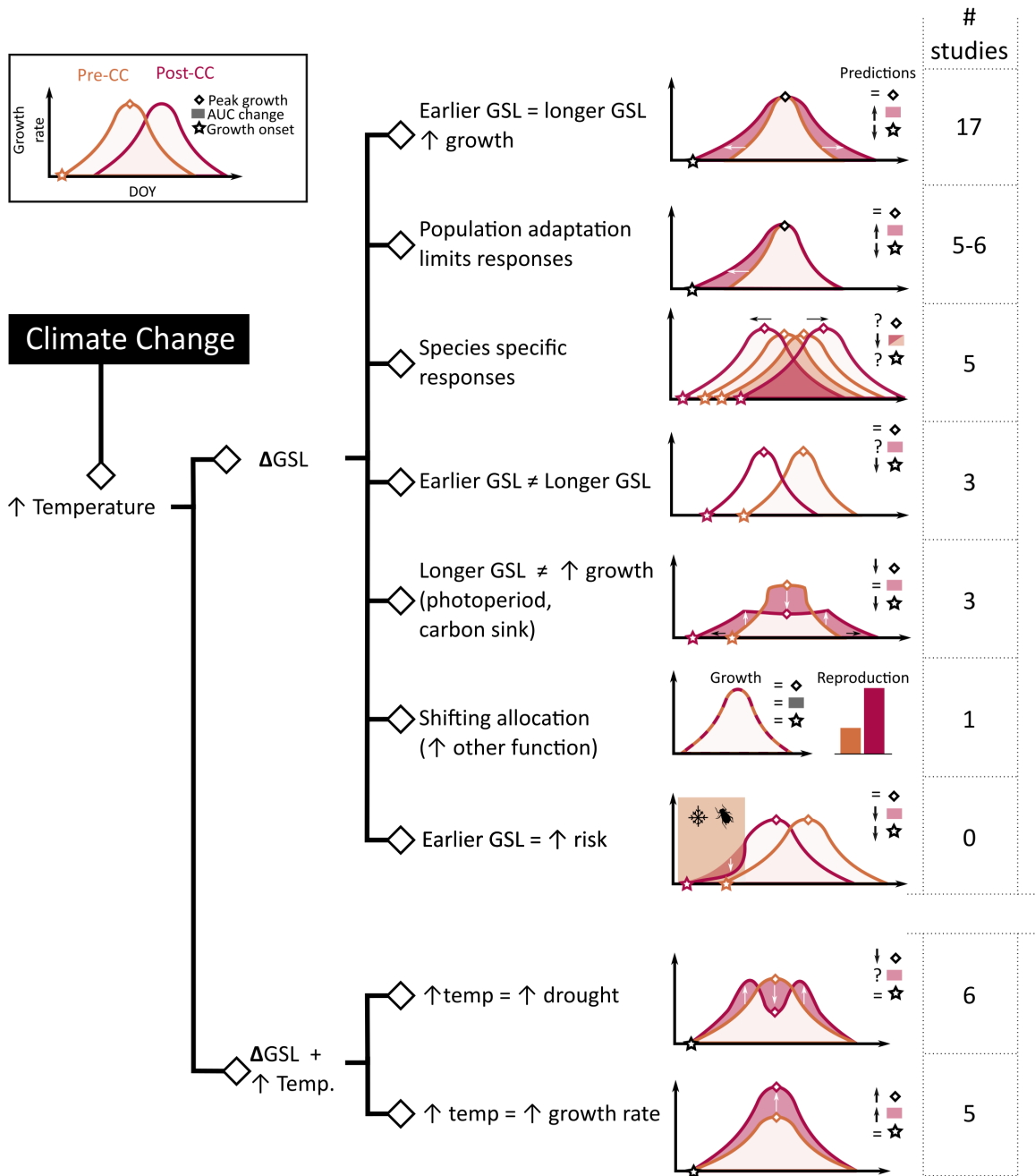


Figure 1: Pathways through which climate change could alter growing season length and growth.

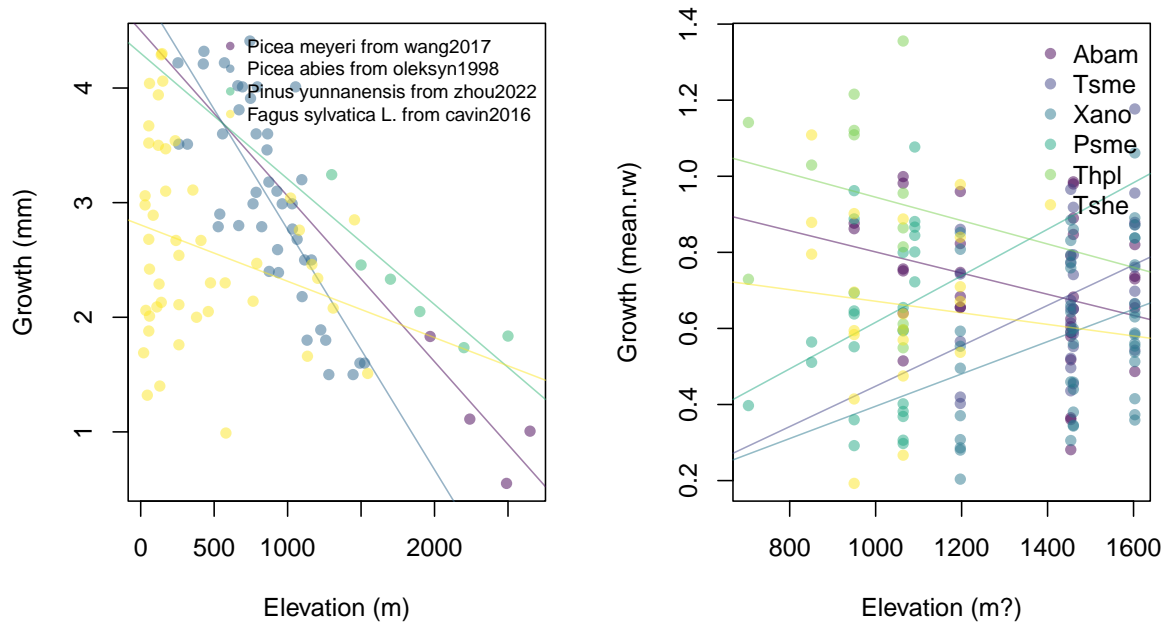


Figure 2: Growth  $\times$  elevation studies (from the literature, left) and results from across species at one location—Mount Tahoma/Rainier (right).

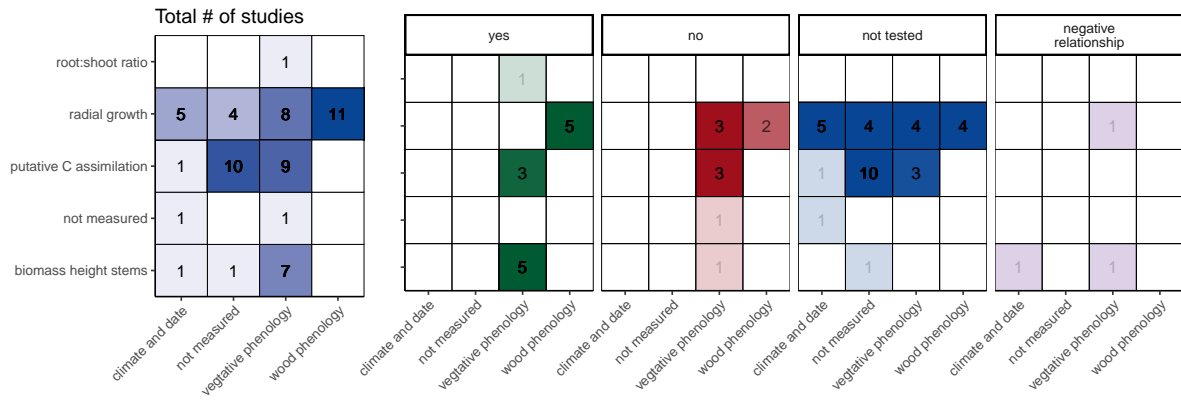


Figure 3: A review of growth × growing season length relationship studies spanned a diversity of methods, but there was no coherency in which methods did or did not find a positive relationship. Not directly testing for the relationship was surprisingly common across methods. See Supplement for review details.



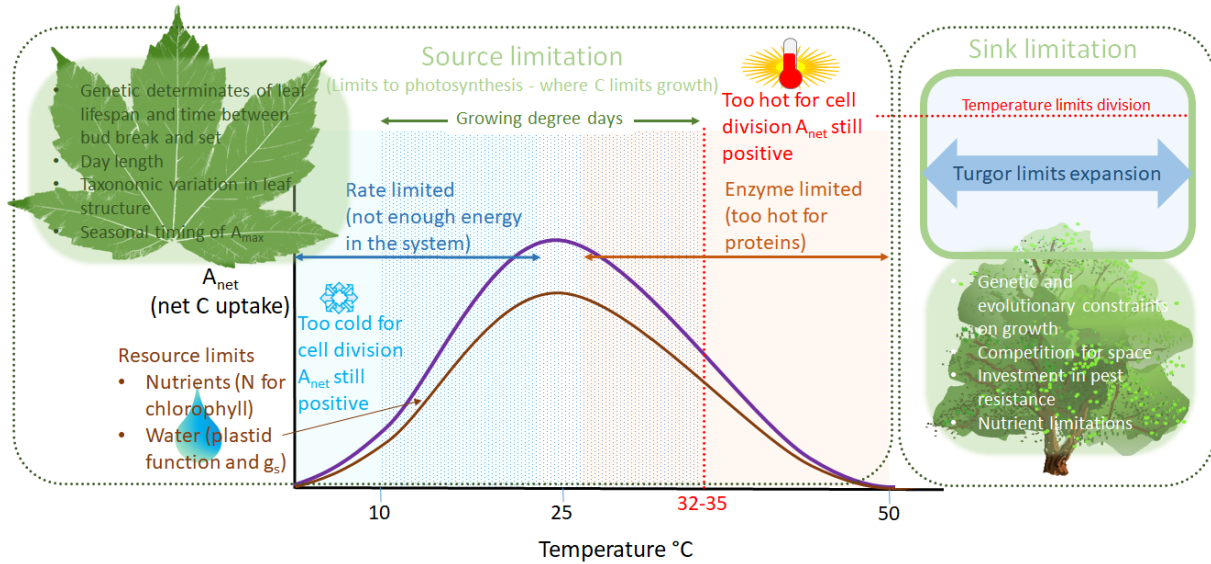


Figure 4: Less simplified version of how temperature works, including lots of limits at high and low temperatures (we need to update to make more asymmetric and to have the language match the language in the paper more ... or we need to add a box to this figure to explain all the terms).

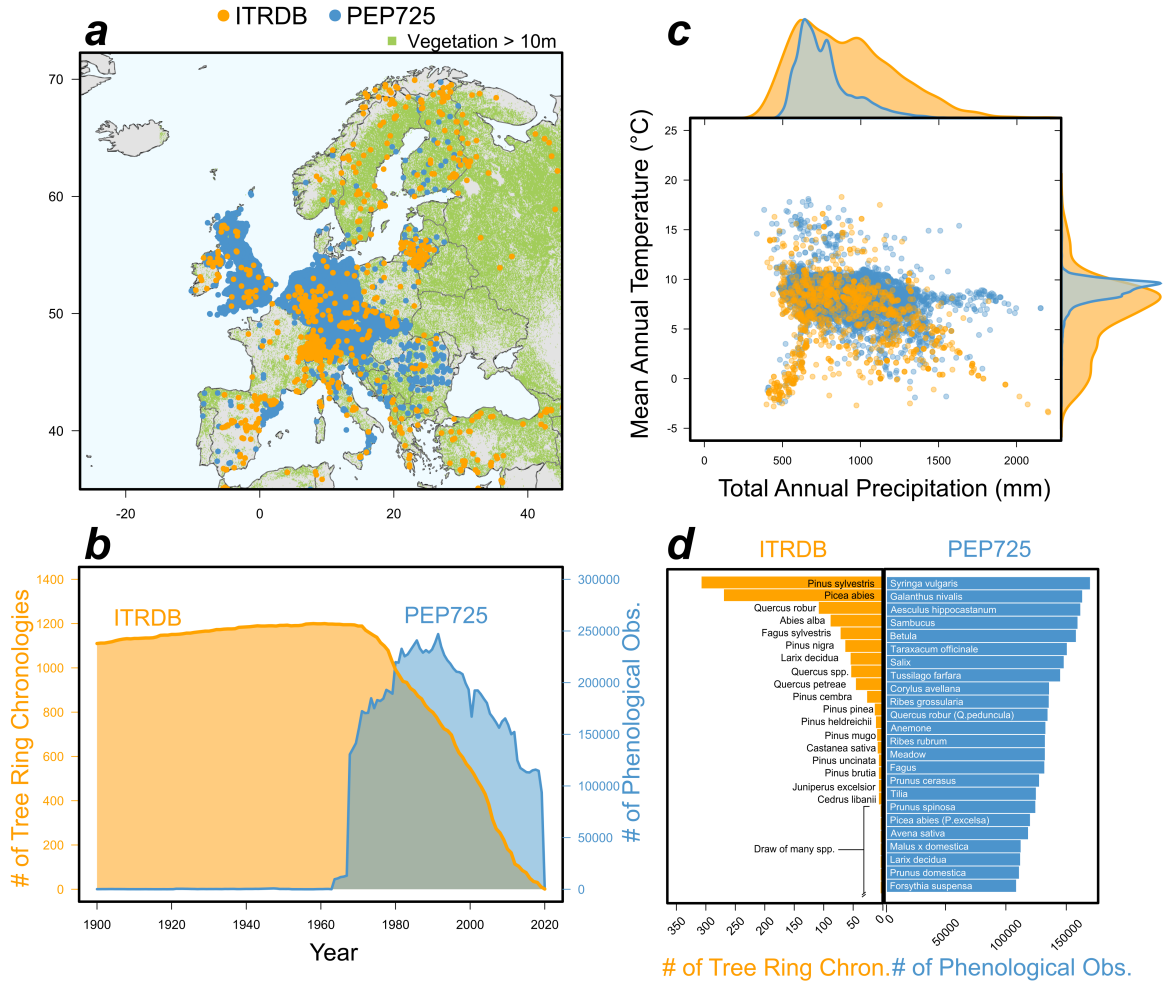


Figure 5: Data overlap between the two major databases of growth (International Tree Ring Data Bank, ITRDB, orange) and plant phenology (Pan European Phenology Project, PEP725, blue). Both databases are compared in terms of their spatial distributions (a), temporal overlaps (b), coverage of environmental 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.

### 3 References

- Ackerly, D. (2009) Conservatism and diversification of plant functional traits: Evolutionary rates versus phylogenetic signal. *Proceedings of the National Academy of Sciences of the United States of America* **106**, 19699–19706.
- Ackerly, D.D., Dudley, S.A., Sultan, S.E., Schmitt, J., Coleman, J.S., Linder, C.R., Sandquist, D.R., Geber, M.A., Evans, A.S., Dawson, T.E. *et al.* (2000) The evolution of plant ecophysiological traits: recent advances and future directions: new research addresses natural selection, genetic constraints, and the adaptive evolution of plant ecophysiological traits. *Bioscience* **50**, 979–995.
- Aitken, S.N. & Bemmels, J.B. (2016) Time to get moving: assisted gene flow of forest trees. *Evol Appl* **9**, 271–90.
- Anderson-Teixeira, K.J. & Kannenberg, S.A. (2022) What drives forest carbon storage? the ramifications of source–sink decoupling. *New Phytologist* **236**.
- Aubinet, M., Hurdebise, Q., Chopin, H., Debacq, A., De Ligne, A., Heinesch, B., Manise, T. & Vincke, C. (2018) Inter-annual variability of net ecosystem productivity for a temperate mixed forest: A predominance of carry-over effects? *Agricultural and Forest Meteorology* **262**, 340–353.
- Augsburger, C.K. & Bartlett, E.A. (2003) Differences in leaf phenology between juvenile and adult trees in a temperate deciduous forest. *Tree Physiology* **23**, 517–525.
- Baas, P. & Wheeler, E. (2011) Wood anatomy and climate change. *Climate change, ecology and systematics* **78**, 141–155.
- Babst, F., Bouriaud, O., Poulter, B., Trouet, V., Girardin, M.P. & Frank, D.C. (2019) Twentieth century redistribution in climatic drivers of global tree growth. *Science Advances* **5**, eaat4313.
- Berdanier, A.B. & Klein, J.A. (2011) Growing season length and soil moisture interactively constrain high elevation aboveground net primary production. *Ecosystems* **14**, 963–974.
- Cabon, A., Kannenberg, S.A., Arain, A., Babst, F., Baldocchi, D., Belmecheri, S., Delpierre, N., Guerrieri, R., Maxwell, J.T., McKenzie, S. *et al.* (2022) Cross-biome synthesis of source versus sink limits to tree growth. *Science* **376**, 758–761.
- Camarero, J.J., Campelo, F., Colangelo, M., Valeriano, C., Knorre, A., Solé, G. & Rubio-Cuadrado, Á. (2022) Decoupled leaf-wood phenology in two pine species from contrasting climates: Longer growing seasons do not mean more radial growth. *Agricultural and Forest Meteorology* **327**, 109223.
- Chen, W., Black, T., Yang, P., Barr, A., Neumann, H., Nesic, Z., Blanken, P., Novak, M., Eley, J., Ketler, R. *et al.* (1999) Effects of climatic variability on the annual carbon sequestration by a boreal aspen forest. *Global Change Biology* **5**, 41–53.

- Chen, W., Chen, J., Liu, J. & Cihlar, J. (2000) Approaches for reducing uncertainties in regional forest carbon balance. *Global Biogeochemical Cycles* **14**, 827–838.
- Cleland, E.E., Allen, J.M., Crimmins, T.M., Dunne, J.A., Pau, S., Travers, S.E., Zavaleta, E.S. & Wolkovich, E.M. (2012) Phenological tracking enables positive species responses to climate change. *Ecology* **93**, 1765–1771.
- Cook, E.R. & Kairiukstis, L.A. (2013) *Methods of dendrochronology: applications in the environmental sciences*. Springer Science & Business Media.
- Cosgrove, D.J. (1987) Wall relaxation and the driving forces for cell expansive growth. *Plant physiology* **84**, 561–564.
- Cosgrove, D.J. (2005) Growth of the plant cell wall. *Nature reviews molecular cell biology* **6**, 850–861.
- Cosgrove, D.J. (2023) Structure and growth of plant cell walls. *Nature Reviews Molecular Cell Biology* pp. 1–19.
- Cuapio-Hernández, L., Reyes-Ortiz, J.L., De La Rosa, A.B., Pavón, N.P., López-Herrera, M., Villanueva-Díaz, J. & Sánchez-González, A. (2022) Is there a response pattern between radial growth of trees and elevation gradient? *Tree-Ring Research* .
- Cuny, H.E., Rathgeber, C.B., Lebourgeois, F., Fortin, M. & Fournier, M. (2012) Life strategies in intra-annual dynamics of wood formation: example of three conifer species in a temperate forest in north-east france. *Tree physiology* **32**, 612–625.
- Davies, T.J., Wolkovich, E.M., Kraft, N.J.B., Salamin, N., Allen, J.M., Ault, T.R., Betancourt, J.L., Bolmgren, K., Cleland, E.E., Cook, B.I., Crimmins, T.M., Mazer, S.J., McCabe, G.J., Pau, S., Regetz, J., Schwartz, M.D. & Travers, S.E. (2013) Phylogenetic conservatism in plant phenology. *Journal of Ecology* **101**, 1520–1530.
- de Sauvage, J.C., Vitasse, Y., Meier, M., Delzon, S. & Bigler, C. (2022) Temperature rather than individual growing period length determines radial growth of sessile oak in the pyrenees. *Agricultural and Forest Meteorology* **317**, 108885.
- Diaz, S., Kattge, J., Cornelissen, J.H.C., Wright, I.J., Lavorel, S., Dray, S., Reu, B., Kleyer, M., Wirth, C., Prentice, I.C., Garnier, E., Bonisch, G., Westoby, M., Poorter, H., Reich, P.B., Moles, A.T., Dickie, J., Gillison, A.N., Zanne, A.E., Chave, J., Wright, S.J., Sheremet'ev, S.N., Jactel, H., Baraloto, C., Cerabolini, B., Pierce, S., Shipley, B., Kirkup, D., Casanoves, F., Joswig, J.S., Gunther, A., Falczuk, V., Ruger, N., Mahecha, M.D. & Gorne, L.D. (2016) The global spectrum of plant form and function. *Nature* **529**, 167–U73.
- Ding, W., Cong, W.F. & Lambers, H. (2021) Plant phosphorus-acquisition and-use strategies affect soil carbon cycling. *Trends in Ecology & Evolution* **36**, 899–906.
- Doughty, C.E., Malhi, Y., Araujo-Murakami, A., Metcalfe, D.B., Silva-Espejo, J.E., Arroyo, L., Heredia, J.P., Pardo-Toledo, E., Mendizabal, L.M., Rojas-Landivar, V.D. *et al.* (2014) Allocation trade-offs dominate the response of tropical forest growth to seasonal and interannual drought. *Ecology* **95**, 2192–2201.

- Dow, C., Kim, A.Y., D'Orangeville, L., Gonzalez-Akre, E.B., Helcoski, R., Herrmann, V., Harley, G.L., Maxwell, J.T., McGregor, I.R., McShea, W.J. *et al.* (2022) Warm springs alter timing but not total growth of temperate deciduous trees. *Nature* **608**, 552–557.
- Eckert, C., Sharmin, S., Kogel, A., Yu, D., Kins, L., Strijkstra, G.J. & Polle, A. (2019) What makes the wood? exploring the molecular mechanisms of xylem acclimation in hardwoods to an ever-changing environment. *Forests* **10**, 358.
- Ensminger, I., Chang, C.Y.Y. & Bräutigam, K. (2015) Tree responses to environmental cues. *Advances in botanical research* **74**, 229–263.
- Fang, J., Lutz, J.A., Shugart, H.H. & Yan, X. (2020) A physiological model for predicting dynamics of tree stem-wood non-structural carbohydrates. *Journal of Ecology* **108**, 702–718.
- Finzi, A.C., Giasson, M.A., Plotkin, A.A.B., Aber, J.D., Boose, E.R., Davidson, E.A., Dietze, M.C., Ellison, A.M., Frey, S.D., Goldman, E., Keenan, T.F., Melillo, J.M., Munger, J.W., Nadelhoffer, K.J., Ollinger, V. S., Orwig, D.A., Pederson, N., Richardson, A.D., Savage, K., Tang, J., Thompson, J.R., Williams, C.A., Wofsy, S.C., Zhou, Z. & Foster, D.R. (2020) Carbon budget of the harvard forest long-term ecological research site: pattern, process, and response to global change. *ECOLOGICAL MONOGRAPHS* **90**.
- Flinker, R.H., Cardenas, M.B., Caldwell, T.G., Flerchinger, G.N., Roy, R. & Reich, P.B. (2021) Promise and pitfalls of modeling grassland soil moisture in a free-air co2 enrichment experiment (biocon) using the shaw model. *Pedosphere* **31**, 783–795.
- Frank, D., Fang, K. & Fonti, P. (2022) Dendrochronology: Fundamentals and innovations. *Stable Isotopes in Tree Rings: Inferring Physiological, Climatic and Environmental Responses*, pp. 21–59, Springer International Publishing Cham.
- Friedlingstein, P., O'sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I.T., Olsen, A., Peters, G.P. *et al.* (2022) Global carbon budget 2022. *Earth System Science Data Discussions* **2022**, 1–159.
- Gantois, J. (2022) New tree-level temperature response curves document sensitivity of tree growth to high temperatures across a us-wide climatic gradient. *Global Change Biology* **28**, 6002–6020.
- George, S.S. (2014) An overview of tree-ring width records across the northern hemisphere. *Quaternary Science Reviews* **95**, 132–150.
- Gill, A.L., Gallinat, A.S., Sanders-DeMott, R., Rigden, A.J., Gianotti, D.J.S., Mantooth, J.A. & Templer, P.H. (2015) Changes in autumn senescence in northern hemisphere deciduous trees: a meta-analysis of autumn phenology studies. *Annals of Botany* **116**, 875–888.
- Green, J.K. & Keenan, T.F. (2022) The limits of forest carbon sequestration. *Science* **376**, 692–693.
- Grime, J.P. (1977) Evidence for existence of 3 primary strategies in plants and its relevance to ecological and evolutionary theory. *American Naturalist* **111**, 1169–1194.

- Hacket-Pain, A., Foest, J.J., Pearse, I.S., LaMontagne, J.M., Koenig, W.D., Vacchiano, G., Bogdziewicz, M., Caignard, T., Celebias, P., Van Dormolen, J. *et al.* (2022) Mastree+: Time-series of plant reproductive effort from six continents. *Global Change Biology* **28**, 3066–3082.
- Hacket-Pain, A., Friend, A., Lageard, J. & Thomas, P. (2016a) Tree rings and masting: considering reproductive phenomena when interpreting tree rings? *Tree Rings in Archaeology, Climatology and Ecology* **14**, 78–85.
- Hacket-Pain, A.J., Cavin, L., Friend, A.D. & Jump, A. (2016b) Consistent limitation of growth by high temperature and low precipitation from range core to southern edge of european beech indicates widespread vulnerability to changing climate. *European Journal of Forest Research* **135**, 897–909.
- Hanson, P.J., Riggs, J.S., Nettles, W.R., Phillips, J.R., Krassovski, M.B., Hook, L.A., Gu, L., Richardson, A.D., Aubrecht, D.M., Ricciuto, D.M. *et al.* (2017) Attaining whole-ecosystem warming using air and deep-soil heating methods with an elevated co<sub>2</sub> atmosphere. *Biogeosciences* **14**, 861–883.
- Hilty, J., Muller, B., Pantin, F. & Leuzinger, S. (2021) Plant growth: The what, the how, and the why. *New Phytologist* **232**, 25–41.
- Ito, G., Romanou, A., Kiang, N.Y., Faluvegi, G., Aleinov, I., Ruedy, R., Russell, G., Lerner, P., Kelley, M. & Lo, K. (2020) Global carbon cycle and climate feedbacks in the nasa giss modele2. 1. *Journal of Advances in Modeling Earth Systems* **12**, e2019MS002030.
- Jensen, A.M., Warren, J.M., King, A.W., Ricciuto, D.M., Hanson, P.J. & Wullschleger, S.D. (2019) Simulated projections of boreal forest peatland ecosystem productivity are sensitive to observed seasonality in leaf physiology. *Tree Physiology* **39**, 556–572.
- Juvany, M., Müller, M. & Munné-Bosch, S. (2013) Photo-oxidative stress in emerging and senescing leaves: a mirror image? *Journal of experimental botany* **64**, 3087–3098.
- Keenan, T.F., Gray, J., Friedl, M.A., Toomey, M., Bohrer, G., Hollinger, D.Y., Munger, J.W., O’Keefe, J., Schmid, H.P., Wing, I.S. *et al.* (2014) Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nature Climate Change* **4**, 598–604.
- King, G.M., Gugerli, F., Fonti, P. & Frank, D.C. (2013) Tree growth response along an elevational gradient: climate or genetics? *Oecologia* **173**, 1587–1600.
- Klesse, S., DeRose, R.J., Guiterman, C.H., Lynch, A.M., O’Connor, C.D., Shaw, J.D. & Evans, M.E. (2018) Sampling bias overestimates climate change impacts on forest growth in the southwestern united states. *Nature communications* **9**, 5336.
- Kolář, T., Giagli, K., Trnka, M., Bednářová, E., Vavřík, H. & Rybníček, M. (2016) Response of the leaf phenology and tree-ring width of european beech to climate variability. *Silva Fennica* **50**.
- Körner, C., Möhl, P. & Hiltbrunner, E. (2023) Four ways to define the growing season. *Ecology Letters* .

- Kramer, P. (2012) *Physiology of woody plants*. Elsevier, New York.
- La Porta, N., Capretti, P., Thomsen, I., Kasanen, R., Hietala, A. & Von Weissenberg, K. (2008) Forest pathogens with higher damage potential due to climate change in europe. *Canadian Journal of Plant Pathology* **30**, 177–195.
- Lange, H., Økland, B. & Krokene, P. (2006) Thresholds in the life cycle of the spruce bark beetle under climate change. *Interjournal for Complex Systems* **1648**, 1–10.
- Larcher, W. (1980) *Plant Physiological Ecology*. Springer-Verlag.
- Leuning, R. (2002) Temperature dependence of two parameters in a photosynthesis model. *Plant, Cell & Environment* **25**, 1205–1210.
- Locosselli, G.M. & Buckeridge, M.S. (2017) Dendrobiochemistry, a missing link to further understand carbon allocation during growth and decline of trees. *Trees* **31**, 1745–1758.
- Manzanedo, R.D. & Pederson, N. (2019) Towards a more ecological dendroecology. *Tree-Ring Research* **75**, 152–159.
- Marchand, L.J., Dox, I., Gričar, J., Prislan, P., Van den Bulcke, J., Fonti, P. & Campioli, M. (2021) Timing of spring xylogenesis in temperate deciduous tree species relates to tree growth characteristics and previous autumn phenology. *Tree Physiology* **41**, 1161–1170.
- Martinez-Meier, A., Sanchez, L., Pastorino, M., Gallo, L. & Rozenberg, P. (2008) What is hot in tree rings? the wood density of surviving douglas-firs to the 2003 drought and heat wave. *Forest Ecology and Management* **256**, 837–843.
- McKown, A.D., Guy, R.D. & Quamme, L.K. (2016) Impacts of bud set and lammas phenology on root: shoot biomass partitioning and carbon gain physiology in poplar. *Trees* **30**, 2131–2141.
- Michelot, A., Simard, S., Rathgeber, C., Dufrêne, E. & Damesin, C. (2012) Comparing the intra-annual wood formation of three european species (*fagus sylvatica*, *quercus petraea* and *pinus sylvestris*) as related to leaf phenology and non-structural carbohydrate dynamics. *Tree physiology* **32**, 1033–1045.
- Mitton, J.B. & Ferrenberg, S.M. (2012) Mountain pine beetle develops an unprecedented summer generation in response to climate warming. *The American Naturalist* **179**, E163–E171.
- Myneni, R.B., Keeling, C., Tucker, C.J., Asrar, G. & Nemani, R.R. (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **386**, 698–702.
- Nehrbass-Ahles, C., Babst, F., Klesse, S., Nötzli, M., Bouriaud, O., Neukom, R., Dobbertin, M. & Frank, D. (2014) The influence of sampling design on tree-ring-based quantification of forest growth. *Global change biology* **20**, 2867–2885.
- Nobel, P.S. *et al.* (1983) *Biophysical plant physiology and ecology*. WH Freeman and company.

- Peters, R.L., Steppe, K., Cuny, H.E., De Pauw, D.J., Frank, D.C., Schaub, M., Rathgeber, C.B., Cabon, A. & Fonti, P. (2021) Turgor—a limiting factor for radial growth in mature conifers along an elevational gradient. *New Phytologist* **229**, 213–229.
- Poorter, H., Fiorani, F., Pieruschka, R., Wojciechowski, T., van der Putten, W.H., Kleyer, M., Schurr, U. & Postma, J. (2016) Pampered inside, pestered outside? differences and similarities between plants growing in controlled conditions and in the field. *New Phytologist* **212**, 838–855.
- Rollinson, C.R., Alexander, M.R., Dye, A.W., Moore, D.J., Pederson, N. & Trouet, V. (2021) Climate sensitivity of understory trees differs from overstory trees in temperate mesic forests. *Ecology* **102**, e03264.
- Rozendaal, D.M., Brien, R.J., Soliz-Gamboa, C.C. & Zuidema, P.A. (2010) Tropical tree rings reveal preferential survival of fast-growing juveniles and increased juvenile growth rates over time. *New Phytologist* **185**, 759–769.
- Schaber, J. & Badeck, F.W. (2002) Evaluation of methods for the combination of phenological time series and outlier detection. *Tree Physiology* **22**, 973–982.
- Schweiger, A., Awdamet, F.T., Drenckhan, W. & Berauer, B.J. (2022) Transgenerational effects of elevated  $\text{CO}_2$ : Downregulation of photosynthetic efficiency and stomatal sensitivity to drought .
- Silvestro, R., Zeng, Q., Buttò, V., Sylvain, J.D., Drolet, G., Mencuccini, M., Thiffault, N., Yuan, S. & Rossi, S. (2023) A longer wood growing season does not lead to higher carbon sequestration. *Scientific reports* **13**, 4059.
- Simard, S., Giovannelli, A., Treydte, K., Traversi, M.L., King, G.M., Frank, D. & Fonti, P. (2013) Intra-annual dynamics of non-structural carbohydrates in the cambium of mature conifer trees reflects radial growth demands. *Tree Physiology* **33**, 913–923.
- Smith, B., Wårlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J. & Zaehle, S. (2014) Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. *Biogeosciences* **11**, 2027–2054.
- Smith, M.D., Wilcox, K., Sala, O., Phillips, R., Luo, Y., Knapp, A. & Lemoine, N.P. (2016) Drought-net: A global network merging observations, experiments, and modeling to forecast terrestrial ecosystem sensitivity to drought. *AGU Fall Meeting Abstracts*, vol. 2016, pp. B11J–06.
- Soolanayakanahally, R.Y., Guy, R.D., Silim, S.N. & Song, M. (2013) Timing of photoperiodic competency causes phenological mismatch in balsam poplar (*Populus balsamifera* L.). *Plant, cell & environment* **36**, 116–127.
- Sturrock, R., Frankel, S., Brown, A., Hennon, P., Kliejunas, J., Lewis, K., Worrall, J. & Woods, A. (2011) Climate change and forest diseases. *Plant pathology* **60**, 133–149.



- Thomas, S.C. (2011) Age-related changes in tree growth and functional biology: The role of reproduction. *Size- and Age-Related Changes in Tree Structure and Function* (eds. F.C. MEINZER, B. Lachenbruch & T.E. Dawson), chap. 2, pp. 33–64, Springer.
- Thompson, R.A., Adams, H.D., Breshears, D.D., Collins, A.D., Dickman, L.T., Grossiord, C., Manrique-Alba, À., Peltier, D.M., Ryan, M.G., Trowbridge, A.M. *et al.* (2023) No carbon storage in growth-limited trees in a semi-arid woodland. *Nature Communications* **14**, 1959.
- Vitasse, Y., Lenz, A., Hoch, G. & Körner, C. (2014) Earlier leaf-out rather than difference in freezing resistance puts juvenile trees at greater risk of damage than adult trees. *Journal of Ecology* **102**, 981–988.
- Way, D.A. & Oren, R. (2010) Differential responses to changes in growth temperature between trees from different functional groups and biomes: a review and synthesis of data. *Tree physiology* **30**, 669–688.
- Went, F.W. (1957) The experimental control of plant growth. *The experimental control of plant growth*. **17**.
- Zhao, S., Pederson, N., D’Orangeville, L., HilleRisLambers, J., Boose, E., Penone, C., Bauer, B., Jiang, Y. & Manzanedo, R.D. (2019) The international tree-ring data bank (itrd) revisited: data availability and global ecological representativity. *Journal of Biogeography* **46**, 355–368.
- Zohner, C.M., Mirzaghali, L., Renner, S.S., Mo, L., Rebindaine, D., Bucher, R., Palouš, D., Vitasse, Y., Fu, Y.H., Stocker, B.D. *et al.* (2023) Effect of climate warming on the timing of autumn leaf senescence reverses after the summer solstice. *Science* **381**, eadf5098.
- Zweifel, R., Sterck, F., Braun, S., Buchmann, N., Eugster, W., Gessler, A., Häni, M., Peters, R.L., Walthert, L., Wilhelm, M. *et al.* (2021) Why trees grow at night. *New Phytologist* **231**, 2174–2185.