

Thesis Proposal

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December 4, 2025

1 Introduction

1.1 Climate change impacts on tree phenology

Research from the past decades has shown convincing evidence that human activity is increasingly affecting many worldwide environmental processes (Ceballos *et al.*, 2017; Intergovernmental Panel On Climate Change (Ipcc), 2023; Laurance, 2007; Parmesan & Yohe, 2003). This can be through land use change and destruction, pollution, invasive species, resource overexploitation and climate change (Driscoll *et al.*, 2018; Parmesan *et al.*, 1999; Wu, 2013). Though some immediate actions can be deployed to mitigate these impacts (e.g. (Campbell *et al.*, 2014)), reversing 150 years of human-induced greenhouse gas emissions is harder. These emissions have affected Earth's climate and are projected to keep changing it for many centuries (Intergovernmental Panel On Climate Change (Ipcc), 2023). While there is a scientific consensus that observed climate change is human-caused (Change, 2014; Lynas *et al.*, 2021; Oreskes, 2004), the magnitude and the extent of the consequences that a warming climate will have on biological processes are still debatable (Huey *et al.*, 2012).

1.1.1. Trends of spring and autumn phenological events and their drivers

1.1.1.1. Changes in phenology: The most frequently observed biological impact of climate change over the past decades is major changes in spring and autumn phenology —the timing of recurring life history events (Parmesan & Yohe, 2003; Cleland *et al.*, 2007; Lieth *et al.*, 1974; Woolway *et al.*, 2021; Menzel *et al.*, 2006). Together, shifts in spring and autumn phenology modify when the growing season starts and when it ends. Understanding the consequences of changing growing season length on ecosystems requires understanding how much, and why it has changed (Duputié *et al.*, 2015).

1.1.1.2. Drivers of spring phenology: Spring phenological events (e.g. budburst and leafout) have been advancing from 0.5 (Wolfe *et al.*, 2005) to 4.2 days/decade (Chmielewski & Rötzer, 2001; Fu *et al.*, 2014) and are mainly driven by temperature (Chuine, 2010; Cleland *et al.*, 2007; Peñuelas & Filella, 2001). In the winter, when trees are still in dormancy, they accumulate cold temperatures (chilling) for which a certain amount is required to be ready to accumulate heat (forcing) (Vitasse *et al.*, 2014). Then, in the spring, a certain amount of forcing triggers budburst (Fu *et al.*, 2015). Heat requirement is met sooner in warm springs, thus explaining the advancement of spring events and earlier onset of growing season over the last decades (Fu *et al.*, 2015, 2013; Laube *et al.*, 2014).

1.1.1.3. Drivers of autumn phenology: In contrast, autumn phenology (e.g. budset and leaf senescence) is delayed, though to a much lesser extent than spring (Gallinat *et al.*, 2015; Jeong & Medvigy, 2014). The drivers regulating autumn phenology are far less understood than those of spring because it has attracted much less attention compared to spring (Piao *et al.*, 2019) and because the data is often noisier (Wu *et al.*, 2024). However, there is a general belief that autumn phenophases are driven by shortening photoperiod and colder temperatures (Cooke *et al.*, 2012; Flynn & Wolkovich, 2018; Körner & Basler, 2010; Delpierre *et al.*, 2016). Several hypotheses can explain delayed autumn phenophases. First, warmer autumn temperatures may extend the activity of photosynthetic enzymes which causes decreases the degradation rate of chlorophyll, thus delaying the timing of leaf senescence (Yan *et al.*, 2021). Second, summer droughts

could pause the activity schedule of trees and delay senescence to increase carbon assimilation (Dox *et al.*, 2022). Third, there could be an antagonistic effect of warming and brightening—caused by reductions in atmospheric pollution and cloud cover (Sanchez-Lorenzo *et al.*, 2015)—on leaf senescence (Wu *et al.*, 2021). Brightening accelerates the leaf senescence processes and reduces the temperature sensitivity during that period, counteracting the expected warming-induced delays in leaf senescence (Wu *et al.*, 2021).

1.1.2. How these shifts translate into effects on trees/forests is not clear - Pros and cons of early/late start/end of season

Shifts in spring and autumn phenology support a long-lasting and intuitive assumption that earlier spring and delayed autumn events lead to longer seasons—and thus increased growth (Keenan *et al.*, 2014; Stridbeck *et al.*, 2022). However, research from the past three years has cast doubt on this hypothesis (Dow *et al.*, 2022; Green & Keenan, 2022; Silvestro *et al.*, 2023b). For instance, (Dow *et al.*, 2022) showed that despite an earlier growth onset, longer seasons did not increase neither growth rate nor overall annual increment. This could substantially affect carbon-cycle model projections and thus feedbacks to future climate (Richardson *et al.*, 2013; Swidrak *et al.*, 2013). Starting to grow earlier and stopping later both have different consequences (Figure 1).

Understanding these findings requires answering why trees do not grow more despite longer growing seasons. While carbon allocation to above-ground biomass is one of the largest carbon sinks, how this carbon is allocated into wood is poorly understood. Indeed, the linear relationship assumption between wood growth and carbon assimilation is not well supported mechanistically and represents an important limitation of vegetation models (Cabon *et al.*, 2022). Net primary production represents the difference between photosynthesis and plant respiration, but this commonly used metric completely omits the representation of growth processes. This is perhaps because of a long-lasting paradigm of source-limited photosynthesis. This has now been debunked with carbon fertilization experiments, supporting evidence that direct environmental constraints on growth may be stronger than those on photosynthesis (Friend *et al.*, 2019; Parent *et al.*, 2010). This opens up a new—poorly tested—temperature sensitivity relationship between cambial activity and photosynthesis. Growing evidence suggests that cambial activity may be more sensitive than photosynthesis to a range of environmental conditions, such as water and nutrient availability, and temperature (Cabon *et al.*, 2022, 2020; Muller *et al.*, 2011; Peters *et al.*, 2021). This demonstrates that carbon projection models that heavily rely on vegetation alone may mislead the amount of carbon sequestered in our forests.

1.1.3. Growing season shifts and consequences on forest ecosystems and services

Spring and fall phenological events are shifting with debatable consequences on tree growth. The sensitivity of cambial activity to water, temperature and nutrients has the potential to have far-reaching consequences given the hard-to-predict nature of future climate change, where any of these variables could vary from low to high amplitude (Almagro *et al.*, 2025; Cabon *et al.*, 2022). This expected asymmetry of future environmental changes makes understanding the internal and external limits to growth critical. Especially, the capacity to tease apart different biomes—as for example boreal vs tropical forests are expected to react differently (REF)—is critical and empirical data coming from experiments, but also from observations are paramount to predict the changes of forest carbon offset from human GHG emissions (Wolkovich *et al.*, 2025).

1.2 Nature of the problem, and how to address it

1.2.1. Past phenological trends can help (or not) predict future phenological changes

We cannot directly use observed phenological trends in the last decades to extrapolate future phenological changes because: (1) the mechanisms guiding them aren't clear, and (2) phenological responses of trees to warming are very likely to be non-linear (Ettinger *et al.*, 2020; Fu *et al.*, 2013). Indeed, accurate predictions require an in-depth, accurate mechanistic understanding of phenophases and their sensitivities to environmental drivers, especially to temperature and photoperiod (Fu *et al.*, 2013). Therefore, the very foundation of the assumption that longer seasons increase growth may shift with future climate change. The well-observed advance in spring phenology may decelerate, and delayed fall phenology may shift towards earlier leaf senescence (through summer drought-induced growth cessation).

1.2.2. The assumption that longer seasons lead to increased growth is called into question

1.2.2.1. *Absence of growth despite better conditions and strategies that can be used* Recent work shows an absence of increased growth despite apparent better environmental conditions, thus casting doubt on a simple and intuitive positive relationship between growing season length and growth. This paradox further emphasizes the need to better understand the drivers regulating growth across biomes, but also how these drivers vary across the species within these biomes. Phenology varies greatly across species (e.g. closely related species tend to budburst at similar times under similar conditions) (Wolkovich *et al.*, 2014), but so does the relationship between growth and season length, which may explain the wide variation of this relationship within communities (Buckley & Kingsolver, 2012). This highlights another weakness of current carbon sequestration models that pool species together, likely overpassing important nuances in the growth responses that could be explained by species differences. Excluding species differences in models may mislead the future of forest carbon source-sink ratios (Green & Keenan, 2022; Cabon *et al.*, 2022; Wolkovich *et al.*, 2025). Different strategies can help in understanding how different species respond to warming.

1.2.2.2. *Experiments:* First, experiments are paramount to robustly tease apart the external vs internal drivers (e.g. warmer springs from severe drought later in the season—a common co-occurring reality in natural environments) (Morin *et al.*, 2010; Primack *et al.*, 2015). However, experiments are most often performed on juvenile trees, which are critical for their role in forest regeneration projections, but their responses hardly translate to mature trees, which hold the overwhelming carbon biomass proportion of forests (Augsburger & Bartlett, 2003; Silvestro *et al.*, 2023b; Vitasse, 2013).

1.2.2.3. *Ground based observations:* Second, leaf phenology through ground-based observations can provide valuable insights into the growth temporality trees that are not suitable for experimental trials. Since cambial and leaf phenology are closely linked to the other, having the more accessible leaf phenology data can act as a reliable proxy for the onset and end of tree growth. It is to say that knowing when leaves elongate and colour can guide when trees start and stop growing—fundamental metrics to determine the growing season length. Ground observations have the advantage of providing accurate data on phenological events for specific sites and species. Recently, the widespread use of smartphones has opened a whole new world of possible phenological monitoring through citizen scientists’ records of data over much larger areas and for a wider range of species (Dickinson *et al.*, 2012; Hufkens *et al.*, 2019; Piao *et al.*, 2019). While there are drawbacks to these observations (e.g. non-standard protocols, highly uneven spatiotemporal distribution of these observations), these methods have a huge potential to diversify the phenology data.

1.2.3. Goals of my thesis

Using citizen science data, a common garden study and a large-scale experiment, I aim to better understand how different tree species, at different lifespan stages, vary in their growth responses to different season length. Answering these patterns requires specifying the definitions of growth and the growing season.

1.3 Complexity of measuring growth and defining growing season length

1.3.1.1. What is a growing season?

To understand how trees respond to growing season conditions, it is important to clarify what is a growing season and growth.

The definition of the growing season itself is not a well-defined concept and an array of definitions are used differently across studies. Recently, Körner *et al.* (2023) proposed four definitions addressing this issue: (1) true growing season, based on measurable growth; (2) phenological season, based on visible phenological markers; (3) the productive season, based on primary production and (4) meteorological season, based on environmental conditions.

Here, I will focus on how definition (2), incorporating (4), affects definition (1) as the data collected for this thesis can’t address (3). I will use definition (2) to infer a “window of opportunity”, to calculate growing degree days (GDD)—a measure of heat accumulation—using meteorological conditions. I am using the meteorological season within a constrained window, instead of simply using it irrespective of phenology because of the illusion that an absolute increase in GDD over the last decades—irrespective of the timing of phenophases—also increases growth. Springs are warmer, falls are also sometimes warmer, and summers are warmer, which together increase the number of GDD, which may appear to be a reliable proxy for better

environmental conditions. However, models that accumulate GDD before and/or after trees grow could mislead about how this variable drives growth.

1.3.1.2. What is growth?

Wood formation (xylogenesis) consists of allocating carbon for long-term storage in woody plants. Xylogenesis starts with cambial activation and cell production which produces xylem and phloem cells (Etzold *et al.*, 2022; Silvestro *et al.*, 2025). The rate and duration of these phases lead to irreversible radial growth increments usually represented through tree rings. In these, secondary xylem cells account disproportionately to the number of cells produced because they divide more than phloem cells (Plomion *et al.*, 2001; Rathgeber *et al.*, 2016).

1.3.2. Traditional diameter measurements miss the resolution of annual growth increment

Foresters have measured tree diameter and height for decades, but these measurements are not suitable for interpreting a relationship between growth and environmental conditions. Diameter and height are used in allometries that could give in how much wood could be harvested in a forest (e.g. (Meyer, 1940; Saunders & Wagner, 2008)). The widely used method in forestry is to measure diameter at breast height at punctual time intervals (Yuancai & Parresol, 2001). However, these measurements don't provide short-term indicators of growth, and are likely to miss extreme events affecting growth. In addition, many forest inventories only report diameter measurements and exclude height, because of logistical constraints ((Saunders & Wagner, 2008)), which reduces biomass estimation quality. This growth data lacks the temporal resolution necessary to properly infer a relationship between growth and environmental conditions.

Alongside the diameter-height allometric relationship, dendroecology—applications of dendrochronological techniques to problems in ecology (Fritts & Swetnam, 1989)—emerged to answer ecological problems as well as to hindcast (e.g. (Bergeron *et al.*, 2004)) and forecast ecological processes both at the regional (Gazol *et al.*, 2018) and global scale (Manzanedo & Pederson, 2019; Büntgen *et al.*, 2018). Now, these methods can be used to understand more precise growth patterns and their relationship with different environmental factors. This is why I will use tree ring width as a reliable proxy for how much trees grew in any given year.

1.3.3. Asynchrony between primary and secondary growth (internal growth control?)

I argue that internal growth control in trees may shape their growth responses to growing season length, and these can be split into two categories: primary and secondary growth synchronicity and growth determinancy.

Primary (shoot elongation) and secondary (xylem and phloem formation) growth both contribute to how much carbon is stored in plant tissue, but how much they differ in their responses to environmental drivers is poorly understood. After a dormancy period, trees will start growing, both vertically (primary) and horizontally (secondary), but there is high variation among species as to when each growth starts, for how long it lasts and when it stops. For instance, ring-porous species initiate primary growth early in the season, sometimes even before budburst (e.g. oaks) (Stridbeck *et al.*, 2022), whereas xylogenesis in diffuse-porous species is usually more synchronized with budburst. These two examples highlight how more complicated it might be to infer general conclusions as to how growing season shifts may also shift growth, where some species may extend their primary growth, but restrict their secondary growth and vice versa.

In addition to differences in primary and secondary growth synchronicity, the role of internal growth control—often overlooked—may misshape our understanding of growth responses to growing season length (Baumgarten *et al.*, 2025). In perennial plants, two dichotomous growth strategies are commonly mentioned: determinate and indeterminate growth, though it appears that species exist along a gradient of these (Baumgarten *et al.*, 2025). Indeterminate growth is usually associated with short-lived and fast growth species, where these life-history strategies may give them a competing advantage as tissue growth can be produced quickly in response to changing environmental conditions. However, this comes with a higher risk of late spring and early fall frost as well as late droughts (Baumgarten *et al.*, 2025; Brien *et al.*, 2020). At the opposite side of the spectrum, determinate species are usually long-lived and slow-growing and are mainly constrained by conditions during bud formation; this may increase bud survival at the detriment of opportunistic growth in face of better-than-expected conditions (Baumgarten *et al.*, 2025).

Thus, primary versus secondary growth allocation, coupled with growth determinancy, are variables often overlooked, but which greatly vary across species and that are likely to affect how trees respond to shifting season length.

204 1.4 Objectives

205 My objectives for Fuelinex are to assess tree species' potential to prolong or stretch their activity schedule
 206 by artificially manipulating growing season length and analyze how this translates (or not) into growth,
 207 during the current year (2024) and in the following year (2025). I will also conduct a secondary experiment
 208 to examine whether trees can absorb nutrients late in the season and if that translates into growth during
 209 the following season. For the WildSpotters projects, I will investigate how the timing of phenological events
 210 affects growth across years for juvenile and mature trees, using observational phenology data and tree ring.
 211 Together, my two chapters will allow me to address the paradox of the absence of increased growth
 212 despite longer growing seasons.

213 1.5 Research questions

214 Fuelinex: How do extended growing seasons affect tree growth across different species, both immediately (in
 215 the same year as the extended season) and in subsequent years? WildSpotters: How does phenology regulate
 216 tree growth in urban ecosystems?
 217

218 2 Methodology

219 2.1 Coringtreespotters

220 2.1. Studies locations **Common garden** In 2014-2015, we collected seeds from four field sites in northeastern
 221 North America spanning approximately a 3.5° latitudinal gradient. The four field sites included Harvard
 222 Forest (42.55°N, 72.20°W), the White Mountains (44.11°N, 71.40°W), Second College Grant, (44.79°N,
 223 71.15°W), and St. Hippolyte, QC, CAN (45.98°N, 74.01°W). We transported all seeds back to the Weld
 224 Hill Research Building at the Arnold Arboretum in Boston Massachusetts (42.30°N, 71.13°W) where we
 225 germinated seeds following standard germination protocols, and grew them to seedling stages in the research
 226 greenhouse. In the spring of 2017 we out-planted seedlings to establish the garden. Plots were regularly
 227 weeded and watered throughout the duration of the study and were pruned in the fall of 2020.

228 In the spring of 2023, we collected 1 tree core on some trees and cross-sections for other trees. Both the
 229 cores and cross-sections were left to dry at ambient temperature for three months.

230 **2.1. Coringtreespotters** The citizen science programs, the Treespotters was started in 2015 and aimed
 231 to train citizen scientist for accurate and rigorous phenological monitoring. From 2015 to 2024, hundreds of
 232 citizen scientists monitored * trees of * species regularly from the early phenostage in the spring until leaf
 233 colouring in the fall. The BBCH scale was used (check if that's true).

234 From 20 to 22 April 2025, we collected a 2 5-mm diameter core, 15-cm length at 1.3 meter above
 235 ground from 50 trees of the 11 species (Table XX) that were previously monitored for phenology, using
 236 an increment borer (Mora Borer, Haglöfs Sweden, Bromma, Stockholm, Sweden). The cores were collected
 237 perpendicularly to the slope and at 180 degrees from each other. We cleaned the increment borer with alcohol
 238 (70% ethanol?) and the inside with a brush before collecting each core. We stored the cores in paper straws
 239 that were previously labelled and punched to help drying. They were stored at ambient temperature for
 240 three months.

241 **Sample processing, imaging and measuring** Then we mounted the cores on wooden mounts, and
 242 sanded the cores and cross-sections using progressively fine grit (150, 300, 400, 600, 800, 1000). We scanned
 243 the cores and cross-sections at a resolution of ***dpi using a homemade great scanner (Tina2026?) We
 244 used the digitalized images to measure the tree ring widths with Fiji Image J. Then, we performed visual
 245 crossdating using Dplr, but no statistical crossdating was performed because of the short chronologies that
 246 limit the capacity for these analyses.

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3 Supplemental material

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3.1. Spring frosts

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Definition:	Late spring frosts are below-freezing temperatures in late spring (Zohner <i>et al.</i> , 2020)
Mechanisms	Early warm spells → early leaf out → hard frost (<-2Celsius) → tissue death = loss of photosynthetic capacity (Polgar & Primack, 2011); Response: second cohort of leaves are more efficient and mitigate carbon sequestration loss (Reinmann <i>et al.</i> , 2023)
Global trend of occurrence	Most vulnerable regions are the ones with no past risk of occurrence (); ↑ in Europe and East Asia, but ↓ North America; Global trend is controversial (Reinmann <i>et al.</i> , 2023)
Consequences (Individual and Ecosystem level consequences)	Loss of vegetative tissue = ↓ photosynthesis = ↓ and remobilization of NSC to repair damaged tissues = ↓ secondary growth (Meyer <i>et al.</i> , 2024); Loss of reproductive tissue (higher flower mortality) (Sgubin <i>et al.</i> , 2018); Costs for orchards and stuff (Reinmann <i>et al.</i> , 2023)
Differences across species/provenance	

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3.2. Drought

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Definition:	"Drought is a prolonged absence or marked deficiency of precipitation that results in water shortage or a period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance (Trenberth <i>et al.</i> , 2014; Intergovernmental panel on climate change, 2007).
Mechanisms	<ul style="list-style-type: none"> — Hot temperature + low precipitation (aka global-change-type drought (Tyree & Zimmermann, 2002)) = \uparrow evapotranspiration \rightarrow less water in soil \rightarrow cavitation \rightarrow embolism \rightarrow hydraulic failure (Tyree & Zimmermann, 2002) = tissue death (Choat <i>et al.</i>, 2018); — Earlier spring phenology = longer GS \rightarrow increases vegetative growth \rightarrow increases evapotranspiration \rightarrow increases drawdown of soil moisture = progressive water stress (Li <i>et al.</i>, 2023) — Long-term vs short-term stomatal responses and consequences on tissue death (Choat <i>et al.</i>, 2018); — Recovery and its determinants (Choat <i>et al.</i>, 2018; Li <i>et al.</i>, 2023)
Global trend of occurrence	<ul style="list-style-type: none"> — \uparrow precipitation anomalies since 1990 (Trenberth <i>et al.</i>, 2014); — Models often exclude PDO/ENSO which limit the capacity to attribute increasing droughts to CC (Trenberth <i>et al.</i>, 2014); — Weak evidence of detection and attribution of changes in meteorological drought since the mid-20th century (Change, 2014); — Using a spacial, model-based perspective, anthropogenic forcing increased the frequency, duration and intensity of SPI-based droughts for North America (Hidalgo <i>et al.</i>, 2009), Europe and the Mediterranean (Spinoni <i>et al.</i>, 2018), (Kurnik <i>et al.</i>, 2011) and E Asia (Chiang <i>et al.</i>, 2021; Marvel <i>et al.</i>, 2019; Spinoni <i>et al.</i>, 2014)
Consequences (Individual and Ecosystem level consequences)	<ul style="list-style-type: none"> — Recurring droughts may limit trees' ability to recover from other types of stress. — Tree mortality (e.g. Texas and California extreme droughts are estimated to have killed 300 and 102 million trees (Li <i>et al.</i>, 2023))
Differences across species/provenance	

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3.3. Heat waves

Definition:	Heat wave is a period of excessively hot weather (5 or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the average maximum temperature by 5 °C), which may be accompanied by high humidity (Marx <i>et al.</i> , 2021).
Mechanisms	<p>↑ atmospheric CO₂ = ↑ temperature → ↑ heat waves... More specifically: A mechanism for the increase occurrence of heat waves is a weakening of the polar jet stream (important weather factor for middle latitude regions of North America, Europe and Asia) caused by global warming which increases the occurrence of stationary weather, resulting in heavy rain falls or heat waves (Marx <i>et al.</i>, 2021). Extreme heat → growth either through (1) Directly via cell processes disruption or (2) indirectly via effects of rising leaf-to-air vapour deficit (VPD) (Gagne <i>et al.</i>, 2020).</p> <p>Increased temperature leads to reduced photosynthesis which can be attributed to: 1. Damage to photosynthetic machinery 2. Inactivation of RUBISCO 3. Reduction to RuBP regeneration 4. Membrane stability 5. Increased mitochondrial respiration and photorespiration (Hauck <i>et al.</i>, 2025)</p>
Global trend of occurrence	Heat waves have increased (Gagne <i>et al.</i> , 2020; Meehl & Tebaldi, 2004; Teskey <i>et al.</i> , 2015) and are expected to increase under future climate change (Dosio <i>et al.</i> , 2018; Change, 2014; Teskey <i>et al.</i> , 2015). Summertime extreme temperatures associated with prolonged heat waves, lasting for several weeks, now impact approximately 10% of land surfaces, up from only 1% in the 1960s. (Teskey <i>et al.</i> , 2015). The more intense and more frequently occurring heat waves cannot be explained solely by natural climate variations and without human-made climate change (Marx <i>et al.</i> , 2021).
Consequences (Individual and Ecosystem level consequences)	- Reduced photosynthesis - Increased mortality - Photosynthetic tissue loss (Gagne <i>et al.</i> , 2020).
Differences across species/provenance	Some species have thermal photosynthetic/respiratory acclimation while others don't. Growth and survival will change depending on species to thermally acclimate to both photosynthesis and respiration - This is explained by growth strategies of gymnosperms vs angiosperms (which are usually better)

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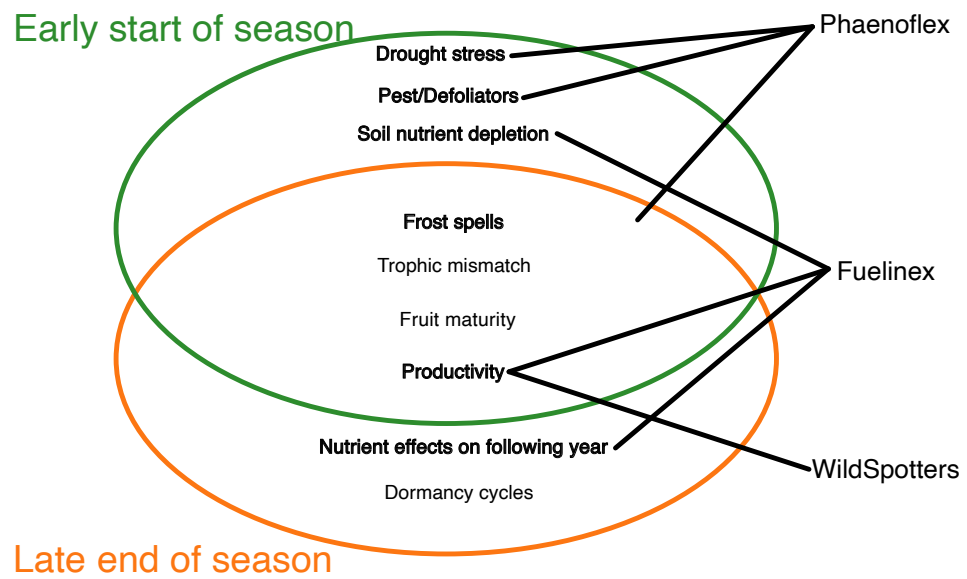


Figure 1: Pros and cons of early start and late end of growing season.

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