Thesis Proposal

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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 loss, pollution, invasive species, resource overexploitation and climate change (Driscoll *et al.*, 2018; Parmesan *et al.*, 1999; Wu, 2013). Though some immediate actions can 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). Yet, the extent of the consequences that a warming climate will have on biological processes is still debated (Huey *et al.*, 2012), in part because it requires accurate predictions of current and future trends in some of the most reported and direct biological impacts of climate change, as I review below. And also because it requires understanding the complex additional effects of these impacts, which I propose to study for my thesis.

Trends and drivers of spring and autumn phenological events
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).

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 requirements are met sooner in warm springs, thus explaining the advancement of spring events and earlier onset of growing seasons over the last decades (Fu *et al.*, 2015, 2013; Laube *et al.*, 2014).

Drivers of autumn phenology: In contrast, autumn phenology (e.g. budset and leaf senescence) has delayed with climate change—though shifts in the autumn have been much smaller than those in the spring (Gallinat *et al.*, 2015; Jeong & Medvigy, 2014)—and its drivers are also far less understood. These differences may be caused in part by the lesser attention payed to autumn phenology (Piao *et al.*, 2019) and because the data is often noisier (Wu *et al.*, 2024). However, some of these differences are likely due to different drivers of autumn phenology, as these phenophases appear to be driven by shortening photoperiod and colder temperatures (Cooke *et al.*, 2012; Flynn & Wolkovich, 2018; Körner & Basler, 2010; Delpierre *et al.*, 2016). Given that colder temperatures can lead to senescence, warmer autumns may delay leaf senescence, possibly by extending the activity of photosynthetic enzymes which causes decreases the degradation rate of

chlorophyll (Yan *et al.*, 2021). Additionally, summer droughts could pause the activity schedule of trees and delay senescence to increase carbon assimilation (Dox *et al.*, 2022). Finally, 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 in trees 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.*, 2023). For instance, (Dow *et al.*, 2022) showed that despite an earlier growth onset, longer seasons did not increase the growth rate nor overall annual increment in trees. This could substantially affect forest carbon-cycle model projections on 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 assumption of a linear relationship 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 (Friend *et al.*, 2019; Parent *et al.*, 2010). Whether a tree's growth is source (photosynthetic activity determines sink activity) or sink (growth, respiration, and other metabolic processes determines the carbon source) controlled depends upon a closely coordinated sequence of dynamic responses and is still an area of active debate. However, Gessler & Zweifel (2024) recently suggested that neither source or sink control systematically dominate. This complex dynamic enforces the importance of understanding the temperature sensitivity relationship between growth 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). Thus, this demonstrates that carbon projection models that solely rely on vegetation alone may mislead carbon sequestration dynamics of 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 physiological constraints (via genetic and developmental control), and external limits (via extreme temperatures or moisture deficit) to growth critical, which I aim to investigate with experiments and observations.

1.2 Experiments and observations to understand the future of growth and season length relationship

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 are not 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

Recent work emphasizing the need to understand the drivers regulating growth across biomes has highlighted strong species-level variation that may be critical to accurate projections.

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 future carbon dynamic models (Green & Keenan, 2022; Cabon *et al.*, 2022; Wolkovich *et al.*, 2025). Different strategies can help understanding how different species respond to warming and thus improve carbon sequestration projections.

1.2.2.1. Experiments: First, experiments are extremely useful in teasing apart co-occurring realities in natural environments. For example, warm springs, and severe droughts later in the summer often happen together within a single year making it difficult to tease these effects apart from observational data. Manipulative experiments, in contrast, have the capacity to separate the relative effect of each phenomenon(Morin *et al.*, 2010; Primack *et al.*, 2015), but also have major limitations, especially when working on trees. Logistical constraints of working with adult trees, mean that experiments are most often performed on juvenile trees. While saplings are critical for their role in forest regeneration projections, their responses often do not directly translate to mature trees, which hold the overwhelming carbon biomass proportion of forests (Augspurger & Bartlett, 2003; Silvestro *et al.*, 2023; Vitasse, 2013). However, even if young trees are often more plastic than adult forms, their responses can still provide valuable insights in differences across species and populations (Wolkovich *et al.*, 2025).

1.2.2.2. Ground based observations: Second, leaf phenology can provide valuable and accessible insights into the growth temporality of trees that are not suitable for experimental trials. Cambial phenology, which is a direct measure of wood growth, is very hard data to gather and requires expensive equipment (REF). In contrast, leaf phenology through ground-based observations are low-cost methods that provide direct evidence of changing phenophases (Piao *et al.*, 2019). Cambial and leaf phenology are often closely synchronized, therefore, the more accessible leaf phenology data can act as a reliable proxy for the onset and end of tree growth. In other words, knowing when leaves elongate and colour can guide as to when trees start and stop growing, which is a fundamental metric to determine the growing season length. Additionally, unlike other methods, ground observations have the advantage of providing accurate measurements of phenological events for specific sites and species. Recently, the widespread use of smartphones has considerably simplified the phenological monitoring by citizen scientists which has the potential to vastly increase the range of studied species and areas. (Dickinson *et al.*, 2012; Hufkens *et al.*, 2019; Piao *et al.*, 2019). While there are drawbacks to observations by citizen science programs (e.g. non-standard protocols, highly uneven spatiotemporal distribution of these observations), they have a great potential to diversify the phenology data.

1.2.3. Goals of my thesis

I aim to understand how different tree species, at different lifespan stages, vary in their growth responses to different season length. To achieve this, I worked across different methods. First, for my large-scale experiment named Fuelinex, I artificially controlled the growing season length for seven species of tree saplings (2-3 years old). Under Wildchrokie, I leveraged leaf phenology data from a common garden project of four species of juvenile trees (5-8 years old). Then, with coringTreespotters I used the phenology data collected by citizen scientists on eleven species of fully mature trees (¿30 years old). Answering the growth patterns of the trees across these three projects requires specifiying 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?

The definition of the growing season itself is not a well-defined concept and an array of definitions are used differently accross 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 may not be suitable for determining relationships between growth and environmental conditions. The widely used method in forestry is to measure diameter at breast height at punctual time intervals. Combined with height, these data help develop allometries foresters can use to estimate how much wood they can harvest in a forest (e.g. (Meyer, 1940; Saunders & Wagner, 2008)). These metrics work to determine wood in forests, but their coarse temporal scale—measuring every 5 or more years—are likely to miss extreme events affecting growth.

1.3.3. Dendroecology to analyses growth responses to changing growing season length

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 rings as a proxy for how much trees grew in any given year.

1.4 Objectives

The objectives for my experiment (Fuelinex) are to assess tree species' potential to prolong or stretch their activity schedule by artificially manipulating growing season length and analyze how this translates (or not) into growth, during the current year (2024) and in the following year (2025). I will also conduct a secondary experiment to examine whether trees can absorb nutrients late in the season and if that translates into growth during the following season. For the observational data projects (Wildchrokie and coringTreespotters), I will investigate how the timing of phenological events affects growth across years for juvenile and mature trees, using observational phenology data and tree ring.

Together, my two chapters will allow me to address the paradox of the absence of increased growth despite longer growing seasons.

1.5   Research questions

Fuelinex: How do extended growing seasons affect tree growth across different species, both immediately (in the same year as the extended season) and in subsequent years? WildSpotters: How does phenology regulate tree growth in urban ecosystems?
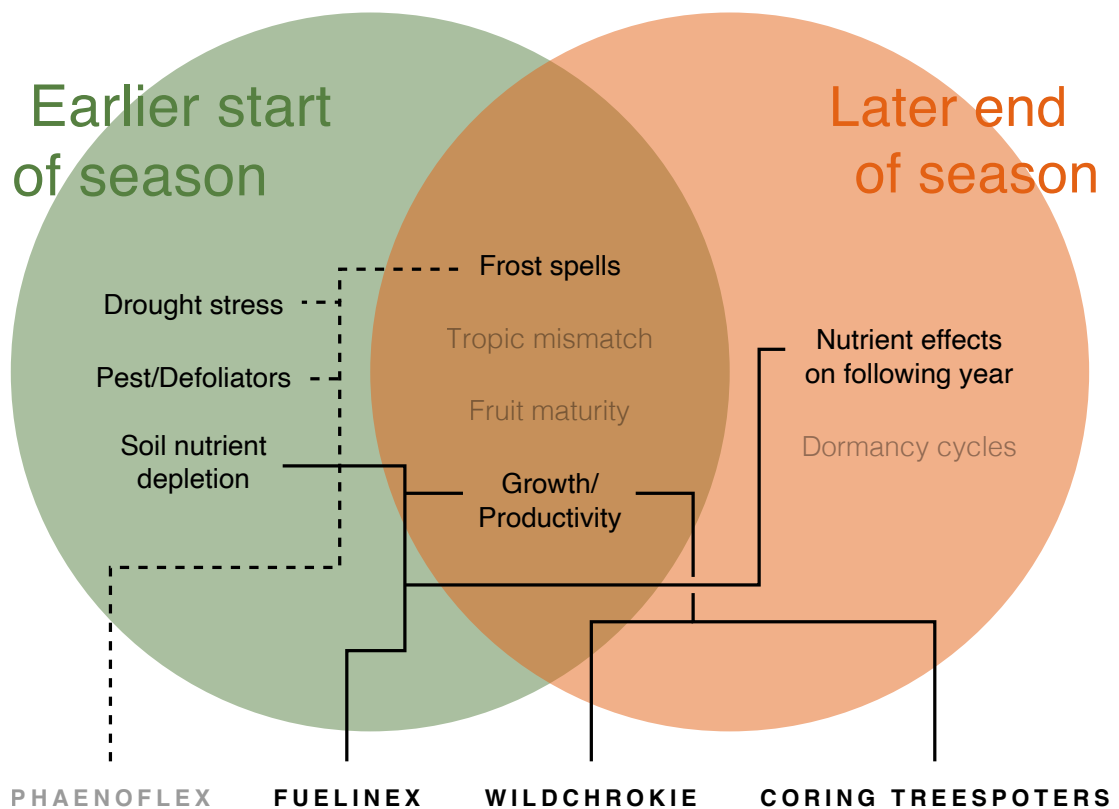
Figure 1: The effects that an earlier start and later end of season can have on trees. In bold are the effects that were studied over the course of this thesis. Phaenoflex (in grey) is a related experimental project, that is not part of this thesis, but one I collaborated on in XX years.

2 Methodology

2.1 Wildchrokie

2.1. Studies locations

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

In the spring of 2023, we collected cross-sections for most trees and 1 tree core on a few individuals. Both the cores and cross-sections were left to dry at ambient temperature for three months.

Phenological monitoring For the years of 2018-2019, we made phenological observations of all individuals in the common garden twice per week from February to December. In 2020 due to the COVID 19 pandemic, we monitored once per week from March to November. We describe phenological stages using a modified BBCH scale (**?**) a common metrics for quantify woody plant phenological progression. We observed all major vegetative stages (budburst BBCH 07, leafout BBCH 15, end of leaf expansion BBCH 19, leaf coloration/drop BBCH 97, reproductive phases flowering BBCH 60-65, fruiting BBCH 72-79 and fruit/cones fully ripe BBCH 89). We added additional phases for budset and labelled full budset as BBCH 102.

Coringtreespotters The Treespotters is a citizen science program that started in 2015 and aimed to train citizen scientist for accurate and rigorous phenological monitoring. From 2015 to 2024, hundreds of citizen scientists monitored 50 trees of 11 species regularly from budburst in the spring to leaf colouring in the fall using NPN phenophases (DENNY2014). Not all phenophases were recorded for every tree, for every year, and some trees miss several several years of data.

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

Sample processing, imaging and measuring for WildSpotters We mounted the cores on wooden mounts, and sanded the cores and cross-sections using progressvely fine grit (150, 300, 400, 600, 800, 1000). We scanned the cores and cross-sections at a resolution of ***dpi using a homemade great scanner (Tina2026?) We used the digitalized images to measure the tree ring widths with Fiji ImageJ. Then, we performed visual crossdating using Dplr, we did not performed statistical crossdating because of the short chronologies that limit the capacity of these analyses.

Statistical analyses

2.2 Fuelinex

2.3 Species selection

We used seven species of tree sapling for our experiment (Fuelinex). Paper birch (*Betula papyfera*), Choke Cherry (*Prunus virgiana*), Bur oak (*Quercus macrocarpa*) were purchased from Peel's nursery in November 2023 and arrived at Totem Field studios 49.26 °N, -123.25 °W where the other four species were stored until the spring of 2023. Manitoba maple (*Acer negundo*), Eastern white pine (*Pinus strobus*), Balsam poplar (*Populus balsamifera*) and Giant sequoia (*Sequoiadendron giganteum*) were purchased in 2022 for 2023 Phaenoflex's experiment but were watered weekly and remained at ambiant condition for the 2023 growing season. We randomly selected 90 individuals among them.

Because Pobas were too large, that they are fast-growing and that Fuelinex is a two-year experiment, we took cuttings from Poba and replanted them in soil with the following methodology. The cuttings were stored in climate chambers with the corresponding temperature (see Hobo loggers) from February 13, 2024 to Feb 20, 2024. The tree cuttings were planted at that time. 30 cm long shoot tip cuttings of balsam poplar were soaked at the cut wound for 15 minutes in a solution of 20 mL indole-butyric acid 0.4% (Wilson Liquid root stimulator) diluted in 2 litres of warm tap water. (0.004% concentration). 180 1-gallon pots were filled up to 1 inch from the lip with pre-moistened peat-based potting mix containing large pumice chunks. Soil was pressed firmly to compact. Cuttings were placed into the soil at the depth such that pre-drawned paint lines could still be visible just above the soil surface.

2.4   Tree measurements

The following measurements were performed from Feb 7, 2024 to Feb 11, 2024. Using red paint, we marked the trees on their trunk at 3 cm from the soil. Then we measured the diameter at the top of that mark using a digital caliper and from that point to the bottom of the highest apical we measured height with a metal ruler (precision of 0.1 mm). We measured those two same points in the winter (2024 growing season) and in the fall (2025 growing season) of 2025. For those two subsequent measurements, if the measured shoot died, we noted the previous measurement as invalid (because of insects, accidently broken it, etc.) and measured the highest lateral shoot.

2.5   Shoot elongation

: To facilitate and improve the quality of the shoot elongation monitoring, we attached paper rulers on the following species A. negundo, B. papyfera, P. balsamifera and Q. macrocarpa. We used A3 RiteIntheRain paper so they remain in good condition under the rain. We also taped the end of each ruler with packaging tape for 2 reasons: 1. Increase the the fusion of the tape with the ruler and 2. Increase the durability of the fixation to the tree. We used Band Aid medical tape to fix the paper rulers to the trees in order for the trunk to be able to breath.

Prior to the installation, using red pain, we marked where the reference point for the measurement. This was the bottom of the new-year apical shoot. For species on which we couldn't install the paper rulers, we took those same measurements, but with a metal ruler.

2.6   Fertilizer

Using fertilizer premix from UBC's garden, we fertilized the trees twice during the growing season of 2024 and three times during 2025, just enough to keep the trees alive.

2025 : On Friday 11 April 2025, 125mL of undiluted liquid fertlizer (same as 2024) was added to all trees, excluding the nitro boost treatment replicates. The latter didn't get any nutrients in spring and will get some only later on in the summer. Since we dropped the nitro treatments for the segi, all of these replicates got fertilizer. See note

2.7   Hobo loggers

Hobo loggers (Temp/humidity) were set up in the climate chambers at the beginning of the Cool Spring treatments. They were then transferred to Totem Field at different locations and hidden behind a white sheet of paper to avoid the sun from hitting them directly.

On June 7, 2024, Hobo loggers (Temp/light) were placed in 3 different blocks at Totem Field. They were placed at the top of PVC pipes at a height of 1m from the ground. They were placed in a position where the foliage covers of the trees would not shade them. I set 6/block. This was performed after I notice that there will be a big light difference. The plants that are the farthest from the greenhouse door receive far less light then the one closest to the door. They were configured on Sunday June 9, 2024. I also installed 4 loggers on the greenhouse roof in case the ones positionned at 1m above the soil don't record the light properly.

2.8 Spring and Fall treatments

The Cool Spring treatment consisted of placing the CS replicates in climate chambers to delay the start of their growing season on March 6 2024. The WS replicates remained at Totem Field studios

The Warm Fall treatment consisted of placing WS/WF, CS/WF and WSWF_nitro treatments in the climate chambers on 4 September 2024. The photoperiod was set every week on Wednesday to fit the local sunrise and sunset and was ramped until it reached full light. The temperature was set to fit the mean 30 years daily maximum temperature of one prior month. E.g. the the temperature for the first week of September was set to the temperature regime of the first week of August. The CF treatments remained at Totem Field Studios.

For both climate chamber treatment, the trees were rotated and watered weekly to minimize the effects the climate chambers could have on the trees.

2.9 Senescence monitoring

Every week, starting on September ***, senescence was monitored by two methods. The first being a visual assessment of the remaining green leaf cover. We used a systemic aproach to estimate what percentage of green leaf cover was remaining by comparing to what would be 100% of cover.. From September **** to September 25, we used a chlorophylll content meter ***. On October 2, because of device failure, we switched to SPAD-502DL Plus (Konica Minolta) from Loren Rieseberg's lab. To calibrate the two instruments to values that are comparable, we used****. check: https://nph.onlinelibrary.wiley.com/doi/full/10.1046/j.0028-646X.2001.00289.x

2.10 Shoot elongation measurements

In 2024 and 2025, shoot elongation measurements were conducted using two distinct methods. But for both methods, the following were conducted: in 2024, we selected the shoot coming off the apical meristem when possible. If the bud died or if the shoot snapped off, we selected the closest lateral shoot. In the case of Prvi on which there are no obvious apical shoot (sometimes there will be 2 branches of equal height) we selected the highest one and if that one died, we selected the other. Then we went on the lateral shoot if both died. Then using rain paint, we marked the base of the chosen bud.

In 2025, we preferably chose the continuous shoot that was measured the previous year. If that shoot died, we chose another shoot acording to the previous criterias.

Two methods:

1. Paper rulers using rite in the rain paper and printed a 38cm ruler. For the species on which there was trunk/branch space on which we could safely install a paper ruler, we installed one. The species were: Acne, Bepa, Poba, Quma. Since the ruler was positioned at the bottom of the red mark, we didn't have to adjust it every time we measured shoot elongation. Then the shoot elongation was measured at the botttom of the apical bud.

2. Metal rulers: using a metal scientific ruler, we measured the shoot from the bottom of the red mark to the bottom of the apical bud for deciduous species. We measured until the top of the apical meristem for Pist.

Shoot elongation was measured weekly for all species. For determinate growth species, after two weeks of little or no change in elongation, we started monitoring them every second week. For indeterminate growth species, they kept on being monitored every week.

2.11 Leaf count

In order to determine whether nutrient addition treatments in the fall affected leaf primordia formation, we counted the leaves on 27 May for the determinate growth species only i.e. Acne, Prvi and Quma. We counted the leaves only for the shoot coming out of the apical meristem. We always counted all the leaves on the current-year shoot measured for shoot elongation measurements.

9

2.12 Biomass collection

In the fall of 2025, when all the individuals from a species have lost all their leaves, we proceeded to remove the trees from their pots, remove the dirt by shaking them first and washing off the dirt off the roots gently with regular water gun. Then, we moved the trees, 1 bloc at a time in the drying ovens where they were left to dry for 72 hours at 70C. Not in paper bags. Then below and above ground biomass were separated by cutting the tree at 1cm above the highest root. We weighted biomass at a precision of 0.01gr

3 Supplemental material

3.1 Wildchrokie

1. Common garden from 2015 to 2023

2. Four species within the Betulacea family (Table 2)

3. Data: phenology, height, tree rings

4. Analysis: Hierarchical model to understand how tree ring width relates to GDD

3.2 Treespotters

1. Citizen scie nce project from 2015 to today (Table 3)

2. Tree coring

3. Data: phenology, tree rings

4. Analysis: Hierarchical model to understand how tree ring width relates to GDD

3.1. Spring frosts

Definition:	Late spring frosts are below-freezing temperatures in late spring (Zohner *et al.*, 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 *et al.*, 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 *et al.*, 2023)
Consequences (Individual and Ecosystem level consequences)	Loss of vegetative tissue = ↓ photosynthesis = ↓ and remobilization of NSC to repair damaged tissues = ↓ secondary growth (Meyer *et al.*, 2024); Loss of reproductive tissue (higher flower mortality) (Sgubin *et al.*, 2018); Costs for orchards and stuff (Reinmann *et al.*, 2023)
Differences across species/provenance	

Table 1: Fuelinex species grouped by tree type, life history, and wood anatomy.

Deciduous Trees			
Common Name (Latin)	**Life History Strategy**	**Wood Anatomy**	**n (approx)**
Bur oak (*Quercus macrocarpa*)	Slow-growth, long life	Ring-porous	87
Bitter cherry (*Prunus virginiana*)	Fast-growth, short life	Diffuse-porous	78
Box elder (*Acer negundo*)	Fast-growth, short life	Diffuse-porous	90
Balsam poplar (*Populus balsamifera*)	Fast-growth, short life	Diffuse-porous	84
Paper birch (*Betula papyrifera*)	Fast-growth, short life	Diffuse-porous	90
Evergreen Trees			
White pine (*Pinus strobus*)	Slow-growth, long life		89
Giant Sequoia (*Sequoiadendron giganteum*)	Slow-growth, long life		54

Table 2: Wilchrokie species grouped by tree type, life history, and wood anatomy.

Deciduous Trees			
Common Name (Latin)	**Life History Strategy**	**Wood Anatomy**	**n**
Paper birch (*Betula papyrifera*)	Fast-growth, short life	Diffuse-porous	8
Yellow birch (*Betula alleghaniensis*)	Moderate-growth, moderate life	Diffuse-porous	21
Grey birch (*Betula populifolia*)	Fast-growth, short life	Diffuse-porous	29
Grey alder (*Alnus incana*)	Fast-growth, short life	Diffuse-porous	31

Table 3: Treespotters species grouped by tree type, life history, and wood anatomy.

Deciduous Trees			
Common Name (Latin)	**Life History Strategy**	**Wood Anatomy**	**n**
American basswood (*Tilia americana*)	Fast-growth, moderate life	Diffuse-porous	5
Eastern cottonwood (*Populus deltoides*)	Fast-growth, short life	Diffuse-porous	4
Northern red oak (*Quercus rubra*)	Moderate-growth, long life	Ring-porous	4
White oak (*Quercus alba*)	Slow-growth, long life	Ring-porous	5
Pignut hickory (*Carya glabra*)	Slow-growth, long life	Ring-porous	4
Shagbark hickory (*Carya ovata*)	Slow-growth, long life	Ring-porous	4
River birch (*Betula nigra*)	Fast-growth, short life	Diffuse-porous	5
Yellow birch (*Betula alleghaniensis*)	Moderate-growth, moderate life	Diffuse-porous	4
Sugar maple (*Acer saccharum*)	Slow-growth, long life	Diffuse-porous	5
Red maple (*Acer rubrum*)	Slow-growth, long life	Diffuse-porous	4
Yellow buckeye (*Aesculus flava*)	Moderate-growth, moderate life	Diffuse-porous	5

3.2. Drought

Definition:	"Drought is a prolonged absence or marked deficiency of precipitation that results in water shortage or or a period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance (Trenberth *et al.*, 2014; Intergouvernemental panel on climate change, 2007).
Mechanisms	— Hot temperature + low precipitation (aka global-change-type drought (Tyree & Zimmermann, 2002))= ↑ evapotranspiration→ less water in soil → cavitation → embolism → hydraulic failure (Tyree & Zimmermann, 2002) = tissue death (Choat *et al.*, 2018); — Earlier spring phenology = longer GS → increases vegetative growth → increases evapotranspiration → increases drawdown of soil moisture = progressive water stress (Li *et al.*, 2023) — Long-term vs short-term stomatal responses and consequences on tissue death (Choat *et al.*, 2018); — Recovery and its determinants (Choat *et al.*, 2018; Li *et al.*, 2023)
Global trend of occurrence	— ↑ precipitation anomalies since 1990 (Trenberth *et al.*, 2014); — Models often exclude PDO/ENSO which limit the capacity to attribute increasing droughts to CC (Trenberth *et al.*, 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 *et al.*, 2009), Europe and the Mediterreanean (Spinoni *et al.*, 2018), (Kurnik *et al.*, 2011) and E Asia (Chiang *et al.*, 2021; Marvel *et al.*, 2019; Spinoni *et al.*, 2014)
Consequences (Individual and Ecosystem level consequences)	— 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 *et al.*, 2023))
Differences across species/provenance	

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 *et al.*, 2021).
Mechanisms	$\uparrow$ atmospheric CO2 $= \uparrow$ temperature $\rightarrow \uparrow$ heat waves... More specifically: A mechanism for the increase occurence of heat waves is a weakeking 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 occurence of stationnary weather, resulting in heavy rain falls or heat waves (Marx *et al.*, 2021). Extreme heat $\rightarrow$ growth either through (1) Directly via cell processes disruption or (2) indirectly via effects of rising leaf-to-air vapor deficit (VPD) (Gagne *et al.*, 2020). Increased temperature leads to reduced photosynthesis which can be attributed to: 1. Damage to photosynthetic machinery 2. Inactivation of RUBISCO 3. R eduction to RuBP regeneration 4. Membrane stability 5. Increased mitochondrial respiration and photorespiration (Hauck *et al.*, 2025)
Global trend of occurrence	Heat waves have increased (Gagne *et al.*, 2020; Meehl & Tebaldi, 2004; Teskey *et al.*, 2015) and are expected to increase under future climate change (Dosio *et al.*, 2018; Change, 2014; Teskey *et al.*, 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 *et al.*, 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 *et al.*, 2021).
Consequences (Individual and Ecosystem level consequences)	- Reduced photosynthesis - Increased mortality - Photosynthetic tissue loss (Gagne *et al.*, 2020).
Differences across species/provenance	Some species have thermal photosynthetic/respiratory acclimatation 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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