Thesis outline

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1 Introduction

1.1 Climate change impacts on tree phenology

Climate change impacts on biological systems and how phenological trends are already shifting with warming temperatures.

1. Trends of spring and autumn phenological events and their drivers (1)
2. Evidence of declining sensitivity to warming, predominance of winter temperature in spring phenological responses (Ettinger 2020)
3. Mechanisms that could limit growth despite having a longer growing season:
   (a) spring frosts (e.g.: Zohner 20)
   (b) extreme heat induced physiological stress (e.g. Salomón 22, Stangler17)
   (c) increased drought frequency, intensity and duration

Spring frosts

Mechanisms	Early warm spells → early leaf out → hard frost (¡-2C) → tissue death = loss of photosynthetic capacity (Polgar 2011); Response: second cohort of leaves are more efficient and mitigate carbon sequestration loss (Reinmann23)
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 (Reinmann23)
Consequences (Individual and Ecosystem level consequences)	Loss of vegetative tissue = ↓ photosynthesis = ↓ and remobilization of NSC to repair damaged tissues = ↓ secondary growth (Meyer24); Loss of reproductive tissue (higher flower mortality) (REF); Costs for orchards and stuff (Reinmann23)
Differences across species/provenance	

Drought

Mechanisms	— Hot temperature + low precipitation (i.e. global-change-type drought)= ↑ evapotranspiration→ less water in soil → cavitation → embolism → hydraulic failure (Tyree02) = tissue death (2); — Earlier spring phenology = longer GS → increases vegetative growth → increases evapotranspiration → increases drawdown of soil moisture = progressive water stress (Li23) — Long-term vs short-term stomatal responses and consequences on tissue death (2); — Recovery and its determinants (2; 3)
Global trend of occurrence	— ↑ precipitation anomalies since 1990 (Trenberth14); — Models often exclude PDO/ENSO which limit the capacity to attribute increasing droughts to CC (Trenberth14); — Weak evidence of detection and attribution of changes in meteorological drought since the mid-20th century (IPCC AR5); — Using a spacial, model-based perspeective, anthropogenic forcing increased the frequency, duration and intensity of SPI-based droughts for Americas, Mediterreanean, W/S Africa and E Asia (Chiang 21)
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 (Li23)
Differences across species/provenance	

Heat waves

Mechanisms	
Trend mechanism	
Global trend of occurrence	
Consequences (Individual and Ecosystem level consequences)	
Differences across species/provenance	

4. Pros and cons of early/late start of season:

Early SOS

Pros

- Potential competitive ability of carbon uptake at the individual and stand level (increased productivity) (Estiarte, 2015);
- More days to reach fruit maturity (REF).

Cons:

- Trophic mismatch (though limited support) (Loughnan 2024)
- Incre ased summer drought-induced stress (Li23)
- Increases the period that trees are susceptible to LSF (Meyer 24)
- Increased pest and disease pressure (REF)
- Soil nutrient depletion (e.g. Reich 2006)

Late SOS

Pros:

- Photosynthesis can occur for longer, increasing carbon sequestration (Keenan, 2014)
- May increase nutrient resorption efficiency (REF)
- May delay frost exposure (Gunderson, 2012)

Cons:

- Delayed leaf senescence could kill leaves (cold spell) before nutrient resorption (Estiarte, 2015)
- Phenological mismatches (REF)
- Disruption of dormancy cycles –chilling requirements not met
- Extension of pest life cycles (Ayres, 2000)

1.2 Nature of the problem

1. Past phenological trends don't predict future phenological changes. Highlights the importance of understanding the drivers that control phenology and growth,
2. The assumption that longer seasons lead to increased growth is called into question
3. Impacts on carbon source-sink projections

1.3 Tree rings measurements as a proxy for growth

Using tree ring data to investigate the relationship between phenology and growth

1. Triggers and mechanisms behind growth onset, duration and rate.
2. How radial growth is influenced by extreme weather events and their timing.
3. Which is more important? How fast a tree grows or how long it grows for
4. Methods to measure tree growth and why using tree ring images may better capture tree growth response than traditional diameter and height measurements.

1.4 Research questions

1. **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?
2. **CookieSpotters**: How phenological traits regulate tree growth in urban ecosystems?

1.5 Hypothesis

1. **Fuelinex**: Growing season extension modifies a tree's capacity to sequestrate carbon and nitrogen, and this could lead to increased growth in the following season.
2. **Fuelinex**: Species capable of accumulating nutrients after growth cessation while going through leaf senescence might exhibit growth increment in the following growing season
3. **CookieSpotters**: The magnitude of the growth response to longer seasons will differ between juvenile and mature trees.

1.6 Objectives and outreach

1. **Fuelinex**: Assess tree species' potential to prolong or stretch their activity schedule.
2. **Fuelinex**: Determine whether trees can absorb nutrients beyond their theoretical growing season.
3. **Fuelinex**: Examine if increased carbon pools translate into greater growth increment in the following growing season.
4. **CookieSpotters**: Investigate how the timing of phenological events affects growth across years for juvenile and mature trees

2 Methods

2.1 Fuelinex

1. Full factorial design (Fig. 1)
2. 2-year experiment over 2024-2025 (Fig. 2 and 3)
3. Nutrient addition
4. Data: phenology, shoot elongation, diameter, height, biomass, tree rings
5. Analysis: TBD
6. Studied species

2.2 Wildchrokie

1. Common garden from 2015 to 2023 (Table **)
2. Data: phenology, height, tree rings
3. Analysis: Hierarchical model to understand how tree ring width relates to GDD

2.3 Treespotters

1. Citizen science project from 2015 to today (Table **)
2. Tree coring
3. Data: phenology, tree rings
4. Analysis: Hierarchical model to understand how tree ring width relates to GDD

3 Timeline

Fig. **

References

[1] G.-R. Walther, *et al.*, *Nature* **416**, 389 (2002). Publisher: Nature Publishing Group.

[2] B. Choat, *et al.*, *Nature* **558**, 531 (2018).

[3] Y. Li, *et al.*, *Nature Climate Change* **13**, 182 (2023).

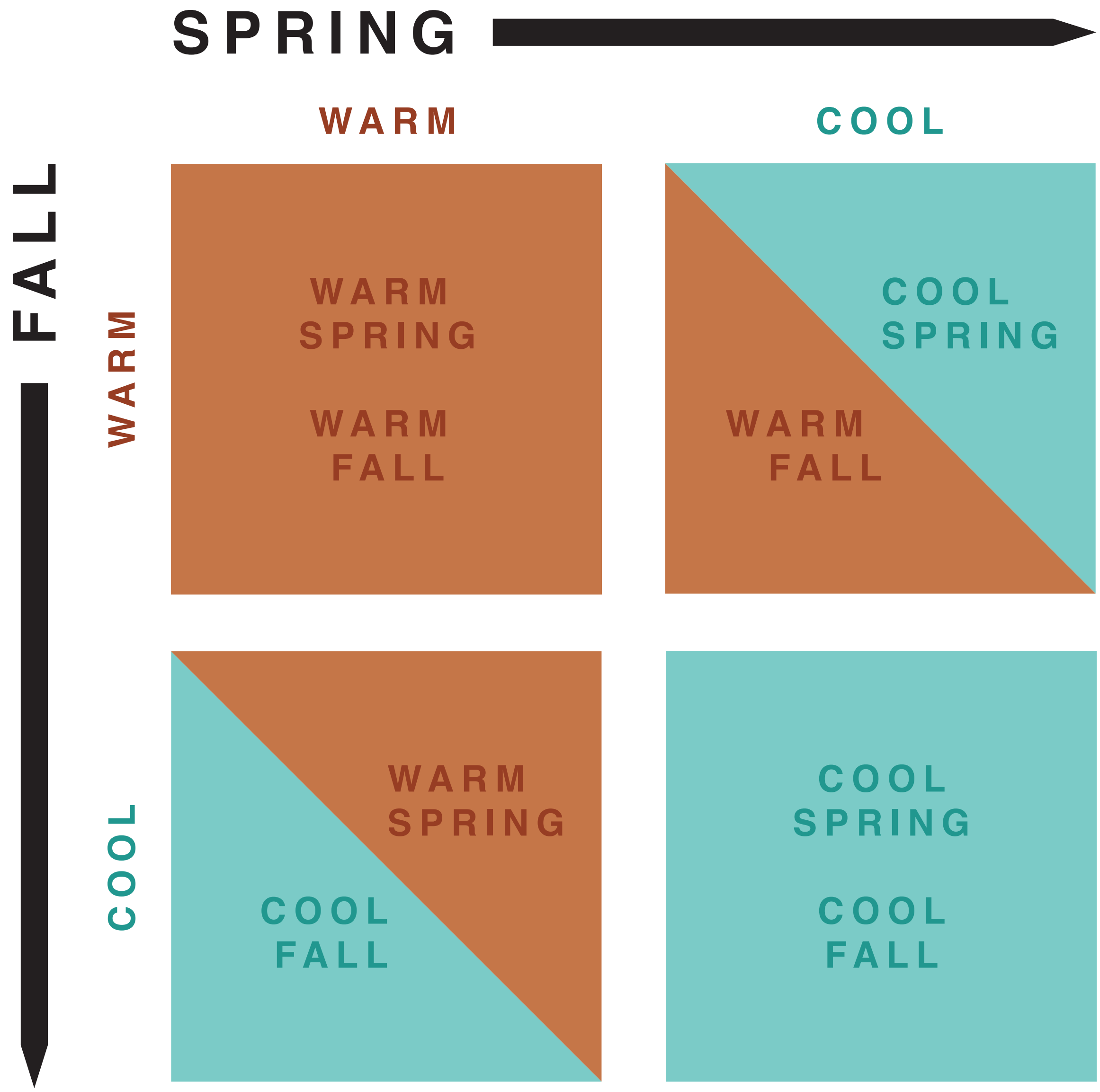

Figure 1: Full factorial design of Cool/Warm Spring and Cool/Warm Fall

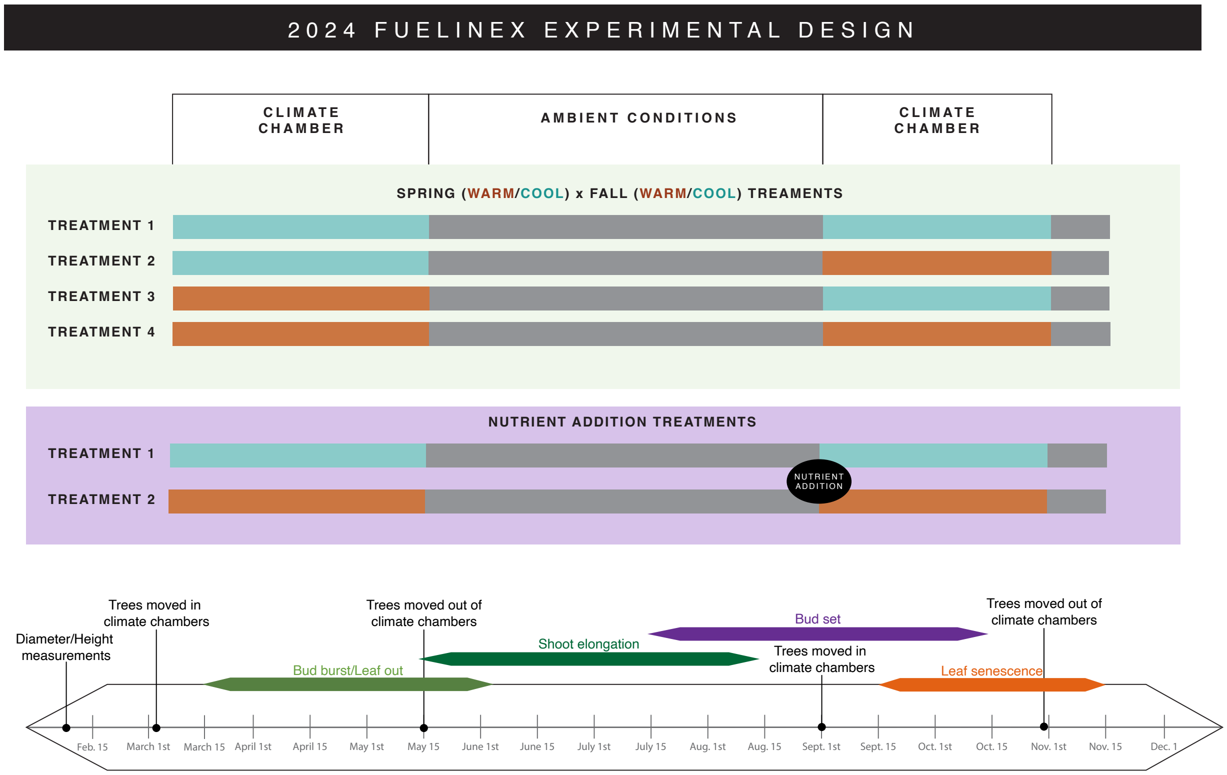

Figure 2: Experimental design of the different treatments that were performed during the growing season of 2024. The timeline displays the periods of the different measurements. Nutrient addition treatments are displayed by the black elipses

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

Deciduous Trees			
Common Name (Latin)	**Life History Strategy**	**Wood Anatomy**	**n**
Bur oak (*Quercus macrocarpa*)	Slow-growth, long life	Ring-porous	
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	**
Yellow birch (*Betula alleghaniensis*)	Moderate-growth, moderate life	Diffuse-porous	**
River birch (*Betula nigra*)	Fast-growth, short life	Diffuse-porous	**
Grey alder (*Alnus incana*)	Fast-growth, short life	Diffuse-porous	**

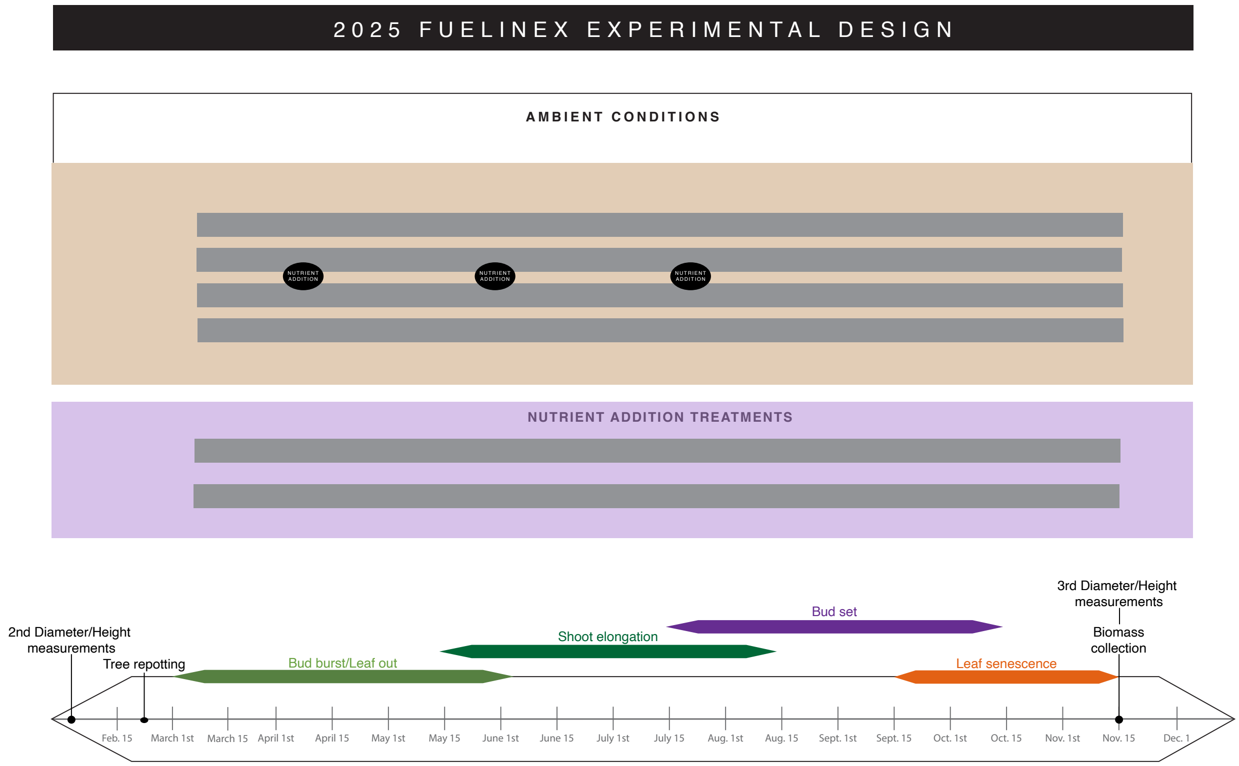

Figure 3: Timeline displaying the periods of the different measurements during the growing season of 2025

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	82
Eastern cottonwood (*Populus deltoides*)	Fast-growth, short life	Diffuse-porous	85
Northern red oak (*Quercus rubra*)	Moderate-growth, long life	Ring-porous	88
Pignut hickory (*Carya glabra*)	Slow-growth, long life	Ring-porous	84
River birch (*Betula nigra*)	Fast-growth, short life	Diffuse-porous	85
Shagbark hickory (*Carya ovata*)	Slow-growth, long life	Ring-porous	83
Sugar maple (*Acer saccharum*)	Slow-growth, long life	Diffuse-porous	86
White oak (*Quercus alba*)	Slow-growth, long life	Ring-porous	90
Yellow birch (*Betula alleghaniensis*)	Moderate-growth, moderate life	Diffuse-porous	88
Yellow buckeye (*Aesculus flava*)	Moderate-growth, moderate life	Diffuse-porous	80

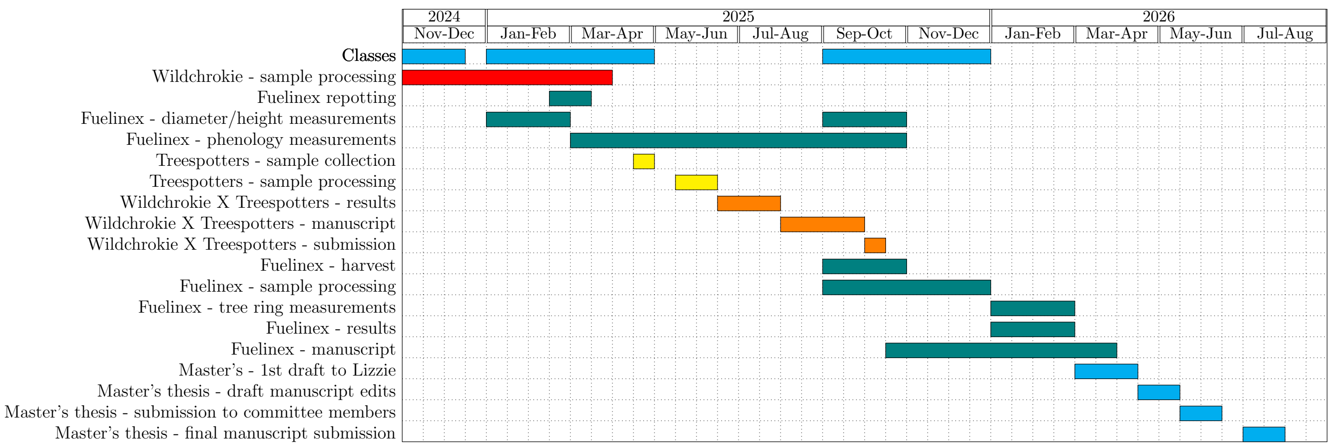

Figure 1: Christophe RD Master's timeline

Figure 4: Gant chart displaying the different milestones to be done over 2025 and 2026