**Title:** Effect of spring temperatures on tree growth phenology in a temperate deciduous forest

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### Abstract

**Keywords**:

### Introduction

As global atmospheric greenhouse gas levels are rising, and little meaningful policy is being implemented to combat this, our planet is expected to surpass the 2.5 degree C warming mark that the Paris accord pledged to avoid. The absence of human intervention increases our reliance on natural systems to soften the blow of climate change.

Forests are an extremely valuable ecosystem for many reasons. They house an astonishing 80% of terrestrial species and are capable of removing the greenhouse gas CO2 from the atmosphere and storing it in the trees or soil. Forests sequester about one-third of all anthropogenic CO2 and store ~45% of all terrestrial carbon (Bonan, 2008). However, their future under the current era of rapid change is uncertain (Friedlingstein et al, 2006). Reducing this uncertainty requires better understanding of the drivers of tree growth (Bugmann et al, 2019). Tree growth is sensitive to climatic factors like precipitation, temperature, and cloudiness in early growing season (Helcoski et al, 2019; Ciais, 2003; Goulden, 1996), as well as other physical factors including nitrogen content of soil, increasing atmospheric CO2, deposition of atmospheric pollutants in acid rain (Mathias & Thomas, 2018), and invasion by pests or pathogens. Understanding how growth is influenced by multiple factors at once is essential for developing accurate models to inform forest managers and policy makers about the role of future forests in climate change mitigation. CO2 concentrations in the atmosphere are increasing, and in a perfect scenario, trees and other plants would simply speed up growth in response to this, increasing photosynthetic efficiency in a process called CO2 fertilization (Strain and Cure, 1986; Huang et al., 2007). However, factors other than CO2 also limit tree growth, and seasonal temperature averages and precipitation patterns are changing concurrently. It is anticipated that, throughout much of the United States, future heat and drought may limit tree growth more strongly than it can be enhanced by elevated CO2 (Charney et al, 2016).

In recent decades, an increase in average early Spring temperatures has been attributed to climate change. As temperatures are increasing, some regions have seen earlier leaf out in deciduous trees, meaning a potentially longer growing season (Ibáñez et al., 2010; Jeong et al., 2011). The effects of this extension of the growing season on leaf phenology and NPP have been well studied (Way, 2011; ), but little work has been done to understand the impacts to intraannual stem-growth variables. Shifts in leaf phenology timing could be coupled with a change in stem-growth phenology, which are likely to affect woody productivity, carbon and nutrient cycling, and water use patterns in temperate forests. Thus, it is important to understand how the warming of Spring changes stem-growth phenology.

The timing of Spring warming has a significant effect on leaf phenology response. Warming events later in Spring were shown to impact leaf emergence timing more than earlier Spring warming (Freidl et al, 2014) and earlier leaf emergence has been shown to cause complex lagged effects on subsequent seasonal growth in European broad leaf deciduous and mixed forests (Crabbe et al, 2016). GIS source Ian sent. However, the fine-scale responses of temperate deciduous species to a warming Spring are not fully understood. Many predictions of phenological shifts like these are based on GIS, eddy-covarience measurements, or other broad scale observations of phenological timing, and do little to discern differences between individual species, where leaf and stem-growth phenology can be decoupled (D’Orangeville et al, in review). In reality, we know little about the growth phenology of temperate deciduous species (see D’Orangeville et al., in revision for more info/ citations)—let alone how these are affected by an early spring.

To date, very little research has been done on the phenology of stem-growth. Timing of intraannual growth is extremely improtant as it can dictate periods of highest drought sensitivity of NPP in temperate forests (Foster, 2014; ). For example, if a drought were to occur when trees were at their peak growth rates, it could decrease that year’s NPP substantially, and subsequently, reduce the total amount of carbon sequestered creating a negative climate feedback loop. Recent results from D’Orangeville et al. (in review) have shown that wood-type plays a significant role in the timing of leaf and wood phenology, as ring-porous trees begin growth earlier in the season compared to diffuse-porous trees, but both reached 75% total annual growth around the same time. This implies evolutionary differences in the mechanisms controlling growth of these species, which have the potential to expose each group to different climate stresses.

It is difficult to map intraannual growth, or compare interspecific responses to Spring warming using leaf emergence timing alone. A solution to this is the use of dendrometer bands. Dendrometer bands allow a look at individual trees’ intraannual growth at a fine temporal scale. Using many measurements taken within a year, we can model the growth of individual trees and extract growth milestones and variables for interspecific, intraspecific, and temporal comparison (McMahon & Parker, 2014). This allows the determination of variable responses of all tree species within a single forest, meaning a better understanding of future growth under projected climate conditions. Here, we use 9 years of biweekly dendrometer band measurements for 4 species to characterize intraannual stem-growth phenology within the ForestGEO plot at SCBI, calculating for each tree in each year where data was available: the day of year (DOY) where 25, 50, and 75% annual growth was achieved; the maximum growth rate; the DOY where maximum growth rate was achieved; and the total growth. Correlation between these variables and pre-season temperatures over the 9 year study period (2011-2019) were assessed using a heirarchal bayesian model.

We hypothesized that (1) ring-porous and diffuse-porous trees would both reach 25, and 50% total annual growth earlier and (2) both wood types would increase total growth in response to warmer early-Spring temperatures.

### Materials and Methods

*Study sites and data*

Study sites included **2/3** temperate forests in the Eastern United states, **both/all** part of the Forest Global Earth Observatory [ForestGEO; Anderson-Teixeira et al. 2015] (**Table 1?**). **Both/all** sites are dominated by broadleaf deciduous trees. *(insert site descriptions, including lat/long, elevation, plot size, climate info, dominant species. If we include SERC and if space permits, we may put this in a table, otherwise just text)*

Within the plot, metal dendrometer bands were installed on *>#* trees and measured approximately every 1-2 weeks within the growing season for *9* years (*list ranges, for each site if different*). *(don’t bother to mention biannual bands, unless you end up using the data–which you could, for annual growth, if you’d like to increase the sample size. You can put exact numbers of bands per year in an SI file.*) The number of bands measured at each site fluctuated somewhat as trees were added or dropped (e.g., because of tree mortality) from the census *(Table S1)*. Across years, the number of bands sampled averaged *~150* at SCBI, # at Harvard Forest*, and # at SERC*. *(summary of how bands were distributed across species, focusing on ring/ diffuse porous distinction. details in an SI table)*

(After cleaning: 2011- 105 trees; 2012 - 102 trees; 2013 - 102 trees; 2014 - 149 trees; 2015 - 149 trees; 2016 - 149 trees; 2017 - 148 trees; 2018 - 146 trees; 2019 - 145 trees *–put this in Table S1*).

Measurements were timed to begin before beginning of spring growth and to continue through the cessation of growth in the fall. *(Give specifics, which may vary by site. Note that we adjusted timing at SCBI when we observed early leaf-out of understory shrubs/herbs)*

The data were manually cleaned by visual inspection. Three classes of mistakes: 1. Error in measurement - weekly measurement was drastically different from previous week and following week. Mistakes were removed from the raw data before modeling. (## cases) 2. Band slip or stuck - measurements freeze and remain unchanged until sudden jump followed by normal growth pattern. Band slips were sometimes followed by measurements indicating the band became stuck; in these cases, the tree was thrown out for the corresponding year. In cases where the slip was followed by normal growth, the initial slip-point was removed, and the following points were shifted down to the pre-slip level. (## cases) 3. Other - cases where data was clearly wrong but with unknown causes. This seemed to happen mostly in 2011, when the program was just beginning. In cases where several measurements were an issue, they were simply removed. If there were no clear solutions to ‘fix’ the data, the entire year was removed from the analysis.

Climate data used was obtained from the National Center for Environmental Information (NCEI) weather station located in Front Royal, Virginia. Average daily maximum temperature for 2011-2019 are from the Daily Summary dataset available on their website (<https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USC00443229/detail>).

leaf phenology data?

• leaf phenology data from NEON and/or satellite-based (leaf phenology network: <https://www.usanpn.org/news/spring>) ?

• NDVI or PRI? <https://onlinelibrary.wiley.com/doi/10.1111/gcb.15112> (from Ian)

• From Ian: I noticed how the growth patterns observed by remote sensing pretty much mirror what Sean was finding with his dendro R package (btw is that functional on CRAN yet?) for both SERC and SCBI dendroband data.

perhaps bring in cores?

• Sean’s model

• Climwin

The period where the phenology milestone(s) were most affected by Spring time temperature was determined using the R package Climwin. This package tests the correlation between climate variables (daily averaged temperature) and biological variables (DOY) within a specified time-frame, reporting the window with the highest correlation as the ‘best-model’. We instructed Climwin to search for the best window within ### to 0 days before the phenology milestone. This was done to find corresponding best-windows for both of our wood-types; ring-porous and diffuse-porous.

*Analysis*

Here, I’ll insert a reference to Sean’s paper (McMahon & Parker, 2015). This is pulled from references.bib.

-Mixed effect model

A mixed effect model was used to test the response of wood phenology variables (25% DOY, max-rate, max-rate DOY, total growth) to fixed effects of wood-type and Spring temperature, and random effects of species and tag. We ran two separate models for each of our major wood-types and one combined model to use for comparison during the bayesian analysis. (talking to Albert about possibly doing this)

• Bayesian heirarchal model

### Results

• variable averages

Pooled across all species and all years the average DOY where max growth rate was achieved is DOY: 158, the DOY where 25% was achieved is DOY: 129, 50% - DOY: 157, 75% - DOY:184.

Ring-porous (1395 obs) max growth rate – DOY: 147, max growth rate = .048 (find units in Sean’s function), 25% - DOY: 113, 50% DOY: 147, 75% - DOY: 181…68 days

Diffuse-porous (993 obs) max growth rate – DOY: 172, max growth rate = .068 (find units in Sean’s function), 25% - DOY: 153, 50% - DOY: 171, 75% - DOY: 190… 37 days

• Climwin results

• Accounting for random effects of species and tag, pre-season temperatures had a greater effect on ring-porous species than diffuse-porous.

• Bayesian variable results (PRE-JOINT MODEL, updating ASAP)

Ring-porous 25% DOY estimate: -2.23 (credible interval: -2.94 - -1.55)

Ring-porous 50% DOY estimate: - 2.10 (credible interval: -2.71 - -1.42)

Ring-porous 75% DOY estimate: -1.89 (credible interval: -2.53 - -1.28)

Ring-porous total growth estimate: 0.0552 (credible interval: 0.00346 - 0.108)

Ring-porous max-rate DOY estimate: -2.20 (credible interval: -2.77 - -1.62)

Ring-porous max-rate estimate: 0.00113 (credible interval: 0.000151 – 0.00208)

Diffuse-porous 25% DOY estimate: -1.83 (credible interval: -2.86 - -0.822)

Diffuse-porous 50% DOY estimate: -2.39 (credible interval: -3.35 - -1.43)

Diffuse-porous 75% DOY estimate: -2.96 (credible interval: -4.03 - -1.92)

Diffuse-porous total growth estimate: -0.0642 (credible interval: -0.172 – 0.0460)

Diffuse-porous max-rate DOY estimate: -2.54 (credible interval: -3.41 - -1.69)

Diffuse-porous max-rate estimate: 0.00209 (credible interval: 0.000118 – 0.00413)

### Discussion

Diffuse-porous 25-75% growth period shrinking leaving trees more vulnerable to drought while ring-porous 25-75% growing, potentially making effect of drought less damaging? But RP still prone to cavitation + longer growth period could mean exposure to higher number of droughts resulting in serious damage to water transport system?

DIfferences in total relationship could be because of response difference in wood types OR could be because the diffuse-porous’ growth occuring during the later summer means it is exposed to drought/heat and on average, not feeling the effects of the earlier spring. differences in wood porosity growth timing means exposure to different periods of climate stress ring porous adaptable to spring temps, diffuse not so much leads to higher growth in ring however, diffuse still more resistant to cavitation potential for more frequent late frost events having large impacts as spring warms? offset of chilling requirements and spring leaf out requirements

much assumed about future forest productivity based on gis different wood types/species may respond differently need to understand at a finer scale what is happening

Content to incorporate: N. American strategies have conservative strategies when it comes to phenology, as historically they’ve been subject to more spring frosts. Thus, climate change is having less impact (Zohner et al., 2020)

### Acknowledgements

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### Authors’ contributions

### References

McMahon, S. M., & Parker, G. G. (2015). A general model of intra-annual tree growth using dendrometer bands. *Ecology and Evolution*, *5*(2), 243–254. <https://doi.org/10.1002/ece3.1117>