Fueling Next Year's Growth of Trees with Carbon and Nitrogen

Context: In temperate and boreal forests, temperature plays a crucial role in setting the boundaries for seasonal physiological activity. Thus, with rising temperatures from anthropogenic climate change, the climatically possible growing season has lengthened in many ecosystems worldwide by up to 11 days.[1,2] Plants have tracked this through shifts in phenology—the study of recurring life history events—which are expected to continue with increasing temperatures.[3] In particular, trees have shifted earlier in the spring and may use these extra days to fix more carbon and increase growth during the current growing season.[4,5] At the same time, fall events in trees (e.g., leaf senescence) have been delayed, but the impacts on their fitness are not well understood. Together earlier spring and delayed fall events are often hypothesized to affect growth in the next growing season. This is rarely tested, however, and tests to date have used adult trees where many co-varying factors make teasing out the effect of longer seasons difficult. Here, I propose an extended season experiment using saplings to mechanistically test this critical hypothesis. My proposed work will provide valuable insight into the regeneration capacity of forests under a warming climate, considering the importance of young trees on forest recruitment.[6]

Research Question: 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?

Hypothesis: I hypothesize that an extension of the growing season could modify a tree's capacity to fill the resources trees store for future growth.[7,8] Trees that use this opportunity by fixing more carbon may experience increased growth in the subsequent growing season.[9,10] Thus, species capable of accumulating nutrients after growth cessation while going through leaf senescence might exhibit growth increment in the following growing season.[11]

Objectives: First, I aim to assess tree species' potential to prolong or stretch their activity schedule. Second, I will determine whether trees can absorb nutrients beyond their theoretical growing season. I will also examine if increased carbon pools translate into greater growth increment in the following growing season. Finally, I will investigate potential variations in these responses across deciduous and evergreen species, to test whether different patterns emerge within these distinct groups.

Methodology: To investigate the impact of manipulated spring and fall temperatures on phenological responses, I successfully conducted experiments in 2024 across seven different tree species under controlled conditions, including species that span both fast and short-life strategies (e.g., *Populus balsamifera*) and slow growth and longer lifespan species (e.g., *Quercus macrocarpa*) and including both deciduous and evergreen species.[12] I used a full factorial design of spring and fall warming with two levels each (control/warmed) resulting in four treatments plus an additional two treatments to test fall nutrient effects, using 15 replicates each for a total of 630 individual trees. Throughout the growing season of 2024, I tracked phenological events weekly from the start of the spring treatments through the end of the fall treatments. For the current growing season (2025), the same measurements are being conducted. In fall 2025, after the trees have grown in ambient temperatures for the season, I will assess growth on the individual (total biomass) and the cellular level, using tree-ring analysis.

Research outreach: Given the widespread impacts of climate change on ecosystems, understanding how forest communities respond to prolonged growing seasons is crucial. Observing the reactions of deciduous and conifer species to extended seasons may reveal potential benefits for some species and harm for others. These shifts are likely to influence forest stand dynamics across North America.

References

1. Körner, C. and Basler, D. Phenology Under Global Warming. *Science* **327**(5972), 1461–1462, March (2010).

2. Menzel, A. and Fabian, P. Growing season extended in Europe. *Nature* **397**(6721), 659–659, February (1999). Number: 6721 Publisher: Nature Publishing Group.

3. Wolkovich, E. M., Cook, B. I., Allen, J. M., Crimmins, T. M., Betancourt, J. L., Travers, S. E., Pau, S., Regetz, J., Davies, T. J., Kraft, N. J. B., Ault, T. R., Bolmgren, K., Mazer, S. J., McCabe, G. J., McGill, B. J., Parmesan, C., Salamin, N., Schwartz, M. D., and Cleland, E. E. Warming experiments underpredict plant phenological responses to climate change. *Nature* **485**(7399), 494–497, May (2012). Number: 7399 Publisher: Nature Publishing Group.

4. Keenan, T. F., Gray, J., Friedl, M. A., Toomey, M., Bohrer, G., Hollinger, D. Y., Munger, J. W., O'Keefe, J., Schmid, H. P., Wing, I. S., Yang, B., and Richardson, A. D. Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nature Climate Change* **4**(7), 598–604, July (2014). Number: 7 Publisher: Nature Publishing Group.

5. Wang, H., Wang, H., Ge, Q., and Dai, J. The Interactive Effects of Chilling, Photoperiod, and Forcing Temperature on Flowering Phenology of Temperate Woody Plants. *Frontiers in Plant Science* **11** (2020).

6. Zohner, C. M., Renner, S. S., Sebald, V., and Crowther, T. W. How changes in spring and autumn phenology translate into growth-experimental evidence of asymmetric effects. *Journal of Ecology* **109**(7), 2717–2728, July (2021).

7. Chapin, F. S., Schulze, E., and Mooney, H. A. The Ecology and Economics of Storage in Plants. *Annual Review of Ecology and Systematics* **21**(1), 423–447, November (1990).

8. Lawrence, B. T. and Melgar, J. C. Variable Fall Climate Influences Nutrient Resorption and Reserve Storage in Young Peach Trees. *Frontiers in Plant Science* **9** (2018).

9. Landhäusser, S. M., Pinno, B. D., Lieffers, V. J., and Chow, P. S. Partitioning of carbon allocation to reserves or growth determines future performance of aspen seedlings. *Forest Ecology and Management* **275**, 43–51, July (2012).

10. Martens, L. A., Landhäusser, S. M., and Lieffers, V. J. First-year growth response of cold-stored, nursery-grown aspen planting stock. *New Forests* **33**(3), 281–295, May (2007).

11. Schott, K. M., Pinno, B. D., and Landhäusser, S. M. Premature shoot growth termination allows nutrient loading of seedlings with an indeterminate growth strategy. *New Forests* **44**(5), 635–647, September (2013).

12. Jönsson, A. M., Eklundh, L., Hellström, M., Bärring, L., and Jönsson, P. Annual changes in MODIS vegetation indices of Swedish coniferous forests in relation to snow dynamics and tree phenology. *Remote Sensing of Environment* **114**(11), 2719–2730, November (2010).