

Climate change and forests: remote sensing and experiments to understand tree growth

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Context: There is increasing evidence that anthropogenic climate change, and particularly increased temperature, affect many natural systems at the global scale (Change, 2014; Parmesan *et al.*, 1999; Rosenzweig *et al.*, 2008). The most observed biological impact of climate change over the past decades are major changes on spring and fall phenology — the timing of recurring life history events (Parmesan & Yohe, 2003; Parmesan *et al.*, 1999). Understanding the consequences of these shifts on ecosystems requires understanding how much the growing season has changed (Duputié *et al.*, 2015). 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 contrast, autumn phenophases (e.g. budset and leaf colouring) are delayed, though to a much lesser extent than spring's (Gallinat *et al.*, 2015; Jeong & Medvigy, 2014) and are driven by shortening photoperiod (Cooke *et al.*, 2012; Flynn & Wolkovich, 2018; Körner & Basler, 2010) and colder temperatures (Cooke *et al.*, 2012; Delpierre *et al.*, 2016). These shifts support a long-lasting and intuitive assumption that earlier spring and delayed fall events lead to longer seasons —and thus increased growth (Keenan *et al.*, 2014). However, research from the past three years has cast doubt on this hypothesis (Dow *et al.*, 2022; Green & Keenan, 2022; Silvestro *et al.*, 2023). Recently, Dow *et al.* (2022) showed that despite an earlier growth onset, neither growth rate nor overall annual increment was increased by longer seasons. This could have large consequences on carbon cycle models with potential feedbacks on future climate change.

Understanding these findings resumes answering what are the mechanisms limiting trees from growing more despite theoretical longer growing seasons? My research focuses on this via considering two possible drivers explaining this phenomenon: external (environmental) (Kolář *et al.*, 2016) or internal (via physiological constraints)(Zohner *et al.*, 2023) limits to growth. The complex nature of climate change makes predicting the external limits to growth hard to quantify at the individual level as they affect communities as a whole. Drought, spring frost and heat waves are commonly mentioned as the main extreme events that could limit tree growth under climate change (Drobyshev *et al.*, 2008). To better comprehend these mechanisms, experiments are paramount because they can 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). This is essential to refine forest carbon sequestration projections (REF). However, experiments are most often performed on juvenile trees, which are critical for their role in forest regeneration projections, but their responses can hardly be translated to mature trees, which hold the overwhelming carbon biomass proportion of forests (Augspurger & Bartlett, 2003; Silvestro *et al.*, 2023; Vitasse, 2013). To investigate how growing season shifts impacts mature trees in their natural environments, Unmanned aerial vehicle (UAV) imagery paired with machine learning have the capacity to acquire huge sample sizes largely

beyond what is achievable via traditional observational ground work, and at a better spatial and temporal resolution than satellites (Berra *et al.*, 2019; Piao *et al.*, 2019; Teng *et al.*, 2025). Here, I propose a combination of two experiments to test internal (Chapter 1) and external (Chapter 2) limits to growth along with a large-scale mixed-forest observational data project using UAV imagery and machine learning (Chapter 3) to address the paradox of the absence of increased growth despite apparently improved growing season conditions.

Chapter 1: Extended growing season experiment (Fuelinex continuation) Shifts in phenological phases have consequences on growth during the current growing season, but experiments to date have yet to quantify if longer seasons have lagging effects over the following years (REF). Therefore, for the first two years of my proposed award tenure, I will expand my Master’s work by analyzing 2025 data and extend the project for a third consecutive year (2026). Along with the continuation of phenological phase monitoring over the whole growing season, I will also collect the biomass and tree cross-sections at the end of the 2026 growing season. I will also collaborate with researchers the WSL from ETH Zurich to do cellular scans of the trees’ cross-sections to understand how treatment affect cell count and morphology. By using growth increment metrics and tree ring cell analysis collected for three seasons, I will investigate how the first year treatments affect growth over the two following years. With the expansion of my Master’s work, I aim to assess different tree species’ potential to stretch their activity schedules and wether or not this translates into increased growth over multiple growing seasons.

Chapter 2: Drought and spring frost experiment With climate change, not only will growing season length shift, but trees will also experience shifts in the timing of moisture deficits from lower precipitation and higher evapotranspiration that may lead to drought stress (Dox *et al.*, 2022). Tree-ring research shows that summer droughts advance growth cessation—leading to an earlier end of season (Kang *et al.*, 2023) and potential tissue loss (Kramer *et al.*, 2012). In addition, warming springs advance budburst, but come with increased frequency and severity of late spring frosts resulting into tissue loss (Baumgarten *et al.*, 2023; Kramer *et al.*, 2012). Trees can recover by reinvesting in a second cohort of leaves (Baumgarten *et al.*, 2023; D’Andrea *et al.*, 2019). However, the lost time that trees cannot photosynthesize along with the increased investment in the second cohort of leaves may lead to significant disadvantages, however it is unclear whether trees exposed to spring frosts also grow less (Chamberlain & Wolkovich, 2021; Baumgarten *et al.*, 2023).

To investigate how these two abiotic drivers affect trees, I will conduct an experiment during the second year of the award tenure that consists of three drought treatments, occuring at different timings during the growing season and an additional two spring frost treatments early and late in the spring. I will use 15 replicates of 12 deciduous North American tree species (six congeneric pairs to avoid potential confounding effects of shared evolutionary history), spanning different life history strategies, for all five treatments and a control, summing a total of 1080 individuals (a sample size consistent with my current sucessful experiment). For spring frost treatments, I will place the trees in growth chambers early in the season at warm temperatures to trigger budburst. When the trees start to burst, I will place the first treatment for one hour in freezing growth chambers, following methods in Chamberlain & Wolkovich (2021). For the second spring frost treatment, I will wait for the leaves to be fully elongated and then place the trees under the same freezing conditions as the first treatment (Zohner *et al.*, 2018).

For the drought treatments, I will move the trees in growth chambers at a warmer temperature and lower air humidity than ambient conditions to maximize evapotranspiration rates. Once the trees have reached their respective wilting point (values at which soil water is not extractable by

the plant), I will remove them from the chambers, one species at a time and move them back to ambient conditions and constant irrigation. The three drought treatments will differ in their timing of occurrence to test the importance of drought timing. Thus, the first treatment will be conducted just after leaf-out; the second will start one week before solstice — period of peak growth for a lot of species (*not sure of this*); the last drought treatment will happen near the end of the season, just before growth cessation. I will monitor phenological phases and shoot elongation every week throughout the growing season. Using allometric equations, I will estimate biomass at the start and end of the growing season. In order to grasp a high temporal resolution of growth responses to treatments, I will equip a subset of trees with magnetic dendrometers that will provide valuable insight into growth temporality in response to treatments.

Chapter 3 : Cambial phenology × drone imagery phenological observations An improved understanding of differences in growth synchronicity with leaf phenology across species is paramount to refining carbon cycles models in the context of Anthropogenic climate change (Klein *et al.*, 2016; Kramer *et al.*, 2000; Richardson *et al.*, 2013; Swidrak *et al.*, 2013). Thus, for the three years of my award tenure, I aim to launch a large-scale project using cutting-edge drone × artificial intelligence technologies (Ball *et al.*, 2023; Teng *et al.*, 2025; Ulku *et al.*, 2022) to gather a large amount of data on tree growth onset and end from a mixed-forest community located at Station biologique des Laurentides (St-Hypolyte (Qc)), during three consecutive growing seasons. Using this site will allow me to follow up on work previously done by my laboratory Flynn & Wolkovich (2018) as well as creating a partnership with Dr. Etienne Laliberté from the Plant Functional Ecology Laboratory (PFEL) who currently uses this site for his research (e.g. ?). To monitor leaf phenology from budburst to leaf drop, I will use high-frequency repeated overflights using UAVs over the canopy to monitor every single tree over the course of the growing season. Then I will use BalSAM, a promising model to accurately and efficiently segment tree crown from repeated UAV images. This will allow me to gather large amount of accurate phenological data from single trees within the forest community (Teng *et al.*, 2025). With this data, I will be able to accurately infer the start and end of the growing season for each species and individuals within this forest community (Berra *et al.*, 2019; Fawcett *et al.*, 2021). Then, I will use 200 DC3 Perimeter Dendrometer placed randomly throughout the site on 40 trees per species. Using high-resolution data across space and time will allow me to robustly infer a relationship between leaf phenophases and growth seasonality.

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 tree 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 with potential feedback with future climate change. Therefore, using two different experiments and a large-scale remote sensing project, I aim to understand how growth dynamics of North American tree species will change with longer growing seasons.

References

References

Augsburger, C.K. & Bartlett, E.A. (2003). Differences in leaf phenology between juvenile and adult trees in a temperate deciduous forest. *Tree Physiology*, 23, 517–525.

- Ball, J.G.C., Hickman, S.H.M., Jackson, T.D., Koay, X.J., Hirst, J., Jay, W., Archer, M., Aubry-Kientz, M., Vincent, G. & Coomes, D.A. (2023). Accurate delineation of individual tree crowns in tropical forests from aerial >RGB imagery using Mask >R-CNN. *Remote Sensing in Ecology and Conservation*, 9, 641–655.
- Baumgarten, F., Gessler, A. & Vitasse, Y. (2023). No risk—no fun: Penalty and recovery from spring frost damage in deciduous temperate trees. *Functional Ecology*, 37, 648–663.
- Berra, E.F., Gaulton, R. & Barr, S. (2019). Assessing spring phenology of a temperate woodland: A multiscale comparison of ground, unmanned aerial vehicle and Landsat satellite observations. *Remote Sensing of Environment*, 223, 229–242.
- Chamberlain, C.J. & Wolkovich, E.M. (2021). Late spring freezes coupled with warming winters alter temperate tree phenology and growth. *New Phytologist*, 231, 987–995.
- Change, I.P.O.C. (2014). Detection and Attribution of Climate Change: from Global to Regional. In: *Climate Change 2013 – The Physical Science Basis*. Cambridge University Press, pp. 867–952. 1st edn.
- Chmielewski, F.M. & Rötzer, T. (2001). Response of tree phenology to climate change across Europe. *Agricultural and Forest Meteorology*, 108, 101–112.
- Chuine, I. (2010). Why does phenology drive species distribution? *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365, 3149–3160.
- Cleland, E., Chuine, I., Menzel, A., Mooney, H. & Schwartz, M. (2007). Shifting plant phenology in response to global change. *Trends in Ecology & Evolution*, 22, 357–365.
- Cooke, J.E.K., Eriksson, M.E. & Junttila, O. (2012). The dynamic nature of bud dormancy in trees: environmental control and molecular mechanisms. *Plant, Cell & Environment*, 35, 1707–1728.
- D’Andrea, E., Rezaie, N., Battistelli, A., Gavrichkova, O., Kuhlmann, I., Matteucci, G., Moscatello, S., Proietti, S., Scartazza, A., Trumbore, S. & Muhr, J. (2019). Winter’s bite: beech trees survive complete defoliation due to spring late-frost damage by mobilizing old C reserves. *New Phytologist*, 224, 625–631.
- Delpierre, N., Vitasse, Y., Chuine, I., Guillemot, J., Bazot, S., Rutishauser, T. & Rathgeber, C.B.K. (2016). Temperate and boreal forest tree phenology: from organ-scale processes to terrestrial ecosystem models. *Annals of Forest Science*, 73, 5–25.
- Dow, C., Kim, A.Y., D’Orangeville, L., Gonzalez-Akre, E.B., Helcoski, R., Herrmann, V., Harley, G.L., Maxwell, J.T., McGregor, I.R., McShea, W.J., McMahon, S.M., Pederson, N., Tepley, A.J. & Anderson-Teixeira, K.J. (2022). Warm springs alter timing but not total growth of temperate deciduous trees. *Nature*, 608, 552–557.
- Dox, I., Mariën, B., Zuccarini, P., Marchand, L.J., Prislan, P., Gričar, J., Flores, O., Gehrman, F., Fonti, P., Lange, H., Peñuelas, J. & Campioli, M. (2022). Wood growth phenology and its relationship with leaf phenology in deciduous forest trees of the temperate zone of Western Europe. *Agricultural and Forest Meteorology*, 327, 109229.

- Drobyshev, I., Niklasson, M., Eggertsson, O., Linderson, H. & Sonesson, K. (2008). Influence of annual weather on growth of pedunculate oak in southern Sweden. *Annals of Forest Science*, 65, 512–512.
- Duputié, A., Rutschmann, A., Ronce, O. & Chuine, I. (2015). Phenological plasticity will not help all species adapt to climate change. *Global Change Biology*, 21, 3062–3073.
- Fawcett, D., Bennie, J. & Anderson, K. (2021). Monitoring spring phenology of individual tree crowns using drone-acquired NDVI data. *Remote Sensing in Ecology and Conservation*, 7, 227–244.
- Flynn, D.F.B. & Wolkovich, E.M. (2018). Temperature and photoperiod drive spring phenology across all species in a temperate forest community. *New Phytologist*, 219, 1353–1362.
- Fu, Y.H., Piao, S., Op De Beeck, M., Cong, N., Zhao, H., Zhang, Y., Menzel, A. & Janssens, I.A. (2014). Recent spring phenology shifts in western Europe based on multiscale observations. *Global Ecology and Biogeography*, 23, 1255–1263.
- Gallinat, A.S., Primack, R.B. & Wagner, D.L. (2015). Autumn, the neglected season in climate change research. *Trends in Ecology & Evolution*, 30, 169–176.
- Green, J.K. & Keenan, T.F. (2022). The limits of forest carbon sequestration. *Science*, 376, 692–693.
- Jeong, S. & Medvigy, D. (2014). Macroscale prediction of autumn leaf coloration throughout the continental United States. *Global Ecology and Biogeography*, 23, 1245–1254.
- Kang, J., Yang, Z., Yu, B., Ma, Q., Jiang, S., Shishov, V.V., Zhou, P., Huang, J.G. & Ding, X. (2023). An earlier start of growing season can affect tree radial growth through regulating cumulative growth rate. *Agricultural and Forest Meteorology*, 342, 109738.
- 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. & Richardson, A.D. (2014). Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nature Climate Change*, 4, 598–604.
- Klein, T., Vitasse, Y. & Hoch, G. (2016). Coordination between growth, phenology and carbon storage in three coexisting deciduous tree species in a temperate forest. *Tree Physiology*, 36, 847–855.
- Kolář, T., Giagli, K., Trnka, M., Bednářová, E., Vavřík, H. & Rybníček, M. (2016). Response of the leaf phenology and tree-ring width of European beech to climate variability. *Silva Fennica*, 50.
- Kramer, K., Bijlsma, R.J., Hickler, T. & Thuiller, W. (2012). Why Would Plant Species Become Extinct Locally If Growing Conditions Improve? *International Journal of Biological Sciences*, 8, 1121–1129.
- Kramer, K., Leinonen, I. & Loustau, D. (2000). The importance of phenology for the evaluation of impact of climate change on growth of boreal, temperate and Mediterranean forests ecosystems: an overview. *International Journal of Biometeorology*, 44, 67–75.

- Körner, C. & Basler, D. (2010). Phenology Under Global Warming. *Science*, 327, 1461–1462. Publisher: American Association for the Advancement of Science.
- Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J.K., Thomas, C.D., Descimon, H., Huntley, B., Kaila, L., Kullberg, J., Tammaru, T., Tennent, W.J., Thomas, J.A. & Warren, M. (1999). Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature*, 399, 579–583.
- Parmesan, C. & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421, 37–42.
- Peñuelas, J. & Filella, I. (2001). Responses to a Warming World. *Science*, 294, 793–795. Publisher: American Association for the Advancement of Science.
- Piao, S., Liu, Q., Chen, A., Janssens, I.A., Fu, Y., Dai, J., Liu, L., Lian, X., Shen, M. & Zhu, X. (2019). Plant phenology and global climate change: Current progresses and challenges. *Global Change Biology*, 25, 1922–1940. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/gcb.14619>.
- Richardson, A.D., Keenan, T.F., Migliavacca, M., Ryu, Y., Sonnentag, O. & Toomey, M. (2013). Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology*, 169, 156–173.
- Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T.L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S. & Imeson, A. (2008). Attributing physical and biological impacts to anthropogenic climate change. *Nature*, 453, 353–357.
- Silvestro, R., Zeng, Q., Buttò, V., Sylvain, J.D., Drolet, G., Mencuccini, M., Thiffault, N., Yuan, S. & Rossi, S. (2023). A longer wood growing season does not lead to higher carbon sequestration. *Scientific Reports*, 13, 4059.
- Swidrak, I., Schuster, R. & Oberhuber, W. (2013). Comparing growth phenology of co-occurring deciduous and evergreen conifers exposed to drought. *Flora - Morphology, Distribution, Functional Ecology of Plants*, 208, 609–617.
- Teng, M., Ouaknine, A., Laliberté, E., Bengio, Y., Rolnick, D. & Larochelle, H. (2025). Bringing SAM to new heights: Leveraging elevation data for tree crown segmentation from drone imagery. ArXiv:2506.04970 [cs].
- Ulku, I., Akagunduz, E. & Ghamisi, P. (2022). Deep Semantic Segmentation of Trees Using Multispectral Images. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 15, 7589–7604.
- Vitasse, Y. (2013). Ontogenic changes rather than difference in temperature cause understory trees to leaf out earlier. *New Phytologist*, 198, 149–155.
- Wolfe, D.W., Schwartz, M.D., Lakso, A.N., Otsuki, Y., Pool, R.M. & Shaulis, N.J. (2005). Climate change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. *International Journal of Biometeorology*, 49, 303–309.
- Zohner, C., Rockinger, A. & Renner, S. (2018). Increased autumn productivity permits temperate trees to compensate for spring frost damage. *The New phytologist*, 221 2, 789–795.

Zohner, C.M., Mirzaghali, L., Renner, S.S., Mo, L., Rebindaine, D., Bucher, R., Palouš, D., Vitasse, Y., Fu, Y.H., Stocker, B.D. & Crowther, T.W. (2023). Effect of climate warming on the timing of autumn leaf senescence reverses after the summer solstice. *Science*, 381, eadf5098.