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We conducted a review to find studies focused on relationships between growing season length and tree wood growth, though contrasting terminology made it challenging to identify papers through one search. After reviewing several recent papers (Dow *et al.*, 2022; Zohner *et al.*, 2023), we searched ISI Web of Science for “growing season length” AND “tree ring*” (ALL FIELDS) on 12 April 2023, which returned 33 citations. We next reviewed abstracts and discarded papers that did not mention the relationship between growing season length and growth. We further reviewed all citations within all papers for additionally relevant papers and included them in our review. In total we report on 36 papers after reviewing over 107 potentially relevant papers and discarding one paper (Bruening *et al.*, 2017, which used tree lines as a metric of both growth and growing season length).

Given the large diversity of metrics we found, we did not extract quantitative estimates of growing season length, growth, or their relationship. Instead, we extracted data on location, species, how they measured growing season length, growth, what relationship they found and what internal and external drivers they mentioned (full dataset with more details available on the Knowledge Network for Biocomplexity at publication).

Papers often reported dozens or more statistical tests from different analyses of data or different types or subsets of data, thus we recorded a unique meta-analytic observation within each paper (which we call a ‘study’) when papers reported: (1) distinctly different datasets (e.g., a global analyses of observations and a short-term experiment); (2) multiple distinctly different measures of growth (e.g., tree ring width and flux tower) and/or growing season length (e.g., they reported both end of season as budset and end of wood growth through xylogenesis); (3) distinctly different results for growth \times growing season length depending on metric (e.g., using budset for growing season length they find a growth \times growing season length relationship, but using leaf coloring they do not).

References

- Brand, R., Srur, A.M. & Villalba, R. (2022) Contrasting growth trends in *Nothofagus pumilio* upper-elevation forests induced by climate warming in the Southern Andes. *Agricultural and Forest Meteorology* **323**.
- Bruening, J.B., Tran, T.J., Bunn, A.G., Weiss, S.B. & Salzer, M.W. (2017) Fine-scale modeling of bristlecone pine treeline position in the great basin, usa. *Environmental Research Letters* **12**.
- Buermann, W., Forkel, M., O’sullivan, M., Sitch, S., Friedlingstein, P., Haverd, V., Jain, A.K., Kato, E., Kautz, M., Lienert, S. *et al.* (2018) Widespread seasonal compensation effects of spring warming on northern plant productivity. *Nature* **562**, 110–114.
- Camarero, J.J., Campelo, F., Colangelo, M., Valeriano, C., Knorre, A., Solé, G. & Rubio-Cuadrado, Á. (2022) Decoupled leaf-wood phenology in two pine species from contrasting climates: Longer growing seasons do not mean more radial growth. *Agricultural and Forest Meteorology* **327**, 109223.

- Chen, J., Chen, W., Liu, J., Cihlar, J. & Gray, S. (2000) Annual carbon balance of Canada's forests during 1895-1996. *Global Biogeochemical Cycles* **14**, 839–849.
- Chen, W., Black, T., Yang, P., Barr, A., Neumann, H., Nesic, Z., Blanken, P., Novak, M., Eley, J., Ketler, R. *et al.* (1999) Effects of climatic variability on the annual carbon sequestration by a boreal aspen forest. *Global Change Biology* **5**, 41–53.
- Čufar, K., De Luis, M., Prislan, P., Gričar, J., Črepinšek, Z., Merela, M. & Kajfež-Bogataj, L. (2015) Do variations in leaf phenology affect radial growth variations in *Fagus sylvatica*? *International journal of biometeorology* **59**, 1127–1132.
- Cuny, H.E., Rathgeber, C.B., Lebourgeois, F., Fortin, M. & Fournier, M. (2012) Life strategies in intra-annual dynamics of wood formation: example of three conifer species in a temperate forest in north-east France. *Tree physiology* **32**, 612–625.
- de Sauvage, J.C., Vitasse, Y., Meier, M., Delzon, S. & Bigler, C. (2022) Temperature rather than individual growing period length determines radial growth of sessile oak in the Pyrenees. *Agricultural and Forest Meteorology* **317**, 108885.
- Delpierre, N., Guillemot, J., Dufrêne, E., Cecchini, S. & Nicolas, M. (2017) Tree phenological ranks repeat from year to year and correlate with growth in temperate deciduous forests. *Agricultural and Forest Meteorology* **234**, 1–10.
- 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. *et al.* (2022) Warm springs alter timing but not total growth of temperate deciduous trees. *Nature* **608**, 552–557.
- Drew, D. & Downes, G. (2018) Growth at the microscale: long term thinning effects on patterns and timing of intra-annual stem increment in radiata pine. *for ecosystem* **5**: 32.
- Eckes-Shephard, A.H., Tiavlovsky, E., Chen, Y., Fonti, P. & Friend, A.D. (2021) Direct response of tree growth to soil water and its implications for terrestrial carbon cycle modelling. *GLOBAL CHANGE BIOLOGY* **27**, 121–135.
- Etzold, S., Sterck, F., Bose, A.K., Braun, S., Buchmann, N., Eugster, W., Gessler, A., Kahmen, A., Peters, R.L., Vitasse, Y. *et al.* (2022) Number of growth days and not length of the growth period determines radial stem growth of temperate trees. *Ecology Letters* **25**, 427–439.
- Finzi, A.C., Giasson, M.A., Plotkin, A.A.B., Aber, J.D., Boose, E.R., Davidson, E.A., Dietze, M.C., Ellison, A.M., Frey, S.D., Goldman, E., Keenan, T.F., Melillo, J.M., Munger, J.W., Nadelhoffer, K.J., Ollinger, V. S., Orwig, D.A., Pederson, N., Richardson, A.D., Savage, K., Tang, J., Thompson, J.R., Williams, C.A., Wofsy, S.C., Zhou, Z. & Foster, D.R. (2020) Carbon budget of the Harvard forest long-term ecological research site: pattern, process, and response to global change. *Ecological Monographs* **90**.
- Francon, L., Corona, C., Till-Bottraud, I., Choler, P., Carlson, B.Z., Charrier, G., Ameglio, T., Morin, S., Eckert, N., Roussel, E., Lopez-Saez, J. & Stoffel, M. (2020) Assessing the effects of earlier snow melt-out on alpine shrub growth: The sooner the better? *Ecological Indicators* **115**.

- Gao, S., Liang, E., Liu, R., Babst, F., Camarero, J.J., Fu, Y.H., Piao, S., Rossi, S., Shen, M., Wang, T. *et al.* (2022) An earlier start of the thermal growing season enhances tree growth in cold humid areas but not in dry areas. *Nature ecology & evolution* **6**, 397–404.
- Grossiord, C., Bachofen, C., Gislér, J., Mas, E., Vitasse, Y. & Didion-Gency, M. (2022) Warming may extend tree growing seasons and compensate for reduced carbon uptake during dry periods. *Journal of Ecology* **110**, 1575–1589.
- 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. *et al.* (2014) Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nature Climate Change* **4**, 598–604.
- 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**.
- McKown, A.D., Guy, R.D. & Quamme, L.K. (2016) Impacts of bud set and lammas phenology on root: shoot biomass partitioning and carbon gain physiology in poplar. *Trees* **30**, 2131–2141.
- Michelot, A., Simard, S., Rathgeber, C., Dufrêne, E. & Damesin, C. (2012) Comparing the intra-annual wood formation of three European species (*Fagus sylvatica*, *Quercus petraea* and *Pinus sylvestris*) as related to leaf phenology and non-structural carbohydrate dynamics. *Tree physiology* **32**, 1033–1045.
- Moser, L., Fonti, P., Büntgen, U., Esper, J., Luterbacher, J., Franzen, J. & Frank, D. (2010) Timing and duration of european larch growing season along altitudinal gradients in the swiss alps. *Tree physiology* **30**, 225–233.
- Oddi, L., Migliavacca, M., Cremonese, E., Filippa, G., Vacchiano, G., Siniscalco, C., Morra di Cella, U. & Galvagno, M. (2022) Contrasting responses of forest growth and carbon sequestration to heat and drought in the alps. *Environmental Research Letters* **17**, 045015.
- Ren, P., Ziacco, E., Rossi, S., Biondi, F., Prislan, P. & Liang, E. (2019) Growth rate rather than growing season length determines wood biomass in dry environments. *Agricultural and Forest Meteorology* **271**, 46–53.
- Richardson, A.D., Andy Black, T., Ciais, P., Delbart, N., Friedl, M.A., Gobron, N., Hollinger, D.Y., Kutsch, W.L., Longdoz, B., Luyssaert, S. *et al.* (2010) Influence of spring and autumn phenological transitions on forest ecosystem productivity. *Philosophical Transactions of the Royal Society B: Biological Sciences* **365**, 3227–3246.
- Sebastian-Azcona, J., Hacke, U. & Hamann, A. (2020) Xylem anomalies as indicators of maladaptation to climate in forest trees: Implications for assisted migration. *Frontiers in Plant Science* **11**.
- 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.

- Soolanayakanahally, R.Y., Guy, R.D., Silim, S.N. & Song, M. (2013) Timing of photoperiodic competency causes phenological mismatch in balsam poplar (*populus balsamifera* l.). *Plant, cell & environment* **36**, 116–127.
- Vitasse, Y., Delzon, S., Bresson, C.C., Michalet, R. & Kremer, A. (2009) Altitudinal differentiation in growth and phenology among populations of temperate-zone tree species growing in a common garden. *Canadian Journal of Forest Research* **39**, 1259–1269.
- Wheeler, J.A., Cortés, A.J., Sedlacek, J., Karrenberg, S., van Kleunen, M., Wipf, S., Hoch, G., Bossdorf, O. & Rixen, C. (2016) The snow and the willows: earlier spring snowmelt reduces performance in the low-lying alpine shrub *salix herbacea*. *Journal of Ecology* **104**, 1041–1050.
- Zani, D., Crowther, T.W., Mo, L., Renner, S.S. & Zohner, C.M. (2020) Increased growing-season productivity drives earlier autumn leaf senescence in temperate trees. *Science* **370**, 1066–1071.
- Zhu, L., Liu, S., Arzac, A., Cooper, D.J., Jin, Y., Yuan, D., Zhu, Y., Zhang, X., Li, Z., Zhang, Y. *et al.* (2021) Different response of earlywood vessel features of *fraxinus mandshurica* to rapid warming in warm-dry and cold-wet areas. *Agricultural and Forest Meteorology* **307**, 108523.
- Zohner, C.M., Mirzaghali, L., Renner, S.S., Mo, L., Rebindaine, D., Bucher, R., Palouš, D., Vitasse, Y., Fu, Y.H., Stocker, B.D. *et al.* (2023) Effect of climate warming on the timing of autumn leaf senescence reverses after the summer solstice. *Science* **381**, eadf5098.
- Zohner, C.M., Mo, L., Pugh, T.A., Bastin, J.F. & Crowther, T.W. (2020) Interactive climate factors restrict future increases in spring productivity of temperate and boreal trees. *Global change biology* **26**, 4042–4055.