

## WEATHER SENSITIVITY OF RADIAL INCREMENT OF PINUS STROBUS IN AN EXPERIMENTAL PLANTATION IN THE WESTERN PART OF LATVIA

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### Abstract

The phenomenon of global climate change holds utmost importance in its impact on forest ecosystems. To mitigate the effects of this phenomenon, several European countries have introduced non-native tree species into their forests. However, comprehensive ecological analysis is needed to assess the suitability of these non-native species. *Pinus strobus* is often considered a potential substitute for native species. Tree-ring analysis is a useful methodology for evaluating the relationship between tree growth and meteorological conditions, given the significant impact of these conditions on tree development. In this study, 25 core samples were collected from an experimental plantation of *Pinus strobus* located in the western part of Latvia for analysis. The plasticity of the tree-ring width of *Pinus strobus* was evaluated using a multiple additive regression model. The analysis revealed that the previous summer precipitation was a significant factor, indicating the drought sensitivity of the increment. Additionally, the temperature in the previous July and August was also found to be a significant meteorological parameter, suggesting some trade-offs between growth and the formation of nutrient reserves. The estimated growth responses suggest that the radial increment of *Pinus strobus* growing outside its native range is highly weather-sensitive, implying uncertainty in its growth with anticipated climatic changes. These findings emphasize the need for further ecological analysis to determine the suitability of non-native tree species and their ability to withstand the climatic changes.

**Key words:** climate-growth relationships, growth response, introduced trees, white pine.

### Introduction

Global climate change is of paramount importance in the current environmental landscape, and its ramifications are already being experienced worldwide (Allen *et al.*, 2015). Occurrences of severe weather events are occurring more frequently and with greater intensity (You & Wang, 2021). These effects can be exacerbated by increased damage caused by insect infestations and wildfires (Spathelf *et al.*, 2014). The increased temperatures linked to global warming are predicted to cause a lengthened growing season, which is expected to benefit the growth of plants; therefore, it is likely to affect forests (Kirilenko *et al.*, 2007). Although the rate of species migration due to climate change can be much more rapid than in the past (Clark, 1998), their rates of migration may still be too slow to adjust to the speed of climate change (Aitken *et al.*, 2013).

Many European countries are introducing non-native tree species into their forests as a strategy for reducing the effects of climate change (Santopuoli *et al.*, 2019). However, the presence of non-native species presents both opportunities and potential risks (Ricciardi *et al.*, 2009). On the one hand, they enhance productivity and biodiversity, yet on the other hand, certain species might become invasive (Felton *et al.*, 2013). While non-native species may not hold the same cultural and historical significance as native species, they can serve as viable replacements in situations where the benefits are clearly evident

(Schlaepfer *et al.*, 2011). To assess the suitability of non-native species in a particular habitat, a comprehensive ecological analysis is necessary (Keča *et al.*, 2019). Retrospective analysis of tree increment is an important method for evaluating the sensitivity and adaptability of trees to various biotic and abiotic factors (Speer, 2011).

*Pinus strobus* is among the tree species that are frequently introduced in Central Europe (Pötzelsberger *et al.*, 2020), which is widely distributed in its native range of North America (van Arsdell, 1961). *Pinus strobus* has been noted for its adaptation to hot and dry temperate climates (Davis, 1983) and rapid growth and long life expectancy (Hepp *et al.*, 2015; Klisz *et al.*, 2022). It typically occurs in multiple forest types, particularly in areas with sandy soils that are moderately to poorly fertile and well-drained (Abrams, 2001). The rate of growth for this species exceeds that of other pines and hardwoods, with increment culminating between 10–20 years of age (Burns *et al.*, 1990), yet exhibits a relatively low shade tolerance when young (Abrams, 2001). Although in its secondary distribution range *Pinus strobus* shows low productivity as a result of its sensitivity to global warming and drought (Klisz *et al.*, 2022; Podrázský *et al.*, 2020). *Pinus strobus* is of significant economic value, providing lumber, paper, and various wood products and its conical form and aesthetic appeal make it a favoured choice for landscaping (Krumm *et al.*, 2016).

Given the broad introduction of *Pinus strobus* in Europe because of its ecological adaptability (Krumm *et al.*, 2016), the current study aimed to evaluate the species sensitivity and growth potential to meteorological conditions when grown outside its native range in a hemiboreal stand (plantation). The study hypothesized that summer precipitation may constrain the growth of *Pinus strobus*.

### Materials and Methods

An experimental plantation (1.13 ha) of *Pinus strobus* situated in western Latvia within the hemiboreal forest zone of the Eastern Baltic region (57.24°N; 22.63°E) was studied. The plantation was established around 1900, yet seed origin is unknown, but likely to be from Northern Germany. The initial spacing of the plantation was 4x4m. To our knowledge, the plantation has not been fenced. Edaphic conditions can be considered mesotrophic, the soil was silty and free draining. Around the year 1950, the plantation was supplemented by planting containerized seedlings of local origin. Natural admixture of Norway spruce (*Pinus sylvestris*), silver birch (*Betula pendula*), silver fir (*Abies alba*), and pedunculate oak (*Quercus robur*) was observed. The diameter and height measurements for the sampled *Pinus strobus* trees had an average value of 41.5 ± 12.7 cm and 25.0 ± 3.1 m respectively.

The studied site's climate can be categorized as moist-continental with coastal features (Kottek *et al.*, 2006) Across the months, the average temperature fluctuated between -2.2 ± 3.0 °C in February to +17.6 ± 1.6 °C in July. The mean annual temperature from 1992 to 2021 was +7.1 ± 0.7 °C, mean temperature for summer months (June–August) 16.5 ± 1.5 °C. The mean annual precipitation was 664 ± 78 mm, and the summer months had the greatest monthly precipitation, with an average of 72 ± 28 mm. The average number of days with rainfall during the summer months was 12.4 ± 2 and minimum eight days with precipitation. Meteorological data were obtained from CRU for grid points situated within a 35 km radius of the location being investigated (Harris *et al.*, 2020).

The trial inventory and sample collection were conducted in March 2020. Pressler's increment corer was used to collect two cores from opposing directions from the stem of each tree; 25 dominant healthy trees were cored in total. After drying, the cores were placed onto wooden mounts and sanded. LINTAB6 was used to measure the width of the tree rings (0.01mm precision) (RinnTech, Heidelberg, Germany). Using the COFECHA tool, tree-ring width (TRW) time series were cross-dated using a combination of graphical and statistical methods (Grissino-Mayer, 2001). Variability in tree-ring width

(TRW) series was characterized using the  $\bar{r}$ , expressed population signal (EPS), mean sensitivity (SENS), first-order autocorrelation (AC1), and signal-to-noise ratio (SNR), which were estimated from detrended data (Wigley *et al.*, 1984). The data was detrended using both a negative exponential curve and a cubic spline (20 years rigidity, 0.5 cut-off frequency). First order autoregressive model ('AR1') was used in the detrended series to eliminate autocorrelation (von Arx *et al.*, 2017), creating a prewhitened dataset. The common period 1970–2020 was analyzed.

A principal component analysis was carried out to assess the differences in radial growth patterns (Buras *et al.*, 2018). The prewhitened dataset was used for the analysis. The residual chronology was derived by utilizing a preprocessed dataset that had been prewhitened, and then applying a statistical method known as a bi-weight robust mean (Bunn, 2008). The study aimed to determine the association between the residual chronology of tree-ring width and different meteorological factors. To achieve this objective, a non-parametric, stationary bootstrapped Pearson correlation analysis was performed (Zang & Biondi, 2013). The climatic variables that were examined were the mean monthly temperature, the total amount of precipitation, and the standardized evapotranspiration index (SPEI) (Vicente-Serrano *et al.*, 2010).

The set of meteorological variables influencing the radial increment of trees was evaluated using multiple additive regression (mixed model) (Wood, 2011). Such a model was used as it allows the evaluation of non-linear responses of growth under a temporal climatic gradient (Wood, 2011). Pre-whitened tree-ring width data series of trees were used as the response. Arbitrary groups of the best meteorological predictors (fixed effects) were selected based on the Akaike Information Criterion. To evaluate the possibility of collinearity among the predictors, the variance inflation factor was used. As crossed random intercepts, tree and year were considered random effects. Diagnostic plots were used to examine the homogeneity and normality of the model residuals. The statistical analysis was performed using R version 4.1.3 (R Core Team, 2022).

### Results and Discussion

From 25 selected trees, the cross-dating of 22 trees spanning the period 1970–2020 was successful. Evaluation of this dataset by the expressed population signal (EPS) yielded values of 0.90 or higher for both periods, surpassing 0.85 (Wigley *et al.* 1984) (Table 1), implying explicit environmental forcing of increment. This was supported by the signal-to-noise ratio (SNR), which was intermediate (17.67). Similar growth patterns between trees (Figure 2) were detected and

mean sensitivity (SENS) of interannual variation of tree-ring width was intermediate (Speer, 2011). The correlation between the current growth and previous

growth, as indicated by the first order autocorrelation, was moderate, and lower in comparison to Scots pine (Matisons *et al.*, 2021).

Table 1

**Descriptive analysis of cross-dated tree-ring width time series for *Pinus strobus***

| Time period | Radial growth (mm/100) |     |        |       | SENS | AC1  | r-bar | EPS   | SNR   |
|-------------|------------------------|-----|--------|-------|------|------|-------|-------|-------|
|             | Max                    | Min | Mean   | SD    |      |      |       |       |       |
| 1907–2020   | 857                    | 14  | 265.19 | 127.9 | 0.24 | 0.51 | 0.419 | 0.909 | 10.03 |
| 1970–2020   | 857                    | 16  | 265.19 | 121.1 | 0.25 | 0.48 | 0.446 | 0.946 | 17.67 |

SENS – mean sensitivity; AC1 – first order autocorrelation; r-bar – mean interseries correlation; EPS – expressed population signal; SNR – signal to noise ratio; SD – standard deviation; Maximal, Minimal, Mean tree-ring width.

The mean tree-ring width time series exhibited similar tendencies with several signature years coinciding among trees. The studied trees showed a decrease in radial growth till 1948 when a growth peak occurred (Figure 1A). Negative signature years coincided with cold and fluctuating temperatures in the early part of the year, as well as warm and dry summers (1970, 1976, 1984, 2004, 2007, and 2014), indicating that trees under marginal conditions (e.g., outside native range) have not been adapted to climate fluctuations and do not take advantage of favorable conditions when available (Allen *et al.*, 2015). The presence of positive signature years was noted in 1975, 1996, and 2012, and were concurrent with warm spring, indicating early commencement is beneficial for growth (Chhin *et al.*, 2018).

despite the differences in the age of trees. Thus, a single chronology was built to portray the high-frequency patterns of variation.

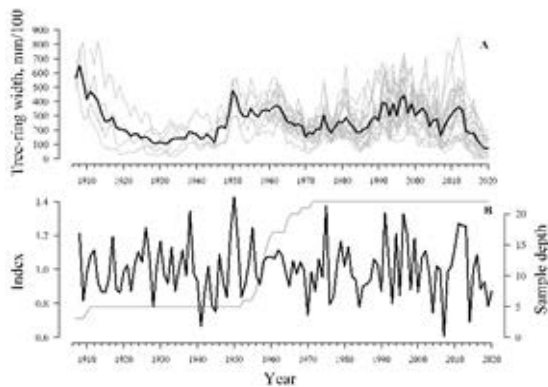


Figure 1. *Pinus strobus* tree-ring width time series: mean time series (A) and residual chronology (B) with sample depth (gray line).

The detrended time series of tree-ring widths revealed two principal components, which accounted for 51.42% of the variation (Figure 2). No distinct grouping was evident, suggesting a continuous gradient of responses with no obvious divergence

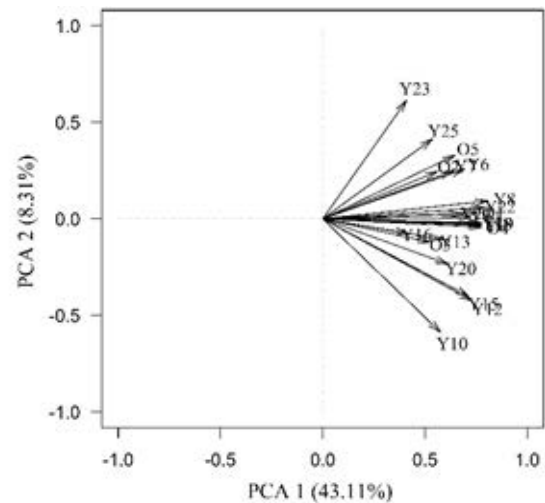


Figure 2. The loadings of the principal components of detrended *Pinus strobus* tree-ring width time series for the 1970–2020 period. The numbers in parentheses indicate the percentage of variance explained by each component.

The developed tree-ring width chronology demonstrated a correlation with 12 of the examined meteorological factors, with a particular emphasis on the temperature and precipitation levels of the preceding summer (Figure 3). The strongest positive correlations were observed with SPEI of the previous July and August, followed by the precipitation of the previous June and July, indicating drought sensitivity of increment (Chhin *et al.*, 2018; Marchand *et al.*, 2012). Similarly, summer precipitation significance in the current year was highlighted in Estonia and *Pinus strobus* native range (Chhin *et al.*, 2018; Läänela

*et al.*, 2019; Marchand *et al.*, 2012). Conversely, statistically significant negative correlations were observed with the temperature of the previous July and August (Figure 3). As temperature increases in late summer, a shift in the allocation of nutrients towards the formation of generative buds occurs, resulting in decreased growth in the vegetative effort (Hacket-Pain *et al.*, 2018).

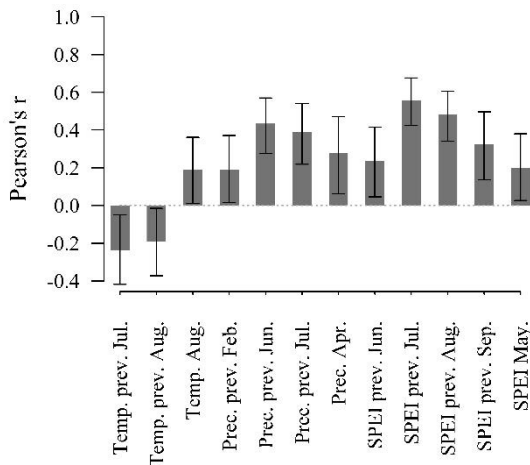


Figure 3. Statistically significant bootstrapped Pearson correlation coefficients (with confidence intervals) between residual chronology of tree-ring and meteorological variables for time period: 1970–2020.

A set of 10 meteorological factors were identified as the primary factors contributing to the high-frequency variations in tree-ring width, accounting for 32% of the overall variation (Table 2). SPEI in the previous July was estimated as the main limiting effect (the highest F-value), followed by precipitation previous February and SPEI in the previous June, indicating principle sensitivity to drought. All of the significant variables were estimated with quadratic or cubic effects on tree-ring width (Figure 4), implying that the studied temporal climatic gradient has been comparable to that genotypes have adapted (Wilmking *et al.*, 2020). This suggests high climatic sensitivity of the species outside its native range. However, the findings also indicated the flexibility of the relationship between weather patterns and tree growth (Matisons *et al.*, 2021). SPEI in the previous July (Figure 4G), which had the most significant effect was estimated to cause a response with an explicit threshold (SPEI=0.0), indicating drought sensitivity of growth (Harvey *et al.*, 2020). Moisture balance in May (Figure 4H), when rapid cell expansion occurs increasing water demand (Muller *et al.*, 2011), had a sigmoid response, indicating a positive effect of

excessive moisture availability. Contrastingly, SPEI of the previous June (Figure 4F) was estimated with a sigmoid response with local maxima and minima around 0.7 and -0.7, respectively. This probably indicates relationships with the amount of solar radiation, as the water table most likely is still high (Strand *et al.*, 2006). The influence of precipitation during the preceding February (Figure 4E) was generally positive (except in low snow conditions), possibly associated with the insulating characteristics of the snow layer (prevention of cold temperature caused root injury) as well as the replenishment of the water table in spring (Chhin *et al.*, 2018; Tierney *et al.*, 2001). The reactions to temperature during the preceding June and July (Figure 4A; 4B) indicated an optimum for radial growth of approximately 14–17 °C, as indicated by the response curves, suggesting a balance between adequate xylogenesis and drought conditions (Muller *et al.*, 2011). Additionally, a positive effect was estimated for temperature in the previous July exceeding 18 °C (Figure 4B). This could potentially be associated with an elevated level of solar radiation (Strand *et al.*, 2006). The temperature in August had both immediate and lasting impacts on

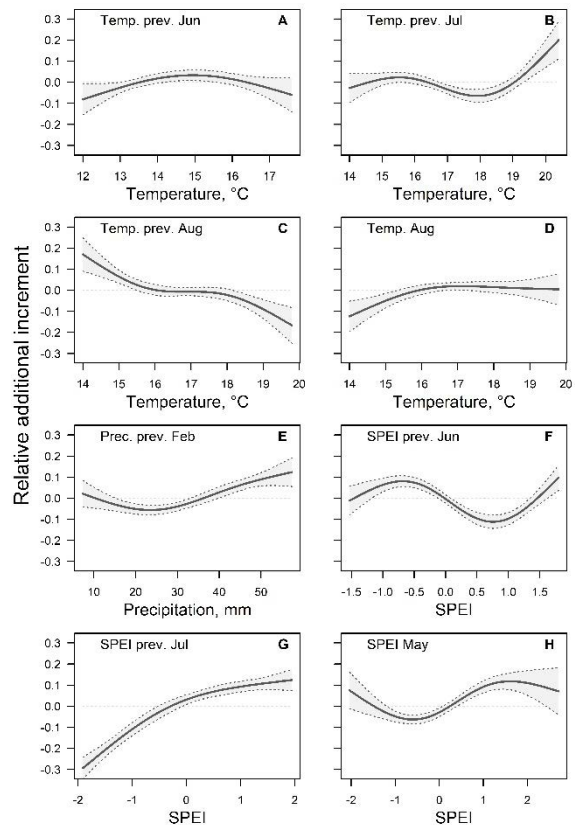


Figure 4. Smoothing spline estimates with 95% confidence intervals of tree-ring width response to meteorological variables (1970–2020) of *Pinus strobus*.

growth, yet the responses were contrasting (Figure 4D). The temperature in the preceding August had a mostly unfavourable impact (Figure 4C), with an interval of irresponsiveness of 16–18 °C, implying some trade-offs between growth and formation of

nutrient reserves. In contrast, low temperatures in current August (<16 °C) had a positive effect, which might be related to the initiation of cold hardening (Beck *et al.*, 2004).

The estimated responses imply that the radial increment of *Pinus strobus* growing outside the native range is highly weather sensitive, suggesting that uncertainty of its growth would increase with anticipated climatic changes. This contradicts with extended ecological plasticity of the species, compared to native populations (Brier *et al.*, 2020), likely as narrowly specialized genotypes (provenance) have been studied. Nevertheless, the plasticity and genetic adaptation of the responses indicate the adaptability of the species to a broader climatic gradient, particularly if enhanced by breeding (Burns *et al.*, 1990).

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Table 2  
**Smoothing Spline statistics from Generalized Additive Mixed Model for *Pinus strobus* tree-ring width and meteorological variables, 1970–2020**

| Fixed effects                      |                             |         |         |
|------------------------------------|-----------------------------|---------|---------|
| Smoothing term                     | Effective degree of freedom | F-value | p-value |
| Temperature in previous June       | 2.35                        | 2.79    | 0.034   |
| Temperature in previous July       | 2.88                        | 8.62    | <0.001  |
| Temperature in previous August     | 2.66                        | 9.55    | <0.001  |
| Temperature in August              | 2.42                        | 5.63    | 0.006   |
| Precipitation in previous February | 2.66                        | 20.70   | <0.001  |
| SPEI in previous June              | 2.94                        | 17.37   | <0.001  |
| SPEI in previous July              | 2.53                        | 62.66   | <0.001  |
| SPEI in May                        | 2.89                        | 14.95   | <0.001  |
| Random effects                     |                             |         |         |
| Groups                             | Standard deviation          |         |         |
| Year                               | <0.001                      |         |         |
| Tree                               | <0.001                      |         |         |
| Residual                           | 0.22                        |         |         |

#### References

- Abrams, M.D. (2001). Eastern white pine versatility in the presettlement forest. *BioScience*, 51(11), 967–979. DOI:10.1641/0006-3568(2001)051[0967:EWPVIT]2.0.CO;2.
- Aitken, S.N., & Whitlock, M.C. (2013). Assisted gene flow to facilitate local adaptation to climate change. *Annual Review of Ecology, Evolution, and Systematics*, 44, 367–388. DOI: 10.1146/annurev-ecolsys-110512-135747.
- Allen, C.D., Breshears, D.D., & McDowell, N.G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, 6(8), 1–55. DOI: 10.1890/ES15-00203.1.
- Beck, E.H., Heim, R., & Hansen, J. (2004). Plant resistance to cold stress: Mechanisms and environmental signals triggering frost hardening and dehardening. *Journal of Biosciences*, 29(4), 449–459. DOI: 10.1007/BF02712118.
- Brier, J. (2020). Provenance variation among different populations of *Pinus strobus* from Canada and the United States. 21(1), 1–9. Retrieved April 14, 2023, from <http://journal.um-surabaya.ac.id/index.php/JKM/article/view/2203>.
- Bunn, A.G. (2008). A dendrochronology program library in R (dplR). *Dendrochronologia*, 26(2), 115–124. DOI: 10.1016/j.dendro.2008.01.002.
- Buras, A., & Menzel, A. (2018). Projecting tree species composition changes of European forests for 2061–2090 under RCP 4.5 and RCP 8.5 scenarios. *Frontiers in Plant Science*, 9(January), 1–13. DOI: 10.3389/fpls.2018.01986.
- Burns, R.M., & Honkala, B.H. (1990). *Silvics of North America*. Agriculture Handbook 654, 2, 877. Retrieved April 14, 2023, from [http://www.na.fs.fed.us/spfo/pubs/silvics\\_manual/table\\_of\\_contents.htm](http://www.na.fs.fed.us/spfo/pubs/silvics_manual/table_of_contents.htm).
- Chhin, S., Zalesny, R.S., Parker, W.C., & Brissette, J. (2018). Dendroclimatic analysis of white pine (*Pinus strobus* L.) using long-term provenance test sites across eastern North America. *Forest Ecosystems*, 5(1). DOI: 10.1186/s40663-018-0136-0.
- Clark, J.S. (1998). Why Trees Migrate So Fast: Confronting Theory with Dispersal Biology and the Paleorecord. *The American Naturalist*, 152(2), 204. DOI: 10.1086/286162.
- Davis, M.B. (1983). Quaternary History of Deciduous Forests of Eastern North America and Europe. *Annals of the Missouri Botanical Garden*, 70(3), 550. DOI: 10.2307/2992086.
- D.Grissino-Mayer, H. (2001). Evaluating crossdating accuracy: A Manual and Tutorial for the computer program COFECHA. *Tree-Ring Research*, Vol 57(2). pp. 205–221. 57(2), 205–221. Retrieved April 14, 2023, from <https://repository.arizona.edu/handle/10150/251654>.
- Felton, A., Boberg, J., Björkman, C., & Widenfalk, O. (2013). Identifying and managing the ecological risks

- of using introduced tree species in Sweden's production forestry. *Forest Ecology and Management*, 307, 165–177. DOI: 10.1016/j.foreco.2013.06.059.
- Hackett-Pain, A.J., Ascoli, D., Vacchiano, G., Biondi, F., Cavin, L., Conedera, M., Drobyshev, I., Liñán, I.D., Friend, A.D., Grabner, M., Hartl, C., Kreyling, J., Lebourgeois, F., Levanič, T., Menzel, A., van der Maaten, E., van der Maaten-Theunissen, M., Muffler, L., Motta, R., ... Zang, C.S. (2018). Climatically controlled reproduction drives interannual growth variability in a temperate tree species. *Ecology Letters*, 21(12), 1833–1844. DOI: 10.1111/ele.13158.
- Harris, I., Osborn, T.J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, 7(1), 1–18. DOI: 10.1038/s41597-020-0453-3.
- Harvey, J.E., Smiljanić, M., Scharnweber, T., Buras, A., Cedro, A., Cruz-García, R., Drobyshev, I., Janecka, K., Jansons, Ā., Kaczka, R., Klisz, M., Läänelaid, A., Matisons, R., Muffler, L., Sohar, K., Spyt, B., Stolz, J., van der Maaten, E., van der Maaten-Theunissen, M., ... Wilmking, M. (2020). Tree growth influenced by warming winter climate and summer moisture availability in northern temperate forests. *Global Change Biology*, 26(4), 2505–2518. DOI: 10.1111/gcb.14966.
- Hepp, T.E., Vimmerstedt, J.P., Smalley, G.W., & McNab, W.H. (2015). Estimating yields of unthinned Eastern White pine plantations from current stocking in the Southern Appalachians. *Forest Science*, 61(1), 114–122. DOI: 10.5849/forsci.13-620.
- Keča, L., Marčeta, M., Božič, G., Perić, S., Tsvetkov, I., Andreassen, K., Stijović, A., Mandzukovski, D., Zlokapa, B., & Nicolescu, V.N. (2019). Non-Native Tree Species: Strategies for Sustainable Management in Europe. *International Forestry Review*, 21(3), 295–314. DOI: 10.1505/146554819827293222.
- Kirilenko, A.P., & Sedjo, R.A. (2007). Climate change impacts on forestry. *Proceedings of the National Academy of Sciences of the United States of America*, 104(50), 19697–19702. DOI: 10.1073/pnas.0701424104.
- Klisz, M., Jevšenak, J., Prokopuk, Y., Gil, W., Mohytych, V., & Puchałka, R. (2022). Coping with Central European climate – xylem adjustment in seven non-native conifer tree species. *Dendrobiology*, 88(November), 105–123. DOI: 10.12657/denbio.088.008.
- Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, 15(3), 259–263. DOI: 10.1127/0941-2948/2006/0130.
- Krumm, F., & Vitkova, L. (2016). Introduced tree species in European forests: opportunities and challenges. In *Focus – Managing Forests in Europe*. Retrieved April 14, 2023, from [https://www.researchgate.net/profile/Frank\\_Krumm/publication/311229246\\_Introduced\\_tree\\_species\\_in\\_European\\_forests\\_opportunities\\_and\\_challenges/links/583fc91508ae61f75dc79ed7/Introduced-tree-species-in-European-forests-opportunities-and-challenges.pdf](https://www.researchgate.net/profile/Frank_Krumm/publication/311229246_Introduced_tree_species_in_European_forests_opportunities_and_challenges/links/583fc91508ae61f75dc79ed7/Introduced-tree-species-in-European-forests-opportunities-and-challenges.pdf).
- Läänelaid, A., & Helama, S. (2019). Climatic determinants of introduced Sitka spruce in Hiiumaa Island, Estonia. *Baltic Forestry*, 25(1), 161–167. DOI: 10.46490/vol25iss1pp161.
- Marchand, N., & Fillion, L. (2012). False rings in the white pine (*Pinus strobus*) of the Outaouais hills, Québec (Canada), as indicators of water stress. *Canadian Journal of Forest Research*, 42(1), 12–22. DOI: 10.1139/X11-151.
- Matisons, R., Elferts, D., Krišāns, O., Schneck, V., Gärtner, H., Wojda, T., Kowalczyk, J., & Jansons, Ā. (2021). Nonlinear weather–growth relationships suggest disproportional growth changes of Norway spruce in the Eastern Baltic region. *Forests*, 12(6), 1–17. DOI: 10.3390/f12060661.
- Muller, B., Pantin, F., Génard, M., Turc, O., Freixes, S., Piques, M., & Gibon, Y. (2011). Water deficits uncouple growth from photosynthesis, increase C content, and modify the relationships between C and growth in sink organs. *Journal of Experimental Botany*, 62(6), 1715–1729. DOI: 10.1093/jxb/erq438.
- Podrázský, V., Vacek, Z., Vacek, S., Vítámvás, J., Gallo, J., Prokūpková, A., & D'Andrea, G. (2020). Production potential and structural variability of pine stands in the Czech Republic: Scots pine (*Pinus sylvestris* L.) vs. introduced pines – Case study and problem review. *Journal of Forest Science*, 66(5), 197–207. DOI: 10.17221/42/2020-JFS.
- Pötzelsberger, E., Spiecker, H., Neophytou, C., Mohren, F., Gazda, A., & Hasenauer, H. (2020). Growing Non-native Trees in European Forests Brings Benefits and Opportunities but Also Has Its Risks and Limits. *Current Forestry Reports*, 6(4), 339–353. DOI: 10.1007/s40725-020-00129-0.
- R Core Team, (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved April 14, 2023, from <https://www.R-project.org/>.
- Ricciardi, A., & Simberloff, D. (2009). Assisted colonization is not a viable conservation strategy. *Trends in Ecology and Evolution*, 24(5), 248–253. DOI: 10.1016/j.tree.2008.12.006.
- Santopuoli, G., di Cristofaro, M., Kraus, D., Schuck, A., Lasserre, B., & Marchetti, M. (2019). Biodiversity conservation and wood production in a Natura 2000 Mediterranean forest. A trade-off evaluation focused

- on the occurrence of microhabitats. *IForest*, 12(1), 76–84. DOI: 10.3832/ifor2617-011.
- Spathelf, P., van der Maaten, E., van der Maaten-Theunissen, M., Campioli, M., & Dobrowolska, D. (2014). Climate change impacts in European forests: The expert views of local observers. *Annals of Forest Science*, 71(2), 131–137. DOI: 10.1007/s13595-013-0280-1.
- Speer, H. (2011). Fundamentals of tree-ring research. James H. Speer. *Geoarchaeology*, 26(3), 453–455. DOI: 10.1002/gea.20357.
- Strand, M., Löfvenius, M.O., Bergsten, U., Lundmark, T., & Rosvall, O. (2006). Height growth of planted conifer seedlings in relation to solar radiation and position in Scots pine shelterwood. *Forest Ecology and Management*, 224(3), 258–265. DOI: 10.1016/j.foreco.2005.12.038.
- Tierney, G.L., Fahey, T.J., Groffman, P.M., Hardy, J.P., Fitzhugh, R.D., & Driscoll, C.T. (2001). Soil freezing alters fine root dynamics in a northern hardwood forest. *Biogeochemistry*, 56(2), 175–190. DOI: 10.1023/A:1013072519889.
- van Arsdel, E.P. (1961). Growing white pine in the Lake States to avoid blister rust. USDA Forest Service, Lake States Forest Experiment Station, Station P. 12.
- Vicente-Serrano, S.M., Beguería, S., & López-Moreno, J.I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, 23(7), 1696–1718. DOI: 10.1175/2009JCLI2909.1.
- von Arx, G., Arzac, A., Fonti, P., Frank, D., Zweifel, R., Rigling, A., Galiano, L., Gessler, A., & Olano, J.M. (2017). Responses of sapwood ray parenchyma and non-structural carbohydrates of *Pinus sylvestris* to drought and long-term irrigation. *Functional Ecology*, 31(7), 1371–1382. DOI: 10.1111/1365-2435.12860.
- Wigley, T.M.L., Briffa, K.R., & Jones, P.D. (1984). On the Average Value of Correlated Time Series, with Applications in Dendroclimatology and Hydrometeorology. 21(1), 1–9. Retrieved April 14, 2023, from <http://journal.um-surabaya.ac.id/index.php/JKM/article/view/2203>.
- Wilmking, M., van der Maaten-Theunissen, M., van der Maaten, E., Scharnweber, T., Buras, A., Biermann, C., Gurskaya, M., Hallinger, M., Lange, J., Shetti, R., Smiljanic, M., & Trouillier, M. (2020). Global assessment of relationships between climate and tree growth. *Global Change Biology*, 26(6), 3212–3220. DOI: 10.1111/gcb.15057.
- Wood, S.N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Yuanzineng Kexue Jishu/Atomic Energy Science and Technology*, 73(1), 3–36. DOI: 10.7538/yzk.2014.48.11.1969.
- You, J., & Wang, S. (2021). Higher Probability of Occurrence of Hotter and Shorter Heat Waves Followed by Heavy Rainfall. *Geophysical Research Letters*, 48(17), 1–11. DOI: 10.1029/2021GL094831.
- Zang, C., & Biondi, F. (2013). Dendroclimatic calibration in R: The bootRes package for response and correlation function analysis. *Dendrochronologia*, 31(1), 68–74. DOI: 10.1016/j.dendro.2012.08.001.