SUPPLEMENTARY INFORMATION

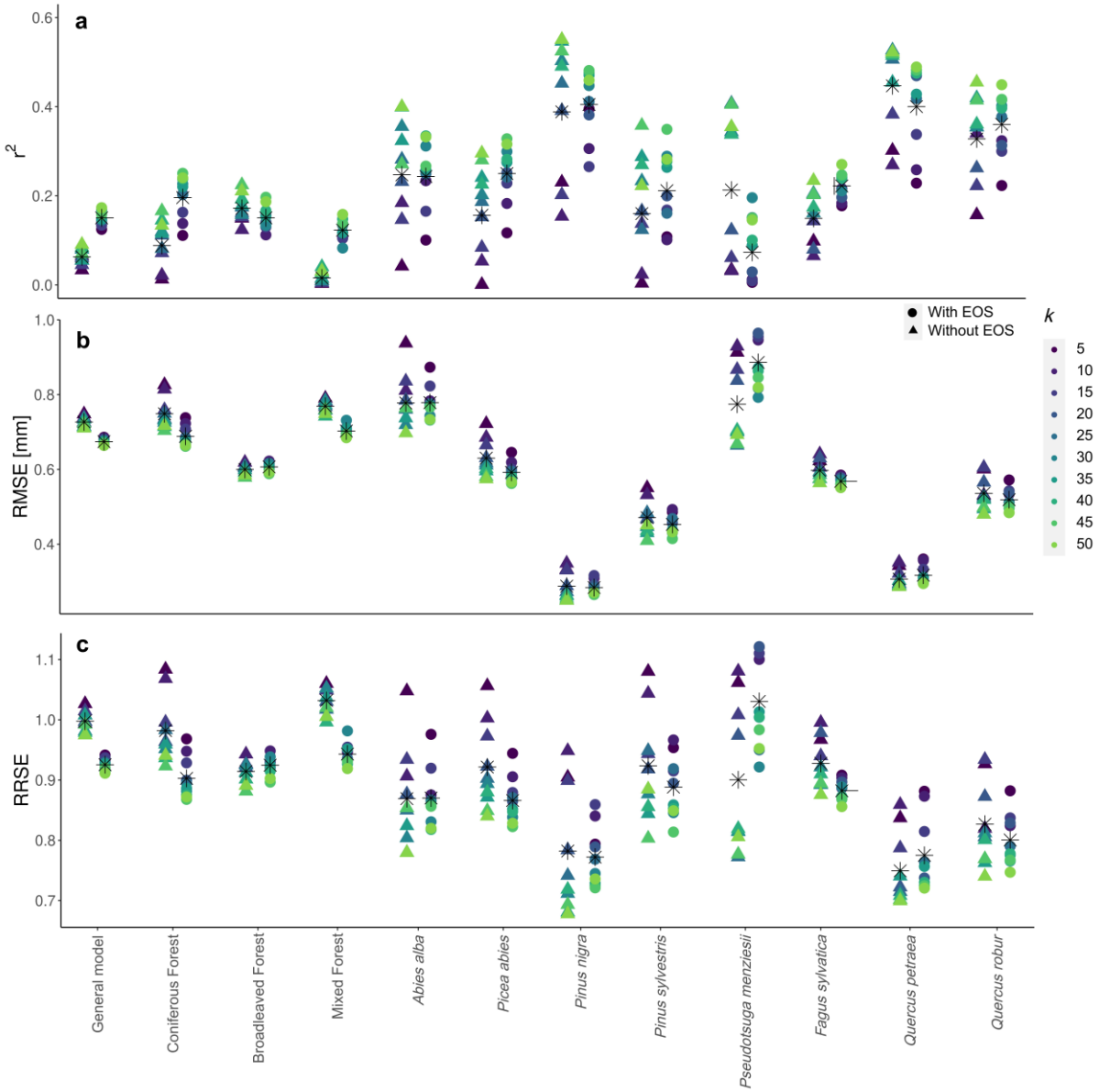
Incorporating high-resolution climate, remote sensing and topographic data to map annual forest growth in central and eastern Europe

Jernej Jevšenak[1, 2, *], Marcin Klisz[3], Jiří Mašek[4], Vojtěch Čada[5], Pavel Janda[5], Miroslav Svoboda[5], Ondřej Vostarek[5], Vaclav Treml[4], Ernst van der Maaten[6], Andrei Popa[7, 8], Ionel Popa[7], Marieke van der Maaten-Theunissen[6], Tzvetan Zlatanov[9], Tobias Scharnweber[10], Svenja Ahlgrimm[10], Juliane Stolz[6, 11], Irena Sochová[12, 13], Cătălin-Constantin Roibu[14], Hans Pretzsch[1], Gerhard Schmied[1], Enno Uhl[1, 15], Ryszard Kaczka[4], Piotr Wrzesiński[3], Martin Šenfeldr[16], Marcin Jakubowski[17], Jan Tumajer[4], Martin Wilmking[10], Nikolaus Obojes[18], Michal Rybníček[12, 13], Mathieu Lévesque[19], Aleksei Potapov[20], Soham Basu[21], Marko Stojanović[13], Stefan Stjepanović[22], Adomas Vitas[23], Domen Arnič[24], Sandra Metslaid[20], Anna Neycken[19], Peter Prislan[24], Claudia Hartl[25, 26], Daniel Ziche[27], Petr Horáček[12, 13], Jan Krejza[21, 13], Sergei Mikhailov[12, 13], Jan Světlík[21, 13], Aleksandra Kalisty[28], Tomáš Kolář[12, 13], Vasyl Lavnyy[29], Maris Hordo[20], Walter Oberhuber[30], Tom Levanič[31, 32], Ilona Mészáros[33], Lea Schneider[34], Jiří Lehejček[35], Rohan Shetti[35], Michal Bošeľa[36], Paul Copini[37, 38], Marcin Koprowski[39, 40], Ute Sass-Klaassen[37, 41], Şule Ceyda Izmir[42], Remigijus Bakys[43], Hannes Entner[30], Jan Esper[44], Karolina Janecka[10, 45], Edurne Martinez del Castillo[44], Rita Verbylaite[46], Mátyás Árvai[47], Justine Charlet de Sauvage[19], Katarina Čufar[48], Markus Finner[30], Torben Hilmers[1], Zoltán Kern[49, 50], Klemen Novak[48], Radenko Ponjarac[51], Radosław Puchałka[39, 40], Bernhard Schuldt[52], Nina Škrk Dolar[48], Vladimir Tanovski[53], Christian Zang[54, 1], Anja Žmegač[54, 1], Cornell Kuithan[6], Marek Metslaid[55], Eric Thurm[11], Polona Hafner[31], Luka Krajnc[31], Mauro Bernabei[56], Stefan Bojić[22], Robert Brus[57], Andreas Burger[10], Ettore D'Andrea[58, 59], Todor Đorem[22], Mariusz Gławęda[60], Jožica Gričar[61], Marko Gutalj[22], Emil Horváth[62], Saša Kostić[51], Bratislav Matović[51, 22], Maks Merela[48], Boban Miletić[22], András Morgós[63], Rafał Paluch[64], Kamil Pilch[64], Negar Rezaie[58], Julia Rieder[52], Niels Schwab[65], Piotr Sewerniak[66], Dejan Stojanović[51], Tobias Ullmann[67], Nella Waszak[40], Ewa Zin[64, 68], Mitja Skudnik[2, 57], Krištof Oštir[69], Anja Rammig[1], Allan Buras[1]

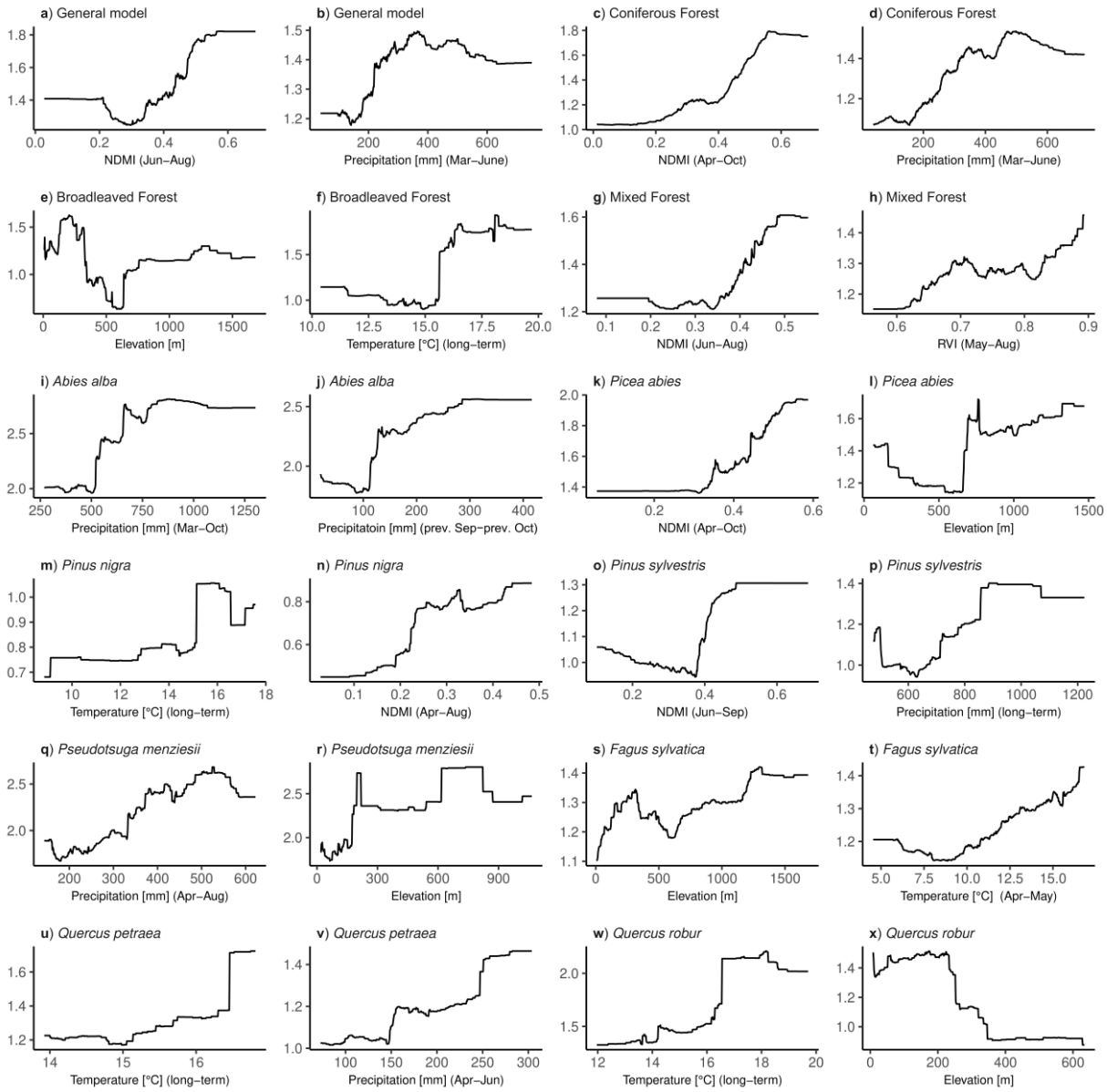
[1]TUM School of Life Sciences, Technical University of Munich, Germany
[2]Department for Forest and Landscape Planning and Monitoring, Slovenian Forestry Institute, Slovenia
[3]Dendrolab IBL, Department of Silviculture and Forest Tree Genetics, Forest Research Institute, Poland
[4]Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Czech Republic
[5]Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Czech Republic
[6]Chair of Forest Growth and Woody Biomass Production, TU Dresden, Germany
[7]National Institute for Research and Development in Forestry "Marin Drăcea", Romania
[8]Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Romania
[9]Institute of Biodiversity and Ecosystem Research, Bulgarian Academy of Sciences, Bulgaria
[10]DendroGreif, Institute of Botany and Landscape Ecology, Greifswald University, Germany
[11]Department of Forest Planning/Forest Research/Information Systems, Research Unit Silviculture and Forest Growth, Landesforst Mecklenburg-Vorpommern, Germany

[12]*Department of Wood Science and Wood Technology, Mendel University in Brno, Czech Republic*
[13]*Global Change Research Institute of the Czech Academy of Sciences, Czech Republic*
[14]*Forest Biometrics Laboratory, Faculty of Forestry, "Stefan cel Mare" University of Suceava, Romania*
[15]*Bavarian State Institute of Forestry, Germany*
[16]*Department of Forest Botany, Dendrology and Geobiocoenology, Mendel University in Brno, Czech Republic*
[17]*Department of Forest Utilisation, Faculty of Forest and Wood Technology, Poznań University of Life Sciences, Poland*
[18]*Institute for Alpine Environment, Eurac Research, Italy*
[19]*Silviculture Group, Institute of Terrestrial Ecosystems, ETH Zurich, Switzerland*
[20]*Chair of Forest and Land Management and Wood Processing Technologies, Estonian University of Life Sciences, Estonia*
[21]*Department of Forest Ecology, Mendel University in Brno, Czech Republic*
[22]*Department of Forestry, Faculty of Agriculture, University of East Sarajevo, Bosnia and Herzegovina*
[23]*Vytautas Magnus University, Lithuania*
[24]*Department for Forest Technique and Economics, Slovenian Forestry Institute, Slovenia*
[25]*Nature Rings – Environmental Research and Education, Germany*
[26]*Panel on Planetary Thinking, Justus-Liebig-University, Germany*
[27]*Faculty of Forest and Environment, Eberswalde University for Sustainable Development, Germany*
[28]*Faculty of Forestry, Bialystok University of Technology, Poland*
[29]*Department of Silviculture, Ukrainian National Forestry University, Ukraine*
[30]*Department of Botany, University of Innsbruck, Austria*
[31]*Department of Forest Yield and Silviculture, Slovenian Forestry Institute, Slovenia*
[32]*Faculty of Mathematics, Natural Sciences and Information Technologies, University of Primorska, Slovenia*
[33]*Department of Botany, Faculty of Science and Technology, University of Debrecen, Hungary*
[34]*Department of Geography, Justus-Liebig-University, Germany*
[35]*Department of Environment, Faculty of Environment, Jan Evangelista Purkyně University, Czech Republic*
[36]*Department of Forest Management Planning and Informatics, Faculty of Forestry, Technical University in Zvolen, Slovakia*
[37]*Forest Ecology and Forest Management (FEM), Wageningen University & Research, The Netherlands*
[38]*Wageningen Environmental Research, Wageningen University & Research, The Netherlands*
[39]*Department of Ecology and Biogeography, Faculty of Biological and Veterinary Sciences, Nicolaus Copernicus University, Poland*
[40]*Centre for Climate Change Research, Nicolaus Copernicus University, Poland*
[41]*van Hall Larenstein Applied University, The Netherlands*
[42]*Department of Forest Botany, Faculty of Forestry, Istanbul University-Cerrahpaşa, Turkey*
[43]*Department of Forestry, Kaunas Forestry and Environmental Engineering University of Applied Sciences, Lithuania*
[44]*Department of Geography, Johannes Gutenberg University, Germany*
[45]*Climate Change Impacts and Risks in the Anthropocene (C-CIA), Institute for Environmental Sciences, University of Geneva, Switzerland*
[46]*Department of Forest Genetics and Tree Breeding, Lithuanian Research Centre for Agriculture and Forestry, Lithuania*
[47]*Institute for Soil Sciences, HUN-REN Centre for Agricultural Research, Hungary*
[48]*Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Slovenia*
[49]*Institute for Geological and Geochemical Research, HUN-REN Research Centre for Astronomy and Earth Sciences, Hungary*
[50]*CSFK, MTA Centre of Excellence, Budapest, Hungary*
[51]*Institute of Lowland Forestry and Environment, University of Novi Sad, Serbia*
[52]*Chair of Forest Botany, TU Dresden, Germany*
[53]*Hans Em, Faculty of Forest Sciences, Landscape Architecture and Environmental Engeneering, Ss. Cyril and Methodius, University in Skopje, North Macedonia*
[54]*Department of Forestry, University of Applied Sciences Weihenstephan-Triesdorf, Germany*
[55]*Institute of Forestry and Engineering, Estonian University of Life Sciences, Estonia*
[56]*Institute of BioEconomy, National Research Council, Italy*
[57]*Department of Forestry and Renewable Forest Resources, Biotechnical Faculty, University of Ljubljana, Slovenia*
[58]*Research Institute on Terrestrial Ecosystems (IRET), National Research Council of Italy (CNR), Italy*
[59]*National Biodiversity Future Centre – NBFC, Italy*
[60]*Stefan Żeromski High School No 2 with Bilingual Departments in Sieradz, Poland*
[61]*Department of Forest Physiology and Genetics, Slovenian Forestry Institute, Slovenia*
[62]*Independent researcher, Hungary*
[63]*Consart Bt., Hungary*
[64]*Dendrolab IBL, Department of Natural Forests, Forest Research Institute (IBL), Poland*
[65]*Centre for Earth System Research and Sustainability (CEN), Institute of Geography, Universität Hamburg, Germany*
[66]*Department of Soil Science and Landscape Management, Nicolaus Copernicus University, Poland*
[67]*Department of Remote Sensing, Institute of Geography and Geology, University of Würzburg, Germany*
[68]*Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences (SLU), Sweden*
[69]*Faculty of Civil and Geodetic Engineering, University of Ljubljana, Slovenia*

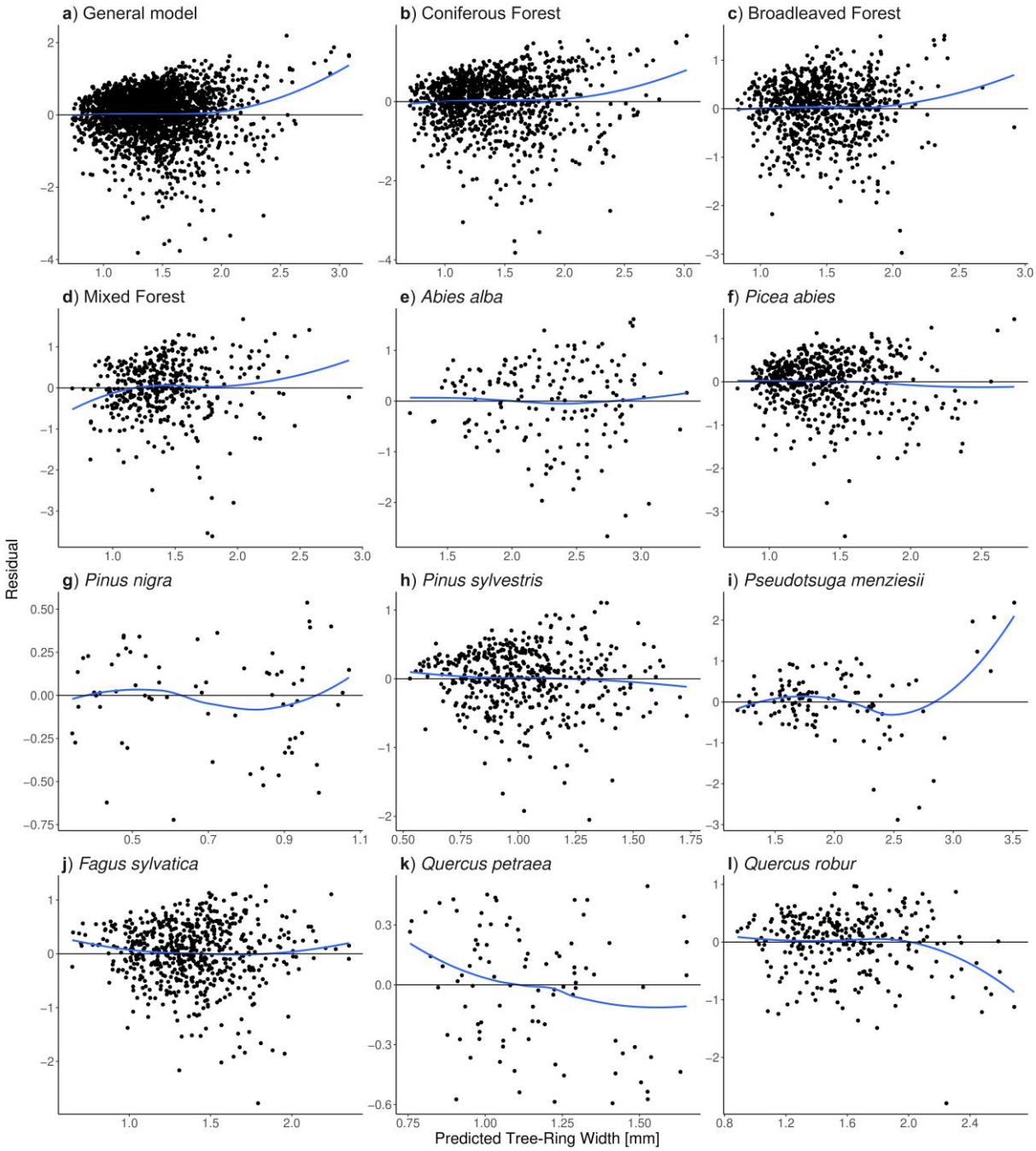
[*]*Correspondence: jernej.jevsenak@gozdis.si*



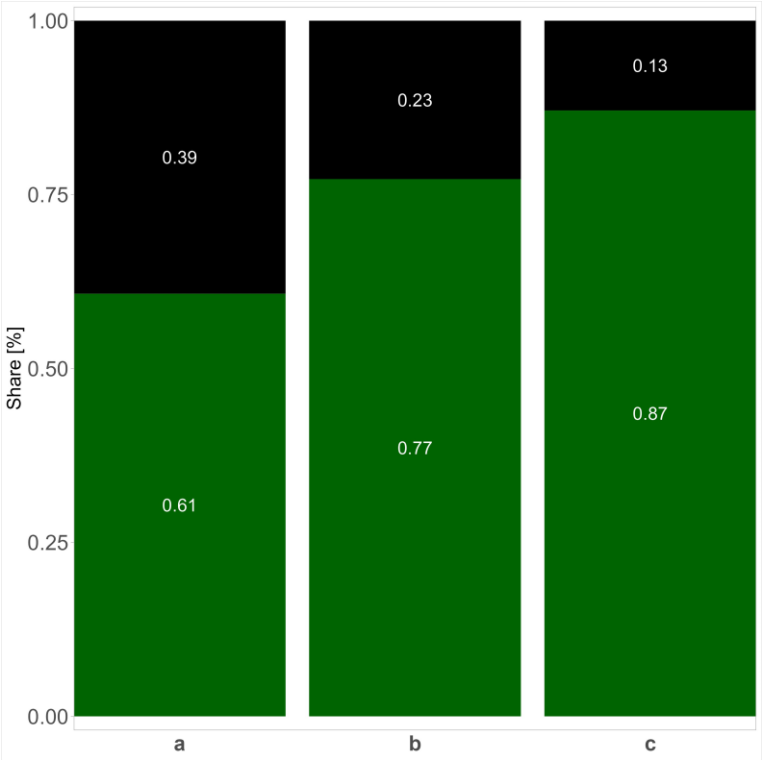
Supplementary Fig. 1: The variation in the explained variance (R^2) (**a**), root mean square error (RMSE) (**b**) and root relative square error (**c**) as a function of the chosen *k* in *k*-fold blocked cross-validation for the modelling approach with and without the inclusion of Earth observation by satellites (EOS). The "*" symbols indicate mean values.



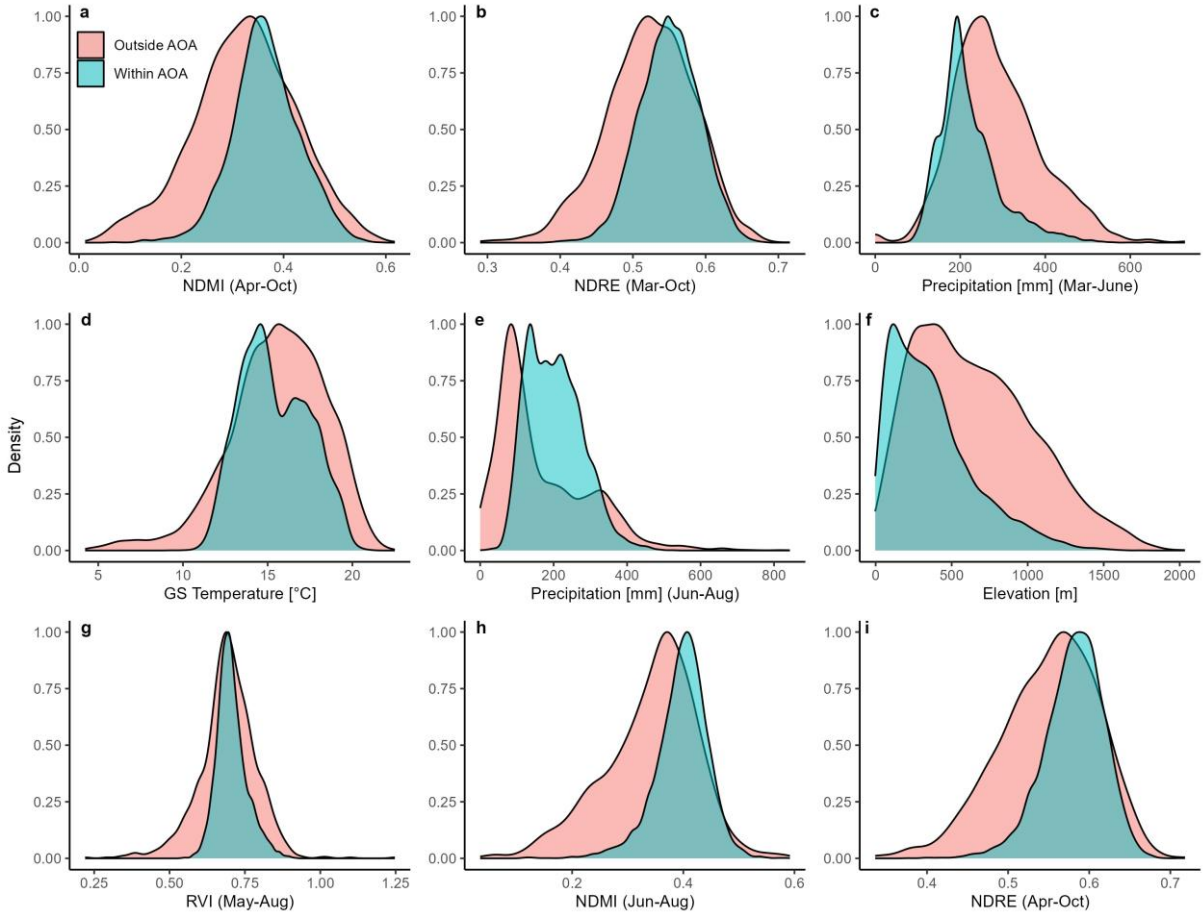
Supplementary Fig. 2: **Partial dependence plots depicting marginal effects of predictor variables on radial tree growth.** For each model, we highlight two of the most important predictor variables. Vegetation indices (NDMI and RVI), seasonal temperatures and precipitation sums generally have positive relationships with tree growth. NDMI – normalised difference moisture index, RVI – radar vegetation index.



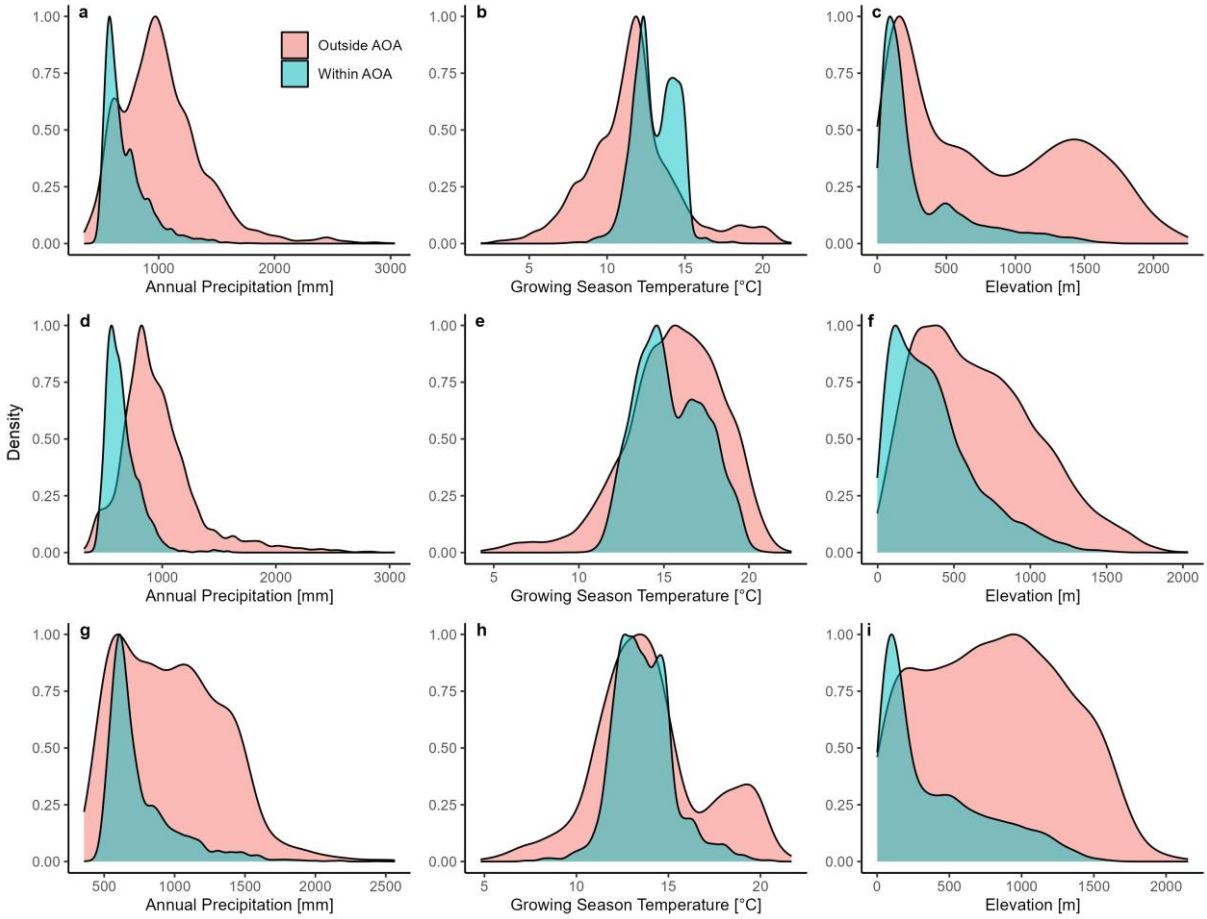
Supplementary Fig. 3: The residual plot analyses indicate minor prediction bias for large increments, which are generally underrepresented in the current TREOS network. The blue line depicts loess smoothing.



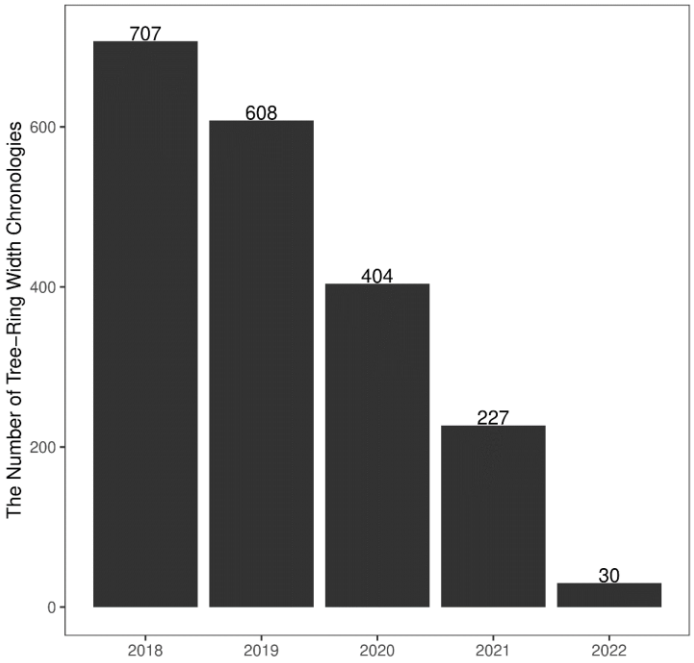
Supplementary Fig. 4: The share of pixels within (green colour) and outside (black colour) the area of applicability (AOA) for the three forest-type models: broadleaved forests (**a**), coniferous forests (**b**) and mixed forests (**c**).



Supplementary Fig. 5: Density plots of key predictor variables within and outside the area of applicability (AOA) for predicting tree-ring width for three different forest types: conifers (**a–c**), broadleaves (**d–f**) and mixed forests (**g–i**). GS – long-term (2000–2022) growing season (April–September) mean temperature. NDMI – normalised difference moisture index, NDRE – normalised difference red edge index, RVI – radar vegetation index.



Supplementary Fig. 6: Density plots of long-term (2000–2022) growing season (April–September) mean temperatures and annual (January–December) precipitation sums and elevations for pixels within and outside the area of applicability (AOA) for predicting tree-ring width for three different forest types: conifers (**a–c**), broadleaves (**d–f**) and mixed forests (**g–i**).



Supplementary Fig. 7: Number of tree-ring width chronologies within TREOS for each year over the period 2018–2022.

Supplementary Table 1: Variable importance following the permutation principle of the 'mean decrease in accuracy' in random forest models. Relative importance was obtained by dividing variable importance by the sum of importance within each model. The long-term (2000–2022) averages for temperatures refer to the growing season (from April to September), while for precipitation and climatic water balance, they were calculated for the entire year – that is, from January to December. NDMI – normalised difference moisture index, NDRE – normalised difference red edge index, EVI – enhanced vegetation index, RVI – radar vegetation index, NDMI – normalised difference moisture index, RVI – radar vegetation index, VV (vertical–vertical) and VH (vertical–horizontal) backscattering coefficients.

Model	Variable	Importance	Relative importance
General model	NDMI (Jun–Aug)	0.08	**0.24**
General model	Precipitation [mm] (Mar–June)	0.06	**0.18**
General model	NDRE (Mar–Oct)	0.05	**0.16**
General model	Elevation [m]	0.03	**0.11**
General model	Temperature [°C] (long-term)	0.02	**0.07**
General model	EVI (Apr–Aug)	0.02	**0.07**
General model	Precipitation [mm] (pr.Sep–pr.Oct)	0.02	**0.06**
General model	RVI (Mar–Jun)	0.02	**0.05**
General model	Temperature [°C] (Apr–May)	0.01	**0.04**
General model	VV (Apr–May)	0.01	**0.03**
Coniferous Forest	NDMI (Apr–Oct)	0.10	**0.26**
Coniferous Forest	Precipitation [mm] (Mar–June)	0.06	**0.17**
Coniferous Forest	NDRE (Mar–Oct)	0.06	**0.15**
Coniferous Forest	Elevation [m]	0.05	**0.13**
Coniferous Forest	EVI (Apr–Aug)	0.05	**0.13**
Coniferous Forest	Precipitation [mm] (pr.Sep–pr.Oct)	0.02	**0.06**
Coniferous Forest	VV (May–Aug)	0.02	**0.05**
Coniferous Forest	RVI (Mar–Jun)	0.02	**0.05**
Broadleaved Forest	Elevation [m]	0.18	**0.41**
Broadleaved Forest	Temperature [°C] (long-term)	0.11	**0.24**
Broadleaved Forest	Precipitation [mm] (Jun–Aug)	0.06	**0.14**
Broadleaved Forest	Precipitation [mm] (pr.Sep–pr.Oct)	0.05	**0.12**
Broadleaved Forest	Precipitation [mm] (long-term)	0.03	**0.07**
Broadleaved Forest	Temperature [°C] (Apr–May)	0.01	**0.03**
Mixed Forest	NDMI (Jun–Aug)	0.12	**0.44**
Mixed Forest	RVI (May–Aug)	0.04	**0.15**
Mixed Forest	NDRE (Apr–Oct)	0.03	**0.11**
Mixed Forest	VH (Jun–Aug)	0.02	**0.07**
Mixed Forest	Water Balance (Jul–Aug)	0.02	**0.07**
Mixed Forest	Elevation [m]	0.01	**0.05**
Mixed Forest	VH (Apr–May)	0.01	**0.04**
Mixed Forest	Precipitation [mm] (Jun–Aug)	0.01	**0.04**
Mixed Forest	EVI (Apr–Aug)	0.01	**0.03**
Abies alba	Precipitation [mm] (Mar–Oct)	0.18	**0.40**
Abies alba	Precipitation [mm] (pr.Sep–pr.Oct)	0.10	**0.22**
Abies alba	Elevation [m]	0.06	**0.13**
Abies alba	RVI (Mar–Jun)	0.05	**0.12**
Abies alba	Water Balance (Apr–May)	0.05	**0.11**
Abies alba	NDRE (Jun–Aug)	0.01	**0.02**

continues on the next page …

… continued …

Model	Variable	Importance	Relative importance
Picea abies	NDMI (Apr–Oct)	0.13	**0.38**
Picea abies	Elevation [m]	0.06	**0.18**
Picea abies	Precipitation [mm] (Apr–Jun)	0.05	**0.13**
Picea abies	Precipitation [mm] (long-term)	0.04	**0.10**
Picea abies	NDRE (Mar–Oct)	0.03	**0.08**
Picea abies	EVI (Mar–Oct)	0.02	**0.05**
Picea abies	RVI (Apr–Aug)	0.02	**0.05**
Picea abies	Precipitation [mm] (Jul–Aug)	0.01	**0.04**
Pinus nigra	Temperature [°C] (long-term)	0.05	**0.40**
Pinus nigra	NDMI (Apr–Aug)	0.04	**0.32**
Pinus nigra	VH (Jul–Aug)	0.03	**0.25**
Pinus nigra	VV (Apr–May)	0.00	**0.03**
Pinus sylvestris	NDMI (Jun–Sep)	0.07	**0.33**
Pinus sylvestris	Precipitation [mm] (long-term)	0.03	**0.14**
Pinus sylvestris	Elevation [m]	0.03	**0.13**
Pinus sylvestris	RVI (Mar–Jun)	0.02	**0.10**
Pinus sylvestris	EVI (Apr–Oct)	0.02	**0.09**
Pinus sylvestris	Precipitation [mm] (Mar–Aug)	0.02	**0.08**
Pinus sylvestris	Water Balance (long-term)	0.02	**0.07**
Pinus sylvestris	Temperature [°C] (pr.Sep–pr.Oct)	0.01	**0.06**
Pseudotsuga menziesii	Precipitation [mm] (Apr–Aug)	0.14	**0.52**
Pseudotsuga menziesii	Elevation [m]	0.09	**0.34**
Pseudotsuga menziesii	Water Balance (long-term)	0.03	**0.13**
Fagus sylvatica	Elevation [m]	0.05	**0.21**
Fagus sylvatica	Temperature [°C] (Apr–May)	0.03	**0.15**
Fagus sylvatica	Precipitation [mm] (Apr–Jun)	0.03	**0.14**
Fagus sylvatica	EVI (Apr–Aug)	0.03	**0.12**
Fagus sylvatica	NDRE (Mar–Sep)	0.03	**0.11**
Fagus sylvatica	Precipitation [mm] (pr.Sep–pr.Oct)	0.02	**0.10**
Fagus sylvatica	NDRE (Jun–Sep)	0.01	**0.05**
Fagus sylvatica	Precipitation [mm] (long-term)	0.01	**0.05**
Fagus sylvatica	Temperature [°C] (pr.Aug–pr.Oct)	0.01	**0.04**
Fagus sylvatica	NDMI (Mar–Sep)	0.01	**0.04**
Quercus petraea	Temperature [°C] (long-term)	0.05	**0.51**
Quercus petraea	Precipitation [mm] (Apr–Jun)	0.03	**0.32**
Quercus petraea	Elevation [m]	0.01	**0.06**
Quercus petraea	Precipitation [mm] (pr.Aug–pr.Oct)	0.01	**0.05**
Quercus petraea	Precipitation [mm] (long-term)	0.01	**0.05**
Quercus robur	Temperature [°C] (long-term)	0.25	**0.56**
Quercus robur	Elevation [m]	0.07	**0.16**
Quercus robur	VV (Jul–Aug)	0.05	**0.12**
Quercus robur	Temperature [°C] (Apr–May)	0.02	**0.06**
Quercus robur	Precipitation [mm] (Jul–Aug)	0.02	**0.06**
Quercus robur	Precipitation [mm] (Mar–June)	0.01	**0.03**
Quercus robur	NDRE (Mar–Aug)	0.01	**0.02**