

DR. JESUS JULIO CAMARERO (Orcid ID : 0000-0003-2436-2922)

DR. RAÚL SÁNCHEZ-SALGUERO (Orcid ID : 0000-0002-6545-5810)

DR. EMILIA GUTIERREZ (Orcid ID : 0000-0002-6085-5700)

DR. ENRIC BATLLORI (Orcid ID : 0000-0002-2130-0489)

DR. MARCO CARRER (Orcid ID : 0000-0003-1581-6259)

PROF. ANNIKA HOFGAARD (Orcid ID : 0000-0001-6919-5537)

DR. ERYUAN LIANG (Orcid ID : 0000-0002-8003-4264)

DR. JUAN CARLOS LINARES (Orcid ID : 0000-0001-8375-6353)

DR. GABRIEL SANGÜESA-BARREDA (Orcid ID : 0000-0002-7722-2424)

PROF. MARTIN WILMKING (Orcid ID : 0000-0003-4964-2402)

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Global fading of the temperature-growth coupling at alpine and polar treelines

Running head: Temperature-growth uncoupling at treeline

J. Julio Camarero^{1*}, Antonio Gazol¹, Raúl Sánchez-Salguero^{1,2}, Alex Fajardo³, Eliot J.B. McIntire⁴, Emilia Gutiérrez⁵, Enric Batllori^{5,6}, Stéphane Boudreau⁷, Marco Carrer⁸, Jeff Diez⁹, Geneviève Dufour-Tremblay⁷,

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Narayan P. Gaire^{10,11}, Annika Hofgaard¹², Vincent Jomelli¹³, Alex Kirilyanov^{14,15}, Esther Lévesque¹⁶, Eryuan Liang¹⁷, J. Carlos Linares², Ingrid E. Mathisen¹⁸, Pavel A. Moiseev¹⁹, Gabriel Sangüesa-Barreda²⁰, Krishna B. Shrestha²¹, Johanna M. Toivonen²², Olga V. Tutubalina²³ and Martin Wilmking²⁴

¹Instituto Pirenaico de Ecología (IPE-CSIC), Avda. Montañana 1005, E-50192 Zaragoza, Spain

²Depto. de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, Crta. Utrera km. 1, E-41013 Sevilla, Spain

³Centro de Investigación en Ecosistemas de la Patagonia (CIEP), Coyhaique, Chile

⁴Natural Resources Canada, Pacific Forestry Centre, Victoria, BC, Canada

⁵Dept. Biología Evolutiva, Ecología i Ciències Ambientals, Univ. Barcelona, Av. Diagonal, 643, E-08028 Barcelona, Spain

⁶Centre for Ecological Research and Forestry Applications (CREAF), E-08193 Bellaterra, Spain

⁷Centre d'Études Nordiques (CEN), Univ. Laval, Québec, G1V 0A6 QC, Canada

⁸Università degli Studi di Padova, Dip. TeSAF, IT-35020 Legnaro (PD), Italy

⁹Dept. Botany and Plant Sciences, Univ. California, Riverside, CA 92521, USA

¹⁰Nepal Academy of Science and Technology, Lalitpur, Kathmandu, Nepal

¹¹CAS Key Laboratory of Tropical Forest Ecology, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Menglun, Mengla, Yunnan CH-666303, China

¹²Norwegian Institute for Nature Research, NO-7485 Trondheim, Norway

¹³CNRS Cerege, Technopole environnement arbois-mediterranee bp80 13545 Aix en Provence, France

¹⁴Institute of Ecology and Geography, Siberian Federal University, 660041 Krasnoyarsk, Svobodnii 79, Russia

¹⁴V.N.Sukachev Institute of Forest SB RAS, Federal Research Center 'Krasnoyarsk Science 30 Center SB RAS', 660036 Krasnoyarsk, Akademgorodok, Russia 31

¹⁵Institute of Ecology and Geography, Siberian Federal University, 660041 Krasnoyarsk, 32 Svobodnii 79, Russia.

¹⁶Centre d'Études nordiques (CEN), Univ. Québec à Trois-Rivières, QC, Canada

¹⁷Key Laboratory of Alpine Ecology and Biodiversity, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

¹⁸Norwegian Biodiversity Information Centre PB 1058, 7446 Trondheim, Norway

¹⁹Institute of Plant and Animal Ecology UrB RAS, Ekaterinburg, 620144, Russia

²⁰EiFAB-iuFOR, Univ. Valladolid, E-42004 Soria, Spain

²¹Dept. Biology, University of Bergen, PO Box 7803, NO-5020, Bergen, Norway

²²Dept. Biology, University of Turku, FI-20014 Turku, Finland

²³Dept. Geography, M.V. Lomonosov Moscow State University, Moscow, Russia

²⁴DendroGreif, Institute of Botany and Landscape Ecology, Univ. Greifswald, D-17487 Greifswald, Germany.

*Corresponding author:

Dr. J. Julio Camarero

Instituto Pirenaico de Ecología (IPE-CSIC)

50080 Zaragoza, Spain.

E-mail: jjcamarero@ipe.csic.es

ORCID: 0000-0003-2436-2922

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Abstract

Climate warming is expected to positively alter upward and poleward treelines which are controlled by low temperature and a short growing season. Despite the importance of treelines as a bioassay of climate change, a global field assessment and posterior forecasting of tree growth at annual scales is lacking. Using annually resolved tree-ring data located across Eurasia and the Americas, we quantified and modeled the relationship between temperature and radial growth at treeline during the 20th century. We then tested whether this temperature-growth association will remain stable during the 21st century using a forward model under two climate scenarios (RCP 4.5 and 8.5). During the 20th century, growth enhancements were common in most sites, and temperature and growth showed positive trends. Interestingly, the relationship between temperature and growth trends was contingent on tree age suggesting biogeographical patterns in treeline growth are contingent on local factors besides climate warming. Simulations forecast temperature-growth decoupling during the 21st century. The growing season at treeline is projected to lengthen and growth rates would increase and become less dependent on temperature rise. These forecasts illustrate how growth may decouple from climate warming in cold regions and near the margins of tree existence. Such projected temperature-growth decoupling could impact ecosystem processes in mountain and polar biomes, with feedbacks on climate warming.

Keywords: Climate warming; forest limit; growth model; mountain ecosystems; tree rings.

Introduction

Mountain treelines are considered receptive monitors of the effects of climate warming on terrestrial ecosystems (Holtmeier and Broll 2005; Harsch et al. 2009; Smith et al. 2009; Körner 2012). Global average surface air temperature has increased by +0.8 °C since 1900, but climate warming intensified since the 1980s at historically unprecedented rates, and this positive temperature trend is forecasted to continue and exacerbate during the 21st century (IPCC 2014). Rapid climate warming along with the increase in atmospheric CO₂ concentration has translated into acceleration of tree growth at many altitudinal and latitudinal treelines worldwide (Devi et al. 2008; Liang et al. 2011, 2014; Treml and Veblen 2017). At such range-edge tree populations, radial growth is a more sensitive and close tracking cue of the interannual temperature variation than changes in treeline position, which shows lagged or non-linear responses to climate warming due to demographic processes (Camarero and Gutiérrez 2004; Daniels and Veblen 2004; Batllori and Gutiérrez 2008; Fajardo and McIntire 2012).

Warming-triggered growth enhancement at treeline is expected to result in tighter coupling of tree meristems to air temperatures as trees get taller (Körner 2012). The enhanced growth and the relaxation of cold-temperature limitations will lead to enhanced reproduction, tree establishment, and, potentially, could induce long-term treeline shifts (Wiegand et al. 2006; Harsch et al. 2009; Camarero et al. 2017). Such treeline advance into treeless ecosystems could create new and different communities from those found near the forest limit. Forest expansion would affect carbon storage, nutrient cycling and hydrological properties in mountains and boreal biomes, with significant feedbacks on climate warming and human populations which depend on mountain water resources (Greenwood and Jump 2014). If growth rates of treeline trees will be monotonically and tightly coupled to current and forecasted climate warming, treeline advance could be widespread and accelerated in the coming decades. This forests expansion could have large impacts on community assemblage and ecosystem functions. However, to properly project treeline shifts and dynamics, we need a sound global assessment and prediction of tree growth at treelines.

Although during the 20th century tree growth has positively responded to rising temperatures in most treeline sites (Wilmking et al. 2004; Salzer et al. 2009), recent investigations in these heat-limited

environments, have detected weak or even negative associations between growth and temperature due to non-growing season conditions (Piper et al. 2016; Fajardo et al. 2019; Hofgaard et al. 2019). In addition, there is the divergence problem which describes a loss of responsiveness of tree growth to rising growing season temperatures in subarctic regions after the 1960s (Briffa et al. 1998). The low-frequency component of photosynthetic solar radiation has also been shown to explain part of the divergence problem in subarctic regions where tree growth is mainly driven by summer temperature (Kirdyanov et al. 2020). Such complex growth responses to temperature rise may depend on local climate conditions, treeline features (e.g., shape, size) and age structure or species-specific traits, making some treelines less valuable monitors of climate warming than expected (Davis et al. 2020). Moreover, if growth at the treeline is not primarily driven by regional or global changes in temperature, other local factors such as biotic interactions (competition, facilitation or herbivorous activity) and local precipitation regimes should be also considered (Batllori et al. 2009; Liang et al. 2016; Wang et al. 2016; Sidgel et al. 2018). To reduce the uncertainties linked to the climate drivers of tree growth at treeline, we need intercontinental assessments encompassing multiple biomes, subjected to different climate conditions, and formed by different taxa. The current study aims to fill this research gap by analyzing 20th-century growth trends using tree-ring width data from 37 Eurasian and American sites located in 13 regions representing most of the key treeline regions in the world. Reliable predictions of tree growth at treeline must be fed by climate projections, but, importantly, they also must be supported by long-term tree growth data at the margins of tree life-form existence. We need global scale ecosystem forecasts in response to climate warming, and this study aims at fulfilling this demand in the case of treelines.

One of the ecological challenges to accomplish continental assessment and forecasting of tree-growth trends at the treeline is explicitly incorporate local factors including climate, taxon, tree age, stand structure or site topography. Here we use well-validated, climate-driven growth models that allow to: (i) determine the main climate drivers of growth variability, and (ii) forecast growth variability as a function of different climate scenarios. Specifically, we modelled how the temperature-growth association will change for the Representative Concentration Pathway (RCP) 4.5 and 8.5 emission scenarios which forecast moderate (0.9–2.6 °C) to intense (1.4–4.8 °C) warming for the late 21st

century, respectively (see Sánchez-Salguero et al. 2017, 2018). We used the Vaganov-Shashkin-Lite process-based growth model (hereafter VS-Lite model), which is based on the relationships between radial growth and climate (Vaganov et al. 2006, 2011). The relationships between air temperatures and radial growth are well established for alpine treelines (Paulsen et al. 2000; Rossi et al. 2007; Liang and Camarero 2018). Having an increase in air temperature due to climate warming, growth is expected to improve. However, as already mentioned, growth enhancements can be lagged or minimal with respect to the temperature rise due to idiosyncratic regional (e.g., climate trends, radiation) or local (e.g., topography) factors. Our primary goal is to forecast the changes in coupling between rising temperature and growth at treeline over the 21st century (**Fig. 1**).

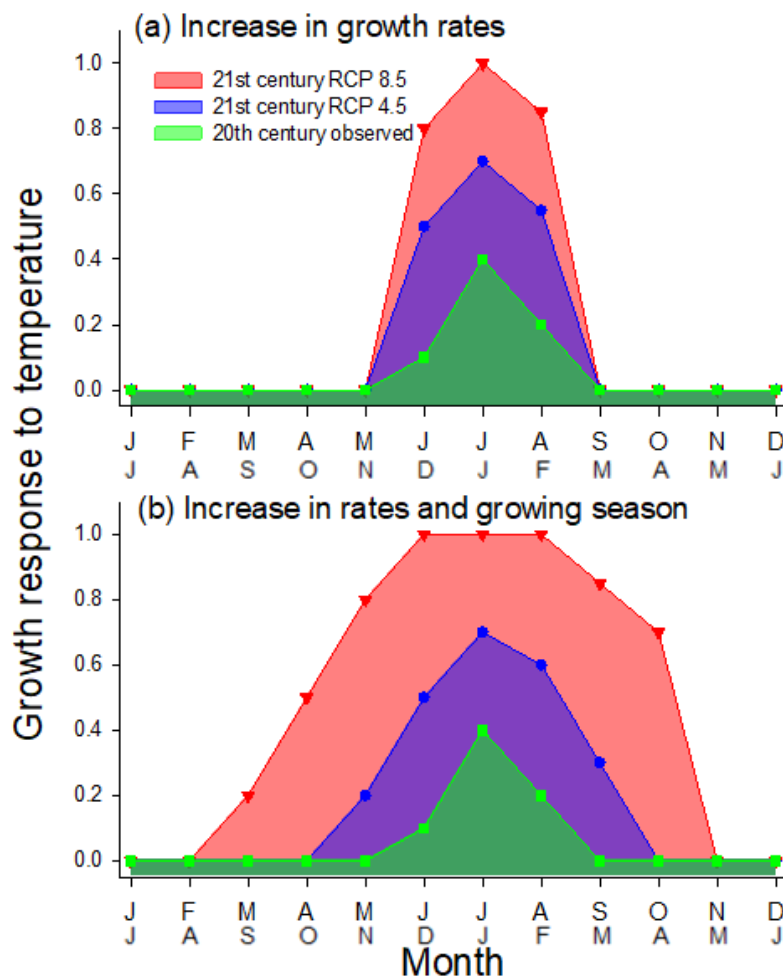


Figure 1. Expected model outputs used to forecast treeline growth responses to climate warming. Future responses could correspond to (a) an increase in growth rates and (b) increases in both growth

rates and growing season length. The figure shows the monthly growth response for temperature (gT, y axes; higher values indicate a lower limitation of growth by low temperatures) using the VS-Lite model for the period 1950–2004 (green lines and areas) and for the 21st-century projected climate under the RCP 4.5 (blue lines and areas) and RCP 8.5 (red lines and areas) scenarios. The temporal window (x axes) spans from January to December in the Northern Hemisphere or from July to June in the Southern Hemisphere. The growing season goes from June to July or from December to January in the Northern and Southern Hemispheres, respectively.

Materials and methods

Study area

We defined the treeline as the ecotone going from the forest limit (with cover above 25%) to the tree limit where at least 2 m single-stemmed tall trees occur (Holtmeier and Broll 2005). Following Harsch and Bader (2011) we classified four types of treeline forms: (i) diffuse, characterized by a gradual decrease in tree density and height with a prevalence of single-stemmed trees; (ii) abrupt, characterized by sharp transitions in tree density and height; (iii) island, characterized by the presence of clumped patches of trees or multi-stemmed, stunted (krummholz) individuals above the forest limit, and (iv) krummholz, characterized by the dominance of stunted, multi-stemmed trees usually forming contiguous bands above the tree limit. Intermediate types between these classes exist. The sampled area encompasses the main ranges where these four treeline types occur (Supporting Information, Figs. S1 and S2, Table S1). Thirty-seven treeline sites were sampled across five main biogeographical regions (Körner 2012) including: the tropical zone (latitude 0–26° S, 2 sites), the warm-temperate zone (latitude 27–32° N; 5 sites), the Mediterranean zone (latitude 32–43° N or S; 11 sites); the temperate zone (latitude 44–57° N or S; 11 sites); and the boreal and subarctic zones (latitude 58–71° N; 8 sites).

Field sampling

During several field campaigns, two to-the-pith long cores were extracted at a height of less than 30 cm from individual trees forming the treeline using increment borers (5.15 mm increment borer (Haglöf, Långsele, Sweden). Stem cores were labelled and placed in a multiwall polycarbonate sheet.

Usually, either transects crossing the treeline ecotone (i.e. following the altitudinal gradient) or rectangular plots were sampled (Camarero and Gutiérrez 2004). Transects or plots were located in undisturbed, open ecotone, topographically homogeneous settings. They contained the uppermost forest limit and the treeline. All trees located in transects or within each plot were sampled and their diameter at breast height (DBH, measured at 1.3 m) and height were measured.

Tree-ring width data

Tree cores were collected to estimate tree age and radial-growth rates. Usually, two cores were extracted from each tree at the direction perpendicular to the maximum slope to avoid sampling reaction wood. Cores were air-dried, mounted in grooved wooden blocks and sanded with sand paper of progressively finer grain size down to 600-800 grit. Samples were then visually cross-dated by detecting and noting characteristic rings. Tree-ring width (TRW) was measured at a resolution of 0.01 mm using sliding stages, and the visual cross-dating was validated using the COFECHA software (Holmes 1983). In those cases where samples had no pith because of the core mispointing or because the innermost rings were lost, pith-offset estimates were calculated. This was accomplished by fitting a geometric pith locator to the innermost rings and converting this distance to the theoretical pith into the number of missing rings (Duncan 1989). We estimated tree age as the maximum number of tree-rings measured or estimated in each individual. We then adjusted this age by adding an estimate of the number of years from the base to the coring height following several field estimates and their high uncertainty (Devi et al. 2008; Liang et al. 2011). We estimated these years by counting annual whorls along the main stems or by counting rings in basal cross-sections of small trees (saplings, seedlings) with heights from 0.1 to 1.5 m (Camarero and Gutiérrez 2004).

The annually-resolved TRW measurements (in mm) were transformed into basal area increments (BAI, in mm²) to account for the geometric constraints of an increasing surface area in ageing trees. We converted TRW into basal area increments (BAI) assuming a circular outline of stem cross-sections. Then, individual TRW and BAI series were obtained for the period 1901–2004, which was the overall best replicated time window, and site averages were also calculated. Normalized BAI for

each tree at each site was calculated as the annual BAI for any given year divided by the sum of BAI values for the site.

We also converted TRW into dimensionless, ring-width indices (TRWi) to remove long term trends in growth due to tree ageing by 67% cubic smoothing splines with a 50% cutoff frequency, which allows retaining information on common low-frequency tree-growth forcing (Helama et al. 2016). The resulting detrended series were pre-whitened with low-order autoregressive models to remove year-to-year growth persistence. Individual TRWi series were averaged for each site to obtain mean site series of TRWi using robust bi-weight means (Fritts 1976, Cook and Kairiukstis 1990). All stages of chronology building and growth-climate analyses were performed using the R statistical software (R Core Team 2019). The dplR package was used to detrend tree-ring width series and to calculate mean series or site chronologies of ring-width indices (Bunn et al. 2020).

Climate data

The homogenized and quality-checked CRU T.S. 4.01 dataset (<http://www.cru.uea.ac.uk/data>) was used for the period 1901–2004 providing a reliable climate data source across all the study sites (Harris et al. 2014). This dataset contains monthly mean temperature and precipitation sum data gridded at a 0.5° spatial resolution that have been checked for homogeneity. We downscaled temperature and precipitation using the newly released (~1 km) data from the Climatologies at High Resolution for Earth's Land Surface Areas (<http://chelsa-climate.org>) product, which includes orographic predictors such as valley exposure for downscaling both precipitation and temperature (Karger et al. 2017). We calculated the climate parameters at every treeline site from that grid point of the 1-km pixel containing the closest location to the study site. The remaining elevational distance was accounted for by assuming a common altitudinal lapse rate of air temperature of -0.0055 K m^{-1} during the growing season (Körner 2012).

Climate-growth associations

To quantify climate-growth associations we calculated mean tree-ring width series at the site level. Within the developed TRWi chronologies, we considered the period 1950–2004, which corresponded

to the most reliable time window of climate data. The relationships between monthly climate data (mean temperatures and precipitation) and TRWi series were assessed by calculating bootstrapped Pearson correlation coefficients, and also by fitting Generalized Least Squares (GLS) regression models using the nlme R package (Pinheiro et al. 2018). Based on previous studies (Camarero and Gutiérrez 2004, Wilmking et al. 2004, Salzer et al. 2009, Liang et al. 2011), the temporal window of growth-climate comparisons included from the previous September to the current October in North Hemisphere and from previous March to current April in South Hemisphere.

Climate projections

Only those climate variables highly correlated with TRWi ($r > |0.30|$, $p < 0.05$) were considered in the climate-based models and TRWi projections under different climate scenarios. These variables were summer or winter temperatures in the northern and southern hemispheres, respectively. The climate data projected for the 21st century were downloaded and downscaled at a 0.5° spatial resolution from the fifth phase of the Coupled Model Intercomparison Project (ensemble CMIP5) (Moreno and Hasenauer 2016, Taylor et al. 2012). We used data for the scenario (RCP 8.5) that most closely tracked recent historical emissions (van Vuuren et al. 2011), and one lower-emission scenario (RCP 4.5) in which the increase in annual emissions is more gradual during the early 21st century and declines after the mid-21st century. Specifically, the 4.5 and 8.5 RCP scenarios correspond to radiative forcing values in 2100 of 4.5 and 8.5 W m^{-2} , respectively (van Vuuren et al. 2011).

Statistical analyses of growth trends

The basic idea of these analyses was to compare and relate growth trends (BAI) as a function of growing-season temperature trends for the period 1950–2005. For each tree-ring series, the temporal trends in BAI and temperature were estimated using two simple linear regressions, each with calendar year as the explanatory variable (Huang et al. 2017). Specifically, we used BAI and growing season temperature (June-July in the Northern Hemisphere, December-January in the Southern Hemisphere) as response variables. Only trees with at least 25 rings measured in the period 1950–2004 were considered in the analyses.

To test for the relationship between growth and temperature trends we applied linear mixed-effects models (Pinheiro and Bates 2000). We used growth trend as response variable, tree age and growing-season temperature trend as fixed factors, and site as a random factor. Site was a factor representing the different “treeline x species” interaction (37 levels). A first graphical examination of the model showed a heterogeneous distribution of residuals (Zuur et al. 2009), so we included a power variance structure to account for the spread of variation in the data as a function of estimated tree age (Supporting Information, Fig. S5). To select the most parsimonious model we used a multi-model inference approach based on information theory (Burnham and Anderson 2002). We ranked all potential models according to the second-order Akaike information criterion (AICc). The model showing the lowest AICc value and the largest Akaike weight (w_i , relative probability quantifying if the selected model is the best one) was selected as the best one. All statistical analyses were performed in the R environment (R Core Team 2019). The lme function of the nlme package was used to fit the linear mixed-effects (Pinheiro et al. 2018). The MuMIn package was used to calculate the pseudo- R^2 of the model (Barton 2012). The visreg R package was used to visualize regression models and calculate least-squares means (Breheny and Burchett 2017).

Process-based growth model

To understand the climatic drivers of tree growth and how they may change into the future, we estimated temperature parameters. We chose the VS-Lite model formulation (Tolwinski-Ward et al. 2011) that contains three parameters: a growth-temperature parameter (gT) and its two sub-parameters (T1 and T2). The gT parameter indicates the relationship between temperature and growth at a monthly temporal resolution. T1 and T2 indicate the threshold temperature below which growth cannot occur and the temperature above which growth is not limited by temperature, respectively. These two VS-Lite temperature parameters simulate nonlinear growth response to temperature by considering the threshold temperature (T1) of cambial reactivation based on xylogenesis studies (usually from 3° to 8 °C; see Rossi et al. 2007), and the lower bound on temperature for optimal growth (T2) which would be between 9° and 20 °C (Tolwinski-Ward et al. 2011). To estimate model parameters, we followed a Bayesian approach (Tolwinski-Ward et al. 2013). Following Tolwinski-Ward et al. (2013, 2016), the VS-Lite model relates the annual growth responses (from September of

the year prior to growth to October of the year of tree-ring formation in the Northern Hemisphere and from previous March to current April in the Southern Hemisphere (Rossi et al. 2007, Vaganov et al. 2011) to the sum of the minimum monthly temperature response (gT), modulated by day length or insolation (gE). This minimum allows for an important process-based non-linearity depending on how temperature is limiting growth at treeline (Körner 2012). We estimated gE from site latitude with no interannual variability. In the VS-Lite modeling approach, parameters were used to build simulated tree-ring width chronologies for the 1950–2004 calibration period ($TRW_{i_{VSL}}$). We then related the simulated tree-ring chronologies to the observed tree-ring chronologies (TRW_i) from the observed tree-ring data (Tolwinski-Ward et al. 2013), allowing for estimation of all the above parameters. We assumed uniform priors for the growth function parameters, and independent, normally distributed errors for TRW_i , and ran for 12,000 iterations with 3 chains (Tolwinski-Ward et al. 2011). We present the posterior median for each parameter (gT, T1, T2) for the calibration period to understand the temperature drivers on growth in the recent past. We also divided this calibration period into two sub-periods to evaluate the temporal stability of the calibrated growth response functions (1950–1979, 1980–2004), withholding the second half for validation of the parameters estimated in the first half. Other parameters used in the VS-Lite model formulation (e.g., runoff, root depth) were retrieved from published studies (Tolwinski-Ward et al. 2011, 2013, 2016; Sánchez-Salguero et al. 2017, 2018).

Statistical growth models

We fitted growth models with climate covariates using GLS models (Pinheiro et al. 2018). All continuous predictor variables were standardized to give them the same weight in the fitted models (i.e., the mean was subtracted from each value and divided by the standard deviation), enabling the interactions to be tested and compared (Pinheiro and Bates 2000). In addition, we evaluated the existence of multicollinearity among explanatory variables by calculating the variance inflation factor (VIF), which was always < 2 , indicating no redundancy problems (i.e. those variables are not collinear with the other variables in the model). The VIF was calculated as the ratio of the overall model variance to the variance of models including single independent variables. The stability and validity of GLS models were tested by a split-sample procedure by dividing the period into two sub-

periods of similar length (Fritts 1976). We used the function step of the stats R package stats (R Core Team 2019) and selected the final regression equations as those showing the lowest AICc values.

Projected growth-climate associations

We used GLS models to project the TRWi of each site (hereafter TRWip) for the 2015–2049 and 2050–2100 periods under the two selected RCP scenarios. The VS-Lite model was fitted to estimate parameters (gT , $T1$, $T2$) from the TRWip. This allowed us to infer whether the relationships between climate and growth changed from the observed period (1950–2004) to the projected period (2015–2100) by comparing the gT in the two periods. We then generated a second synthetic tree-ring width projection from VS-Lite ($TRWi_{VSLp}$), and compared the two projected tree-ring width indices through Pearson correlations.

Results

Temperature and growth trends at treeline

We found a general growth increase during the 20th century, with a more pronounced rising trend from the 1980s onwards. There was, however, substantial variability among regions (**Fig. 2a**). Overall, 80% of sites showed positive and significant ($p < 0.05$) growth trends. Growing season temperature trends were positive in most sites (Supporting Information, Table S3).

Tree growth and growing-season temperature trends were positively related (**Fig. 2c**). Higher growth and stronger temperature trends were observed in Pyrenees sites, whereas negative growth rates were found in some of the Rocky and Scandes Mountains sites (Table S3). Additionally, some sites in the Southern Hemisphere showed substantial positive growth trends but no significant temperature trends (points in top left area of **Fig. 2c**). Models also showed that basal area growth trends were related to tree age, but trees established before the 20th century also presented positive growth trends (Supporting Information, Figs. S3 and S4).

Current temperature-growth associations

Growing-season (June-July or December-January) temperature was the most commonly observed and important driver of growth in 17 out of 37 sites during the 20th century (Fig. 2c; Supporting Information, Tables S4 and S5). On average, 50% of growth variation was explained by temperature. In the growth rate regression models (Supporting Information, Table S5), 60% and 40% of the parameters retained by model selection corresponded to temperature and precipitation variables, respectively. At high-latitude sites, 80% of the regression parameters corresponded to July-August temperatures, whilst in mid- to low-latitude sites 80% of the parameters corresponded to non-thermal factors. In one of the equatorial treeline sites (Cordillera Real-Peru) growth was negatively associated with temperature. The explanatory strength of temperature varied across locations, from 26% in that equatorial site to 70-81% at high-latitude ones (Siberia, Scandes and southern Andes). The percentage of growth variance explained by temperature (R^2_{adj} in Table S5) increased as treeline elevation decreased ($r = -0.33$, $p = 0.049$), and it was higher in abrupt *Nothofagus* treelines ($R^2_{adj} = 0.60 \pm 0.05$) than in diffuse ($R^2_{adj} = 0.48 \pm 0.03$) treelines ($t = 2.18$, $p = 0.037$).

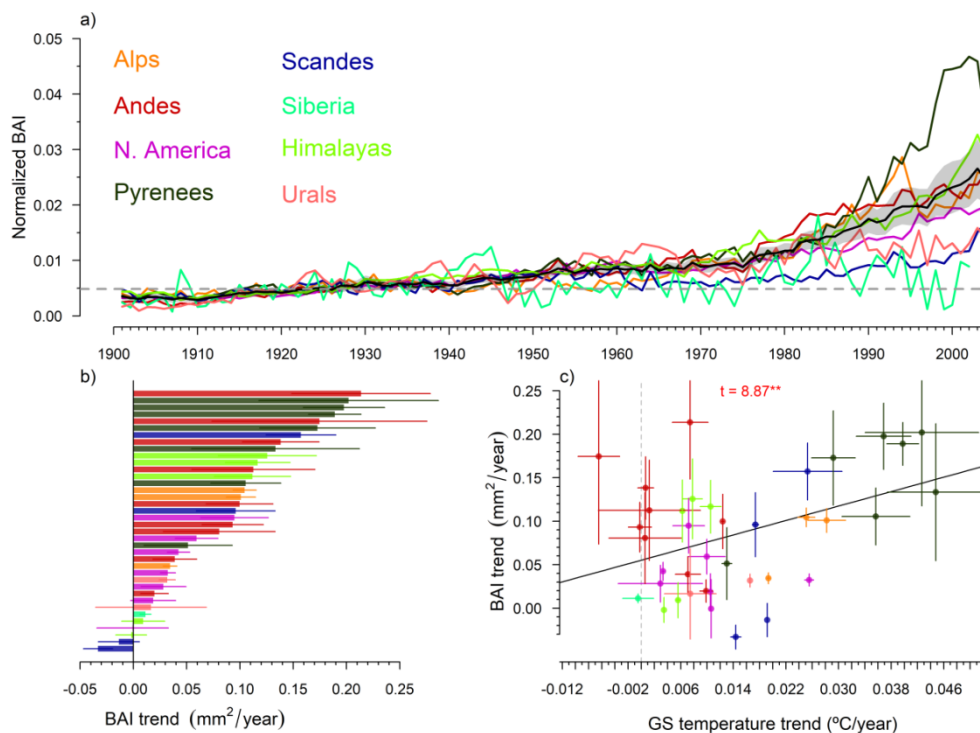


Figure 2. Observed and predicted growth (BAI) trends. (a) Growth trends (normalized basal area increment, BAI) during the 20th century for all study treeline sites. Coloured lines indicate the growth for the 1901–2004 period in each region. The shaded area shows the 95% confidence intervals (CIs) of the averaged normalized growth across all treeline sites. (b) Observed BAI trends and (c) observed (points) and predicted (regression) BAI based on linear-mixed effect models as a function of growing-season (GS) temperature (June-July in the Northern Hemisphere, December-January in the Southern Hemisphere). Error bars indicate the 95% CIs. In the plot (c) the t statistic of the regression is shown (** $p < 0.01$). The vertical dashed line indicates the zero value for the GS trend. In all plots treeline sites and regions are presented with the same colors.

Forecasted growth responses to climate

Currently, non-limiting thermal conditions during at least one month within the growing season are observed in 8% of the sites, whereas this is projected to occur in 52% of them after 2050. This indicated that during the 21st century temperature might no longer constrain growth rates on over half of the treeline sites worldwide. This will effectively decouple tree growth from rising temperature trends (**Fig. 3**).

The VS-Lite model reproduced the role played by low growing-season temperatures as the main constraint of tree growth in the 20th century (**Fig. 3**; see also Tables S6, S7 and S8 in Supporting Information). In 80% of sites, the model predicted enhanced growth together with longer growing seasons in the warmest RCP 8.5 scenario, whereas 20% of sites featured just higher growth rates. However, under RCP 4.5 scenario, only 50% of the sites are forecasted to show higher growth rates and longer growing seasons. In some sites, we found trivial differences in the growing-season temperature parameters between RCP 4.5 and 8.5 scenarios (e.g., Rocky Mountains, Alps, Pyrenees). This indicates that growth limitation by low temperatures could already fade out with the RCP 4.5 scenario. In a few sites (e.g., Peru, California, southern Urals), the predicted growing season would extend from 2 to 6 months in the late 21st century when considering the RCP 8.5 scenario. The minimum temperature threshold for growth (T1) will decrease mainly in Fennoscandian, Siberian,

tropical and Mediterranean sites, and should be related to a relaxation in temperature limitation during the onset of the growing season. This would suggest for the next decades an earlier anticipation of the growing season toward current spring months. The decrease of T1 will be more marked in sites where increasing growth rates are predicted.

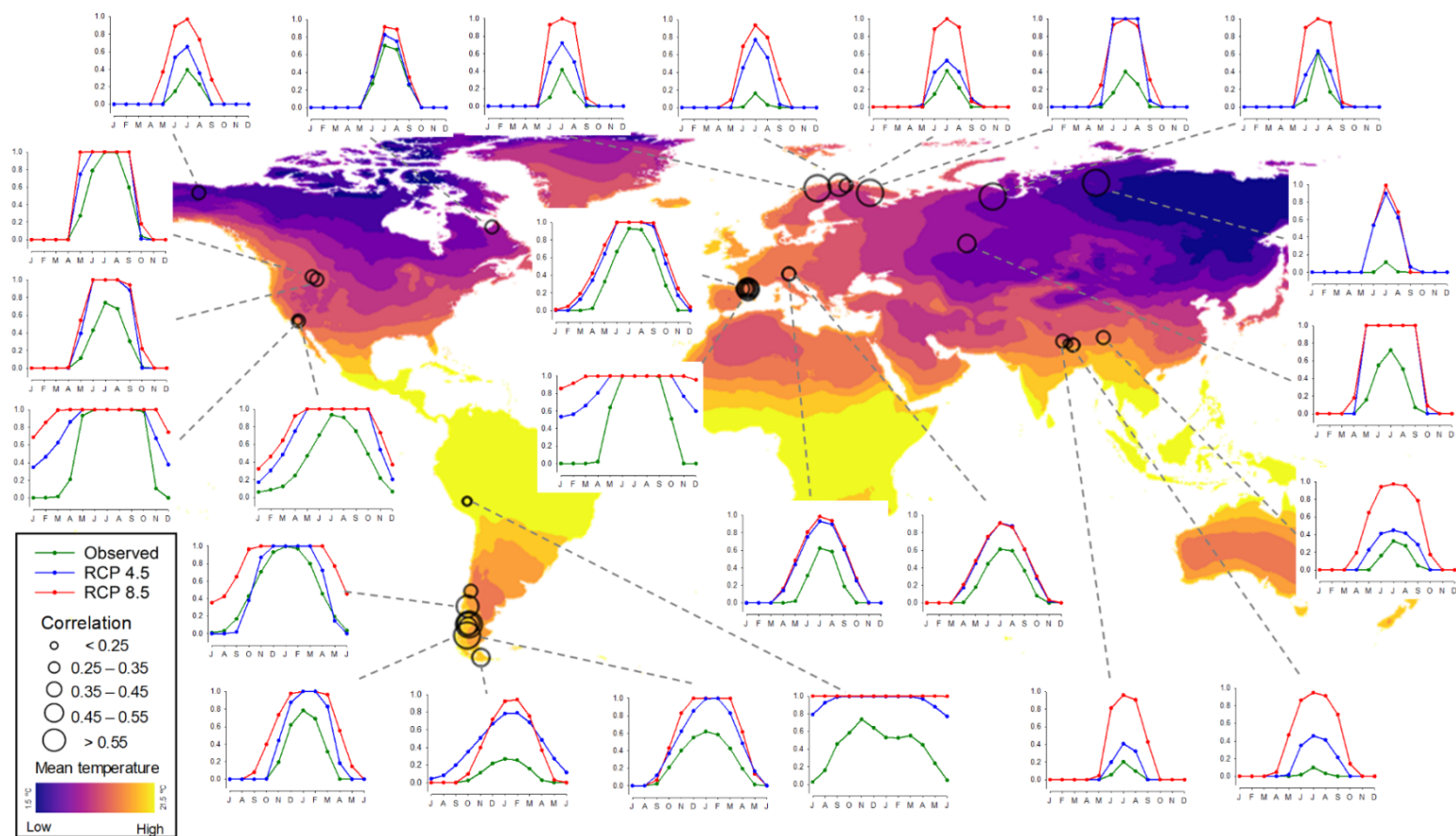


Figure 3. Simulated monthly growth response to temperature (gT) using VS-Lite model. Monthly growth response curves for temperature (gT, y axes) using the VS-Lite model for the period 1950–2004 (green lines), and for 2050–2100 under the RCP 4.5 (blue lines) and RCP 8.5 (red lines) emission scenarios. The size of map symbols is proportional to Pearson's correlation coefficients calculated between

observed and fitted mean ring-width site series. Correlation values higher than $|0.25|$ are significant at $p < 0.05$. Colored background shows mean growing-season temperatures.

Discussion

In this study, we showed that trees growing in most treelines on four continents exhibited increasing growth rates over the past century – with a particularly acute acceleration since the 1980s – and these changes are strongly correlated with concurrent warming occurring at most sites. These findings and the 21st-century predictions of increasing growth rates are in line with previous xylogenesis studies, performed in the last 10 years when temperature increases have been the highest, which estimated that 75% of the final ring width depends on growth rate and 25% depends on the length of the growing season (Cuny et al. 2015). Despite the potential issue of the no-analogue bias in defining the actual growth trends (i.e. old, slow-growing trees may be rare or absent in some treelines), recent warming trends have important implications for tree growth and productivity in currently heat-limited sub-arctic and sub-alpine treeline environments (Camarero and Gutiérrez 2004, Salzer et al. 2009, Körner 2012). Nonetheless, our approach with the adoption of a forward model to detect future changes in physiological limitations to growth shows great potential for predicting non-linear changes in treelines and other marginal ecosystems (Hofgaard et al. 2019, Vaganov et al. 2006, Sánchez-Salguero et al. 2018).

We identified that the 20th-century growth enhancements occurred at most of our sites underlining the previous conditions limited by temperature. However, projection of these same trees and sites to year 2100 suggest that this thermal limitation could disappear in half of the cases, leading to an increase in productivity and promoting treeline encroachment. A divergence between growing-season climate and growth has been interpreted as a loss of sensitivity to climate (divergence problem), particularly in boreal forests (Briffa et al. 1998). However, divergences from previous climate–growth associations may indicate the fading in climate constraints on growth as observed in arctic treelines (Hofgaard et al. 2019), and as forecasted by our simulations. It must also be considered the expected upward and poleward of current treelines (Harsch and Bader 2011), even though the response of treeline positions to warming can be lagged (Liang et al. 2011). If tree growth in the current treeline stands decouples from temperature at the end of 21st century, this could be because those stands will

become part of subalpine or boreal forests and not being part of treeline ecotones anymore (McIntire et al. 2016).

We found several important biogeographic variability in growth trends, climate trends, patterns of temperature limitation, and forecasted treeline dynamics (Camarero et al. 2017), which should be considered in further investigations. First, tree growth in the equatorial treeline (Peru) was poorly related to temperature as compared to high-latitude sites (Siberia, Scandes and southern Andes). This finding was expected given the peculiar climatic conditions in equatorial treelines (Körner 2012), and suggests for these regions the inclusion of non-thermal growth drivers, as precipitation or radiation, in future modeling approaches (Morales et al. 2004; Liang et al. 2014). Second, our statistical models performed well (i.e. featuring high percentage of explained growth variance) in high-latitude sites, but with regional or local differences. The explanatory power not evenly increasing with elevation suggests the presence of threshold responses to temperature or the additional influences of local factors such as wind or aspect (McIntire et al. 2016). Third, counter to expectations, the abrupt high-latitude *Nothofagus* treelines in the southern Andes seemed more responsive to temperature than diffuse treelines (Harsch and Bader 2011). This conflicting result highlights the need to include radial growth data in treeline monitoring studies as a main component of treeline dynamics. Fourth, mid-latitude treelines exhibited high variability growth rates. These high (e.g., Pyrenees) to low (e.g., Rocky Mountains) values may be the result of different local and regional climate trends or be conditioned by size and age structures of those treelines (Camarero et al. 2017). More realistic projections of treeline growth should also consider demographic dynamics, recognizing that reliable, long-term data on recruitment and mortality rates are scarce.

Our study scrutinized tree growth by means of tree rings and age estimations and has an inherent uncertainty in slow-growing treeline trees (Körner 2012). Understanding whether the temperature-growth coupling of the past century was due to physiological acclimations related to rising temperatures or to CO₂ fertilization and improved water-use efficiency should also be addressed (Camarero et al. 2015). We detected current growth coupling with temperature at treelines, and forecasted a decoupling over the 21st century in almost half of our sites. As the association between

temperature and growth fades out, other factors, such as non-growing season conditions or tree-to-tree interactions, will become crucial. How treeline trees will acclimate to further warming is essential to project forest development in cold biomes. More mechanistic models could also be used to check this acclimation such as the full VS-model (Vaganov et al. 2006, Tychkov et al. 2019) to consider the effects of elevated temperatures under rapidly warming climatic scenarios which could constrain growth in cold sites by reducing soil moisture availability (see Sánchez-Salguero et al. 2018). Such non-linear association between temperature and growth was not accounted for by the equations used to predict growth as a function of forecasted climate which were based on linear relationships. Since the VS-Lite model deals with the non-linear growth responses of trees to climate, future studies should implement non-linear statistical models to forecast growth.

Filtering out the observed growth trends by age, younger trees showed a much stronger increase of basal area increment than older ones. One possible explanation for this is that the younger the trees, the more likely is they established under warm conditions. Genetic selection or acclimation could lead to enhanced growth in such trees, but this should be tested by assessing long-term changes in tree size and biomass to account for any ontogenetic bias (Duchesne et al. 2019). However, we must stress that there were no systematic effects of age on the results interpretation, i.e., younger treeline sites did not shape the growth trend distribution between regions. In treeline sites where temperature-growth couplings were more (e.g., Pyrenees) or less strong (e.g., southern Andes), the overall growth enhancement was maintained even when considering just the old individuals. These results highlight that patterns in treeline growth are complex and depend also on local factors, as size and age structures, in addition to climate (Camarero et al. 2017). Our results suggest that growth enhancement at treeline was widespread during the 20th century.

Conclusions

We found that the rapid temperature rise observed during the 20th century was positively associated with tree growth at most treelines excepting subarctic regions showing the aforementioned divergence problem. Rising trends in temperature and growth were globally observed with the exception of tropical treelines where growth seems not as limited by low temperatures as in extra-tropical regions.

However, our predictions suggest that during the 21st century, growth will stop tracking temperature. This decoupling would suggest that tree growth at treeline will be no longer limited by low temperature. Additional factors, such as non-growing season conditions and biotic interactions, should be taken into account at regional and local level. If these novel drivers of growth at treeline will play a pivotal role during the 21st century, global vegetation models should consider these outcomes to fully represent the complexity of future growth responses at treeline.

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Conflict of interest

Authors declare no conflict of interest.

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