Projecting tree-growth responses into future climate: a study case from a Danish-wide common garden

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22   **Abstract**

23   Assessing growth responses to climate variations from common garden experiments is vital to identify a
24   species portfolio matching future climate. In the present study we make use of a 50 years old common
25   garden experiment spanning six sites with different soil types across Denmark to i) analyse climate-growth
26   responses and resilience to drought and ii) model future growth predictions for six non-native conifers and
27   two native broadleaved tree species. Species-specific response-functions and Superposed Epoch Analysis of
28   drought events are used to assess differences in sensitivity to drought.

29   The results show that the growth of all species, except for *Quercus robur* L., are significantly ($P < 0.05$) and
30   negatively correlated with summer drought from June-August in at least one of the sites, whereby *Larix*
31   *kaempferi* (Lamb.) Carr, *Abies grandis* (Dougl.) Lindl., *Picea sitchensis* (Bong.) Carr., and *Picea abies* (L.)
32   Karst. are the less resilient. Negative effects of previous warm autumn or late summer were found for *P.*
33   *abies*, *A. grandis*, *Abies alba* Mill. and *Pseudotsuga menziesii* (Mirb.) Franco. Moreover, independently of
34   the site conditions, our model projections of growth responses under future climate prediction (RCP4.5
35   emission scenario) forecast that growth of *L. kaempferi*, *A. grandis*, *P. abies* and *Fagus sylvatica* L. will be
36   reduced by up to 10-16% by 2100. Minor changes in growth responses are expected for *P. sitchensis*, *A. alba*
37   and *P. menziesii*, while *Q. robur* will increase by 12%.

38   This study demonstrates how such projections based on old common garden experiments could be used as
39   inputs to today's forest management decisions.

40

41   **Keywords:** Climate change; Drought; Dendroecology; Common garden; Growth prediction

42   **1. Introduction**

43   Today's composition and structure of European forests are often the results of management decisions taken
44   decades or even centuries ago. These decisions were based on the assessment of the growth behaviour of the
45   tree species at the given site and by an assessment of future needs. However, due to uncertainties related to
46   expected shift in climate, today's forest management decisions are additionally challenged by the fact that
47   future forest ecosystems might soon be exposed to unprecedented environmental conditions ([Kirilenko and](#)
48   [Sedjo, 2007](#)). Current scenarios of climate change are predicting important modifications in both temperature
49   and precipitation regimes in many regions, with in particular the intensification of extreme events and
50   disturbances ([Dai, 2013](#); [Field et al. 2014](#)). In Denmark for example, depending on the greenhouse gases
51   concentration scenarios, it is expected that by the year 2100 the temperature will increase between 1 and 4 °C
52   ([Kjellström et al., 2011](#); [Olesen et al. 2014](#)) with an increased risk of more frequent and longer drought spells
53   in summer ([Olesen et al. 2014](#)).

54   Climatic changes will profoundly affect the interactions between trees and their physical and biological
55   environments, with important implications for tree growth and mortality ([Anderegg et al., 2015](#)). Indeed,
56   widespread episodes of mortality have already been observed all over the globe, either directly linked to
57   climate events (e.g. [Allen et al., 2010](#)) or indirectly through modifications of the relationships with pests and
58   diseases ([Gaylord et al., 2013](#); [Jactel et al., 2012](#)). Drought is one of the main constraints on forest
59   productivity especially at soils with low water holding capacity ([Weber et al., 2007](#)). Drought events trigger
60   abrupt growth decline ([Orwig and Abrans, 1997](#)) and mortality ([McDowell et al., 2011](#)), which may have
61   important consequences for the structure and functions of Earth's forest ecosystems ([Lindner et al., 2014](#)).
62   Drought episodes, defined as episodes of severe climatic water deficit, have been reported to reduce growth
63   and induce incomplete recovery for 1 to 4 years after the event, with pervasive legacy effect most prevalent
64   in dry ecosystems ([Anderegg et al. 2015](#)).

65   For appropriate species selection and management of future forest resources a deeper insight into tree growth

66 and mortality responses is needed (Sass-Klaassen et al., 2016). To survive under rapid climate changes, a
67 high degree of phenotypic plasticity and a high adaptive potential of species are required. For example,
68 previous studies have reported that *Quercus* spp and *Abies alba* Mill. are more competitive than *Fagus*
69 *sylvatica* L., while *Picea abies* (L.) Karst. is more sensitive than *A. alba* and *F. sylvatica* under dry and warm
70 summers (Bolte et al., 2010; Leuschner et al., 2001a; Mette et al., 2013; Zang et al., 2014). It is thus expected
71 that *P. abies* will shift northward and be replaced by more drought tolerant species at low elevations in
72 central Europe (e.g. *Quercus* spp and *Pseudotsuga menziesii* (Mirb.) Franco) (Hanewinkel et al., 2013). Forest
73 managers are requiring more and more indications on how growth and survival of different tree species will
74 develop in a changing climate in order to compose an optimal species portfolio and guarantee forests are
75 preserved to meet future generation needs (Forest Europe et al., 2015). However, this is a challenging task,
76 since the mechanisms of responses are complex, diverse, and may differ between species. Often they do not
77 only depend on the magnitude and frequency of the climatic factors, but also on the genetic characteristics,
78 life stage, and life history of trees (Reichstein et al., 2013). More data on the genetic and environmental
79 sources of variability in response to climatic events are thus necessary to address this challenge and to
80 provide better prediction about where and how different tree species will survive and perform under future
81 climates.

82 An important contribution towards a better understanding of how climate and other environmental factors
83 can affect growth and survival of different trees species or provenances is offered by the common garden
84 experiments. Old common garden experiments represent an important source of information, since they often
85 combine information about the genetic background of the planted trees and provide a long history of how
86 trees responded to the environmental conditions occurring at the site. Through the use of
87 dendrochronological approaches, these settings represent an opportunity to evaluate how different tree
88 species have responded to climate variations and extreme climatic events. Depending on the location of the
89 experiments, this can be achieved even outside the natural range of the species.

In this study we use a nationwide Danish common garden experiment established in 1964 and 1965 that included several native and non-native tree species in order to assess how growth responded to climate conditions and extremes events across sites and species. Specifically, (i) we identified which climatic factor mostly affected the growth of several species at different field trials; (ii) we assessed species differences in growth resilience to drought; (iii) and used obtained results to project growth into future climate scenarios.

2. Materials and methods

2.1. The common garden experiment

This study is based on a nationwide Danish common garden experiment ([Fig. 1](#)) established between autumn 1964 and spring 1965. The common garden was established by the *Danish Forest Experiment Station*, now part of the University of Copenhagen, with the aim of assessing the growth potential for high quality wood production in Denmark ([Holmsgaard and Bang, 1977](#)). The whole common garden includes 13 field trials with a total of 10 conifer and 2 broadleaved species, both native and non-native to Denmark. Each species is represented by the same Danish landrace or provenance at all sites ([Holmsgaard and Bang 1977](#)). Field trials are composed by 0.17 to 0.31 ha monospecific plots randomly located within each trial. The trees were planted at an age of two to four years and with a spacing of 1.3×1.3 m for conifers and 1.3×0.65 m for broadleaved species. The plots were thinned regularly in order to favour the higher quality candidates and limit competition between trees. The applied thinning regimes were from below, but over time it included also co-dominant and dominant trees. Thinning activities started at the time when the canopy of the plots closed (year 1974 to 1982 depending on site and species) and were subsequently made every four years according to the management practices of the owners of the field trials and with few exceptions in case of windfall.

2.2. Site selection and collection of wood material

114 For this study, we selected six field trials to cover the range of common Danish site and climatic conditions
115 (Table 1) and to share the same species (Fig. 1). The soils at the six trial sites were classified as Luvisols,
116 Arenosols and Podzols, some with seasonally shallow groundwater. Soil texture classes vary from coarse
117 sand to sandy loam with subsoil clay percentages ranging from 2% (1013) to 23% (1011) (Callesen, 2003),
118 representing water holding capacities from relatively dry to moist (Table 1). The climate at the trial sites is
119 characterized by the typical Danish temperate climate with mild winters and cool summers. According to the
120 Climate Research Unit grid data (CRU TS v.3.22; Harris et al., 2014), the mean annual temperature of the
121 trial sites from 1961 to 2012 ranged between 7.7 and 8.5 °C, while precipitation was fairly well distributed
122 with an annual sum ranging between 572 and 855 mm yr⁻¹ (Table 1).

123 Each selected field trial included six non-native conifer and two native broadleaved species, namely *P. abies*,
124 *Picea sitchensis* (Bong.) Carr., *A. alba*, *Abies grandis* (Dougl.) Lindl., *P. menziesii*, *Larix kaempferi* (Lamb.)
125 Carr., *Quercus robur* L. and *F. sylvatica*. Stem discs were collected from 6 individuals per species plot and
126 site, with the exception of *P. sitchensis* (at site 1014 and 1013) and *P. menziesii* (at site 1009), for a total of
127 268 stem discs. Stem discs were collected at stem breast height (1.3 m) during a thinning aimed at reducing
128 competition performed in winter 2012. The diameter at breast height (DBH) of the sampled trees was similar
129 or slightly smaller than DBH of all the standing trees in 2012 and thus represents the growth of co-dominant
130 trees (Table 2).

131

132 2.3. Tree-ring width measurements and ring chronology

133 The selected stem discs were oven-dried to avoid decay and then polished with sandpaper. A flatbed
134 distortion-free scanner (Epson, Expression 11000XL) was used to collect digital images of the disc surfaces.
135 The widths of the annual growth rings of four to five radii per disc were measured on the digital image using
136 the WinDendro software (Regent Instruments Canada Inc., 2012). Each individual time-series (radius) was
137 visually cross-dated, and dating was verified using the COFECHA software (Holmes, 1983). Individual time

series were then detrended using a 10-year cubic smoothing spline to only preserve high-frequency climatic information (Cook and Peters, 1981). Site and species chronologies were built using a biweight robust mean of the detrended tree-ring width indexes (Cook and Kariukstis, 1990). The strength of the common signal among radii was quantified as the mean inter-trees correlation (R_{bar}) and the expressed population signal (EPS) from the detrended chronologies (Wigley et al., 1984). All calculations were performed with the “dplR” package within the R environment (Bunn, 2008).

144

145 **2.4. Growth responses to climate**

For each site and species, growth-climate relationships were assessed with bootstrapped principal component regression (PCR) analyses (Biondi and Waikul, 2004) using the growth chronologies as dependent variables and the monthly climate data as independent variables. Bootstrapped correlation coefficients were calculated with the R package *bootRes* (Zang and Biondi, 2013) including climate variables from June of the previous year to September of the current year. The statistical significance of the response coefficients was assessed by calculating the 95% confidence levels based on 1000 random samplings with replacement. As climate data we used the monthly mean temperature (T_m) and a monthly drought index (DI) estimated as monthly precipitation minus monthly potential evapotranspiration. Estimates of monthly temperature, precipitation and potential evapotranspiration at each site were obtained from the 0.5° gridded estimates of CRU TS v.3.22 (Harris et al., 2014). These estimates are based on data from 7-107 stations depending on site and year. Despite daily climatic data are more appropriate to assess droughts which are not confined within monthly periods, we decided to work with monthly resolution data to reduce the number of explanatory climatic parameters to be included into the model (see below).

To evaluate growth resilience in response to drought, we applied superposed epoch analysis (SEA, Lough and Fritts, 1987). SEA analysis tests the significance of a mean tree growth response to certain events (such as drought episodes) by calculating the departures from the mean tree-ring index values of specified events

and/or subsequent years from the years prior to the event using a bootstrap resampling. In our case we used 1000 random sets to test the significance ($P < 0.05$) of the growth reduction in comparison to the 3 years prior to selected drought events. As drought events we selected the three years (2006, 1992 and 1976) within the study period (1967-2012) that had the lowest June and July drought indices (herein *DI67*). *DI67* for these years were lower than -175 mm, while the overall site averages ranged between -47 mm and -88 mm. Field observations reported that these drought episodes impacted the forests in Denmark with occurrence of dieback, shoot- and leaf shed (Fog, 1977; Larsen et al., 1993; Thomsen, 2008; Yde-Andersen, 1977). Additionally, we calculated three different resilience components according to Lloret et al. (2011): Resistance: $R_t = Dr/PreDr$, i.e. the ratio between growth during drought and the growth prior to drought; Resilience: $R_s = PostDr/PreDr$, i.e. the after-drought ability to reach performance levels observed prior to drought; and the Relative resilience: $RR_s = (PostDr - Dr)/PreDr$, i.e the resilience weighted by the impact experienced during drought. These components were calculated based on the individual tree-ring index (*RWI*) for the drought year (*Dr*), for the average of the three years before (*PreDr*) and after (*PostDr*) the drought. To test for differences in drought-induced growth reductions (from SEA) and R_t , R_s and RR_s among species and sites we applied a linear model with species and site as class variables. Tukey tests were applied for pairwise comparisons in case of overall significant difference between species. For the analysis we used the MIXED procedure in the statistical software SAS (SAS Institute Inc. 2015).

180

181 2.5. Prediction of future growth

For the growth projections into future climate scenarios we used multiple regression models based on monthly climatic parameters to achieve the best fits to the ring-width indices of each species. The model was defined as:

$$185 \quad RWI_{ij} = \mu + \beta_1 X_{1j} + \beta_2 X_{2j} + \dots + \beta_n X_{nj} + e_{ij} \quad [1]$$

186 Where RWI_{ij} is the mean tree-ring index in field trial i ($i=1,2,\dots,6$) and year j , μ is the general mean, $X_{1j} \dots$
 187 X_{nj} are climate variables 1 to n in year j , $\beta_1 \dots \beta_n$ are regression coefficients for climate variables 1 to n ,
 188 and e_{ij} is the residual. As climatic variables we used monthly or multi-months averages of temperatures (Tm)
 189 and cumulated aridity indices (mt) observed over the period 1972-2012. The aridity index mt was calculated
 190 as $P/(Tm + 10)$, where P is the monthly precipitation and Tm the monthly average temperature in degree
 191 Celsius (De Martonne, 1926). Due to the large number of explanatory variables, we performed a pre-
 192 selection of climate parameters based on climate-growth Pearson correlations ($P < 0.05$). The final selection
 193 of climate variables was performed for each tree species using the MIXED procedure in SAS (SAS Institute
 194 Inc. 2015) with a first-order autoregressive structure between years within sites.
 195 The Akaike's information criterion (AIC; Akaike, 1974) was used to select among models (Burnham and
 196 Anderson, 2002). Only statistical significant variables were retained in the model. The above model was
 197 expanded to test for site-specific climate regressions by including site-by-climate effects. Regression
 198 coefficients from univariate analysis with the selected explanatory variables were compared with regression
 199 coefficients from the multiple regression analysis to check multicollinearity in the models and were
 200 supported by estimation of variance inflation factors (VIF) using the REG procedure of SAS (Chatterjee and
 201 Hadi, 2006).
 202 As future climatic scenario we used the Global Climate Model (AOGCMs) of the CMIP5 multi-model
 203 (corresponding to the 5th IPCC Assessment Report (2013)) that provides projections for monthly climatic
 204 data based on the emission scenarios (RCP4.5). This scenario projects an average global warming increase of
 205 $+1.4^\circ\text{C}$ (± 0.5) by the 2050s and $+1.8^\circ\text{C}$ (± 0.7) by the 2080s in comparison to the period 1991-2009. Future
 206 climatic data were generated with the ClimateEU v4.63 software package for three time windows (2011-
 207 2040; 2041-2070 and 2071-2100), as available at <http://tinyurl.com/ClimateEU>. Growth projections were
 208 estimated from the final multiple regression model and by use of mean climate estimates for the time

209 windows including the reference period 1991-2009. Finally, the predicted growth for the three time windows
210 was compared with the reference period, i.e.

$$211 \quad FD(\%) = \frac{(PD_f - PD_c) \times 100}{PD_c} \quad [2]$$

212 Where $FD(\%)$ is the percentage change in growth for the three periods 2011-2040, 2041-2070 and 2071-
213 2100 compared with the reference period 1991-2009, PD_f is the predicted growth in the future three time
214 windows; PD_c is the predicted growth for the reference period (1991-2009) applying the regression model.

215

216 **3. Results**

217 **3.1. Characteristics of sampled trees and tree-ring chronologies**

218 Although being the results of a thinning, the sizes of sampled trees (tree height and mean diameter) were
219 similar to the remaining trees (Table 2), meaning that the growth of the sampled trees were similar to the co-
220 dominant trees at the sites. Depending on species and site, the mean diameter at breast height (DBH) of the
221 sampled trees ranged from 11.8 to 43.1 cm. In general the slowest growth was observed at the sites 1013 and
222 1014, while the species at other sites, with few exceptions, were growing faster (Fig. 2). Over the period
223 1975 to 2012, the mean annual radial growth ranged from 1.26 to 4.46 mm (Table 2). Conifers grew faster
224 than broadleaved trees. *Q. robur* showed the slowest diameter growth and *A. grandis* the fastest. *A. grandis*
225 displayed the highest growth variability among sites, ranging from 2.19 to 4.46 mm/year, while the smallest
226 was observed for *Q. robur* (1.26 to 2.74 mm/year).

227 When considering the growth pattern, trees within the same species were synchronous across all sites since
228 all chronologies reached the critical level of $EPS \geq 0.85$ and the average Rbar is 0.42 (Table 2). The highest
229 agreement was found for the site 1014, with *L. kaempferi* and *Q. robur* having the highest common signals
230 (Rbar = 0.66).

231

232 3.2. Climate-growth relationships

233 The climate-growth relationships highlighted the importance of June, July and August *DI* for the growth of
234 all species, except for *Q. robur* (Fig. 3a). *RWI* correlated significantly and positively ($P < 0.05$) with June,
235 July and/or August *DI* in at least one of the sites for all the other species (one site for *F. sylvatica* and up to
236 five for *L. kaempferi*). This means that tree growth benefitted from high water availability during summer, or
237 absence of summer drought stress. However, no clear pattern in correlations emerged with regard to the site
238 soil water storage capacity (i.e. site 1013 and 1014 with poor growing conditions and lower growth rate did
239 not always show stronger climate relationships).

240 Other important patterns were emerging from the correlations with the mean monthly temperatures (*Tm*),
241 (Fig. 3b). Significant correlations of *RWI* with *Tm* of previous fall and current spring were in some cases
242 supported by across site tendencies. Three conifers (*P. abies*, *A. alba* and *A. grandis*), showed consistent
243 tendencies to a negative correlation of *RWI* with previous-year September and October *Tm*, while *P. abies*
244 and *A. alba* positively responded to previous December *Tm* and *P. menziesii* and *A. grandis* to February
245 and/or March *Tm*. In contrast, the *RWI* of the broadleaved species significantly profited from warm
246 temperatures at the beginning of the growing season (April for *F. sylvatica* and May for *Q. robur*) and to
247 previous-year October (*Q. robur*).

248 Significant correlations of *RWI* with *DI* and *Tm* related to a single species and/or site were also observed for
249 other months. *RWI* was significantly correlated with *DI* in previous year June and August for *L. kaempferi*,
250 previous August for *Q. robur*, and previous September or October for *P. abies*, *A. grandis*, *P. menziesii*, and
251 *A. alba*. As regard the responses to *Tm*, *Q. robur* responded negatively to high *Tm* in September, *L.*
252 *kaempferi* to previous July *Tm* and *P. abies* to current June *Tm*.

253

254 3.3. Species-specific resilience to drought

255 The results from the Superposed Epoch Analysis (SEA) assessing the magnitude and the significance of the

growth departures during and following severe drought events are shown in [Figure 4](#). The analyses showed significant negative growth departures during the drought year for all the species. For example, *P. abies* and *A. grandis* showed significant growth departures at five and four out of six sites, respectively. Except for *L. kaempferi*, which at one site still showed a significant growth reduction persisting also in the subsequent year at site 1013, all the other species were able to recover without any significant departure.

The analyses of the components of resilience indicated that the species were not different as regard the resistance to drought (R_t) and the relative resilience (RR_s) ([Table 3](#)). However, *Q. robur*, *F. sylvatica*, *A. alba*, and *P. menziesii* showed significantly higher resilience than *P. abies*, *P. sitchensis*, *A. grandis* and *L. kaempferi* ([Table 3](#)). The comparison of the RWI departure in the drought years (1976, 1992 and 2006) showed a site effect on the response ([Table 4](#)), as the sites 1014 and 1008 had a statistically larger growth reduction.

3.4. Prediction of future growth among tree species

The 95% confidence interval of the average temperature T_m and cumulated aridity index mt for the period 1972-2012, which was used for the development of the climate response models, were within the range of future predicted mean temperature and cumulated aridity index estimates ([Table 5](#)). The final multiple regression models for the different species in general included similar climate variables as emerged from the climate-growth relationships. The main difference is related to the model used for *P. menziesii*, which included a negative effect of previous late summer and early autumn T_m and an effect of previous year cumulated mt for May and June, which was not recognized from the by site correlation analysis ([Fig.3b](#)). The climate response model for *A. alba* did not include previous-autumn temperature in contrast to the results from the by site correlation analysis ([Fig. 3b](#)). Additionally, the prediction model of *A. alba* suggest a negative effect of previous-year cumulated aridity index from March-July ([Table 5](#)). The inclusion of the site-by-climate effects into the model did not improve the final multiple regression models (according to the

280 AIC criterion, data was not shown), thus indicating that the site conditions were not significantly improving
281 the model for any species.

282 The multiple regression models applied to the RCP4.5 climate scenarios predicts that the growth (*RWT*) of *P.*
283 *abies*, *L. kaempferi*, *A. grandis* and *F. sylvatica* will decrease moderately by 4-8% from 2011-2040, and
284 more strongly by 10-16% from 2071-2100. The growth of *P. menziesii*, *A. alba* and *P. sitchensis* will stay
285 unchanged, while the growth of *Q. robur* is projected to increase moderately (+12% by 2071-2100) due to
286 higher spring and autumn temperatures (Table 5).

287 Summer drought (characterized by low aridity index indices and high temperatures) will negatively affect the
288 growth of all conifers except for *P. menziesii* (Table 5). High temperatures of the previous late summer
289 and/or autumn will result in more severe growth reductions for *P. abies*, *A. grandis* and *P. menziesii* by 9%,
290 8% and 7% in 2071-2100, respectively (Table 5).

291

292 4. Discussion

293 4.1. Opportunity offered by the research setting

294 Previous studies have shown the usefulness of common garden experiments to assess survival rates and
295 reconstruct species responses to past environmental conditions (e.g. Eilmann et al., 2014; Eilmann and
296 Rigling, 2012; Lévesque et al., 2014). This study, based on a common garden experiment established in the
297 mid 60ies, enabled us to compare the growth responses of forestry-relevant species growing at a range of
298 sites over almost the last 4 decades. Thanks to this outstanding research setting we were able to compare
299 species reactions to extreme climatic years (e.g. the summer drought events of 2006, 1992 and 1976)
300 occurring when trees were already in a more advanced stage of maturity. Experimental settings rarely permit
301 studies of stress reactions of mature trees (>30 years old). Moreover, the design of our common garden trials
302 characterized by several sites distributed over the Danish territory (Holmsgaard and Bang, 1977) allowed us
303 to study the variability of the responses in relation to the site conditions.

304 A limitation is that our growth models are solely based on relationship between growth and climatic
305 variables of a given landrace or provenance. The model did not include the adaptation of tree phenotypic
306 plasticity (e.g. possible modifications of the root/shoot ratio, leaf area index, rate of photosynthesis, xylem
307 anatomical features), which may strongly influence the growth response to future climate change (Grulke,
308 2010; Rita et al., 2015; Sabaté et al., 2002; Wohlgemuth, 2015). This means also that our growth forecast
309 does not include the effect of other environmental factors, as for example the impact of increasing
310 atmospheric CO₂ concentrations. Indeed, elevated concentrations of CO₂ are expected to increase
311 photosynthetic rates and water use efficiency, which may offset drought stress of trees (Ainsworth and
312 Rogers, 2007; Picon et al., 1996). Furthermore, the growth models do not consider that the future climate
313 will also encompass more extreme drought events that possibly will be beyond the drought events
314 experienced in the years from 1972-2012 covered by the growth models in this study.

315

316 4.2. Growth performance of species

317 Our results indicated that the considered species clearly diverged in terms of annual productivity and
318 sensitivity to climate, but that the different site conditions were not modifying the main patterns of climate
319 responses observed among the species. In particular, the six conifer species grew faster than the broadleaved
320 species, with the non-native *A. grandis* showing about 2 to 2.5 fold faster radial growth than the slow
321 growing *Q. robur* (Table 2). Despite the differences in growing conditions among the field trials, with two
322 sites which are clearly less fertile (i.e. 1013 and 1014), the ranking of productivity among the species did not
323 change substantially (Fig. 2), although Callesen et al. (2006) in contrast to the conifers found a positive total
324 growth volume of *Q. robur* and *F. sylvatica* to soil nutrient status, soil water storage capacity and mean
325 annual temperature, including also thinning volumes. Furthermore, correlations between growth and *DI* in
326 spring and summer (Fig. 3a) and the growth departures for the dry years were not stronger at sites with lower
327 soil water storage capacity as e.g. 1013 (Table 1 and 4). Similarly, the multiple regression models did not

show significant interaction between sites and climate for all investigated species. We therefore interpret this lack of site-specific responses either as an indication that site conditions were not as large among the sites to determine differing responses to drought, or that other factors as e.g. root depths, groundwater table and nutrient differences among sites have masked these potential responses.

4.3. Species specific sensitivity to climate

The observed differences in strength and seasonality of the growth responses among species obtained from the multiple regressive model resulted in large dissimilarities when projecting species growth performance into a future climate scenario characterized by warmer annual temperatures ($+1.8^{\circ}\text{C} \pm 0.7$) and dryer summer ($-0.52 \text{ mm}^{\circ}\text{C}^{-1} \pm 0.20$) in comparison to the period 1991-2009 (Fig. 1). In particular, our model forecasts that by the year 2080s the slow-growing *Q. robur* will increase the growth by 12%, while in contrast *L. kaempferi* and *P. abies* will reduce growth by 15-16% (Table 5). The other species considered are within this range, but towards a growth reduction. Generally, the results from the multiple regression models are in agreement with the climate-growth correlations from the bootstrapping, but with few differences, which reflect the uncertainty of the models. In this context, *Q. robur*, the only species expected to increase growth, is also the species that showed a lack of significant relationships with drought related climate variables. The forecasted increase in growth is mainly due to the benefits from the positive response to previous-autumn and current-spring warming combined with relative less sensitivity to summer drought (Fig. 3) and better resilience to drought events (Table 3), which might be due to a deep tap root system (Čermák and Fér, 2007).

These observations are consistent with studies on *Quercus petraea*, which distribution range extensively overlaps with *Q. robur*. It has been found that the tree-ring width of *Q. petraea* is also positively affected by previous October-November and current year May temperatures (Lebourgeois et al., 2004). The importance of the previous autumn conditions for carbon storage to sustain next year growth is stressed by the finding that *Q. petraea* stem growth started 10 days before bud burst (Barbaroux and Bréda, 2002) and about 30% of

352 the total annual stem increment (mainly earlywood formation) is added before bud burst in ring-porous
 353 species (Bréda and Granier, 1996; Hinckley and Lassoie, 1981) and hence before the soil water content is
 354 reduced during the growing season (Barbaroux and Bréda, 2002). Moreover, an early and warm spring
 355 enhances both photosynthesis and the use of the carbon reserve (Corcuera et al., 2005), explaining the
 356 positive response to spring temperatures. On the other hand, it has also been reported that *Q. petraea* during
 357 drought maintains a consistently better water status than *F. sylvatica* due to its ability to access water in deep
 358 soil layers (Leuzinger et al., 2005). This can be explained by the fact that at soil depth between 50 and 90
 359 cm, *F. sylvatica* has lower density of coarse roots and higher fine root mortality during drought than *Q.*
 360 *petraea* (Leuschner et al., 2001a; 2001b). This growth behaviour also suggests that *Q. petraea* distributes the
 361 growth effort over the full growing season, reducing the impact of the summer when growth conditions in
 362 dry sensitive environments are usually unfavourable. It is therefore not surprising that the genus, in
 363 particularly dry environments as in the Rhone Valley in Switzerland, is out-competing *Pinus sylvestris* L.
 364 (e.g., Weber et al., 2008, 2007). Both *Q. petraea* and *Q. robur* displayed a high degree of tolerance to
 365 drought due to deep-root system, high transpiration and stomatal conductance under drought (Epron and
 366 Dreyer, 1993). However, *Q. petraea* might be more competitive than *Q. robur* with higher leaf specific
 367 conductivity and intrinsic water-use efficiency than *Q. robur* after severe drought (Cochard et al., 1992;
 368 Epron and Dreyer, 1993).
 369 Contrastingly, the growth of *P. abies*, *P. sitchensis*, *A. alba*, *A. grandis* and *L. kaempferi*, *F. sylvatica* and *P.*
 370 *menziesii* were observed to be significantly reduced during dry years and/or under high summer temperatures
 371 (Fig. 3). These observations confirm results from numerous other studies showing their general sensitivity to
 372 drought (e.g. Bolte et al., 2010; Bošel'a et al., 2014; Bouriaud and Popa, 2009; Desplanque et al., 1999;
 373 Eilmann and Rigling, 2012; Feliksik and Wilczyński, 2008; Lebourgeois et al., 2010; Lévesque et al., 2014;
 374 Tegel et al., 2014; Zang et al., 2014). Among this group of species, *L. kaempferi* and *P. abies* are expected to
 375 have the largest growth reduction, since they are particularly sensitive to drought. Although observations of

species root behaviour at the sites are missing, knowledge that both species are generally shallow-rooted (Puhe 2003; Sakai et al., 2007) makes us speculate that these two species either have a wood properties more prone to hydraulic failures (Bréda et al., 2006; Choat et al., 2012; Cochard et al., 1992) or are more sensitive to soil water deficits than other deep-rooted species (Lévesque et al., 2013). Indeed, *L. kaempferi* was, among the six conifers, the species with the lowest growth resilience to drought (Table 3) and with a lagged negative response to previous summer temperature. The previous-year summer temperature could potentially influence bud initiation, fruit set, and respiration and thus reduce carbon reserves for next year's growth (Oleksyn and Fritts, 1991). Thus, *L. kaempferi* seems not only less resilient, but also more liable to the negative effect of climate warming. Similarly *A. grandis* showed significant reductions in the dry years, but a deeper root system might make it more tolerant to drought than *P. abies* (Xu et al., 1997). In this case however, the expected reduced growth is exacerbated by the negative responses to warm temperatures in the previous autumn and/or current summer on *P. abies* and *A. grandis*. The negative effects of previous warm September-October found in this study could be the effect of high evapotranspiration combined with poor soil water availability at the end of the growing season. As there is no correlation with drought at this time of the season, an alternative interpretation could be a negative carbon balance due to high respiration as observed in France (Lebourgeois et al., 2010) and suggested by Bouriaud and Popa (2009). Finally, the radial growth of *A. alba*, *P. sitchensis* and *P. menziesii* were less impacted by future climate variability than the other coniferous species. Except for *P. menziesii*, which still show some negative response to previous year temperature, these species appeared insensitive to both previous year temperature and less affected to current summer drought and warm temperature. In the case of *P. menziesii*, this might be related to a higher proportion of latewood-like cells which are resistant to drought-induced cavitation, but still sufficient hydraulic conductive (Domec and Gartner, 2002; Huang et al., in preparation; Martinez-Meier et al., 2008). This insensitivity might also be due to its deeper root systems. In the case of *P. sitchensis*, the growth prediction model is possibly underestimating the importance of the summer drought since the

400 climate-growth correlations and the SEA analysis have indicated certain sensitivity to drought.
401 Even though *A. alba* showed a significant negative effect from previous autumn temperature, warm winter
402 can initiate its winter photosynthesis and improve carbohydrate storage for the following growing season
403 (Bouriaud and Popa, 2009; Guehl et al., 1985; Lebourgeois, 2007; Lebourgeois et al., 2010; Van Der
404 Maaten-Theunissen et al., 2013). As a deep taproot species which allows *A. alba* trees reaching deeper water
405 resources it will be more tolerant to water deficit than sensitive conifer species (Larcher, 1995). In addition,
406 *P. menziesii* displayed a positive response to years with a warm and dry spring that helped to compensate the
407 negative effect of warming during other times of the growing season. This is a positive effect that has also
408 been observed in a stand in Western Pomerania (Feliksik and Wilczyński, 2009).

409

410 **5. Conclusions**

411 We assessed the growth responses of six conifers and two broadleaves to climatic variability and severe
412 drought events in six Danish field trials. The growth rate was diverse between sites with contrasting soil
413 types, but the climatic response was not obviously different among field trials. The responses to climatic
414 variability and drought were not uniform and varied among species in relation to their growth behaviour. The
415 model predictions indicate that *Q. robur* is the only species which will benefit from the predicted climate
416 changes in Denmark with increased temperatures and unchanged or slightly reduced precipitation in the
417 growing season. *L. kaempferi* and *P. abies* were the most sensitive species to summer drought events due to
418 their low resilience and high sensitivity to previous season warmth and current season drought. This study
419 not only provides important observations on past growth, but also demonstrates that old common gardens
420 can be a valuable tool for addressing forest management questions on species portfolios that match future
421 climates.

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428   **References**

- 429   Ainsworth, E.A., Rogers, A., 2007. The response of photosynthesis and stomatal conductance to rising [CO₂]:
 430   mechanisms and environmental interactions. *Plant, Cell Environ.* 30, 258–270. doi:10.1111/j.1365-
 431   3040.2007.01641.x
- 432   Akaike, H., 1974. A new look at the statistical model identification. *IEEE Trans. Autom. Control* 19, 716–723.
 433   doi:10.1109/TAC.1974.1100705
- 434   Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A.,
 435   Breshears, D.D., Hogg, E.H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.H.,
 436   Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree
 437   mortality reveals emerging climate change risks for forests. *For. Ecol. Manage.* 259, 660–684.
 438   doi:10.1016/j.foreco.2009.09.001
- 439   Anderegg, W.R.L., Hicke, J.A., Fisher, R.A., Allen, C.D., Aukema, J., Bentz, B., Hood, S., Lichstein, J.W., Macalady,
 440   A.K., McDowell, N., Pan, Y., Raffa, K., Sala, A., Shaw, J.D., Stephenson, N.L., Tague, C., Zeppel, M., 2015.
 441   Tree mortality from drought, insects, and their interactions in a changing climate. *New Phytol.* 208, 674–683.
 442   doi:10.1111/nph.13477
- 443   Barbaroux, C., Bréda, N., 2002. Contrasting distribution and seasonal dynamics of carbohydrate reserves in stem wood
 444   of adult ring-porous sessile oak and diffuse-porous beech trees. *Tree Physiol.* 22, 1201–1210.
 445   doi:10.1093/treephys/22.17.1201
- 446   Biondi, F., Waikul, K., 2004. DENDROCLIM2002: A C++ program for statistical calibration of climate signals in tree-
 447   ring chronologies. *Comput. Geosci.* 30, 303–311. doi:10.1016/j.cageo.2003.11.004
- 448   Bolte, A., Hilbrig, L., Grundmann, B., Kampf, F., Brunet, J., Roloff, A., 2010. Climate change impacts on stand
 449   structure and competitive interactions in a southern Swedish spruce-beech forest. *Eur. J. For. Res.* 129, 261–276.
 450   doi:10.1007/s10342-009-0323-1
- 451   Bošel’a, M., Sedmák, R., Sedmáková, D., Marušák, R., Kulla, L., 2014. Temporal shifts of climate-growth relationships
 452   of Norway spruce as an indicator of health decline in the Beskids, Slovakia. *For. Ecol. Manage.* 325, 108–117.
 453   doi:10.1016/j.foreco.2014.03.055
- 454   Bouriaud, O., Popa, I., 2009. Comparative dendroclimatic study of Scots pine, Norway spruce, and silver fir in the
 455   Vrancea Range, Eastern Carpathian Mountains. *Trees - Struct. Funct.* 23, 95–106. doi:10.1007/s00468-008-0258-
 456   z
- 457   Bréda, N., Granier, A., 1996. Intra- and interannual variations of transpiration, leaf area index and radial growth of a
 458   sessile oak stand (*Quercus petraea*). *Ann. For. Sci.* 53, 521–536. doi:10.1051/forest:19960232
- 459   Bréda, N., Huc, R., Granier, A., Dreyer, E., 2006. Temperate forest trees and stands under severe drought: a review of
 460   ecophysiological responses, adaptation processes and long-term consequences. *Ann. For. Sci.* 63, 625–644. doi:
 461   10.1051/forest:2006042

- Bunn, A.G., 2008. A dendrochronology program library in R (dplR). *Dendrochronologia* 26, 115–124. doi:10.1016/j.dendro.2008.01.002
- Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multi-Model inference: A Practical Information- Theoretic Approach. Springer- Verlag, Heidelberg, 60-74 pp.
- Callesen, I., 2003. Transfer functions for carbon sequestration, nitrogen retention, and nutrient release capability in forest soils based on soil texture classification. PhD Thesis, Skov & Landskab, University of Copenhagen.
- Callesen, I., Raulund-Rasmussen, K., 2004. Base cation, aluminium, and phosphorus release potential in Danish forest soils. *J. Plant Nut. Soil Sci.* 167: 169–176. doi: 10.1002/jpln.200321202
- Callesen, I., Raulund-Rasmussen, K., Jørgensen, B.B., and Kvist-Johannsen, V. 2006. Growth of beech, oak, and four conifer tree species along a soil fertility gradient. *Balt. For.* 12: 14–23.
- Čermák, P., Fér, F., 2007. Root systems of forest tree species and their soil-conservation functions on the Krušné hory Mts. slopes disturbed by mining. *J. For. Sci.* 53: 561–566.
- Chatterjee, S., Hadi, A.S., 2006. Analysis of Collinear Data, in *Regression Analysis by Example*, Fourth Edition, John Wiley & Sons, Inc., Hoboken, NJ, USA. doi: 10.1002/0470055464.ch9
- Choat, B., Jansen, S., Brodribb T.J., Cochard, H., Delzon, S., Bhaskar, R., Bucci, S.J., Field, T.S., Gleason, S.M., Hacke, U.G., Jacobsen, A.L., Lens, F., Maherali, H., Martínez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell, P.J., Nardini, A., Pittermann, J., Pratt, R.B., Sperry, J.S., Westoby, M., Wright, I.J., Zanne, A.E., 2012. Global convergence in the vulnerability of forests to drought. *Nature* 491, 752–756. doi:10.1038/nature11688
- Cochard, H., Bréda, N., Granier, A., Aussenac, G., 1992. Vulnerability to air embolism of three European oak species (*Quercus petraea* (Matt) Liebl, *Q. pubescens* Willd, *Q. robur* L). *Ann. For. Sci.* 49, 225–233. doi:10.1051/forest:19920302
- Cook, E.R., Kairiukstis, L. (Eds.), 1990. *Methods of Dendrochronology: Applications in the Environmental Sciences*. Kulwer, The Netherlands.
- Cook, E.R., Peters, K., 1981. The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bull.* 41, 45–53.
- Corcuera, L., Morales, F., Abadía, A, Gil-Pelegrín, E., 2005. Seasonal changes in photosynthesis and photoprotection in a *Quercus ilex* subsp. *ballota* woodland located in its upper altitudinal extreme in the Iberian Peninsula. *Tree Physiol.* 25, 599–608. doi:10.1093/treephys/25.5.599
- Dai, A., 2013. Increasing drought under global warming in observations and models. *Nat. Clim. Chang.* 3, 52–58. doi:10.1038/nclimate1633
- De Martonne E., 1926. Une nouvelle fonction climatologique: L'indice d'aridité. *La Meteorologie*, 449-458.
- Desplanque, C., Rolland, C., Schweingruber, F.H., 1999. Influence of species and abiotic factors on extreme tree ring modulation: *Picea abies* and *Abies alba* in Tarentaise and Maurienne (French Alps). *Trees - Struct. Funct.* 13, 218–227. doi:10.1007/s004680050236
- Domec, J-C., Gartner, B.L., 2002. How do water transport and water storage differ in coniferous earlywood and

latewood? J. Exp. Bot. 53, 2369–2379. doi:10.1093/jxb/erf100

Eilmann, B., Rigling, A., 2012. Tree-growth analyses to estimate tree species' drought tolerance. Tree Physiol. 32, 178–187. doi:10.1093/treephys/tps004

Eilmann, B., Sterck, F., Wegner, L., De Vries, S.M.G., Von Arx, G., Mohren, G.M.J., Den Ouden, J., Sass-Klaassen, U., 2014. Wood structural differences between northern and southern beech provenances growing at a moderate site. Tree Physiol. 34, 882–893. doi:10.1093/treephys/tpu069

Epron, D., Dreyer, E., 1993. Long-term effects of drought on photosynthesis of adult oak trees [*Quercus petraea* (Matt.) Liebl. and *Quercus robur* L.] in a natural stand. New Phytol. 125, 381–389.

Feliksik, E., Wilczyński, S., 2009. The effect of climate on tree-ring chronologies of native and nonnative tree species growing under homogenous site conditions. Geochronometria 33, 49–57. doi:10.2478/v10003-009-0006-4

Feliksik, E., Wilczyński, S., 2008. Tree-ring chronology as a source of information on susceptibility of Sitka spruce to climatic conditions of Pomerania (Northern Poland). Geochronometria 30, 79–82. doi:10.2478/v10003-008-0002-0

Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L., 2014. IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

Fog, O., 1977. Tørkeskader. Skoven 9, 248.

Forest Europe, UNECE, and FAO (2015). “State of Europe’s forests 2015”, in Ministerial Conference on the Protection of Forests in Europe (Madrid), 314 pp.

Gaylord, M.L., Kolb, T.E., Pockman, W.T., Plaut, J.A., Yezzer, E.A., Macalady, A.K., Pangle, R.E., McDowell, N.G., 2013. Drought predisposes piñon– juniper woodlands to insect attacks and mortality. New Phytol. 567–578. doi:10.1111/nph.12174

Grulke, N.E., 2010. Plasticity in physiological traits in conifers: Implications for response to climate change in the western U.S. Environ. Pollut. 158, 2032–2042. doi:10.1016/j.envpol.2009.12.010

Guehl, J.M., Clerc, B., Desjeunes, J.M., 1985. Etude comparée des potentialités hivernales d’assimilation carbonée de trois conifères de la zone tempérée (*Pseudotsuga menziesii* Mirb., *Abies alba* Mill. et *Picea excelsa* Link.). Ann. For. Sci. 42, 23–38.

Hanewinkel, M., Cullmann, D.A., Schelhaas, M., Nabuurs, G., Zimmermann, N.E., 2013. Climate change may cause severe loss in the economic value of European forest land. Nat. Clim. Chang. 3, 203–207. doi:10.1038/nclimate1687

Hansen, K., Bastrup-Birk, A., Bille-Hansen, J., Vesterdal, L., Gundersen, P., 2003. Chapter 6. Jordbundens rolle i skove [in Danish]. In: Hansen, K (ed.) (2003): Næringsstofkredsløb i skove – Ionbalanceprojektet – Forest and Landscape Research, No 33-2003. ISBN 97-7903-156-0. Kandrups Bogtrykkeri. Hørsholm, Denmark.

532 Harris, I., Jones, P.D., Osborn, T.J., Lister, D.H., 2014. Updated high-resolution grids of monthly climatic observations
533 - the CRU TS3.10 Dataset. *Int. J. Climatol.* 34, 623–642. doi:10.1002/joc.3711

534 Hinckley, T.M., Lassoie, J.P., 1981. Radial growth in conifers and deciduous trees: a comparison. *Proc. IUFRO Conf.*
535 *Physiol. Asp. For. Ecol. Mitteil.* d, 17–56.

536 Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-ring Bull.* 43, 69–78.

537 Holmsgaard, E., Bang, C., 1977. Et træartsforsøg med nåletræer, bøg og eg; de første 10 år [A species trial with
538 conifers, beech and oak; the first 10 years]. *Forstl. Forsøgsvæs. Dan* 35: 159-196 (In Danish).

539 IPCC, 2013. *Climate Change 2013: The Physical Science Basis. Working Group I: Contribution to the Fifth Assessment*
540 *Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United
541 Kingdom and New York, NY, USA, 1535 pp. doi:10.1017/CBO9781107415324

542 Jactel, H., Petit, J., Desprez-Loustau, M.L., Delzon, S., Piou, D., Battisti, A., Koricheva, J., 2012. Drought effects on
543 damage by forest insects and pathogens: a meta-analysis. *Glob. Chang. Biol.* 18, 267–276. doi:10.1111/j.1365-
544 2486.2011.02512.x

545 Kirilenko, A.P., Sedjo, R.A., 2007. Climate change impacts on forestry. *Proc. Natl. Acad. Sci. U.S.A.* 104, 19697–702.
546 doi:10.1073/pnas.0701424104

547 Kjellström, E., Nikulin, G., Hansson, U., Strandberg, G., Ullerstig, A., 2011. 21st century changes in the European
548 climate: uncertainties derived from an ensemble of regional climate model simulations. *Tellus Ser. A Dyn.*
549 *Meteorol. Oceanogr.* 63A, 24–40. doi:10.1111/j.1600-0870.2010.00475.x

550 Larcher, W., 1995. *Physiological plant ecology.* Springer, Berlin, DE.

551 Larsen, J.B., Koch, J., Münster-Swendsen, M., Saxe, H., 1993. Skovenes sundhed på udvalgte distrikter i efteråret 1992.
552 *Skoven* 25, 261-264.

553 Lebourgeois, F., 2007. Climatic signal in annual growth variation of silver fir (*Abies alba* Mill.) and spruce (*Picea abies*
554 Karst.) from the French Permanent Plot Network (RENECOFOR). *Ann. For. Sci.* 64, 333–343.
555 doi:10.1051/forest:2007010

556 Lebourgeois, F., Cousseau, G., Ducos, Y., 2004. Climate-tree-growth relationships of *Quercus petraea* Mill. stand in
557 the Forest of Bercé (“Futaie des Clos”, Sarthe, France). *Ann. For. Sci.* 61, 361–372. doi: 10.1051/forest:2004029

558 Lebourgeois, F., Rathgeber, C.B.K., Ulrich, E., 2010. Sensitivity of French temperate coniferous forests to climate
559 variability and extreme events (*Abies alba*, *Picea abies* and *Pinus sylvestris*). *J. Veg. Sci.* 21, 364–376.
560 doi:10.1111/j.1654-1103.2009.01148.x

561 Leuschner, C., Backes, K., Hertel, D., Schipka, F., Schmitt, U., Terborg, O., Runge, M., 2001a. Drought responses at
562 leaf, stem and fine root levels of competitive *Fagus sylvatica* L. and *Quercus petraea* (Matt.) Liebl. trees in dry
563 and wet years. *For. Ecol. Manage.* 149, 33–46.

564 Leuschner, C., Hertel, D., Coners, H., Büttner, V., 2001b. Root competition between beech and oak: a hypothesis.
565 *Oecologia* 126, 276–284. doi:10.1007/s004420000507

566 Leuzinger, S., Zotz, G., Asshoff, R., Körner, C., 2005. Responses of deciduous forest trees to severe drought in Central

Europe. *Tree Physiol.* 25, 641–650. doi:10.1093/treephys/25.6.641

Lévesque, M., Rigling, A., Bugmann, H., Weber, P., Brang, P., 2014. Growth response of five co-occurring conifers to drought across a wide climatic gradient in Central Europe. *Agric. For. Meteorol.* 197, 1–12. doi:10.1016/j.agrformet.2014.06.001

Lévesque, M., Saurer, M., Siegwolf, R., Eilmann, B., Brang, P., Bugmann, H., Rigling, A., 2013. Drought response of five conifer species under contrasting water availability suggests high vulnerability of Norway spruce and European larch. *Glob. Chang. Biol.* 19, 3184–3199. doi:10.1111/gcb.12268

Lindner, M., Fitzgerald, J.B., Zimmermann, N.E., Reyser, C., Delzon, S., van der Maaten, E., Schelhaas, M.J., Lasch, P., Eggers, J., van der Maaten-Theunissen, M., Suckow, F., Psomas, A., Poulter, B., Hanewinkel, M., 2014. Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? *J. Environ. Manage.* 146, 69–83. doi:10.1016/j.jenvman.2014.07.030

Lloret, F., Keeling, E.G., Sala, A., 2011. Components of tree resilience: effects of successive low-growth episodes in old ponderosa pine forests. *Oikos* 120, 1909–1920. doi:10.1111/j.1600-0706.2011.19372.x

Lough, J.M., Fritts, H.C., 1987. An assessment of the possible effects of volcanic eruptions on North American climate using tree-ring data, 1602 to 1900 A.D. *Clim. Change* 10, 219–239. doi:10.1007/BF00143903

Madsen, H.B., Platou, S.W., 1983. Land use planning in Denmark: The use of soil physical data in irrigation planning. *Nord. Hydrol.* 267–276.

Martinez-Meier, A., Sanchez, L., Pastorino, M., Gallo, L., Rozenberg, P., 2008. What is hot in tree rings? The wood density of surviving Douglas-firs to the 2003 drought and heat wave. *For. Ecol. Manage.* 256, 837–843. doi:10.1016/j.foreco.2008.05.041

McDowell, N.G., Beerling, D.J., Breshears, D.D., Fisher, R.A., Raffa, K.F., Stitt, M., 2011. The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends Ecol. Evol.* 26, 523–532. doi:10.1016/j.tree.2011.06.003

Mette, T., Dolos, K., Meinardus, C., Bräuning, A., Reineking, B., Blaschke, M., Pretzsch, H., Beierkuhnlein, C., Gohlke, A., Wellstein, C., 2013. Climatic turning point for beech and oak under climate change in Central Europe. *Ecosphere* 4, 145. doi:10.1890/ES13-00115.1

Oleksyn, J., Fritts, H.C., 1991. Influence of climatic factors upon tree rings of *Larix decidua* and *L. decidua* x *L. kaempferi* from Pulawy, Poland. *Trees - Struct. Funct.* 5, 75–82. doi:10.1007/BF00227488

Olesen, M., Madsen, K.S., Ludwigsen, C.A., Boberg, F., Christensen, T., Cappelen, J., Christensen, O.B., Andersen, K.K., Christensen, J.H., 2014. Fremtidige klimaforandringer i Danmark [Future climate changes in Denmark]. Danmarks Klimacenter, rapport no. 6, Danmarks Meteorologiske Institut.

Orwig, D.A., Abrams, M.D., 1997. Variation in radial growth responses to drought among species, site, and canopy strata. *Trees - Struct. Funct.* 11, 474–484.

Picon, C., Guehl, J., Aussenac, G., 1996. Growth dynamics, transpiration and water-use efficiency in *Quercus robur* plants submitted to elevated CO₂ and drought. *Ann. des Sci. For.* 53, 431–446. doi:10.1051/forest:19960225

602 Puhe, J., 2003. Growth and development of the root system of Norway spruce (*Picea abies*) in forest stands—a review.
603 For. Ecol. Manage. 175, 253–237. doi:10.1016/S0378-1127(02)00134-2

604 Regent Instruments Canada Inc, 2012. WINDENDRO for Tree-ring Analysis. Quebec, Canada.

605 Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M.D., Seneviratne, S.I., Zscheischler, J., Beer, C., Buchmann,
606 N., Frank, D.C., Papale, D., Rammig, A., Smith, P., Thonicke, K., van der Velde, M., Vicca, S., Walz, A.,
607 Wattenbach, M., 2013. Climate extremes and the carbon cycle. Nature 500, 287–295. doi:10.1038/nature12350

608 Rita, A., Cherubini, P., Leonardi, S., Todaro, L., Borghetti, M., 2015. Functional adjustments of xylem anatomy to
609 climatic variability: insights from long-term *Ilex aquifolium* tree-ring series. Tree Physiol. 35, 817–828.
610 doi:10.1093/treephys/tpv055

611 Sabaté, S., Gracia, C.A., Sánchez, A., 2002. Likely effects of climate change on growth of *Quercus ilex*, *Pinus*
612 *halepensis*, *Pinus pinaster*, *Pinus sylvestris* and *Fagus sylvatica* forests in the Mediterranean region. For. Ecol.
613 Manage. 162, 23–37. doi:10.1016/S0378-1127(02)00048-8

614 Sakai, Y., Takahashi, M., Tanaka, N., 2007. Root biomass and distribution of a *Picea-Abies* stand and a *Larix-Betula*
615 stand in pumiceous Entisols in Japan. J. For. Res. 12, 120–125. doi:10.1007/s10310-006-0270-3

616 SAS Institute Inc., 2015. SAS/STAT® 14.1 User’s Guide. Cary, NC: SAS Institute Inc.

617 Sass-Klaassen, U., Fonti, P., Cherubini, P., Gričar, J., Robert, E.M.R., Steppe, K., Bräuning, A., 2016. A tree-centered
618 approach to assess impacts of extreme climatic events on forests. Front. Plant Sci. 7, 1069.
619 doi:10.3389/fpls.2016.01069

620 Tegel, W., Seim, A., Hakelberg, D., Hoffmann, S., Panev, M., Westphal, T., Büntgen, U., 2014. A recent growth
621 increase of European beech (*Fagus sylvatica* L.) at its Mediterranean distribution limit contradicts drought stress.
622 Eur. J. For. Res. 133, 61–71. doi:10.1007/s10342-013-0737-7

623 Thomsen, I. M., 2008. De danske skoves sundhedstilstand. Resultat af overvågningen i 2006. Arbejdsrapport Skov &
624 Landskab nr. 40-2008. Skov & Landskab, Københavns Universitet, Hørsholm

625 Van Der Maaten-Theunissen, M., Kahle, H.P., Van Der Maaten, E., 2013. Drought sensitivity of Norway spruce is
626 higher than that of silver fir along an altitudinal gradient in southwestern Germany. Ann. For. Sci. 70, 185–193.
627 doi:10.1007/s13595-012-0241-0

628 Weber, P., Bugmann, H., Fonti, P., Rigling, A., 2008. Using a retrospective dynamic competition index to reconstruct
629 forest succession. For. Ecol. Manage. 254, 96–106. doi:10.1016/j.foreco.2007.07.031

630 Weber, P., Bugmann, H., Rigling, A., 2007. Radial growth responses to drought of *Pinus sylvestris* and *Quercus*
631 *pubescens* in an inner-Alpine dry valley. J. Veg. Sci. 18, 777–792. doi:10.1111/j.1654-1103.2007.tb02594.x

632 Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in
633 dendroclimatology and hydrometeorology. J. Clim. Appl. Meteorol. 23, 201–213. doi:10.1175/1520-
634 0450(1984)023<0201:OTAVOC>2.0.CO;2

635 Wohlgemuth, T., 2015. Climate change and tree responses in Central European forests. Ann. For. Sci. 72, 285–287.
636 doi:10.1007/s13595-015-0474-9

637 Xu, Y., Röhrig, E., Fölster, H., 1997. Reaction of root systems of grand fir (*Abies grandis* Lindl.) and Norway spruce
638 (*Picea abies* Karst.) to seasonal waterlogging. For. Ecol. Manage. 93, 9–19. doi:10.1016/S0378-1127(96)03951-5
639 Yde-Andersen, A., 1977. Tørke og trædød. Skoven 9, 250.
640 Zang, C., Biondi, F., 2013. Dendroclimatic calibration in R: The *bootRes* package for response and correlation function
641 analysis. Dendrochronologia 31, 68–74. doi:10.1016/j.dendro.2012.08.001
642 Zang, C., Hartl-Meier, C., Dittmar, C., Rothe, A., Menzel, A., 2014. Patterns of drought tolerance in major European
643 temperate forest trees: climatic drivers and levels of variability. Glob. Chang. Biol. 20, 3767–3779.
644 doi:10.1111/gcb.12637

645 **Table 1:** Characteristics of the selected field trials

Site	Tree species ^a	Lat. (N)	Long. (E)	Former land use and other specific site characteristics (from Callesen, 2003; Callesen and Raulund- Rasmussen, 2004; Hansen, 2003)	Soil texture [class]	Soil water storage capacity ^b [mm]	Mean annual temperature ^c [°C]	Mean annual precipitation ^c [mm]
1008	<i>Fs, Qr, Ps, Pa, Ag, Pm, Aa, Lk</i>	56°27'29.0"	10°31'54.6"	Cropland following heathland, medium- poor soil nutrient status	Sand	89	8.1	572
1009	<i>Fs, Qr, Ps, Pa, Ag, Aa, Lk</i>	55°56'23.1"	9°12'26.3"	Cropland, seasonal high water tables, very poor soil nutrient status	Sand	84	7.7	844
1010	<i>Fs, Qr, Ps, Pa, Ag, Pm, Aa, Lk</i>	55°32'32.6"	11°49'37.2"	Cropland, rich soil nutrient status	Sandy loam	95	8.3	595
1011	<i>Fs, Qr, Ps, Pa, Ag, Pm, Aa, Lk</i>	55°57'21.3"	12°21'14.1"	Cropland, rich soil nutrient status	Sandy loam	122	8.2	605
1013	<i>Fs, Qr, Pa, Ag, Pm, Aa, Lk</i>	57°11'35.2"	9°32'59.3"	Sand dunes with <i>Pinus mugo</i> and hay, seasonal high water tables, very poor soil nutrient status, possible salt spray from the sea	Sand	72	7.8	680
1014	<i>Fs, Qr, Pa, Ag, Pm, Aa, Lk</i>	56°17'32.5"	8°25'40.1"	Heathland of <i>Calluna vulgaris</i> , very poor soil nutrient status	Sand	64	8.5	855

646 ^a *Fs* = *Fagus sylvatica*, *Qr* = *Quercus robur*, *Ps* = *Picea sitchensis*, *Pa* = *Picea abies*, *Ag* = *Abies grandis*, *Pm* = *Pseudotsuga menziesii*, *Aa*
647 = *Abies alba*, *Lk* = *Larix kaempferi*.

648 ^b Available soil water storage capacity to a depth of 60 cm estimated according to the equations of Madsen and Platou (1983).

649 ^c Average over the period 1961-2012.

Table 2: Tree characteristics and properties of tree-ring time series

Site	Species ^a	Tree/radi i	Period ^b	Tree DBH ^c [cm]	Stand DBH ^d [cm]	Ring width ^b [mm]	Ring width ^c [mm]	Rbar	EPS
1008	<i>Fs</i>	6/24	1969-2012	24.7 ± 6.9	28.5 ± 8.8	2.58 ± 1.36	2.71 ± 1.36	0.28	0.90
	<i>Qr</i>	6/27	1972-2012	17.1 ± 4.5	18.1 ± 7.5	1.77 ± 0.95	1.76 ± 0.96	0.44	0.95
	<i>Ps</i>	6/24	1969-2012	34.0 ± 5.4	33.0 ± 12.7	3.54 ± 1.31	3.57 ± 1.34	0.34	0.92
	<i>Pa</i>	6/24	1969-2012	34.8 ± 6.7	32.7 ± 5.7	3.34 ± 1.76	3.19 ± 1.76	0.42	0.94
	<i>Ag</i>	6/24	1969-2012	43.1 ± 8.2	43.8 ± 10.3	4.60 ± 1.91	4.46 ± 1.84	0.31	0.91
	<i>Pm</i>	6/24	1969-2012	36.6 ± 7.5	39.2 ± 7.9	3.57 ± 1.94	3.18 ± 1.59	0.39	0.94
	<i>Aa</i>	6/24	1975-2012	27.6 ± 7.7	29.6 ± 6.3	3.28 ± 1.65	3.29 ± 1.67	0.41	0.93
	<i>Lk</i>	6/24	1969-2012	31.4 ± 3.5	30.6 ± 4.3	2.90 ± 1.45	2.50 ± 1.76	0.49	0.96
	$\bar{X}$			31.2 ± 8.0	31.9 ± 7.6	3.20 ± 0.82	3.08 ± 0.80	0.39	0.93
1009	<i>Fs</i>	6/24	1980-2012	17.1 ± 4.1	16.2 ± 5.9	2.31 ± 1.35	2.33 ± 1.35	0.46	0.94
	<i>Qr</i>	6/24	1970-2012	18.0 ± 3.2	20.2 ± 4.5	1.86 ± 0.82	1.81 ± 0.81	0.44	0.94
	<i>Ps</i>	6/24	1969-2012	33.0 ± 6.8	37.4 ± 7.4	3.45 ± 1.53	3.53 ± 1.57	0.36	0.93
	<i>Pa</i>	6/24	1970-2012	28.9 ± 6.9	35.2 ± 7.3	3.35 ± 1.59	3.19 ± 1.59	0.32	0.90
	<i>Ag</i>	6/24	1972-2012	31.6 ± 7.0	36.6 ± 7.4	3.50 ± 1.61	3.56 ± 1.64	0.44	0.94
	<i>Aa</i>	6/24	1980-2012	23.5 ± 7.6	25.4 ± 5.7	3.30 ± 1.87	3.32 ± 1.88	0.36	0.91
	<i>Lk</i>	6/24	1967-2012	32.2 ± 3.6	37.6 ± 5.2	2.91 ± 1.61	2.56 ± 1.13	0.45	0.95
	$\bar{X}$			26.3 ± 6.8	29.8 ± 9.0	2.95 ± 0.64	2.90 ± 0.67	0.40	0.93
1010	<i>Fs</i>	6/24	1968-2012	25.3 ± 6.4	27.2 ± 7.4	2.59 ± 1.07	2.58 ± 1.07	0.47	0.95
	<i>Qr</i>	6/25	1970-2012	21.9 ± 4.3	25.0 ± 6.2	2.26 ± 1.15	2.11 ± 1.08	0.40	0.94
	<i>Ps</i>	6/24	1967-2012	27.6 ± 7.2	30.5 ± 7.1	2.76 ± 1.46	2.52 ± 1.26	0.39	0.94
	<i>Pa</i>	6/24	1969-2012	28.7 ± 10.3	31.8 ± 6.1	3.04 ± 1.84	2.85 ± 1.75	0.46	0.95
	<i>Ag</i>	6/24	1968-2012	36.8 ± 7.2	42.5 ± 8.9	3.70 ± 1.64	3.49 ± 1.49	0.34	0.92
	<i>Pm</i>	6/26	1969-2012	30.9 ± 8.5	33.9 ± 8.5	3.15 ± 1.77	2.83 ± 1.42	0.25	0.89
	<i>Aa</i>	5/20	1972-2012	28.2 ± 10.7	32.9 ± 13.6	3.29 ± 1.93	3.16 ± 1.87	0.48	0.94
	<i>Lk</i>	6/24	1967-2012	27.1 ± 5.2	30.9 ± 4.0	2.35 ± 1.54	2.01 ± 1.24	0.43	0.95
	$\bar{X}$			28.3 ± 4.3	31.8 ± 5.2	2.89 ± 0.49	2.69 ± 0.50	0.40	0.94
1011	<i>Fs</i>	6/30	1971-2012	21.9 ± 11.4	24.9 ± 6.0	2.46 ± 1.57	2.45 ± 1.60	0.32	0.92
	<i>Qr</i>	6/24	1977-2012	22.1 ± 8.0	21.0 ± 6.0	2.74 ± 1.31	2.74 ± 1.31	0.29	0.88
	<i>Ps</i>	6/29	1968-2012	33.9 ± 4.5	36.1 ± 5.9	3.46 ± 1.76	3.10 ± 1.40	0.41	0.95
	<i>Pa</i>	6/24	1970-2012	28.9 ± 6.0	33.0 ± 5.0	3.05 ± 1.47	2.87 ± 1.31	0.38	0.93
	<i>Ag</i>	6/25	1972-2012	38.7 ± 9.0	44.6 ± 9.8	4.17 ± 2.12	4.15 ± 2.10	0.33	0.92
	<i>Pm</i>	5/20	1972-2012	38.0 ± 9.1	38.5 ± 7.6	3.86 ± 1.99	3.73 ± 1.96	0.49	0.94
	<i>Aa</i>	6/26	1974-2012	28.1 ± 7.7	34.3 ± 6.5	3.47 ± 1.83	3.49 ± 1.84	0.37	0.93
	<i>Lk</i>	6/26	1968-2012	33.1 ± 3.8	34.3 ± 4.8	3.08 ± 1.84	2.58 ± 1.22	0.44	0.95
	$\bar{X}$			30.6 ± 6.5	33.3 ± 7.4	3.29 ± 0.57	3.14 ± 0.60	0.38	0.93
1013	<i>Fs</i>	6/24	1972-2012	11.8 ± 4.8	9.2 ± 6.1	1.48 ± 0.98	1.50 ± 1.00	0.23	0.85
	<i>Qr</i>	6/24	1970-2012	12.8 ± 4.4	11.6 ± 4.6	1.37 ± 0.64	1.34 ± 0.63	0.54	0.96

	<i>Pa</i>	6/24	1972-2012	17.7 ± 5.9	21.2 ± 5.8	2.05 ± 1.49	1.96 ± 1.44	0.33	0.91
	<i>Ag</i>	6/24	1972-2012	21.4 ± 7.9	23.8 ± 6.9	2.27 ± 1.47	2.19 ± 1.47	0.50	0.96
	<i>Pm</i>	6/24	1972-2012	22.9 ± 4.5	30.8 ± 7.7	2.61 ± 1.30	2.64 ± 1.32	0.42	0.94
	<i>Aa</i>	6/24	1973-2012	20.4 ± 7.1	20.2 ± 9.6	2.34 ± 1.19	2.36 ± 1.21	0.40	0.93
	<i>Lk</i>	6/24	1968-2012	23.8 ± 1.6	25.0 ± 3.6	2.24 ± 1.60	1.93 ± 1.26	0.49	0.96
	$\bar{X}$			18.7 ± 4.8	20.3 ± 7.6	2.05 ± 0.46	1.99 ± 0.46	0.42	0.93
1014	<i>Fs</i>	6/24	1970-2012	16.0 ± 5.2	14.7 ± 6.8	1.66 ± 0.93	1.59 ± 0.93	0.60	0.97
	<i>Qr</i>	6/24	1969-2012	14.9 ± 4.0	13.7 ± 4.6	1.41 ± 0.84	1.26 ± 0.73	0.66	0.98
	<i>Pa</i>	6/24	1971-2012	19.8 ± 5.2	22.3 ± 4.2	2.17 ± 1.12	2.05 ± 0.99	0.59	0.97
	<i>Ag</i>	6/24	1972-2012	26.1 ± 7.9	31.6 ± 8.9	2.89 ± 1.44	2.92 ± 1.46	0.46	0.95
	<i>Pm</i>	6/24	1971-2012	27.5 ± 5.5	32.6 ± 7.0	2.80 ± 1.45	2.55 ± 1.19	0.49	0.96
	<i>Aa</i>	6/24	1972-2012	21.7 ± 4.5	22.9 ± 7.0	2.44 ± 1.20	2.44 ± 1.24	0.51	0.96
	<i>Lk</i>	6/24	1968-2012	24.1 ± 3.1	27.3 ± 4.2	2.24 ± 1.48	1.75 ± 0.64	0.66	0.98
	$\bar{X}$			21.4 ± 4.8	23.6 ± 7.5	2.23 ± 0.55	2.08 ± 0.59	0.57	0.97

651 ^a *Fs* = *Fagus sylvatica*, *Qr* = *Quercus robur*, *Ps* = *Picea sitchensis*, *Pa* = *Picea abies*, *Ag* = *Abies grandis*, *Pm* = *Pseudotsuga menziesii*, *Aa* = *Abies*
652 *alba*, *Lk* = *Larix kaempferi*. ^b common period to all sampled trees; ^c Tree DBH = mean DBH of sample trees; ^d Stand DBH = mean DBH of all the
653 standing trees in 2012; ^e period 1975-2012; Rbar = mean inter-series correlation; EPS = expressed population signal.

654 **Table 3:** Estimators of resistance (Rt), resilience (Rs) and relative resilience (RRs) after the drought events.

Species ^a	Rt	Rs	RRs
<i>Fs</i>	0.839 ± 0.021	1.033 ± 0.017 b	0.194 ± 0.023
<i>Qr</i>	0.874 ± 0.021	1.104 ± 0.017 a	0.230 ± 0.023
<i>Ps</i>	0.800 ± 0.025	1.007 ± 0.021 bc	0.206 ± 0.028
<i>Pa</i>	0.812 ± 0.020	1.012 ± 0.017 bc	0.202 ± 0.023
<i>Ag</i>	0.821 ± 0.020	0.972 ± 0.017 c	0.151 ± 0.022
<i>Pm</i>	0.873 ± 0.023	1.046 ± 0.019 b	0.172 ± 0.025
<i>Aa</i>	0.858 ± 0.025	1.058 ± 0.018 ab	0.200 ± 0.024
<i>Lk</i>	0.807 ± 0.020	0.978 ± 0.017 c	0.171 ± 0.022
<i>P-value</i>	0.068	<.0001	0.330

655 ^a *Fs* = *Fagus sylvatica*, *Qr* = *Quercus robur*, *Ps* = *Picea sitchensis*, *Pa* = *Picea abies*, *Ag* = *Abies grandis*, *Pm* = *Pseudotsuga menziesii*, *Aa* = *Abies*
656 *alba*, *Lk* = *Larix kaempferi*.
657 Rt = Resistance = the ratio between growth during drought and the growth prior to drought, i.e., *Dr/PreDr*; Rs = Resilience = the ability to reach
658 performance levels observed prior to drought, i.e., *PostDr/PreDr*; RRs = Relative resilience = the resilience weighted by the reduction experienced
659 during drought, i.e., : $RRs = (PostDr - Dr)/PreDr$, according to [Lloret et al. \(2011\)](#).
660 a, ab, b, bc, c indicate significantly different estimators of the general linear model ($P < 0.05$, Tukey test).

661 **Table 4:** Estimators of the departure of the ring width index (ΔRWT) as obtained from the superposed epoch analysis
 662 (SEA) of the selected drought years (1976, 1992 and 2006).

Sites	ΔRWT
1013	-0.809 ± 0.134 a
1010	-0.894 ± 0.134 a
1011	-1.163 ± 0.134 a
1009	-1.195 ± 0.134 a
1014	-1.301 ± 0.134 b
1008	-1.500 ± 0.134 b
DF	25
<i>P</i> -value	0.013

663 *a, b, indicate significantly different estimators of the general linear model ($P < 0.05$, Tukey test).*

664 **Table 5:** Growth projection as obtained from the multiple regression model relating *RWI* with climate for the eight
 665 species considered in this study. The predicted *RWI* for the periods A (2011-2040), B (2041-2070) and C (2071-2100)
 666 are based on the RCP4.5 scenario and shown as the percentage deviation from the mean *RWI* from the reference period
 667 1991-2009.

Species ^a	Model ^b	Estimate ± sd	CI range ^c	Reference ^d	Period mean climate			Growth change ^e [%]		
			5-95% [°C or mm°C ⁻¹]	1991-2009 [°C or mm°C ⁻¹]	A	B	C	A	B	C
<i>Fs</i>	Intercept	1.665±0.128		-	-	-	-	-	-	-
	Tm6	-0.048±0.009	11.9-16.3	14.4	15.9	16.7	17.1	-8	-12	-13
Σ								-8	-12	-13
<i>Qr</i>	Intercept	0.728±0.133		-	-	-	-	-	-	-
	lag1Tm10	0.034±0.006	7.0-12.8	9.0	10.3	11.1	11.5	5	7	9
	Tm35	0.055±0.009	5.1-9.2	7.0	7.5	8.2	8.5	3	7	9
	Tm9	-0.034±0.008	11.3-15.9	13.6	14.1	14.8	15.2	-2	-4	-6
Σ								6	10	12
<i>Ps</i>	Intercept	0.834±0.003		-	-	-	-	-	-	-
	mt67	0.033±0.005	0.9-8.7	4.7	4.7	4.5	4.3	0	0	-1
Σ								0	0	-1
<i>Pa</i>	Intercept	1.604±0.127		-	-	-	-	-	-	-
	lag1Tm910	-0.046±0.008	9.9-13.7	11.3	12.2	12.9	13.3	-4	-7	-9
	Tm35	0.029±0.009	4.9-9.2	7.0	7.5	8.2	8.5	1	3	4
	Tm6	-0.031±0.008	11.9-16.4	14.4	15.9	16.7	17.1	-5	-7	-8
	mt67	0.029±0.004	1.0-8.6	4.8	4.8	4.6	4.3	0	-1	-1
Σ								-8	-12	-15
<i>Ag</i>	Intercept	1.405±0.085		-	-	-	-	-	-	-
	lag1Tm910	-0.040±0.007	9.8-13.7	11.3	12.2	12.9	13.3	-4	-7	-8
	mt6	0.027±0.005	-0.2-4.8	2.5	2.2	2.1	2.0	-1	-1	-1
Σ								-4	-8	-10
<i>Pm</i>	Intercept	1.337±0.127		-	-	-	-	-	-	-
	lag1Tm89	-0.035±0.009	13.0-17.1	15.3	15.7	16.4	16.9	-2	-5	-7
	Tm34	0.036±0.007	2.6-7.5	4.8	5.1	5.8	6.2	1	4	6
	lag1mt56	0.020±0.005	1.3-7.9	4.7	4.5	4.3	4.3	-1	-1	-1
Σ								-1	-2	-2
<i>Aa</i>	Intercept	1.056±0.004		-	-	-	-	-	-	-
	mt6	0.034±0.007	-0.2-4.8	2.5	2.2	2.1	2.0	-1	-1	-2
	lag1mt37	-0.010±0.002	7.3-20.1	12.7	13.2	12.7	12.5	-1	0	0
Σ								-1	-1	-2
<i>Lk</i>	Intercept	1.785±0.125		-	-	-	-	-	-	-
	lag1Tm7	-0.024±0.006	13.7-19.4	17.0	17.3	18.1	18.5	-1	-3	-4
	Tm6	-0.036±0.008	11.9-16.3	14.4	15.9	16.7	17.1	-6	-9	-10
	mt6	0.045±0.007	-0.1-4.7	2.52	2.24	2.11	2.02	-1	-2	-2

	Σ	-8	-13	-16
668	^a <i>Fs</i> = <i>Fagus sylvatica</i> , <i>Qr</i> = <i>Quercus robur</i> , <i>Ps</i> = <i>Picea sitchensis</i> , <i>Pa</i> = <i>Picea abies</i> , <i>Ag</i> = <i>Abies grandis</i> , <i>Pm</i> = <i>Pseudotsuga menziesii</i> , <i>Aa</i> = <i>Abies</i>			
669	<i>alba</i> , <i>Lk</i> = <i>Larix kaempferi</i> .			
670	^b Climate variables: lag1Tm7, previous-year July temperature; lag1Tm89, previous-year average temperature for August and September; lag1Tm910,			
671	previous-year average temperature for September and October; lag1Tm10, previous-year October temperature; Tm34, average temperature for March			
672	and April; Tm35, average temperature for March, April and May; Tm6, June temperature; Tm9, September temperature; lag1mt37, previous-year			
673	cumulated <i>mt</i> -indices for March to July; lag1mt56, previous-year cumulated <i>mt</i> -indices for May and previous-year June; mt6, <i>mt</i> - index for June;			
674	mt67, cumulated <i>mt</i> - index for June and July.			
675	^c 95% confidence interval of the climate variables 1972-2012 used for the development of the <i>RWI</i> prediction model.			
676	^d reference period 1991-2009. Mean of estimates for field trials where the respective species are represented.			
677	^e deviation from reference period 1991-2009.			

678 **Legends of figures**

679 **Fig. 1.** Map of projected annual temperature and June and July aridity-humidity index anomalies (*DI* index) for the
680 period 2071-2100 compared to the reference period 1991-2009. $mt = P/(Tm + 10)$, where P is the monthly sum of
681 precipitation and Tm is the average temperature in degree Celsius according to [De Martonne \(1926\)](#). Blue dots indicate
682 the location of the 13 field trials, and those with a coloured number refer to the selected field trials. Coloured triangles
683 (conifer) and circles (broadleaf) indicate the species considered at each site. Climate diagram refers to the average
684 monthly precipitation and temperature of six study sites (period 1991-2009).

685

686 **Fig. 2.** Relationship of average ring width grouped by year and sites for the period 1975 to 2012. Lines indicate the
687 results of the linear regression.

688

689 **Fig. 3.** Bootstrapped climate-growth correlation coefficients between the tree-ring indexes and **a)** monthly drought
690 index (*DI*) and **b)** temperature from June of the previous year to September of the current year ($P < 0.05$). Black dots
691 indicate a significant correlation at $P < 0.05$.

692

693 **Fig. 4.** Results from the superposed epoch analysis (SEA) showing departures from the mean ring-width index for the
694 dry years (lag = 0), 3 years before the dry years (lag = -3) and three years after the dry years (lag = 3). Black dots
695 indicate a significant departure from the mean at $P < 0.05$. The number of sites with significant departures at dry years
696 for each species is *Fs* (3), *Qr* (2), *Ps* (3), *Pa* (5), *Ag* (4), *Pm* (2), *Aa* (2), and *Lk* (3).

697

700 **Fig. 2**

701

702 **Fig. 3a**

703

704 **Fig. 3b**

705

706 **Fig. 4**

707