Environmental drivers interactively affect individual tree growth across temperate European forests

Running head: Tree growth and global changes

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59 Abstract

60 Forecasting the growth of tree species to future environmental changes requires a better
61 understanding of its determinants. Tree growth is known to respond to global-change drivers
62 such as climate change or atmospheric deposition, as well as to local land-use drivers such as
63 forest management. Yet, large geographical-scale studies examining interactive growth
64 responses to multiple global-change drivers are relatively scarce, and rarely consider
65 management effects. Here, we assessed the interactive effects of three global-change drivers
66 (temperature, precipitation, nitrogen deposition) on individual tree growth of three study
67 species (*Quercus robur/petraea*, *Fagus sylvatica*, *Fraxinus excelsior*). We sampled trees
68 along spatial environmental gradients across Europe, and accounted for the effects of
69 management for *Quercus*. We collected increment cores from 267 trees distributed over 151
70 plots in 19 forest regions, and characterized their neighboring environment to take into
71 account potentially confounding factors such as tree size, competition, soil conditions, and
72 elevation. We demonstrate that growth responds interactively to global-change drivers, with
73 species-specific sensitivities to the combined factors. Simultaneously high levels of
74 precipitation and deposition benefited *Fraxinus*, but negatively affected *Quercus*' growth,
75 highlighting species-specific interactive tree growth responses to combined drivers. For
76 *Fagus*, a stronger growth response to higher temperatures was found when precipitation was
77 also higher, illustrating the potential negative effects of drought stress under warming for this
78 species. Furthermore, we show that past forest management can modulate the effects of
79 changing temperatures on *Quercus*' growth: individuals in plots with a coppicing history
80 showed stronger growth responses to higher temperatures. Overall, our findings highlight
81 how tree growth can be interactively determined by global-change drivers, and how these
82 growth responses might be modulated by past forest management. By showing future growth
83 changes for scenarios of environmental change, we stress the importance of considering
84 multiple drivers, including past management, and their interactions, when predicting tree
85 growth.

86   **Introduction**

87   Forests are key providers of numerous ecosystem services such as water protection or carbon
88   uptake, but it remains unclear how forests will respond to future environmental changes
89   (Aber *et al.*, 2001; Doblas-Miranda *et al.*, 2017; Keenan, 2015; Lindner *et al.*, 2014; Reyer,
90   2015; Schröter *et al.*, 2005; Trumbore, Brando, & Hartmann, 2015). Altered precipitation
91   amounts and distribution, climate warming, and increased atmospheric deposition of nitrogen
92   and sulphur causing eutrophication and/or acidification are amongst the most important
93   global-change drivers affecting forests (Laubhann, Sterba, Reinds, & de Vries, 2009). By
94   influencing tree growth, these global-change drivers can alter the future composition and
95   functioning of forests (Aber *et al.*, 2001).

96   Trees in Europe are also exposed to these environmental changes. In Central and Western
97   European forests, an overall warming trend accompanied by more frequent and intense heat
98   waves and droughts during summer is expected, as well as increases in heavy precipitation
99   events (Christensen *et al.*, 2007; Jacob *et al.*, 2014; Orlowsky & Seneviratne, 2012). At the
100   same time, studies have projected both a decreased as well as increased future nitrogen
101   deposition for Europe throughout the 21st century, while sulfur deposition is expected to
102   remain constant or decrease (EEA, 2007; Engardt, Simpson, Schwikowski, & Granat, 2017;
103   Leip *et al.*, 2011). Diverging effects of global-change drivers on tree growth have been
104   observed among forests in Europe (Laubhann *et al.*, 2009; Ruiz-Benito *et al.*, 2014). For
105   instance, while nitrogen deposition has been identified as the main driver of increased growth
106   in the 20th century (Camarero & Carrer, 2016; de Vries *et al.*, 2009; Fowler *et al.*, 2013;
107   Magnani *et al.*, 2007), it has also been shown to decrease growth in regions where critical
108   nitrogen loads are exceeded (Aber, 1992; Bobbink *et al.*, 2010; Sutton *et al.*, 2014). Different
109   tree species also show divergent growth responses to global-change drivers due to their
110   different autecological characteristics (e.g. competitive ability, drought sensitivity; Bosela *et al.*
111   *et al.*, 2016; Charru, Seynave, Hervé, Bertrand, & Bontemps, 2017; Mette *et al.*, 2013). In
112   addition, interactive effects of multiple drivers acting simultaneously upon trees might cause
113   tree growth responses to differ from those in single-factor studies, highlighting the need for
114   multi-factor studies (Braun, Schindler, & Rihm, 2017; Laubhann *et al.*, 2009).

115   Forests are managed throughout the world, but particularly intensively in Europe over the
116   past few centuries (McGrath *et al.*, 2015). Forest management may have even greater
117   influence on tree growth in Europe than global-change drivers (Altman *et al.*, 2013; De Vries

et al., 2007; Foster, Finley, D'Amato, Bradford, & Banerjee, 2016). Forest management can influence tree growth by altering the availability and uptake of resources (e.g. nutrients, light) and conditions (e.g. temperature) to which trees are subjected (Altman et al., 2013). Two widespread historical forest management systems in Europe, i.e. high forest and coppice(-with-standards), differ strongly in management regime, hence they might differently affect tree growth (McGrath et al., 2015; Sjölund & Jump, 2013; Stojanović et al., 2017). In coppice systems, canopy opening occurs regularly through cutting multi-stemmed individuals on relatively short rotation cycles ('coppicing' occurs typically every 7-30 years) with an undisturbed period in between. This creates a cyclic variation in light and warm temperatures, whereas high forests often show a more continuous disturbance regime, e.g. through continuous removal of thinned trees (Buckley, 1992; Kopecký, Hédli, & Szabó, 2013; Sjölund & Jump, 2013). By altering the resources and conditions available for trees (e.g. temperature, light, and nutrient availability), and shaping the present structure and composition of the current forests, past forest management may have influenced their growth, and may also modulate growth responses to global-change drivers such as temperature (Stojanović et al., 2017; Vayreda, Martinez-Vilalta, Gracia, & Retana, 2012).

Previous studies have explored how global-change drivers affect tree growth, but mostly on a restricted geographical scale (Bauwe, Jurasinski, Scharnweber, Schröder, & Lennartz, 2016; Braun et al., 2017; Ibáñez, Zak, Burton, & Pregitzer, 2018; Martinez-Vilalta, Lopez, Adell, Badiella, & Ninyerolas, 2008). Tree growth studies covering larger geographical scales and taking into account interactions between global-change drivers at the same time (e.g. Laubhann, Sterba, Reinds, & de Vries, 2009; Solberg et al., 2009) are relatively scarce. Tree growth studies that additionally also consider the effects of land-use legacies such as forest management (e.g. Stojanović et al., 2017; Vayreda et al., 2012) across large geographical scales are, to our knowledge, even lacking. Yet, in order to make accurate projections of future tree growth responses, we need a better understanding of the growth determinants of trees at large geographical scales (Babst, Poulter, Bodesheim, Mahecha, & Frank, 2017; Bowman, Brien, Gloor, Phillips, & Prior, 2013; Mäkinen et al., 2003). By evaluating (past) growth responses to large *spatial* gradients in different global-change drivers, and by controlling for confounding factors, we may infer responses to *temporal* changes in these drivers in different regions. Furthermore, seeing the impact that forest management can have on tree growth and the potential of interaction with other global-change drivers (Vayreda et

al., 2012), it is key to also take management legacies into account in such large-scale tree growth studies (Mausolf et al., 2018; Noormets et al., 2015).

Our study aims to assess interactive tree growth responses to large spatial gradients in environmental variables, representing the global-change drivers – i.e. for the three study species. Furthermore, we want to assess whether plot management histories (i.e. disturbance regimes) influenced tree growth, and potentially modulated tree growth responses to global-change drivers – i.e. for *Quercus* only. We chose 19 temperate deciduous Central-Western European forest regions in such a way that we maximized differences in global-change drivers (temperature, precipitation, and deposition) *between* the regions, reflecting three important global environmental changes (climate warming, changing precipitation, and eutrophication/acidification); while maximizing past and current forest management differences *within* regions. We minimized the effects of potentially confounding factors such as tree size, local competition, soil conditions, and elevation. In every region, we collected increment cores of three economically and ecologically important European tree species (*Quercus robur/petraea*, *Fagus sylvatica*, and *Fraxinus excelsior*) combined with in-situ measurements of the local soil and stand conditions, and reconstructed plot management histories.

We expect to find interactive effects between the global-change drivers on tree growth, and hypothesize that the type of interaction and magnitude may differ between the study species due to the different ecological characteristics of the species. Furthermore, we hypothesize that *Quercus*' growth response to the global-change drivers might be modulated by the past forest management context of the plots.

Materials and Methods

To assess tree growth response, we calculated basal area increment (BAI) from tree cores in plots situated across temperate Europe along environmental (all study species) and management (*Quercus* only) gradients. Sampling trees ‘across’ spatial gradients of environmental variables allows to disentangle the interactions among the global-change drivers through an orthogonal design, and for *Quercus*, to assess whether the effects of global-change drivers depends upon past forest management (Verheyen et al., 2017). We collected cores from 267 trees located in 151 20 x 20 m plots across 19 regions, where we characterized region-scale global-change drivers, plot-scale management variables, and potential plot- and tree-level confounding factors.

Study regions

To maximize differences in global-change drivers across our study regions, we selected 19 regions along a spatial environmental gradient of atmospheric deposition and climatic conditions (temperature, precipitation) within the European temperate forest biome (**Fig. 1a, Table S1**). Mean annual temperature (MAT), total annual precipitation (TAP), and nitrogen deposition (Ndep) at the study regions ranged from 6.9 to 12.9 °C, from 472 to 1852 mm/yr, and from 7 to 30 kg/ha yr respectively (**Fig. 1b, Table S1**, values for the year 2000). At the same time, we tried to maximize differences in past and current forest management between plots (i.e. within regions, **Table S2**), while minimizing differences in site conditions such as soil texture or elevation between plots and between regions. All forest regions comprised closed-canopy forests with a diverse tree and shrub layer composition in which forest management had occurred at some point between 1940 and 2015 (except for the Moricsala nature reserve, which had never been managed).

Study species

We cored three tree species across the study regions, representing ecologically and economically important tree species in temperate Europe, i.e. the diffuse-porous *Fagus sylvatica* (73 trees, 50 plots, 10 regions), and the ring-porous *Fraxinus excelsior* (49 trees, 39 plots, 10 regions) and *Quercus robur/petraea* (145 trees, 87 plots, 15 regions) (**Fig. 1a, Table S1**). Since the sample sizes depended on which species was present in the plots, they each cover slightly different environmental gradients (**Fig. 1b**). Since we often could not distinguish *Q. robur* from *Q. petraea* in the field due to hybridization of the two subspecies, they were merged for the analyses and we further denote them as one species ‘*Quercus*

robur/petraea'. *Quercus robur* and *petraea* are thermophilous, light-demanding species that are rather indifferent to nutrient availability and quite drought-tolerant (Ellenberg & Leuschner, 2010). *Fagus sylvatica* is a drought-sensitive, shade-tolerant species, indifferent to nutrient availability, whereas *Fraxinus* is a moderate light-demanding species with high nutrient requirements preferably growing on quite wet, rich soils (Ellenberg & Leuschner, 2010; Scharnweber et al., 2011). We chose these species because they are typically (co-)dominant in temperate broadleaved European forests (Bohn et al., 2003; Leuschner & Ellenberg, 2017), and they show different growth sensitivities to global-change drivers due to the different autecological characteristics (e.g. Laubhann et al., 2009; Mette et al., 2013). Furthermore, they have been commonly used in dendrochronological studies (e.g. Latte, Lebourgeois, & Claessens, 2015; Mette et al., 2013; Rieger, Kowarik, Cherubini, & Cierjacks, 2017).

Data collection

In each 400 m² plot, we recorded the coordinates and elevation (metres) at the center of the plot with a GPS *GARMIN e-TREX 10*; sampled the soil and forest floor (organic litter and organic fragmentation/humus layer); made a description of the soil profile; measured diameters of all trees with a diameter-at-breast-height (DBH) larger than 7.5 cm (i.e. basal area measurements); and measured for each cored tree the diameters of all trees (with DBH > 7.5 cm) within a radius of 9 m around that tree as well as the distances to that tree (i.e. neighborhood measurements). For details on our sampling protocol, see **Table S3**.

We cored dominant trees of the study species to maximize our chances of extracting the longest possible tree-ring series for each species and minimize competition effects from the last few decades. In each plot, we generally sampled the two most dominant trees (max 14.1 m apart, up to three trees were sampled if more than one of the species was dominant (cfr. *Classic sampling design* sensu Nehrbass-Ahles et al. (2014)). From each tree, we took two perpendicular cores at breast height (Buchanan & Hart, 2011; Woodall, 2008). We checked for signs of ash dieback (Vasitis et al., 2017), only coring healthy individuals of *Fraxinus excelsior* to avoid confounding effects of dieback on the tree growth response. After drying the samples (24h at 103°C) to obtain correct wood density estimates, they were scanned with the X-ray Computed Tomography scanner (XCT, 110 µm resolution) (De Mil, Vannoppen, Beeckman, Van Acker, & Van den Bulcke, 2016; Dierick et al., 2014; Van den Bulcke et al., 2014). Ring widths were measured with the Matlab-program *DHXCT* (De Mil et al., 2016). We used the automatic detection procedure based on wood density, and visually inspected for

missing and/or falsely indicated rings. We additionally measured badly visible ring sections with a Lintab^{TM} 6 (RINNTECH, Germany, 10 μm resolution) after planing the samples with a Core Microtome (Gärtner & Nievergelt, 2010). To ensure correctly dated tree-ring series, we crossdated the two cores per tree, all cores of the same species per plot, and ultimately all cores of the same species per region. For details on the crossdating procedure and results see Maes et al. (2017) section 2.5 and **Table S4**. After crossdating, the mean ring-width series (i.e. the average of the two cross-dated cores) of each individual dominant tree was used to calculate its basal area increment (BAI, cm^2/yr) series. Furthermore, we calculated a time series of the previous-year diameter (Dprev, cm) based on the measured diameters and the tree-ring series to take into account tree size, a commonly used proxy for developmental stage (e.g. Kint et al., 2012; Martin-benito, Kint, Muys, & Cañellas, 2011; Rozas, 2014).

Data analysis

Response variable

We used basal area increment as a measure for tree growth. Three very large and two very young trees were excluded from the analyses because of their outlier behaviour, and the sampling years (2014, 2015 or 2016 – region-specific: **Table S1**) were excluded because of unfinished growth for those years. We only investigated the time period of 1940 to 2015 (or 2013/2014 – region-specific) to avoid including juvenile growth (i.e. < 30 years: cf. cambial age limit Aertsen et al., 2014) as well as to minimize the influence of off-pith coring.

Predictor variables

We used time series of two climatic and two atmospheric deposition variables, estimated at the regional scale, to quantify potential tree growth drivers: (i) mean annual temperature (MAT, $^{\circ}\text{C}$), (ii) total annual precipitation (TAP, mm/yr), (iii) atmospheric nitrogen deposition (Ndep, $\text{kg}/\text{ha yr}$), and (iv) acidification rate (AcidRate, $\text{keq}/\text{ha yr}$) (**Table 1, Fig. S4**). We used nitrogen deposition as a measure of potential eutrophication and acidification rate as a measure of potential acidification. For the climatic time series, we extracted monthly climate data from the gridded CRU TS3.24 dataset (Climate Research Unit, 0.1° resolution: Harris, Jones, Osborn, & Lister, 2014). Time series of total nitrogen deposition ($\text{NH}_3 + \text{NO}_x$) and sulphur deposition (SO_x) were created by using data for the year 2000 from the European Monitoring and Evaluation Programme (EMEP) combined with annual correction factors from Duprè et al. (2010) to calculate deposition values for all other years between 1940-2015 (**Fig. S4**). Annual acidification rate (AcidRate) was calculated based on annual nitrogen

(Ndep) and sulphur deposition (Sdep) as (cfr. Verheyen et al., 2012):

$$AcidRate = \frac{N_{dep}}{14} + 2 * \frac{S_{dep}}{32.06}$$

Assuming homogeneous environmental conditions within a region, we extracted all time series on a plot level, and then calculated the mean of the plot-level time series for each region. For the climatic variables, we used the time series of mean annual temperature and total annual precipitation as well as the time series of spring (April-June) and summer (July-September) temperature and precipitation. Seasonal climate effects on tree growth have been demonstrated before, with spring conditions especially important for ring-porous species such as *Quercus* and *Fraxinus*, and summer conditions mainly important for diffuse-porous species such as *Fagus* (e.g. Latte, Lebourgeois, & Claessens, 2016). Because seasonal values were strongly correlated with annual values allowing the inclusion of only one term in each model (see **Fig. S5**), we kept the focus in the main text on the annual results and present the seasonal results in Supporting Information (**Table S10**). We chose annual values because they capture potential drivers from all seasons, reflecting the temporal scale of “annual” ring measurements, as well as they allowed us to create similar models for the three study species.

For each plot, the management history between 1940 and 2015 was reconstructed based on a combination of expert knowledge of our local contact person in each region, a thorough search of site-specific maps and literature (e.g. management plans), and oral interviews. The plots were classified as belonging to one of seven management histories between 1940-2015: Coppice or Coppice-With-Standards (C(WS)) throughout, High Forest (HF) throughout, Zero management (ZM) throughout, C(WS) to HF, C(WS) to ZM, HF to ZM, and C(WS) to HF to ZM (Details: **Table S2**) (McGrath et al., 2015). We derived two categorical variables (**Table 1**) from the management information (**Table S2, S4**). Coppice History (*CoppHist*) reflects whether the studied plot had been managed as coppice or coppice-with-standards between 1940 and 2015 (yes or no, for all 87 *Quercus* plots: **Table S5**). Management History (*ManHist*) reflects whether a plot had been continuously managed as high forest between 1940-2015 or had been converted from coppice or coppice-with-standards to high forest within this period (for a subset of 47 plots: **Table S5**). We could only analyze the effects of forest management for *Quercus*, because for *Fagus* or *Fraxinus*, the different categories of past forest management were not well-represented across their environmental gradients.

The local growing conditions (elevation and soil), competition with neighbouring trees as well as tree size may confound the response of tree growth to the global-change drivers and

past management. Hence, we used several variables related to these potentially confounding factors: elevation, soil depth, soil conditions (two variables) at the plot level, and neighbourhood competition and tree size at the tree level (**Table 1**).

We inferred soil depth (cm), representative of the root growing space for the trees from our soil profile descriptions (0-50 cm deep) per plot. If we reached the bedrock before a depth of 50 cm, the bedrock depth (e.g. 20 cm) was used as soil depth. In all other cases, soil depth was assumed 50 cm. We included information on the soil physical-chemical conditions by performing a principal correspondence analysis (PCA) on the following soil variables: *pH_{KCl}*, *soil texture*, *base saturation*, *total and Olsen Phosphorus*, *Carbon/Nitrogen ratio*, *inorganic Carbon content*, *dry weight of forest floor layer*, *bulk density* (for sampling and chemical analysis details see **Table S3**). The scores from the first two PCA axes were used as two predictors of soil conditions. These axes explained 60 % of the variance (PC1: 48 %, PC2: 12 %), allowing us to reduce the number of potential explanatory variables related to soil conditions in the model and avoid multicollinearity. See **Fig. S1** for details on the PCA. Overall, the plots comprised quite rich (mesic) soil conditions – i.e. mean *pH_{KCl}* of 4.4, mean base saturation of 0.8 (Weil & Brady, 2017), and mean C/N ratio of 13.9.

We calculated the distance-dependent neighbourhood competition index (NCI) from the neighbourhood measurements for each cored tree as:

$$NCI_i = \sum_{j=1}^n \frac{DBH_j}{Dist_{ij}}$$

where *NCI_i* is the current competition index for the subject tree, *DBH_j* is the diameter of the *j*-th competitor, *Dist_{ij}* is the distance from subject tree *i* to the *j*-th competitor, and *n* the number of competitors within a radius of 9 m of the subject tree (Hegyi, 1974). We included tree size as a time series of the previous-year diameter (*D_{prev}*). Several characteristics of the cored tree species (basal area increment, diameters, heights, and competition index) across the study regions are shown in **Table 2** (details per region: **Tables S6-8**).

Modelling

We built species-specific models to study the effects of the global-change drivers on the growth of each of the three study species. Then, we tested whether past forest management additionally affected the growth of *Quercus*. Linear mixed-effect models were built in two stages (similar methodologies as Aertsen et al., 2014; Kint et al., 2012; Martinez-Vilalta, Lopez, Adell, Badiella, & Ninyerolas, 2008).

First, we built a **base model** (M_b) for each species, with predictors that might have influenced tree growth in our study, but are not part of our research questions:

$$M_b: \quad \log(BAI_t + 1) = \beta_0 + \beta_{size}SIZE + \beta_{comp}COMP + \beta_{site}SITE$$

where *SIZE* includes the tree size variables (D_{prev} , D_{prev}^2), *COMP* tree competition (NCI) and *SITE* the plot-level site conditions (Elevation, PC1, PC2, Soil depth). All models assumed a quadratic relation between basal area increment and D_{prev} since a size-mediated effect (related to a tree age effect) is well-known to increase tree growth until a certain maximum is reached, after which growth starts to decline (Gower, McMurtrie, & Murty, 1996; Wykoff, 1990).

Then, to assess the main and interactive effects of the global-change drivers, we built an **environment model** (M_e) for each species. Here, the environmental factors representative of the global-change drivers (*ENV*) and the three two-way interactions between these factors ($ENV:ENV$) were added to the base model.

$$M_e: \quad \log(BAI_t + 1) = M_b + \beta_{env}ENV + \beta_{env_i-env_j}ENV_i:ENV_j$$

where $i, j = MAT, TAP, Ndep$ or $AcidRate$

Because we expected that the effect of precipitation or deposition on tree growth might be quadratic rather than linear, we additionally tested for significant quadratic effects of mean annual precipitation and nitrogen deposition in the environment model.

Finally, to test whether past forest management additionally affected tree growth of *Quercus*, and interacted with the environmental drivers, we built a **forest management model** (M_{fm}) for *Quercus* as:

$$M_{fm}: \quad \log(BAI_t + 1) = M_e + \beta_{fm}FM + \beta_{fm-env_i}FM:ENV_i$$

where $FM = CoppHist$ or $ManHist$ and $i = MAT, TAP, Ndep$ or $AcidRate$. Separate models were built for each of the two forest management variables.

Several variables required a transformation prior to analysis to achieve normality of their distribution. We $\log+1$ transformed the distribution of basal area increment to remove its right-skewness and to avoid negative values of the transformed variable (cfr. Martin-benito, Kint, Muys, & Cañellas, 2011). We also transformed the following predictor variables: mean

annual precipitation (log-transformed, only for *Quercus* and *Fraxinus*), elevation (square-root transformed), NCI (log(x+1) transformed), and soil depth (1/log(x)). We checked for potential confounding and collinearity issues between the predictor variables by means of boxplots and correlograms. We did not find any confounding or multicollinearity issues between the predictors, except for Nitrogen deposition and Acidification rate, which were highly correlated (Pearson $\rho > 0.7$) (**Fig. S3**). Therefore, we built separate models using either Ndep or AcidRate. Finally, all continuous predictors were standardized (scaled and centered) prior to analysis to enable comparison of their effect sizes.

To take into account the hierarchical structure of our data (trees within plots within regions), a nested random intercept ‘Region\Plot\Tree’ was included in the models. To take into account the temporal autocorrelation present in tree-ring series, we added a second-order autoregressive covariance structure (ARMA(2,0)) to the models. The model procedure of Zuur, Ieno, Walker, Saveliev, & Smith (2009) was used to determine the optimal random and fixed effect structure for all models. Significance of fixed effects was tested by performing likelihood ratio tests on nested models, and by comparing Akaike Information Criteria (AIC) between the models by means of the function ‘stepAIC’ in R (backward selection procedure). Only for the forest management model of *Quercus*, we did not use stepAIC, but performed the likelihood ratio tests manually to test for significant improvements of the environment model when adding one of the two forest management variables as a main effect or as an interaction with each of the environmental drivers (**Table S9**). We fitted final models with restricted maximum likelihood (REML), and evaluated their performance graphically by looking at plots of the residuals vs. fitted values, and of the fitted vs. observed values (i.e. ‘goodness of fit’). We also calculated the marginal and conditional R^2 (proportion of variance explained by fixed factors – R^2_m , and by both fixed and random factors – R^2_f) following Nakagawa & Schielzeth (2013), as well as the relative root mean squared error (RMSE, %) between predicted and observed values of BAI. Given the large sample sizes of our dataset (n=10498, 5157, 3182 for *Quercus*, *Fagus*, and *Fraxinus*), we used a significance threshold of 0.001 in our interpretation of effects, but a threshold of 0.05 when comparing between models. All statistical analyses were performed in R (version 3.3.3: R Core Team, 2017) with the packages ‘dplR’, ‘MASS’, ‘nlme’, and ‘ggplot2’ (Bunn, 2008; Pinheiro, Bates, DebRoy, & Sarkar, 2016; Venables & Ripley, 2002; Wickham, 2009).

Future growth scenarios

In order to better understand the implications of our findings in terms of future tree growth response across European forests, we calculated changes in basal area increment (compared to an average scenario, i.e. all continuous predictors set at the observed mean) for different scenarios of future environmental change. Since temperatures will likely rise, but future changes in nitrogen deposition and precipitation are more uncertain and depend on location (Christensen et al., 2007; Engardt et al., 2017; Simpson et al., 2014), we chose four scenarios. All scenarios assume an increase in mean annual temperature of 3°C. The ‘*dry*’ and ‘*wet*’ scenario respectively assume a decrease and increase in total annual precipitation of 100 mm/yr. The ‘*-N*’ and ‘*+N*’ scenario respectively assume a decrease and increase in nitrogen deposition of 10 kg/ha yr. A detailed explanation of the chosen scenarios can be found in the Supporting Information (**Description S1**). We calculated 95% confidence intervals following an informal Bayesian approach (Gelman & Hill, 2007). For each prediction, we drew 1000 random samples from a normal distribution for the mean and standard error of each model parameter for the different scenarios. For each of these samples, we then calculated the percentage basal area increment change compared to the average scenario and computed the confidence intervals around the predictions. We used the environment models for the three study species, and for *Quercus*, we additionally used the forest management model with ‘Coppice History’ as management variable, to compare predictions in the two management categories. Our aim with **Figure 4** is to demonstrate the implication of our findings in terms of future growth predictions

Results

Interactive effects of global-change drivers

The models including the global-change drivers showed good predictions (high R^2_f and R^2_m and low RMSE) (**Table 3**). For *Quercus*, the three global-change drivers (mean annual temperature, total annual precipitation, and nitrogen deposition) significantly increased tree growth (**Table 3, Fig. S6**), while only precipitation significantly affected tree growth in *Fagus* and *Fraxinus*. For *Fraxinus*, the effect of nitrogen deposition on basal area increment was quadratic instead of linear (**Table 3**). The magnitude of the effects in *Quercus* (parameter estimates or effect sizes in **Table 3**) suggests weaker effects of deposition than of precipitation and temperature. Acidification rate was not retained as a fixed effect in any of the models, so we subsequently present and discuss only effects due to nitrogen deposition. When including seasonal (spring, summer) temperature and precipitation instead of annual values, spring conditions seemed more important for *Fagus* tree growth than summer conditions (**Table S10**).

Crucially, the impact of a given main effect on growth depends on the levels of other drivers, at the European scale. Namely, *Quercus* showed an antagonistic linear interaction between nitrogen deposition and precipitation (**Table 3, Fig. 2a**). The positive growth response to increased deposition declined with increasing precipitation levels (**Fig. 2a**). For *Fagus*, we saw a synergistic interaction between temperature and precipitation, with stronger positive growth effects to increased temperatures when precipitation levels were higher (**Fig. 2b**). When using seasonal (spring, summer) temperature and precipitation instead of annual values, this interaction only appeared with spring conditions (seasonal analyses: **Table S10**). In contrast, for *Fraxinus*, a synergistic quadratic interaction between deposition and precipitation was observed, with weaker growth responses to increased deposition when precipitation was also lower, whereas precipitation levels did not seem to matter so much at lower deposition values (**Fig. 2c**).

Forest management effects

For both forest management variables used (i.e. *Coppice history* and *Management history*), a significant interaction between mean annual temperature and the management variable was found for *Quercus* (**Table 4**). The positive growth response to temperature was stronger in plots that had been managed as coppice or coppice-with-standards (CWS) at some point between 1940 and 2015 vs. plots that were not managed as coppice or CWS during that time

period (**Table 4, Fig. 3a**). When comparing only those plots managed as high forest between 1940 and 2015 with those that had been converted from coppice or CWS to high forest, the model similarly showed a stronger growth response to temperature in the plots that had been converted than in the continuously high-forested plots (**Table 4, Fig. 3b**).

Future growth scenarios

When examining changes in basal area increment under four scenarios of environmental change, we clearly see species-specific growth differences, as well as interactive effects (**Figure 4**). For instance, at the mean observed level of deposition, *Quercus* would show growth increases from an increase in deposition, and especially when precipitation also increases; whereas *Fraxinus* shows more chances of decreased growth at the mean deposition level, except for a potential growth increase when both deposition and precipitation increase. The observed interaction between forest management and environmental drivers for *Quercus* also results in future growth changes (**Figure 4**). Namely, when forest management is not taken into account, tree growth is expected to decrease or increase slightly with reduced deposition and increase with greater deposition, regardless of precipitation change. However, if we consider the management history, growth increases in all environmental change scenarios when *Quercus* grows in plots that have a history of coppicing. Without a history of coppicing, there is a tendency for growth to decline, regardless of the environmental change scenario, although there is a lower reliability for this scenario.

Discussion

In this study, the patterns of basal area increment along several environmental gradients of deposition and climate provide evidence for species-specific, main and interactive effects of environmental drivers (i.e. global-change drivers (for the three study species) and past forest management (for *Quercus* only)) on growth of three European tree species at a sub-continental scale. Importantly, the observed interactions along spatial environmental gradients suggest that in relatively nutrient-rich, mesic forests, tree growth responses to environmental change should not be estimated from effects of single drivers alone, nor should drivers be assumed to affect all species equally. Instead, the impact of a given driver depends on the levels of at least one other driver and the species considered. Furthermore, when translating responses over spatial gradients to scenarios of change in a given location for *Quercus*, our results demonstrate that accounting for prior management can alter not only the magnitude, but also the direction, of likely growth response to probable future environmental changes. Here, we present particularly pertinent interactions, discuss potential mechanisms behind the responses observed and suggest that our results have implications for the management of forests to mediate the influence of global-change drivers, and for the estimation of forests as carbon sources/sinks under future conditions.

Species-specific drivers of tree growth across Europe

The global-change drivers had a positive overall effect on basal area increment. The growth of *Quercus* increased with temperature; all tree species showed increased growth with increasing precipitation; and both *Quercus* and *Fraxinus* growth increased with nitrogen deposition (**Table 3; Fig. S6**). This positive response concurs with other studies investigating global-change effects on tree growth (Laubhann et al., 2009; Lindner et al., 2014). Indeed, to a certain extent, and as long as other factors do not become limiting (Martinez-Vilalta et al., 2008), warming may increase growth because of increases in metabolic rates, or longer growing seasons (Way & Oren, 2010). *Quercus* responded more strongly to temperature than to precipitation or deposition (**Table 3**). Other researchers have also suggested that *Quercus* may benefit from a warmer future to a certain extent, as opposed to *Fagus*, which is already showing growth declines (Jump, Hunt, & Penuelas, 2006; Kint et al., 2012; Latte et al., 2015; Piovesan et al., 2008). *Quercus*, *Fagus*, and *Fraxinus* all responded more strongly to precipitation than to nitrogen deposition (**Table 3**). Yet, many other studies have identified deposition as the main driver of tree and forest growth in Europe (Aertsens et al., 2014;

Augustaitis et al., 2016; Kahle et al., 2008; Laubhann et al., 2009; Magnani et al., 2007). The relatively low importance of nitrogen deposition in our study may be explained by the rich, mesic soils of our study regions (mean pH_{KCl} 4.4, mean base saturation 0.8, mean C/N 13.9). In richer soils, the effect of additional nitrogen from atmospheric deposition may be smaller than in studies such as Laubhann et al. (2009). In addition, the higher pH and cation exchange capacity of rich soils also represent a buffer against acidification (Kauppi, Kämäri, Posch, Kauppi, & Matzner, 1986), which may explain why we did not find acidification effects on tree growth. The growth of *Fraxinus*, however, did decline again at high deposition levels, i.e., when deposition exceeded the critical load (ca. 18 kg/ha yr for trees: Bobbink et al., 2017; **Table 3, Fig. S6**). Careful interpretation of the results for ash is warranted though, since ash dieback has affected the growth of a large number of *Fraxinus* trees across Europe since the 1990s and may have had an effect on the studied ash trees as well (Vasitis et al., 2017).

Tree growth responds interactively to global-change drivers

Importantly, we show that only considering simple effects overlooks interactions among drivers. In other words, tree growth response to a certain global-change driver can depend on the level of another driver, as was observed in our study species (**Fig. 2**). First, for *Quercus*, at low levels of nitrogen deposition, higher precipitation led to higher growth rates, whereas precipitation levels did not influence growth rates at higher deposition levels (**Fig. 2a**). Second, for *Fraxinus*, the opposite interaction was found: at lower levels of nitrogen deposition, precipitation did not strongly affect tree growth, whereas higher precipitation led to higher growth rates at higher deposition levels (**Fig. 2c**). Third, *Fagus* showed a much stronger growth response to higher temperatures when precipitation was also higher (**Fig. 2b**), which is consistent with the high sensitivity of *Fagus* to soil water availability. Furthermore, tree growth response to a certain global-change driver can also be modulated by the past forest management (**Fig. 3**). The *Quercus* trees growing in forests with a history of coppice, even when converted to high forest, showed stronger positive growth responses to increased temperatures across the study regions (**Table 4, Fig. 3**). Although very few studies investigating tree growth response to environmental factors have taken into account the past forest management, some studies did evaluate potential interactions between environment and management on tree growth (Latte et al., 2015; Stojanović et al., 2017; Vayreda et al., 2012). Stojanović et al., (2017) also found different climate-growth relationships for *Quercus* trees in past coppiced vs. in high forest stands in the Czech Republic. They also show that

future climatic changes could differently affect the two origins (coppice vs. high forest), confirming the modulating effect that past forest management can have on current and future tree growth rates. Vayreda et al. (2012) also suggested the potential role of forest management within the context of climate change mitigation (e.g. by enhancing tree growth), based on a reduced carbon sink capacity with warming in unmanaged vs. in managed forests in Spain. Interestingly, the potential role of forest management is in contrast with the progressive abandonment of management in many temperate broadleaf European forests over the last decades (Kopecký et al., 2013; Scolastrri, Cancellieri, Iocchi, & Cutini, 2017).

Potential mechanisms underlying interactive effects

Although it is not possible to demonstrate mechanisms behind the interactive effects in this observational study, we provide plausible reasons for what we observe. First, species-specific sensitivities to environmental drivers could lie behind some of the observed interactions. For instance, the contrasting responses in *Quercus* vs. *Fraxinus* to precipitation and nitrogen deposition could be due to their colonization of different site conditions, i.e. *Fraxinus* grows on wetter and richer soils than *Quercus*. Thus, the joint effect of high deposition as well as precipitation might be positive for *Fraxinus*, whereas negative for *Quercus*. On the other hand, *Quercus* might have a competitive advantage over nutrient-demanding species such as *Fraxinus* under conditions of drought and low nitrogen availability, which has also been described by other researchers (Lévesque, Walthert, & Weber, 2016). In *Fagus*, the antagonistic interaction between precipitation and temperature could be explained by the strong sensitivity of this species to low water availability or drought (Ellenberg & Leuschner, 2010; Vanoni, Bugmann, Nötzli, & Bigler, 2016). Higher temperatures resulting in a higher evapotranspiration might lead to increased drought stress and reduce tree growth of *Fagus* (Aber, Neilson, McNulty, et al., 2001; Ciais et al., 2005; Scherrer, Bader, & Körner, 2011). Similar interactive effects have been reported by other researchers (Bauwe et al., 2016; Latte et al., 2015; Martinez-Vilalta et al., 2008; Mette et al., 2013). This sensitivity is supported by the fact that only precipitation, and not temperature or deposition, affected tree growth of *Fagus* across all study regions, and by the significant effect of ‘annual aridity’ on the growth of *Fagus* (additional analysis: see **Table S11**). The antagonistic interaction between temperature and precipitation was not detected for the summer data, but did also occur for the spring data, which suggests that the drought sensitivity of *Fagus* might be associated with spring rather than summer conditions, i.e. when the trees’ growing season starts (**Table S10**). Latte, Lebourgeois, & Claessens (2016) similarly found that intra-annual variation in *Fagus*

growth was driven by current-year spring drought in several Belgian sites. The observed interaction between temperature and precipitation could have serious consequences for the future growth of *Fagus*, with the increasing temperatures and more frequent and extreme heat waves expected in Europe (Christensen et al., 2007).

Second, whether or not ‘critical loads’ had been exceeded in a region might also explain the contrasting responses in *Quercus* vs. *Fraxinus* to precipitation and nitrogen deposition. Smaller or negative effects of nitrogen deposition on tree growth might only occur when deposition levels have exceeded a certain threshold or ‘critical load’ (ca. 18 kg/ha yr for trees: see Bobbink et al., 2017; Eugster & Haeni, 2013; Jones et al., 2014), which is more probable within the observed deposition range of *Quercus* (0.7-38.5 kg/ha yr) than of *Fraxinus* (0.8-28 kg/ha yr and mostly 10-20 kg/ha yr). At the highest deposition levels in *Quercus*, precipitation levels might not influence growth from higher deposition anymore, whereas in *Fraxinus*, it might still facilitate additional nitrogen uptake for growth.

Third, the mycorrhizal dynamics may mediate tree growth responses to environmental changes. The different mycorrhizal communities associated with *Quercus* vs. *Fraxinus*, i.e. respectively ectomycorrhizae (ECM) vs. arbuscular mycorrhizae (AM), might explain their contrasting responses to deposition and precipitation (Lang, Seven, & Polle, 2011; Mohan et al., 2014; Thomas, Canham, Weathers, & Goodale, 2010). Unlike ECM fungi, AM fungi are unable to produce enzymes that breakdown soil organic nitrogen, so they may benefit more from increased deposition or thus increased inorganic nitrogen availability, the latter being their sole source of nitrogen (Thomas et al., 2010).

Finally, the stronger response of trees in plots that have a history of coppicing might be explained by the fact that ‘standard trees’ in *Quercus* coppice-with-standard systems may have better developed (‘bigger’) crowns than in continuous high forest, where tree crowns generally overlap more at similar heights. Thus, their bigger crowns create a larger photosynthetic area, which may increase production with increasing temperatures. Another potential explanation might be related to the vigorous growth of surviving trees after a coppice cut, when the trees can profit from plentiful resources and low competition rates (Altman et al., 2013; Deforce & Haneca, 2015; Stojanović et al., 2017). *Quercus* trees growing in plots with a history of coppicing might thus be phenotypically adapted to utilize sudden and strong temperature increases to boost their growth during the phases with high

light availability (Thom, Rammer, & Seidl, 2017; Trouvé, Bontemps, Collet, Seynave, & Lebourgeois, 2017).

Implications for future tree growth

Here, we evaluated growth responses to *spatial* environmental gradients. Translating these spatial responses into the response of trees to scenarios of *temporal* changes in these environmental drivers in a given place, allows to assess the implications for future tree growth (**Figure 4**). Our results demonstrate that future growth predictions in global-change studies are influenced by the study species, as well as by interactive effects of the global-change drivers. They also demonstrate that for *Quercus*, growth predictions depend on whether or not past management was accounted for (**Figure 4**). Accounting for prior management can alter not only the magnitude, but also the direction, of likely growth responses to probable future environmental changes for this species. In the scenario of increased precipitation and deposition (+100 mm/yr and 10 kg/ha yr) for instance, *Quercus* growth is predicted to increase with 3.9 % when coppice history was not taken into account, whereas an increase of 6.7 % (i.e. 2.8% more), vs. a decrease of -2.5% (i.e. 6.4% less) is expected when we distinguish between plots with a history of coppicing vs. no coppicing history respectively. It should be noted that we examined annual climatic variables here, and that predictions using seasonal climatic variables may differ, depending on the seasonal climate-growth sensitivity. With more frequent and extreme heat waves expected throughout Europe, a drought-sensitive species such as *Fagus* may be considerably impaired in its growth during and after such events (Latte et al., 2015; Tognetti, Lombardi, Lasserre, Cherubini, & Marchetti, 2014).

Our aim with **Figure 4** was to demonstrate the implication of our findings (i.e. species-specificity and interactive effects) in terms of future growth predictions, rather than provide accurate growth predictions. Thus, the actual values should be interpreted with caution, since they are based on the assumption that growth responses to the different global-change drivers do not change over time (nor between 1940-2015, nor in the future), which is not necessarily the case (see additional analysis: **Table S12**). Although investigating temporal changes in the relationship between the global-change drivers and tree growth over time would be an intriguing line of further research, this is beyond the scope of the present paper. Also, accurate prediction of forest growth will not only require taking into account (species-specific) interactive effects, but likely also consideration of (i) stand dynamics (vs. individual growth), (ii) site-specific scenario values (e.g. some regions might show stronger vs. weaker

temperature increases than +3°C), (iii) temporal changes in the relationships between growth and the predictors, (iv) legitimacy of the space-for-time approach, and (v) consideration of seasonal growth predictors.

Neither tree competition, elevation, soil chemistry or soil depth were retained for our study species in the models, suggesting that we achieved a satisfactory sampling strategy, minimizing the effects of confounding factors in this study. A potentially confounding factor that we did not account for here though was the occurrence of biotic disturbances (i.e. pests and diseases) such as the ash dieback fungus (*Hymenoscyphus fraxineus*) for *Fraxinus excelsior* or the oak processionary moth (*Thaumetopoea processionea*) or Winter Moth (*Operophtera brumata*) for *Quercus robur/petraea*. Although we tried to core healthy trees, biotic disturbances may have affected the growth of our cored trees in the past, without visible signs at the time of coring. Additional research is needed on the interaction between biotic disturbances and other growth factors, especially with the anticipated increases in pest impacts on trees and forests with global environmental changes (Ramsfield, Bentz, Faccoli, Jactel, & Brockerhoff, 2016). Regarding the choice of climatic variables in the analyses, we acknowledge that the use of climate data of the current year might obscure lagged effects of previous-year conditions. Masting events could also have affected tree growth and climate-growth relationships (e.g. Hacket-Pain, Friend, Lageard, & Thomas, 2015), but unfortunately we did not have data on masting in our plots. Furthermore, we stress that our results concern the growth of individual (co-)dominant trees and acknowledge that environmental or management effects on suppressed trees may be different (Coomes & Allen, 2007; Ford et al., 2017; Meyer, Bräker, Meyer, Bräker, & Federal, 2017). A drawback of our study is that we could only consider management history for *Quercus* here, hence the potential role of forest management for the other study species' tree growth remains unknown. Finally, as we did not cover the whole distribution area of the study species, we stress that our results should not be extrapolated to trees growing e.g. in more southern forest regions without additional research.

Although we cored a considerable number of trees across the whole study area, and the total sample size is large because one tree provides data from many growth years (e.g. environment models: N = 10498 [*Quercus*], 5157 [*Fagus*], 3182 [*Fraxinus*]), the small number of trees per plot (mostly 2, maximum 3) could be considered as a limitation which might have affected our findings. To evaluate whether the sample size might have impacted our main results (interactive effects) and the values in figure 4, we performed several

656 additional analyses testing the robustness of our results, and report these in Supporting
657 Information (environment models: **Table S13** and **Fig. S7**, forest management models: **Table**
658 **S14** and **Fig. S8**, figure 4: **Table S15**). From this, it did not seem like the sample size affected
659 our results.

660 To conclude, in this study we showed that simultaneously considering multiple global-change
661 drivers as well as the management history might be crucial for solid predictions of tree
662 growth in the face of global environmental change. Tree growth in closed-canopy forests is
663 determined by a complex interaction of factors (e.g. environment, management, soil and
664 stand conditions, tree age/size). Here, we have shown that sampling trees on a larger
665 geographical scale, and across gradients of specific factors of interest (e.g. global-change
666 drivers and forest management), can help in disentangling the effects of these factors. Several
667 species-specific main and interactive effects of the global-change drivers were detected, but
668 additional studies that (i) evaluate management effects for other tree species, (ii) cover other
669 study areas and (iii) investigate temporal growth responses as well, are needed to validate our
670 findings more generally.

671

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Conflict of interest

The authors have no conflicts of interest to declare.

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977 **Tables**

Table 1: Variables used to model the basal area increment of individual trees, reflecting the global-change drivers, forest management history, and potentially confounding factors (local soil and stand conditions + tree size). All variables were continuous except for the categorical variables of past forest management. Variables in **bold** represent the variables of interest (global-change drivers and past forest management); underlined variables were included as time series. C(W) and HF represent the coppice-(with-standards) and high forest management type. Past forest management was only included in the *Quercus* models.

Spatial scale	Predictor	Variable (unit)	Description
Region	<u>Temperature</u>	MAT (°C)	Annual average (+spring, summer – Supp. Info)
	<u>Precipitation</u>	TAP (mm)	Annual total (+spring, summer – Supp. Info)
	<u>N Deposition</u>	Ndep (kg/ha)	Annual total (NO _x , NH ₃)
	<u>Acidification Rate</u>	AcidRate (keq/ha)	Annual total (NO _x , NH ₃ , SO _x)
Plot	Elevation	Elev (m)	Elevation of the plot
	Soil depth	SoilDepth (cm)	Depth of the bedrock
	Soil conditions	PC1, PC2 (dimensionless)	1st and 2nd axis of PCA on chemical soil variables (see Fig. S1)
	Past forest management	CoppHist	Categorical (0 or 1): coppicing between 1940-2015?
		ManHist	Categorical ('C(W) to HF' or 'HF'): management history between 1940-2015?
Tree	<u>Tree size</u>	Dprev (cm) Dprev ² (cm ²)	Previous-year diameter (see Fig. S2)
	Competition	NCI (dimensionless)	Neighbourhood competition index

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Table 2: Minimum-maximum ranges for several tree characteristics of the cored trees across the 19 forest regions. *BAI* represents the basal area increment, *DBH* the diameter-at-breast-height, and *NCI* the neighborhood competition index.

	BAI (cm²/yr)	DBH (cm)	NCI
<i>Quercus robur/petraea</i>	0 - 114.32	26.5 - 107	0 - 2.65
<i>Fagus sylvatica</i>	0 - 112.32	27 - 100	0 - 1.36
<i>Fraxinus excelsior</i>	0.03 - 130.4	22 - 89.25	0.06 - 3.24

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Table 3: Parameter estimates and model evaluation of the final environment (Me) models for the basal area increment of the three study species. The sample size for each model is given by n (number of rings). *Dprev*, *MAT*, *TAP*, *Ndep* respectively refer to previous-year-diameter ('tree size'), mean annual temperature, total annual precipitation, and nitrogen deposition.

	<i>Quercus robur/petraea</i> [n=10498]			<i>Fagus sylvatica</i> [n=5157]			<i>Fraxinus excelsior</i> [n=3182]		
Fixed effects	Estimate	SE	P-value	Estimate	SE	P-value	Estimate	SE	P-value
(Intercept)	2.7580	0.0555	<0.0001**	3.1955	0.0461	<0.0001**	2.8357	0.0628	<0.0001**
Dprev	0.6304	0.02070	<0.0001**	0.0564	0.0267	<0.0001**	0.7760	0.0453	<0.0001**
Dprev ²	-0.1715	0.0103	<0.0001**	-0.2329	0.0164	<0.0001**	-0.3258	0.0294	<0.0001**
Soil shallowness	-	-	-	-0.1225	0.0410	0.0049 ns	-	-	-
MAT	0.0538	0.0062	<0.0001**	-0.0047	0.0091	0.6060 ns	-	-	-
TAP	0.0480	0.0040	<0.0001**	0.0182	0.0047	0.0001**	0.0308	0.0058	<0.0001**
Ndep	0.0370	0.0109	0.0003*	0.0324	0.0172	0.0600 ns	0.0300	0.0181	0.0970 ns
Ndep ²	-	-	-	-	-	-	-0.0336	0.0086	0.0001**
MAT:TAP	-	-	-	0.0214	0.0050	<0.0001**	-	-	-
MAT:Ndep	-	-	-	-0.0182	0.0092	0.0482 ns	-	-	-
TAP:Ndep	-0.0182	0.0039	0.0007*	-	-	-	0.0229	0.0059	0.0001**
Model evaluation	R²_f	R²_m	RMSE	R²_f	R²_m	RMSE	R²_f	R²_m	RMSE
	0.76	0.48	1.27%	0.64	0.49	1.58%	0.63	0.55	10.70%

P-value: ns: p>0.001; *: p≤0.001; **: p≤0.0001. Significant p-values are in bold.

R²_f: conditional R² or proportion explained by fixed and random factors

R²_m: marginal R² or proportion of variance explained by fixed factors

RMSE: root mean squared error between predicted and observed values of basal area increment

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Table 4: Parameter estimates and model evaluation of the final forest management (Mfm) models for the basal area increment of *Quercus robur/petraea*. The forest management models included information on the Coppice history (left) and on the Management history (right) in the plot. The sample size for each model is given by n (number of rings). *Dprev*, *MAT*, *TAP*, *Ndep*, *CoppHist* ('0' or '1') and *ManHist* ('C(WS) to HF' or 'HF') respectively refer to previous-year-diameter ('tree size'), mean annual temperature, total annual precipitation, nitrogen deposition, coppice history, and management history.

Fixed effects	<i>Coppice history</i> [n=10498]			<i>Management history</i> [n=5450]		
	Estimate	SE	P-value	Estimate	SE	P-value
(Intercept)	2.8760	0.0718	<0.0001**	3.0019	0.1184	<0.0001**
Dprev	0.6306	0.0207	<0.0001**	0.5882	0.0277	<0.0001**
Dprev ²	-0.1702	0.0103	<0.0001**	-0.2648	0.0173	<0.0001**
MAT	0.0780	0.0094	<0.0001**	0.1316	0.0142	<0.0001**
TAP	0.0477	0.0040	<0.0001**	0.0568	0.0057	<0.0001**
Ndep	0.0366	0.0108	0.0007*	0.0419	0.0138	0.0025 ns
TAP:Ndep	-0.0182	0.0039	<0.0001**	-0.0174	0.0049	0.0003*
CoppHist=0	-0.1952	0.0822	0.0203 ns	-	-	-
MAT:CoppHist	-0.0420	0.0122	0.0006*	-	-	-
ManHist=HF	-	-	-	-0.0818	0.0989	0.4142 ns
MAT:ManHist	-	-	-	-0.1129	0.0178	<0.0001**
Model	R²f	R²m	RMSE	R²f	R²m	RMSE
evaluation	0.76	0.49	1.30%	0.77	0.53	1.21%

P-value: ns: p>0.001; *: p≤0.001; **: p≤0.0001. Significant p-values are in bold.

R²f: conditional R² or proportion explained by fixed and random factors

R²m: marginal R² or proportion of variance explained by fixed factors

RMSE: root mean squared error between predicted and observed values of basal area increment

All fixed effects were standardized (scaled and centered) prior to analysis.

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987 **Figures****Figure 1:**

(a): The 19 forest regions with the distribution of the cored tree species from each region. Each pie chart visualizes the proportion of cored trees of the three study species per region, with *Quercus*, *Fagus*, and *Fraxinus* respectively displayed in green, orange and purple. The *total number* of cored trees per region and the *Region code* is given next to the pie charts.

(b): Environmental gradients covered by the study species: total annual precipitation (TAP – mm/yr) vs. mean annual temperature (MAT – °C) is plotted, with a pie chart representing the distribution of the cored tree species in each region, and the pie chart size reflecting the nitrogen deposition load in that region (Ndep – kg/ha yr). Environmental values from the year 2000 were used.

Region codes, and *country codes* between brackets, are as follows: BI=Białowieża Forest (PL), BS=Braunschweig (GE), BV=Binnen-Vlaanderen (BE), CO=Compiègne (FR), DE=Devin Wood (CZ), GO=Göttingen (GE), KO=Koda Wood (CZ), LF=Lyons-la-Forêt (FR), MO=Moricsala (LTV), P=Pembrokeshire (UK), PR=Prignitz (GE), SH=Schleswig-Holstein (GE), SKA=Skåne (SW), SK=Slovak Karst (SLK), SP=Speulderbos (NL), TB=Tournibus (BE), WR=Warburg Reserve (UK), WW=Wytham Woods (UK), and ZV=Zvolen (SLK). Details on these regions can be found in **Table S1**.

Figure 2: The interaction between **(a)** nitrogen deposition and total annual precipitation (TAP) on basal area increment (BAI) for *Quercus robur/petraea* (n=10498), **(b)** mean annual temperature (MAT) and total annual precipitation for *Fagus sylvatica* (n=5157), and **(c)** nitrogen deposition and total annual precipitation for *Fraxinus excelsior* (n=3182). Actual data points (*dots*) and model estimates of the effects (*full lines*), in which the values of the other continuous variables were set at their observed mean, are shown.

Figure 3: The interaction between **(a)** mean annual temperature (MAT) and coppice history ('yes' or 'no', n=10498) and **(b)** mean annual temperature and management history ('coppice/coppice-with-standards (C(W)) to high forest (HF) or 'HF throughout'), n=5450), on basal area increment for *Quercus robur/petraea*. Actual data points (*dots*) and model estimate of the effects (*full lines*), in which the values of the other continuous variables were set at their observed mean, are shown.

Figure 4: Percentage basal area increment change for four scenarios of future environmental change based on final model predictions for the three study species (*Quercus spp.* refers to *Quercus robur/petraea* here). All scenarios assume an increase in mean annual temperature of 3°C compared to the observed mean. The 'dry' (red colors) and 'wet' (blue colors) scenarios respectively assume a decrease and increase in total annual precipitation of 100 mm/yr. The '-N' (full lines) and '+N' (dashed lines) scenarios respectively assume a decrease and increase in nitrogen deposition of 10

kg/ha yr compared to the observed mean. The percentage basal area increment change, compared to an average scenario in which all continuous predictors are set at their observed mean, is calculated according to an informal Bayesian approach. The dots represent the median of 1000 random samples from a normal distribution for the mean and standard error of each model parameter, whereas the lines represent 95% confidence intervals.

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(a)

(b)

(a)

(b)

(c)

(a)

(b)

%BAI change

-N-P   -N+P   +N-P   +N+P

Supporting Information for manuscript
“Environmental drivers interactively affect individual tree growth
across European temperate forests”

TABLES

Table S1: Location and characteristics of the 19 forest regions in which trees were cored.

Table S2: Information on the plot management histories between 1940 and 2015 and start years of the tree-ring series per plot.

Table S3: Information on the different in-situ plot measurements (Soil, Forest floor, Basal area measurements, and chemical analyses performed on the collected samples.

Table S4. Statistical parameters of the crossdating (CD) process.

Table S5: The number of trees, plots, and regions for the past forest management variables used in the analyses on past forest management.

Tables S6-8: Minimum-maximum ranges for several tree characteristics of the cored *Quercus* (**Table S6**), *Fagus* (**Table S7**), and *Fraxinus* (**Table S8**) trees for the 19 forest regions

Table S9: Likelihood ratio tests of nested model comparisons for *Quercus robur/petraea*, testing for fixed effects of forest management variables and/or interactions of these with global-change drivers.

Table S10: Parameter estimates and model evaluation of the final environment (Me) models for the basal area increment of the three study species, using seasonal climatic variables.

Table S11: Additional analysis results for *Fagus* on the effect of annual aridity index to test for drought effects.

Table S12: Additional analyses results for the three study species testing for temporal changes in the sensitivity of growth to the global-change drivers between 1940-1980 and 1981-2015.

Table S13: Additional analyses results to test how the sample size might have affected the results of the final environment models for the three study species.

Table S14: Additional analyses results to test how the sample size might have affected the results of the final forest management models for *Quercus robur/petraea*.

Table S15: Additional analyses results to test how the sample size might have affected the results of figure 4.

FIGURES

Fig. S1: Biplot of the first two axes of the PCA on the soil physical-chemical variables.

Fig. S2: The actual basal area increment data and the model estimates of the effects of tree size (i.e. previous-year-diameter or Dprev) for the three study species.

Fig. S3: Pairwise correlation matrix of the continuous predictor variables for the three tree species that were cored.

Fig. S4: Time series of the regional predictor variables : a) mean annual temperature - MAT (°C), b) total annual precipitation - TAP (mm/yr), c) nitrogen deposition - Ndep (kg/ha yr), d) acidification rate - AcidRate (keq/ha yr).

Fig. S5: Pairwise correlation matrix of the annual and seasonal (spring and summer) climatic variables for the three tree species that were cored.

Fig. S6: The actual basal area increment data and the model estimates of the effects of mean annual temperature (*top*: MAT – °C), total annual precipitation (*middle*: TAP – mm/yr), and nitrogen deposition (*bottom*: Ndep – kg/ha yr) for the three study species.

Fig. S7: Additional analyses results (effect sizes and p-values) to test how the sample size might have affected the results of the final environment models for the three study species.

Fig. S8: Additional analyses results (effect sizes and p-values) to test how the sample size might have affected the results of the final forest management models models for *Quercus robur/petraea*.

DESCRIPTIONS

Description S1. Explanation behind the climate and deposition scenarios for the future growth changes presented in **Fig. 4**.

Table S1: Location and characteristics of the 19 forest regions in which trees were cored in November 2014 and May-June 2015 and 2016. *Year* represents the sampling year. *Mean coord* shows the mean coordinates of all plots in the region; *MAT*, *TAP*, *Ndep*, and *AcidRate* the mean annual temperature, total annual precipitation, nitrogen deposition, and acidification rate for the year 2000. *No plots* and *No trees* reflects the number of plots and respectively trees that were included for the three study species. *QR*, *FS*, and *FE* represent *Quercus robur/petraea*, *Fagus sylvatica*, and *Fraxinus excelsior*.

	Year	MAT (°C)	TAP (mm/yr)	Ndep (kg/ha/yr)	AcidRate (keq/ha yr)	No plots (QR-FS-FE)	No trees (QR-FS-FE)
Bialowieża, PL	2016	9.29	540	13.08	1.48	3 – 0 – 0	5 – 0 – 0
Braunschweig, GE	2015	10.47	598	17.22	1.68	10 – 0 – 0	19 – 0 – 0
Binnen- Vlaanderen, BE	2015	11.30	853	21.57	2.45	2 – 0 – 2	2 – 0 – 2
Compiègne, FR	2016	12.42	891	14.41	1.45	4 – 8 – 0	4 – 11 – 0
Devin Wood, CZ	2015	11.17	472	15.73	1.60	1 – 0 – 4	2 – 0 – 5
Göttingen, GE	2015	9.67	611	17.13	1.64	0 – 10 – 8	0 – 12 – 8
Koda Wood, CZ	2015	9.28	557	15.78	1.66	9 – 2 – 0	16 – 2 – 0
Lyons-la- Forêt, FR	2015	12.91	960	15.14	1.54	0 – 9 – 1	0 – 16 – 1
Moricsala, LTV	2016	8.29	651	7.06	0.75	4 – 0 – 0	4 – 0 – 0
Pembrokeshire, UK	2016	10.14	1852	8.30	0.85	6 – 1 – 2	9 – 1 – 2
Prignitz, GE	2015	10.47	681	16.33	1.53	2 – 2 – 4	2 – 2 – 9
Schleswig- Holstein, GE	2016	9.98	686	18.50	1.75	0 – 10 – 2	0 – 16 – 2
Slovak Karst, SLK	2015	9.14	685	12.64	1.25	10 – 1 – 0	18 – 1 – 0
Skane, SW	2014	7.88	696	10.97	1.49	8 – 0 – 0	16 – 0 – 0
Speulderbos, NL	2016	10.78	873	29.61	2.79	6 – 4 – 0	12 – 8 – 0
Tournibus, BE	2015	10.74	986	17.24	1.80	9 – 0 – 2	13 – 0 – 2
Warburg Reserve, UK	2015	10.38	931	14.14	1.44	0 – 3 – 6	0 – 4 – 8
Wytham Woods, UK	2015	10.55	857	11.68	1.44	3 – 0 – 8	4 – 0 – 10
Zvolen, SLK	2015	6.96	850	11.85	1.65	10 – 0 – 0	19 – 0 – 0
All Regions	2014-2016	6.96-12.91	472-1852	7.06-29.61	0.75-2.79	87 – 50 – 39	145 – 73 – 49

Table S2: Information on the plot management histories between 1940 and 2015 and start years of the tree-ring series of all cored trees per plot for the 151 unique plots where trees were cored. *Region* codes are as follows: BI=Białowieża Forest (PL), BS=Braunschweig (GE), BV=Binnen-Vlaanderen (BE), CO=Compiègne (FR), DE=Devin Wood (CZ), GO=Göttingen (GE), KO=Koda Wood (CZ), LF=Lyons-la-Forêt (FR), MO=Moriczsa (LTV), P=Pembrokeshire (UK), PR=Prignitz (GE), SH=Schleswig-Holstein (GE), SKA=Skane (SW), SK=Slovak Karst (SLK), SP=Speulderbos (NL), TB=Tournibus (BE), WR=Warburg Reserve (UK), WW=Wytham Woods (UK), and ZV=Zvolen (SLK). *ManHist* reflects the management history between 1940 and 2015. *C or CWS* reflects whether, in case a period of coppicing was present in the *ManHist* ('C(WS)', it was a coppice (C) or coppice-with-standards (CWS) system. *Trans1* and *Trans2* are the years in which the first or second transition occurred to another management type (if 'NA', the management system did not change between 1940 and 2015). *MT1*, *MT2*, and *MT3* reflects the number of years that the first, second, and third management system was in place in the plot between 1940 and 2015. *Start years* and *Spec* and *Spec 2* comprise the different start years and species ('Q', 'F', and 'FR' represent *Quercus robur/petraea*, *Fagus sylvatica*, and *Fraxinus excelsior*) for all tree-ring series collected from that plot.

Region	PlotID	ManHist	C or CWS	Trans 1	Trans 2	MT1	MT2	MT3	Start years	Spec	Spec2
BI	BI6471	HF - ZM	NA	1979	NA	39	36	NA	1846, 1867	Q	NA
BI	BI6603	HF throughout	NA	NA	NA	NA	NA	NA	1968, 1969	Q	NA
BI	BI9460	HF - ZM	NA	1974	NA	34	41	NA	1863	Q	NA
BS	BS183	HF throughout	NA	NA	NA	NA	NA	NA	1908	Q	NA
BS	BS192	C(WS) - HF	C	1995	NA	55	20	NA	1960, 1965	Q	NA
BS	BS195	C(WS) - HF	C	1995	NA	55	20	NA	1943, 1947	Q	NA
BS	BS203	C(WS) throughout	C	NA	NA	NA	NA	NA	1960, 1964	Q	NA
BS	BS205	C(WS) - HF	C	1950	NA	10	65	NA	1902, 1949	Q	NA
BS	BS331	HF throughout	NA	NA	NA	NA	NA	NA	1894, 1905	Q	NA
BS	BS340	C(WS) throughout	CWS	NA	NA	NA	NA	NA	1880, 1920	Q	NA
BS	BS342	C(WS) throughout	C	NA	NA	NA	NA	NA	1950, 1950	Q	NA
BS	BS359	C(WS) - HF	C	1950	NA	10	65	NA	1920, 1933	Q	NA
BS	BS370	HF throughout	NA	NA	NA	NA	NA	NA	1956, 1961	Q	NA
BV	BV31	C(WS) - HF	C	1950	NA	10	65	NA	1951	Q	NA
BV	BV42	C(WS) - HF	C	1950	NA	10	65	NA	1944	FR	NA
BV	BV46	HF throughout	NA	NA	NA	NA	NA	NA	1860, 1946	Q	FR
CO	CO1	HF - ZM	NA	1970	NA	30	45	NA	1846, 1977	Q	F
CO	CO4.20	HF throughout	NA	NA	NA	NA	NA	NA	1857	Q	NA
CO	CO4.21	HF throughout	NA	NA	NA	NA	NA	NA	1880, 1934	Q	F
CO	CO4.23	HF throughout	NA	NA	NA	NA	NA	NA	1854, 1880	Q	NA
CO	CO4.24	HF throughout	NA	NA	NA	NA	NA	NA	1874, 1880	Q	NA
CO	CO4.25	HF throughout	NA	NA	NA	NA	NA	NA	1970, 1970	F	NA
CO	CO4.27	HF - ZM	NA	1970	NA	30	45	NA	1885, 1897	Q	F
CO	CO5	HF - ZM	NA	1970	NA	30	45	NA	1927	F	NA
CO	CO6	HF - ZM	NA	1970	NA	30	45	NA	1778, 1811	Q	F
CO	CO8	HF - ZM	NA	1970	NA	30	45	NA	1775, 1846	Q	NA

DE	DE129	HF - ZM	NA	1946	NA	6	69	NA	1945	FR	NA
DE	DE28	HF - ZM	NA	1946	NA	6	69	NA	1903, 1913	FR	NA
DE	DE404	HF - ZM	NA	1946	NA	6	69	NA	1917	FR	NA
DE	DE411	HF - ZM	NA	1946	NA	6	69	NA	1929, 1929	Q	NA
DE	DE446	HF - ZM	NA	1946	NA	6	69	NA	1950	FR	NA
GO	GO104	HF throughout	NA	NA	NA	NA	NA	NA	1866, 1883	FR	F
GO	GO116	HF throughout	NA	NA	NA	NA	NA	NA	1877, 1900	FR	F
GO	GO120	HF - ZM	NA	1992	NA	52	23	NA	1893, 1902	FR	F
GO	GO178	HF throughout	NA	NA	NA	NA	NA	NA	1929, 1934	FR	F
GO	GO182	HF throughout	NA	NA	NA	NA	NA	NA	1928, 1932	FR	F
GO	GO216	HF throughout	NA	NA	NA	NA	NA	NA	1919	F	NA
GO	GO237	HF throughout	NA	NA	NA	NA	NA	NA	1900, 1906	FR	F
GO	GO548	HF - ZM	NA	1997	NA	57	18	NA	1885, 1883, 1890	FR	F
GO	GO578	HF throughout	NA	NA	NA	NA	NA	NA	1893, 1899	F	NA
GO	GO83	HF - ZM	NA	1970	NA	30	45	NA	1886, 1903	FR	F
KO	KO775	HF throughout	NA	NA	NA	NA	NA	NA	1897, 1909	Q	F
KO	KO777	HF throughout	NA	NA	NA	NA	NA	NA	1886, 1901	Q	F
KO	KO778	HF throughout	NA	NA	NA	NA	NA	NA	1820, 1853	Q	Q
KO	KO784	HF throughout	NA	NA	NA	NA	NA	NA	1934, 1940	Q	NA
KO	KO785	HF throughout	NA	NA	NA	NA	NA	NA	1881, 1900	Q	NA
KO	KO786	HF throughout	NA	NA	NA	NA	NA	NA	1906	Q	NA
KO	KO787	HF throughout	NA	NA	NA	NA	NA	NA	1917, 1923	Q	NA
KO	KO791	HF throughout	NA	NA	NA	NA	NA	NA	1821, 1886, 1886	Q	NA
KO	KO792	HF throughout	NA	NA	NA	NA	NA	NA	1820, 1885	Q	NA
LF	LF1	HF throughout	NA	NA	NA	NA	NA	NA	1880, 1895	F	NA
LF	LF12	HF throughout	NA	NA	NA	NA	NA	NA	1870, 1872	F	NA
LF	LF14	HF throughout	NA	NA	NA	NA	NA	NA	1915, 1920	F	NA
LF	LF15	HF throughout	NA	NA	NA	NA	NA	NA	1849, 1856	F	NA
LF	LF16	HF throughout	NA	NA	NA	NA	NA	NA	1849, 1864	F	NA
LF	LF3	HF throughout	NA	NA	NA	NA	NA	NA	1929, 1931	F	NA
LF	LF5	HF throughout	NA	NA	NA	NA	NA	NA	1873, 1878	F	NA
LF	LF7	HF throughout	NA	NA	NA	NA	NA	NA	1958, 1959	F	NA
LF	LF9	HF throughout	NA	NA	NA	NA	NA	NA	1976	F	NA
MO	MO11	ZM throughout	NA	NA	NA	NA	NA	NA	1823	Q	NA
MO	MO18	ZM throughout	NA	NA	NA	NA	NA	NA	1823	Q	NA
MO	MO8	ZM throughout	NA	NA	NA	NA	NA	NA	1877	Q	NA
MO	MO9	ZM throughout	NA	NA	NA	NA	NA	NA	1842	Q	NA
P	PAS10	HF - ZM	NA	1950	NA	10	65	NA	1914, 1969	Q	NA
P	PAS11	HF - ZM	NA	1950	NA	10	65	NA	1912	Q	NA
P	PAS14	HF - ZM	NA	1950	NA	10	65	NA	1905, 1911	Q	NA
P	PAS16	HF - ZM	NA	1950	NA	10	65	NA	1962, 1964	Q	F
P	PPY3	C(WS) - ZM	CWS	1947	NA	7	68	NA	1960	FR	NA
P	PPY4	C(WS) - ZM	CWS	1947	NA	7	68	NA	1912, 1954	Q	NA
P	PPY7	C(WS) - ZM	CWS	1947	NA	7	68	NA	1805, 1893	Q	FR
PR	PR125	HF - ZM	NA	1990	NA	50	25	NA	1866, 1920	Q	F
PR	PR196	HF throughout	NA	NA	NA	NA	NA	NA	1953, 1960	FR	NA

PR	PR197	HF throughout	NA	NA	NA	NA	NA	NA	1925, 1927	FR	NA
PR	PR204	HF throughout	NA	NA	NA	NA	NA	NA	1883, 1885, 1965	FR	NA
PR	PR26	HF - ZM	NA	1995	NA	55	20	NA	1953, 1956	FR	NA
PR	PR63	HF throughout	NA	NA	NA	NA	NA	NA	1916	F	NA
PR	PR68	HF throughout	NA	NA	NA	NA	NA	NA	1910	Q	NA
SH	SH1	HF throughout	NA	NA	NA	NA	NA	NA	1917	F	NA
SH	SH10	HF throughout	NA	NA	NA	NA	NA	NA	1906, 1923	F	NA
SH	SH2	HF throughout	NA	NA	NA	NA	NA	NA	1909, 1929	F	NA
SH	SH3	HF throughout	NA	NA	NA	NA	NA	NA	1980	F	NA
SH	SH4	HF throughout	NA	NA	NA	NA	NA	NA	1948, 1962	F	NA
SH	SH5	HF throughout	NA	NA	NA	NA	NA	NA	1917, 1920	F	NA
SH	SH6	HF throughout	NA	NA	NA	NA	NA	NA	1909, 1940	F	NA
SH	SH7	HF throughout	NA	NA	NA	NA	NA	NA	1928, 1936	F	FR
SH	SH8	HF throughout	NA	NA	NA	NA	NA	NA	1954, 1957	F	NA
SH	SH9	HF throughout	NA	NA	NA	NA	NA	NA	1942, 1943	F	NA
SKA	SKA124	HF - ZM	NA	1990	NA	50	25	NA	1906, 1916	Q	NA
SKA	SKA2	HF throughout	NA	NA	NA	NA	NA	NA	1944, 1947	Q	NA
SKA	SKA71	HF - ZM	NA	1980	NA	40	35	NA	1909, 1916	Q	NA
SKA	SKA80	HF - ZM	NA	1990	NA	50	25	NA	1844, 1848	Q	NA
SKA	SKA89	HF throughout	NA	NA	NA	NA	NA	NA	1920, 1932	Q	NA
SKA	SKA9	HF - ZM	NA	1978	NA	40	35	NA	1823, 1854	Q	NA
SKA	SKA92	HF throughout	NA	NA	NA	NA	NA	NA	1935, 1940	Q	NA
SKA	SKA96	HF - ZM	NA	1980	NA	40	35	NA	1846, 1857	Q	NA
SK	SKL1	HF - ZM	NA	1985	NA	45	30	NA	1863, 1941	Q	NA
SK	SKR20	C(WS) - HF - ZM	C	1950	1980	10	30	35	1894, 1900	Q	NA
SK	SKR26	C(WS) - HF - ZM	C	1950	1980	10	30	35	1909, 1921	Q	F
SK	SKR32	C(WS) - HF - ZM	C	1950	1990	10	40	25	1896, 1898	Q	NA
SK	SKR34	C(WS) - HF	C	1950	NA	10	65	NA	1899, 1909	Q	NA
SK	SKR35	C(WS) - HF - ZM	C	1950	1980	10	30	35	1894, 1898	Q	NA
SK	SKT16	C(WS) - HF - ZM	C	1960	1995	20	35	20	1907, 1908	Q	NA
SK	SKT22	C(WS) - HF - ZM	CWS	1950	1980	10	30	35	1895	Q	NA
SK	SKT23	C(WS) - HF - ZM	CWS	1950	1990	10	40	25	1896, 1911	Q	NA
SK	SKT26	C(WS) - HF	C	1950	NA	10	65	NA	1895, 1899	Q	NA
SP	SP1A	HF throughout	NA	NA	NA	NA	NA	NA	1902, 1957	F	NA
SP	SP1B	HF throughout	NA	NA	NA	NA	NA	NA	1927, 1930	F	NA
SP	SP2A	C(WS) - HF	C	1943	NA	3	72	NA	1948, 1954	Q	NA
SP	SP2B	HF throughout	NA	NA	NA	NA	NA	NA	1946, 1953	Q	NA
SP	SP3A	HF throughout	NA	NA	NA	NA	NA	NA	1942, 1956	F	NA
SP	SP3B	HF throughout	NA	NA	NA	NA	NA	NA	1950, 1956	F	NA
SP	SP4A	HF throughout	NA	NA	NA	NA	NA	NA	1936, 1949	Q	NA
SP	SP4B	HF throughout	NA	NA	NA	NA	NA	NA	1941, 1948	Q	NA
SP	SP5A	HF throughout	NA	NA	NA	NA	NA	NA	1878, 1887	Q	NA
SP	SP5B	HF - ZM	NA	1980	NA	40	35	NA	1866, 1880	Q	NA
TB	TB106	C(WS) - HF	CWS	1961	NA	21	54	NA	1907, 1975	Q	FR
TB	TB109	C(WS) - HF	CWS	1961	NA	21	54	NA	1884, 1889	Q	NA
TB	TB120	C(WS) - HF	CWS	1961	NA	21	54	NA	1894, 1946	Q	FR
TB	TB140	C(WS) - HF	CWS	1961	NA	21	54	NA	1902	Q	NA

TB	TB146	C(WS) - HF	CWS	1961	NA	21	54	NA	1904, 1904	Q	NA
TB	TB151	C(WS) - HF	CWS	1961	NA	21	54	NA	1905, 1906	Q	NA
TB	TB181	C(WS) - HF	CWS	1961	NA	21	54	NA	1898	Q	NA
TB	TB80	C(WS) - HF	CWS	1961	NA	21	54	NA	1931	Q	NA
TB	TB97	C(WS) - HF	CWS	1961	NA	21	54	NA	1899, 1921	Q	NA
WR	WR1	C(WS) - ZM	C	1955	NA	15	60	NA	1895, 1933	F	NA
WR	WR2	C(WS) - ZM	C	1955	NA	15	60	NA	1816, 1930	F	FR
WR	WR3	C(WS) - ZM	C	1955	NA	15	60	NA	1864, 1938	FR	NA
WR	WR4	C(WS) - ZM	C	1955	NA	15	60	NA	1962, 1965	FR	NA
WR	WR5	C(WS) - ZM	C	1955	NA	15	60	NA	1947, 1966	F	FR
WR	WR7	HF throughout	NA	NA	NA	NA	NA	NA	1939	FR	NA
WR	WR8	HF throughout	NA	NA	NA	NA	NA	NA	1948	FR	NA
WW	WW1	C(WS) - ZM	CWS	1955	NA	15	60	NA	1817, 1839		NA
WW	WW10	HF throughout	NA	NA	NA	NA	NA	NA	1955, 1959	FR	Q
WW	WW2	C(WS) - ZM	CWS	1955	NA	15	60	NA	1897		NA
WW	WW3	C(WS) - ZM	CWS	1955	NA	15	60	NA	1982	FR	NA
WW	WW4	C(WS) - ZM	CWS	1955	NA	15	60	NA	1958	FR	NA
WW	WW5	C(WS) - ZM	CWS	1955	NA	15	60	NA	1979	FR	NA
WW	WW6	HF throughout	NA	NA	NA	NA	NA	NA	1959	FR	NA
WW	WW7	HF throughout	NA	NA	NA	NA	NA	NA	1953, 1953	FR	NA
WW	WW8	HF throughout	NA	NA	NA	NA	NA	NA	1960	FR	NA
WW	WW9	HF throughout	NA	NA	NA	NA	NA	NA	1953, 1956	FR	NA
ZV	ZVD14	C(WS) - HF - ZM	C	1958	1985	18	27	30	1922, 1928	Q	NA
ZV	ZVD16	C(WS) - HF - ZM	C	1965	1975	18	17	40	1893, 1899	Q	NA
ZV	ZVD29	HF throughout	NA	NA	NA	NA	NA	NA	1903, 1909	Q	NA
ZV	ZVD31	C(WS) - HF - ZM	C	1958	1985	18	27	30	1897, 1931	Q	NA
ZV	ZVD33	C(WS) - HF - ZM	C	1958	1985	18	27	30	1918, 1919	Q	NA
ZV	ZVG24	C(WS) - HF - ZM	C	1958	1985	18	27	30	1925	Q	NA
ZV	ZVG25	C(WS) - HF - ZM	C	1958	1985	18	27	30	1929, 1937	Q	NA
ZV	ZVG26	C(WS) - HF	C	1958	NA	18	57	NA	1935, 1937	Q	NA
ZV	ZVG62	C(WS) - HF - ZM	C	1958	1985	18	27	30	1927, 1927	Q	NA
ZV	ZVY7	HF throughout	NA	NA	NA	NA	NA	NA	1896, 1924	Q	NA

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Table S3: Information on the different in-situ plot measurements (Soil, Forest floor, Basal area measurements, and chemical analyses performed on the collected samples.

Soil

(a) Description of soil profile

[0-50cm] at center location of the plot

To achieve a morphological description of the soil, a soil profile description was performed. The soil profile was sampled by means of a soil auger, going to a depth of 50 cm. Diagnostic horizons (O, A, B, E, C, R) were identified, as well as their depth of occurrence (cm) was noted until 50 cm deep.

(b) Collection of soil samples

[0-10, 10-20, 20-30 cm] at five locations of the plot → chemical analyses

[0-10 cm] at center location → bulk density

To achieve a chemical description of the soil, samples at fixed soil depths were collected for chemical analyses. After removal of the organic soil layers, mixed-soil-samples at [0-10], [10-20] and [20-30] cm were collected and stored in separate pots per interval. Mixed-soil samples were taken in the four corners plus the center of the plot. The soil samples were dried at 40 °C. Besides soil samples, we also collected a soil sample of the [0-10] interval with Kopecky rings at the center of each plot to determine bulk density. The Kopecky samples were dried at 105 °C.

(c) Soil analyses

- **pHKCl [0-10 cm]**

Samples were analysed for pH-KCl by shaking a 1:5 ratio soil/KCl (1M) mixture for 5 min at 300 rpm and measuring with a pH meter Orion 920A with pH electrode model Ross sure-flow 8172 BNWP, Thermo Scientific Orion, USA.

- **soil texture** (clay, sand, loam – %) [10-20 cm]

Soil texture (% clay or 0.4-6 µm, % silt or 6-63 µm, and % sand or 63 µm-2 mm) was analysed with laser diffraction after removal of organic material with H₂O₂ (28.5%) and dispersing the sample with Sodium polyphosphate (6%).

- **base saturation** (BS) [0-10 cm]

The exchangeable K⁺, Ca²⁺, Mg²⁺, Na⁺ and Al³⁺ concentrations were measured by atomic absorption spectrophotometry (AA240FS, Fast Sequential AAS) after extraction in 0.1 M BaCl₂ (NEN 5738:1996). Base saturation was calculated by converting the values from mg/kg to meq/kg so that charge of the cations is included, and then taking the ratio of the sum of K⁺, Ca²⁺, Mg²⁺ and Na⁺ over the sum of K⁺, Ca²⁺, Mg²⁺, Na⁺ and Al³⁺.

- **total and Olsen Phosphorus** (totP, OlsenP – mg/kg) [0-10 cm]

All P-concentrations were measured colorimetrically according to the malachite green procedure (Lajtha and others 1999). Total P was extracted after complete destruction of the soil samples with HClO₄ (65%), HNO₃ (70%) and H₂SO₄ (98%) in teflon bombs for 4 h at 150°C. Bioavailable or Olsen P, which is available for plants within one growing season (Gilbert and others 2009), was extracted in NaHCO₃ (POlsen; according to ISO 195 11263:1994(E)).

- **carbon/nitrogen ratio & inorganic carbon content (C/N, C – %) [0-10 cm]**

Total C (%) and N (%) content was quantified by combusting samples at 1200°C which releases all C and N and then measuring the combustion gases for 185 thermal conductivity in a CNS elemental analyser (vario Macro Cube, Elementar, Germany). Inorganic C content was measured after 1 g of dry soil was ashed for 4 hours at 450°C by gradually increasing temperature. This procedure removes organic C leaving only mineral carbon in the ashes, which were measured using a CNS elemental analyser. Subtracting inorganic C from total C gives the organic C (%). This organic C metric was used to calculate the C:N ratio by taking the ratio of organic C to total N.

- **bulk density (BD – g/cm³) [0-10 cm Kopecky sample]**

Bulk density was calculated as the weight of dry soil divided by the total soil volume of the Kopecky rings (i.e. $3.14 \times \text{ring radius}^2 \times \text{ring height}$ with ring radius = 5 cm and ring height = 10 cm).

Forest floor

To characterize the forest floor, we took samples of the ectorganic horizons in each plot, i.e. the **organic litter and fragmentation/humus layer (OL-OF/OH)**. Mixed samples were collected from two locations along the plot diagonal on either side of the plot centre, using a 20x20 cm² wooden frame and collecting the organic layer within this frame. Before sampling, the ground vegetation present above the organic layer was removed with a garden shear. The samples were dried at 65 °C before weighing the total dry weight of the organic layer (DWOLOF).

Basal area measurements

Forest stand structure and composition was characterized by measuring **diameter-at-breast-height (DBH)** of all trees and shrubs within the plot with DBH > 7.5 cm.

Neighborhood measurements

In order to calculate a neighborhood competition index for each cored tree, we measured the **DBH of all neighboring trees** with DBH > 7.5 cm within a radius of 9 m around each cored tree as well as the **distances of those neighboring trees** to the cored trees.

Table S4. Statistical parameters of the crossdating (CD) process, i.e. crossdating the two cores taken from one tree (*TREE*), the same-species cores from one plot (*PLOT*), and the same-species cores from one region (*REGION*). The mean gleichläufigkeit (glk), t-value after Ballie-Pilcher (TVBP), crossdating index (CDI), and percentage cross-correlation (%CC) from TSAP-Win for the ring-width series are presented for each species.

CD PARAMETER*	SPECIES	TREE ¹	PLOT ²	REGION ³
MEAN GLK	<i>Quercus robur/petraea</i>	72	79	71
	<i>Fagus sylvatica</i>	66	75	65
	<i>Fraxinus excelsior</i>	73	78	72
MEAN TVBP	<i>Quercus robur/petraea</i>	9	14	8
	<i>Fagus sylvatica</i>	6	10	5
	<i>Fraxinus excelsior</i>	8	11	8
MEAN CDI	<i>Quercus robur/petraea</i>	66	121	66
	<i>Fagus sylvatica</i>	43	86	55
	<i>Fraxinus excelsior</i>	62	91	65
MEAN %CC	<i>Quercus robur/petraea</i>	64	79	57
	<i>Fagus sylvatica</i>	57	73	47
	<i>Fraxinus excelsior</i>	73	79	57

¹i.e. crossdating the two cores per tree, i.e. core 1 and 2 are crossdated.

²i.e. crossdating the (same-species) cores per plot, i.e. each core within the plot is crossdated with the plot chronology.

³i.e. crossdating the (same-species) cores per region, i.e. each core within the region is crossdated with the region chronology.

*During the crossdating, we aimed for crossdating parameters of minimum 65 for glk (percentage of simultaneous increases or decreases in ringwidth), 30 for CDI (index of possible best match positions for two or more series), and 6 for TVBP.

Table S5: The number of trees, plots, and regions for the past forest management variables used in the analyses on past forest management (Coppice history ‘*CoppHist*’ and Management history ‘*ManHist*’) for *Quercus robur/petraea*. *CoppHist* reflects whether the studied plot had been managed as coppice or coppice-with-standards (‘C(WS)’) between 1940 and 2015. *ManHist* reflects whether a plot had been continuously managed as high forest (‘HF’) between 1940 and 2015 or had been converted from coppice or coppice-with-standards to high forest (‘C(WS) to HF’) within this period.

Past FM	No trees	No plots	No regions
CoppHist = 0 (no)	57	37	13
CoppHist = 1 (yes)	88	50	9
All	145	87	15
ManHist = C(WS) to HF	30	18	5
ManHist = HF	46	29	7
All	76	47	12

84 **Table S6:** Minimum-maximum ranges for several tree characteristics of the cored *Quercus* trees for
85 the 19 forest regions. *BAI* represents the basal area increment, *DBH* the diameter-at-breast-height, and
86 *NCI* the neighborhood competition index. NA is noted for regions where no *Quercus* trees were cored.

	BAI (cm²/yr)	DBH (cm)	NCI
Bialowieża, PL	0.47-61.74	38-103	0.64-1.41
Braunschweig, GE	0.04-114.32	28.25-78.75	0-2.65
Binnen-Vlaanderen, BE	0.09-43.51	36.5-75.5	0.53-0.65
Compiègne, FR	6.18-40.62	56.75-88.75	0.2-0.55
Devin Wood, CZ	0.92-20.83	30.5-34.5	1.29-1.56
Göttingen, GE	NA	NA	NA
Koda Wood, CZ	0.08-33.9	26.5-59	0.51-1.84
Lyons-la-Forêt, FR	NA	NA	NA
Moricsala, LTV	2.89-44.93	56-82.75	0.19-0.87
Pembrokeshire, UK	0.05-52.78	30.25-90.25	0.26-1.63
Prignitz, GE	12.35-53.04	88.5-106	0-0.19
Schleswig-Holstein, GE	NA	NA	NA
Slovak Karst, SLK	0-41.72	40.5-66	0.33-1.28
Skane, SW	0.25-74.82	46-107	0.14-1.38
Speulderbos, NL	0.03-39.1	27-57.25	0.26-1.06
Tournibus, BE	2.06-89.9	49.75-88.5	0.06-0.66
Warburg Reserve, UK	NA	NA	NA
Wytham Woods, UK	0.35-66.45	43-105.5	0.49-0.86
Zvolen, SLK	0.33-48.97	35.5-59.5	0.29-1.15
All Regions	0-114.32	26.5-107	0-2.65

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89 **Table S7:** Minimum-maximum ranges for several tree characteristics of the cored *Fagus* trees for the
90 19 forest regions. *BAI* represents the basal area increment, *DBH* the diameter-at-breast-height, and
91 *NCI* the neighborhood competition index. NA is noted for regions where no *Fagus* trees were cored.

	BAI (cm²/yr)	DBH (cm)	NCI
Bialowieża, PL	NA	NA	NA
Braunschweig, GE	NA	NA	NA
Binnen-Vlaanderen, BE	NA	NA	NA
Compiègne, FR	0.09-79.76	27-87	0.07-1.36
Devin Wood, CZ	NA	NA	NA
Göttingen, GE	0.47-46.76	34.75-71.5	0.08-0.53
Koda Wood, CZ	3.7-57.04	49.75-52	0.87-0.94
Lyons-la-Forêt, FR	0.06-112.32	30.5-85.25	0-0.57
Moricsala, LTV	NA	NA	NA
Pembrokeshire, UK	0.51-22.69	39-39	0.57-0.57
Prignitz, GE	9.76-103.95	79.75-84.5	0.1-0.64
Schleswig-Holstein, GE	0.1-94.81	34.5-78.5	0.03-1.24
Slovak Karst, SLK	1.4-39.61	41.5-41.5	0.75-0.75
Skane, SW	NA	NA	NA
Speulderbos, NL	0.08-72.9	44.5-91.5	0-0.51
Tournibus, BE	NA	NA	NA
Warburg Reserve, UK	0.64-58.6	45.5-100	0.25-0.73
Wytham Woods, UK	NA	NA	NA
Zvolen, SLK	NA	NA	NA
All Regions	0-112.32	27-100	0-1.36

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Table S8: Minimum-maximum ranges for several tree characteristics of the cored *Fraxinus* trees for the 19 forest regions. *BAI* represents the basal area increment, *DBH* the diameter-at-breast-height, and *NCI* the neighborhood competition index. NA is noted for regions where no *Fraxinus* trees were cored.

	BAI (cm²/yr)	DBH (cm)	NCI
Bialowieża, PL	NA	NA	NA
Braunschweig, GE	NA	NA	NA
Binnen-Vlaanderen, BE	0.35-45.63	42-48.5	0.88-1.43
Compiègne, FR	NA	NA	NA
Devin Wood, CZ	0.19-72.37	29-75	0.32-2.32
Göttingen, GE	1.02-71.9	41.5-83.75	0.24-0.65
Koda Wood, CZ	NA	NA	NA
Lyons-la-Forêt, FR	0.18-27.28	33.75-33.75	0.71-0.71
Moricsala, LTV	NA	NA	NA
Pembrokeshire, UK	0.63-29.81	47-60.5	0.44-1.14
Prignitz, GE	0.12-51.86	37.25-89.25	0.37-3.24
Schleswig-Holstein, GE	0.26-48.62	45.5-57.5	0.36-0.73
Slovak Karst, SLK	NA	NA	NA
Skane, SW	NA	NA	NA
Speulderbos, NL	NA	NA	NA
Tournibus, BE	0.06-130.4	42.25-76.5	0.46-1.22
Warburg Reserve, UK	0.04-33.5	22-71	0.44-1.28
Wytham Woods, UK	0.03-65.42	29.25-43.5	0.06-0.99
Zvolen, SLK	NA	NA	NA
All Regions	0.03-130.4	22-89.25	0.06-3.24

Table S9: Likelihood ratio tests of nested model comparisons for *Quercus robur/petraea*, testing for fixed effects of forest management variables and/or interactions of these with global-change drivers (prior to fitting the final forest management models M_{fm} : **Table 4b-c**). Two variables were used to represent past forest management (in each plot): Coppice History ('CoppHist'), and Management History ('ManHist'). The sample size for each management variable is given by n (number of rings). To test for significant improvements, the environment model for *Quercus* ('Me') was first compared with Me + the forest management variable ('Mfm_CoppHist' or 'Mfm_ManHist'), and then it was tested whether an interaction with the global-change drivers (e.g. Mfm_CoppHist_Ndep i.e. Me + Copp Hist + Ndep + CoppHist:Ndep) additionally improved the model. For each comparison, the most significant model based on the p-value of the test is indicated in bold, as well as the lowest AIC and BIC of the model comparison. Based on these results, we included an interaction between CoppHist/ManHist and MAT in the final forest management models for *Quercus*.

Model	AIC	BIC	LogLik	L. Ratio	P-value
Coppice History (n=10498 rings, 145 trees)					
Me	1578	1673	-776		
Mfm_CoppHist	1574	1676	-773	5.90	0.015 ns
Mfm_CoppHist	1578	1673	-776		
Mfm_CoppHist_Ndep	1576	1685	-773	5.91	0.052 ns
Mfm_CoppHist	1578	1673	-776		
Mfm_CoppHist_MAT	1564	1674	-767	17.68	0.0001**
Mfm_CoppHist	1578	1673	-776		
Mfm_CoppHist_TAP	1570	1679	-770	12.01	0.003 ns
Management Transition (n=5512 rings, 76 trees)					
Me	1194	1280	-584		
Mfm_ManTrans	1195	1287	-583	1.42	0.23
Mfm_ManTrans	1194	1280	-584		
Mfm_ManTrans_Ndep	1195	1293	-582	3.97	0.13 ns
Mfm_ManTrans	1194	1280	-584		
Mfm_ManTrans_MAT	1157	1256	-563	41.58	<0.0001**
Mfm_ManTrans	1194	1280	-584		
Mfm_ManTrans_TAP	1187	1187	-578	11.22	0.004 ns

P-value: ns: $p > 0.001$; *: $p \leq 0.001$; **: $p \leq 0.0001$. Significant p-values are in bold.

Table S10: Parameter estimates and model evaluation of the final environment (Me) models for the basal area increment of the three study species. Instead of annual climatic variables (see main text and **Table 3**), seasonal variables were used here: **A)** spring (April-June), and **B)** summer (July-September temperature and precipitation. The sample size for each model is given by n (number of rings). *Dprev*, *T_SPRING*, *P_SPRING*, *T_SUMMER*, *P_SUMMER*, *Ndep* respectively refer to previous-year-diameter ('tree size'), average spring temperature, total spring precipitation, average summer temperature, total summer precipitation, and nitrogen deposition. P-values are marked in red if their significance is different from the results with the annual climatic variables (**Table 3**): i.e. if a significant effect became non-significant (in red, not in bold), or if a non-significant effect became significant (in red bold).

A)	<i>Quercus robur/petraea</i> [n=10498]			<i>Fagus sylvatica</i> [n=5157]			<i>Fraxinus excelsior</i> [n=3182]		
	Estimate	SE	P-value	Estimate	SE	P-value	Estimate	SE	P-value
(Intercept)	2.7717	0.0517	<0.0001**	3.1985	0.0462	<0.0001**	2.8355	0.0670	<0.0001**
Dprev	0.6473	0.0204	<0.0001**	0.5703	0.0263	<0.0001**	0.7831	0.0458	<0.0001**
Dprev ²	-0.1731	0.0102	<0.0001**	-0.2340	0.0165	<0.0001**	-0.3271	0.0293	<0.0001**
Soil shallowness	-	-	-	-0.1251	0.0410	0.0041 ns	-	-	-
T_SPRING	0.0049	0.0036	0.1796	-0.0020	0.0058	0.0005*	-0.0215	0.0053	<0.0001**
P_SPRING	0.0500	0.0030	<0.0001**	0.0188	0.0037	<0.0001**	0.0324	0.0038	<0.0001**
Ndep	0.0485	0.0107	<0.0001**	0.0327	0.0170	0.0537 ns	0.0354	0.0176	0.0443 ns
Ndep ²	-	-	-	-	-	-	-0.0296	0.0084	0.0004*
T_SPRING: P_SPRING	-	-	-	0.0160	0.0036	<0.0001**	0.0095	0.0035	0.0066 ns
T_SPRING: Ndep	0.0203	0.0036	<0.0001**	-0.0058	0.0058	0.0093 ns	-	-	-
P_SPRING: Ndep	-	-	-	-0.0091	0.0037	0.0125 ns	-	-	-
Model evaluation	R²f	R²m	RMSE	R²f	R²m	RMSE	R²f	R²m	RMSE
	0.76	0.47	1.12%	0.64	0.49	1.59%	0.64	0.54	10.3%

P-value: ns: p>0.001; *: p≤0.001; **: p≤0.0001. Significant p-values are in bold.

R²f: conditional R² or proportion explained by fixed and random factors

R²m: marginal R² or proportion of variance explained by fixed factors

RMSE: root mean squared error between predicted and observed values of basal area increment

B)	<i>Quercus robur/petraea</i>			<i>Fagus sylvatica</i>			<i>Fraxinus excelsior</i>		
	[n=10498]			[n=5157]			[n=3182]		
Fixed effects	Estimate	SE	P-value	Estimate	SE	P-value	Estimate	SE	P-value
(Intercept)	2.7607	0.0517	< 0.0001 **	3.1944	0.0450	< 0.0001 **	2.8481	0.0616	< 0.0001 **
Dprev	0.6360	0.0204	< 0.0001 **	0.0547	0.0261	< 0.0001 **	0.7572	0.0445	< 0.0001 **
Dprev ²	-0.1702	0.0102	< 0.0001 **	-0.2317	0.0162	< 0.0001 **	-0.3213	0.0289	< 0.0001 **
Soil shallowness	-	-	-	-0.1132	0.0400	0.0073 ns	-	-	-
T_SUMMER	0.0247	0.0037	< 0.0001 **	0.0113	0.0057	0.0249 ns	0.0233	0.0060	0.0001 **
P_SUMMER	0.0199	0.0028	< 0.0001 **	0.0061	0.0042	0.1500 ns	0.0098	0.0045	0.0297 ns
Ndep	0.0554	0.0109	0.0003 *	0.0585	0.0171	0.0006 *	0.0377	0.0179	0.0359 ns
Ndep ²	-	-	-	-	-	-	-0.0365	0.0086	0.0001 **
T_SUMMER: P_SUMMER	-0.0063	0.0023	0.0064 ns	-	-	-	-	-	-
T_SUMMER: Ndep	0.0088	0.0037	0.0182 ns	-	-	-	-0.0297	0.0053	0.0001 **
P_SUMMER: Ndep	-0.0101	0.0030	0.0006 *	0.0100	0.0037	0.0074 ns	-	-	-
Model evaluation	R ² f	R ² m	RMSE	R ² f	R ² m	RMSE	R ² f	R ² m	RMSE
	0.76	0.48	1.14%	0.64	0.49	1.51%	0.64	0.55	9.56%

P-value: ns: p>0.001; *: p≤0.001; **: p≤0.0001. Significant p-values are in bold.

Table S11: Additional analysis results for *Fagus* on the effect of annual aridity index to test for drought effects. The same modelling procedure was used as described for the ‘environment model’, but only including main effects, and including ‘annual aridity index’ (AAI) instead of total annual precipitation and mean annual temperature. AAI was included as the Aridity-index of Köppen, which is calculated as [total annual precipitation/(mean annual temperature+33)] (Quan, Han, Utescher, Zhang, & Liu, 2013).

Fixed effects	Estimate	SE	P-value
(Intercept)	3.20	0.046	< 0.0001 **
Dprev	0.57	0.026	< 0.0001 **
Dprev ²	-0.24	0.016	< 0.0001 **
Soil shallowness	-0.12	0.041	0.0053 ns
AAI	0.02	0.005	0.0007 *
Ndep	0.04	0.017	0.0270 ns

P-value: ns: p>0.001; *: p≤0.001; **: p≤0.0001. Significant p-values are in bold.

Table S12: Additional analyses results for the three study species testing for temporal changes in the sensitivity of growth to the global-change drivers between 1940-1980 and 1981-2015. The same modelling procedure was used as described for the ‘environment model’, but with the dataset split into two time periods: 1940-1980 (*left*) and 1981-2015 (*right*). Significant effects are marked in bold. P-values are marked in red if their significance is different between the two time periods.

A)	1940-1980			1981-2015		
	<i>Quercus robur/petraea</i> [n=5551]			<i>Quercus robur/petraea</i> [n=4947]		
Fixed effects	Estimate	SE	P-value	Estimate	SE	P-value
(Intercept)	2.6037	0.0559	<0.0001**	2.9167	0.0743	<0.0001**
Dprev	0.7211	0.0336	<0.0001**	0.3249	0.0275	<0.0001**
Dprev ²	-0.2363	0.0168	<0.0001**	-0.0583	0.0127	<0.0001**
MAT	0.0257	0.0086	0.0029 ns	0.0641	0.0086	<0.0001**
TAP	0.0386	0.0050	<0.0001**	0.0564	0.0065	<0.0001**
Ndep	0.0386	0.0121	0.0015 ns	0.0925	0.0447	0.0383 ns
TAP:Ndep	-0.0296	0.0048	<0.0001**	-0.0016	0.0065	0.8057 ns
Model evaluation	R²f	R²m	RMSE	R²f	R²m	RMSE
	0.81	0.47	0.84%	0.80	0.30	0.18%
B)	<i>Fagus sylvatica</i> [n=2652]			<i>Fagus sylvatica</i> [n=2505]		
	Estimate	SE	P-value	Estimate	SE	P-value
(Intercept)	2.9937	0.0691	<0.0001**	3.3624	0.0629	<0.0001**
Dprev	0.6973	0.0379	<0.0001**	0.2600	0.0295	<0.0001**
Dprev ²	-0.2818	0.0223	<0.0001**	-0.1263	0.0158	<0.0001**
Soil shallowness	-0.0628	0.0551	0.2613 ns	-0.1633	0.0384	0.0001**
MAT	0.0039	0.0122	0.7522 ns	-0.0126	0.0129	0.3256 ns
TAP	0.0040	0.0057	0.4839 ns	0.0362	0.0082	<0.0001**
Ndep	0.0339	0.0192	0.0771 ns	0.0690	0.0451	0.1259 ns
MAT:TAP	0.0101	0.0051	0.0484 ns	0.0292	0.0085	0.0007*
MAT:Ndep	-0.0072	0.0110	0.5119 ns	-0.0225	0.0131	0.0849 ns
Model evaluation	R²f	R²m	RMSE	R²f	R²m	RMSE
	0.76	0.51	1.00%	0.61	0.32	0.10%
C)	<i>Fraxinus excelsior</i> [n=1515]			<i>Fraxinus excelsior</i> [n=1667]		
	Estimate	SE	P-value	Estimate	SE	P-value
(Intercept)	2.6461	0.0833	<0.0001**	3.0719	0.0775	<0.0001**
Dprev	1.0069	0.0622	<0.0001**	0.3911	0.0505	<0.0001**
Dprev ²	-0.4399	0.0430	<0.0001**	-0.1657	0.0317	<0.0001**

TAP	0.0110	0.0078	0.1575 ns	0.0531	0.0084	<0.0001**
Ndep	0.0579	0.0228	0.0112 ns	0.0965	0.0437	0.0274 ns
Ndep ²	-0.0544	0.0141	0.0001*	-0.0250	0.0244	0.3061 ns
TAP:Ndep	0.0140	0.0080	0.0822 ns	0.0332	0.0082	0.0001*
Model	R²f	R²m	RMSE	R²f	R²m	RMSE
evaluation	0.78	0.58	4.53%	0.60	0.35	3.92%

P-value: ns: p>0.001; *: p≤0.001; **: p≤0.0001. Significant p-values are in bold.

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Table S13: Additional analyses results for the three species testing how the sample size might have affected the results. For this, we compare the parameter estimates and p-values of the fixed effects in the final environment models for the three study species (column “Estimate” and “P-value”) with parameter estimates and p-values (in both cases the mean and standard deviation are provided) after fitting the final environment model 1000x to a smaller dataset, i.e. after random removal of 10% of the data. For other abbreviations: see Table 3.

Fixed effects	Estimate	P-value	Mean estimate	SD estimate	Mean p-value	SD p-value
A)	<i>Quercus robur/petraea</i>					
	[n=10498]		1000 x [n=9448]			
(Intercept)	2.7580	<0.0001**	2.7581	0.0017	<0.0001**	0.0000
Dprev	0.6304	<0.0001**	0.6321	0.0032	<0.0001**	0.0000
Dprev ²	-0.1715	<0.0001**	-0.1712	0.0013	<0.0001**	0.0000
MAT	0.0538	<0.0001**	0.0532	0.0023	<0.0001**	0.0000
TAP	0.0480	<0.0001**	0.0499	0.0015	<0.0001**	0.0000
Ndep	0.0370	0.0003*	0.0374	0.0024	0.0010*	0.0009
TAP:Ndep	-0.0182	0.0007*	-0.0173	0.0015	0.0001**	0.0001
B)	<i>Fagus sylvatica</i>					
	[n=5157]		1000 x [n=4641]			
(Intercept)	3.1955	<0.0001**	3.1944	0.0025	<0.0001**	0.0000
Dprev	0.0564	<0.0001**	0.5597	0.0039	<0.0001**	0.0000
Dprev ²	-0.2329	<0.0001**	-0.2322	0.0024	<0.0001**	0.0000
Soil shallowness	-0.1225	0.0049 ns	-0.1212	0.0021	0.0051 ns	0.0007
MAT	-0.0047	0.6060 ns	-0.0027	0.0034	0.7233 ns	0.1789
TAP	0.0182	0.0001**	0.0201	0.0019	0.0002*	0.0004
Ndep	0.0324	0.0600 ns	0.0373	0.0042	0.0402 ns	0.0234
MAT:TAP	0.0214	<0.0001**	0.0228	0.0021	0.0001**	0.0001
MAT:Ndep	-0.0182	0.0482 ns	-0.0179	0.0029	0.0772 ns	0.0503
C)	<i>Fraxinus excelsior</i>					
	[n=3182]		1000 x [n=2864]			
(Intercept)	2.8357	<0.0001**	2.8375	0.0054	<0.0001**	0.0000
Dprev	0.7760	<0.0001**	0.7778	0.0057	<0.0001**	0.0000
Dprev ²	-0.3258	<0.0001**	-0.3236	0.0047	<0.0001**	0.0000
TAP	0.0308	<0.0001**	0.0320	0.0024	<0.0001**	0.0000
Ndep	0.0300	0.0970 ns	0.0336	0.0055	0.0850 ns	0.0557
Ndep ²	-0.0336	0.0001**	-0.0346	0.0026	0.0002*	0.0002
TAP:Ndep	0.0229	0.0001**	0.0240	0.0024	0.0004*	0.0008

P-value: ns: p>0.001; *: p≤0.001; **: p≤0.0001. Significant p-values are in bold.

Table S14: Additional analyses results for *Quercus robur/petraea* testing how the sample size might have affected the results. For this, we compare the parameter estimates and p-values of the fixed effects in the final forest management models for *Quercus robur/petraea* (column “Estimate” and “P-value”) with parameter estimates and p-values (in both cases the mean and standard deviation are provided) after fitting the final forest management model 1000x to a smaller dataset, i.e. after random removal of 10% of the data. Significant effects are marked in **bold**. P-values are marked in **red** if the significance level using the restricted datasets differ from the full dataset. For other abbreviations: see **Table 4**.

Fixed effects	Estimate	P-value	Mean estimate	SD estimate	Mean p-value	SD p-value
A)	<i>Coppice History</i>					
	[n=10498]		1000 x [n=9448]			
(Intercept)	2.8760	< 0.0001 **	2.8761	0.0021	< 0.0001 **	0.0000
Dprev	0.6306	< 0.0001 **	0.6325	0.0032	< 0.0001 **	0.0000
Dprev ²	-0.1702	< 0.0001 **	-0.1700	0.0014	< 0.0001 **	0.0000
MAT	0.0780	< 0.0001 **	0.0768	0.0036	< 0.0001 **	0.0000
TAP	0.0477	< 0.0001 **	0.0494	0.0015	< 0.0001 **	0.0000
Ndep	0.0366	0.0007 *	0.0369	0.0024	0.0012 ns	0.0010
CoppHist	-0.1952	0.0203 ns	-0.1953	0.0024	0.0205 ns	0.0024
TAP:Ndep	-0.0182	< 0.0001 **	-0.0174	0.0014	< 0.0001 **	0.0001
MAT:CoppHist	-0.0420	0.0006 *	-0.0409	0.0045	0.0029 ns	0.0048
B)	<i>Management History</i>					
	[n=5450]		1000 x [n=4905]			
(Intercept)	3.0019	< 0.0001 **	3.0034	0.0047	< 0.0001 **	0.0000
Dprev	0.5882	< 0.0001 **	0.5905	0.0039	< 0.0001 **	0.0000
Dprev ²	-0.2648	< 0.0001 **	-0.2643	0.0024	< 0.0001 **	0.0000
MAT	0.1316	< 0.0001 **	0.1320	0.0056	< 0.0001 **	0.0000
TAP	0.0568	< 0.0001 **	0.0587	0.0020	< 0.0001 **	0.0000
Ndep	0.0419	0.0025 ns	0.0419	0.0029	0.0039 ns	0.0026
ManHist	-0.0818	0.4142 ns	-0.0826	0.0049	0.4107 ns	0.0048
TAP:Ndep	-0.0174	0.0003 *	-0.0165	0.0035	0.0026 ns	0.0033
MAT:ManHist	-0.1129	< 0.0001 **	-0.1134	0.0067	< 0.0001 **	0.0000

P-value: ns: p>0.001; *: p≤0.001; **: p≤0.0001. Significant p-values are in bold.

Table S15: Additional analyses results for the three study species testing how the sample size might have affected figure 4. For this, we compare the median %BAI change under the four scenarios of environmental change (details: see main text), and the confidence intervals from the full dataset (left part with larger sample size (n) per species) with the restricted datasets (i.e. 1000x random removal of 10% of the data). “LC” and “UC” represent the lower and upper confidence limits respectively, while “CI with 0” reflects whether the confidence interval crossed 0 or not using the full dataset (see graphically in figure 4). For the restricted dataset results, we present the mean of the 1000 median values for %BAI change, and the % of the 1000 confidence intervals that crossed zero (i.e. reflecting less reliable results).

Species	Scenario	Median	LC	UC	CI with 0	Mean median	% CI with 0
		[n=10498]				1000 x [n=9448]	
Quercus robur/petraea [Coppice]	-N -P	1.88	0.22	3.43	No	1.79	18
	-N +P	3.85	2.27	5.37	No	3.79	0
	+N -P	6.02	4.73	7.65	No	5.95	0
	+N +P	6.64	5.36	8.29	No	6.66	0
Quercus robur/petraea [No coppice]	-N -P	-7.33	-13.26	-1.57	No	-7.42	0
	-N +P	-5.32	-11.15	0.49	Yes	-5.42	96.4
	+N -P	-3.17	-9.40	2.48	Yes	-3.27	100
	+N +P	-2.54	-8.82	3.14	Yes	-2.56	100
Quercus robur/petraea	-N -P	-0.06	-0.94	0.77	Yes	0.38	100
	-N +P	2.01	1.22	2.79	No	2.48	0
	+N -P	5.40	4.60	6.15	No	4.76	0
	+N +P	6.05	5.18	6.95	No	5.50	0
		[n=5157]				1000 x [n=4641]	
Fagus sylvatica	-N -P	-2.96	-4.65	-1.16	No	-3.10	0
	-N +P	-0.75	-2.46	0.99	Yes	-0.73	100
	+N -P	0.26	-1.52	2.01	Yes	0.52	100
	+N +P	2.52	0.72	4.24	No	2.90	0
		[n=3182]				983 x [n=2864]*	
Fraxinus excelsior	-N -P	-5.45	-8.77	-2.14	No	-5.95	0
	-N +P	-5.82	-9.26	-2.52	No	-6.35	0
	+N -P	-3.03	-6.38	0.24	Yes	-3.03	77
	+N +P	-0.54	-3.98	2.68	Yes	-0.51	100

*983 instead of 1000 restricted datasets for *Fraxinus excelsior* due to model convergence issues in 17 out of the 1000 random restricted datasets.

Fig. S1: Biplot of the first two axes of the PCA on the following soil physical-chemical variables: pHKCl, soil texture (clay and sand - %), base saturation (BS - %), total (TotP – mg/kg) and Olsen Phosphorus (OlsenP – mg/kg), Carbon/Nitrogen ratio (orgC.N), inorganic Carbon content (anorgC - %), dry weight of forest floor layer (DWLOF - g), bulk density (BD – g/cm³). For sampling and chemical analysis details see **Table S2**. These axes explained 60 % of the variance (PC1: 48 %, PC2: 12 %).

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Fig. S2: The actual basal area increment data and the model estimates of the effects of tree size (i.e. previous-year-diameter or Dprev) for the three study species. *Top: Quercus robur*, *Middle: Fagus sylvatica*, *Bottom: Fraxinus excelsior*. The response curve for each species shows the final base model, in which the values of the other continuous variables were set at the observed mean.

Quercus robur/petraea

Fagus sylvatica

Fraxinus excelsior

Fig. S3: Pairwise correlation matrix of the continuous predictor variables for the three tree species that were cored. Each plot contains bivariate scatter plots of the paired predictors below the diagonal, histograms of the single predictor variables on the diagonal, and the Pearson correlation coefficient of the paired predictors above the diagonal. The text size is relative to the maximum value of the correlation coefficient.

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Fig. S4: Time series (1940-2015) of the regional predictor variables : a) mean annual temperature - MAT ($^{\circ}\text{C}$), b) total annual precipitation - TAP (mm/yr), c) nitrogen deposition - Ndep (kg/ha yr), d) acidification rate - AcidRate (keq/ha yr). For explanation on the calculation: see *Material and Methods*. Region codes are as follows: BI=Białowieża Forest (PL), BS=Braunschweig (GE), BV=Binnen-Vlaanderen (BE), CO=Compiègne (FR), DE=Devin Wood (CZ), GO=Göttingen (GE), KO=Koda Wood (CZ), LF=Lyons-la-Forêt (FR), MO=Moricsala (LTV), P=Pembrokeshire (UK), PR=Prignitz (GE), SH=Schleswig-Holstein (GE), SKA=Skane (SW), SK=Slovak Karst (SLK), SP=Speulderbos (NL), TB=Tournibus (BE), WR=Warburg Reserve (UK), WW=Wytham Woods (UK), and ZV=Zvolen (SLK). Details on these regions can be found in **Table S1**.

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Fig. S5: Pairwise correlation matrix of the annual and seasonal (spring and summer) climatic variables for the three tree species that were cored. Each plot contains bivariate scatter plots of the paired variables below the diagonal, histograms of the single variables on the diagonal, and the Pearson correlation coefficient of the paired variables above the diagonal. The text size is relative to the maximum value of the correlation coefficient.

Fig. S6: The actual basal area increment data and the model estimates of the effects of mean annual temperature (*top*: MAT – °C), total annual precipitation (*middle*: TAP – mm/yr), and nitrogen deposition (*bottom*: Ndep – kg/ha yr) for the three study species. The response curve for each driver shows the final environment model, in which the values of the other continuous variables were set at the observed mean. For *Quercus* and *Fraxinus*, mean annual precipitation was log-transformed.

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Fig. S7: Additional analyses results for the three study species testing how the sample size might have affected the results. For this, we compare the parameter estimates (or effect sizes – *left*) and p-values (*right*) of the fixed effects in the final environment models (i.e. one point value, in **blue**) with parameter estimates and p-values after fitting the final forest management model 1000x to a restricted dataset, i.e. after random removal of 10% of the data (i.e. mean values + error bars, in **red**). Results are displayed for the three study species *Quercus robur/petraea* (A), *Fagus sylvatica* (B), and *Fraxinus excelsior* (C). See **Table S13** for detailed results.

A) Coppice History

B) Management History

Fig. S8: Additional analyses results for *Quercus robur/petraea* testing how the sample size might have affected the results. For this, we compare the parameter estimates (or effect sizes – *left*) and p-values (*right*) of the fixed effects in the final forest management models (i.e. one point value, in **blue**) with parameter estimates and p-values after fitting the final forest management model 1000x to a restricted dataset, i.e. after random removal of 10% of the data (i.e. mean values + error bars, in **red**). Results are displayed for the forest management model using Coppice History (**A**) and Management History (**B**) as management variable. See **Table S14** for detailed results.

Description S1.

Explanation behind the climate and deposition scenarios for the future growth predictions (Fig. 4)

Four scenarios:

$\boxed{+T -P -N}$ // $\boxed{+T +P -N}$ // $\boxed{+T -P +N}$ // $\boxed{+T +P +N}$

With T=mean annual temperature, P=total annual precipitation, N=annual Nitrogen deposition

Scenario values:

$\boxed{+T = +3^{\circ}\text{C}}$

$\boxed{+/- P = +/- 100 \text{ mm/yr}}$

$\boxed{+/- N = +/- 10 \text{ kg/ha yr}}$

1. The IPCC (2014, Figure SPM.7a) predicts changes in average surface temperature for Central and Western Europe in the range of 1°C to 1.5°C for 2081–2100 relative to 1986–2005 under the RCP2.6 scenario (i.e. best-case) and in the range of 4°C to 5°C for RCP8.5 (worst-case). We chose an in-between scenario of +3°C for all our study sites.
2. The IPCC (2014, Figure SPM.7b) predicts changes in average surface precipitation for Central and Western Europe in the range of + 0-10% under the RCP2.6 (i.e. best-case) and in the range of -10 to +30% for RCP8.5 (worst-case scenario), for 2081–2100 relative to 1986–2005. We chose a scenario of precipitation increase as well as precipitation decrease. Given that the mean annual precipitation of our study sites in 2000 was ca. 800 mm/year (**Table S1**), we chose a precipitation change of 100 mm/year increase or decrease (i.e. ca. 12.5% increase or decrease in precipitation relative to the mean), consistent across our study sites.
3. Studies have projected both increased as well as decreased future nitrogen deposition for Europe, due to increased emissions of reduced nitrogen (NH₃) in line with increased agricultural activities or decreased emissions of oxidized nitrogen (NO_x) (Engardt et al. 2017; Simpson et al. 2014). In a multimodel evaluation study, Dentener et al. (2006, **Figure 10**) predicted changes in total deposition of reactive nitrogen (Nr) for Central and Western Europe in the range of -30-0% under the Current Legislation scenario (i.e. CLE, consistent with RCP6.0 scenario which is in between worst- and best-case scenario) and in the range of +50 to +100% under the SRES A2 scenario (i.e. consistent with RCP8.5 or worst-case scenario), for 2030 relative to the modelled total deposition for 2000 (Dentener et al. 2006; IPCC 2014)). We chose a scenario of nitrogen deposition increase as well as precipitation decrease. Given that the mean nitrogen deposition of our study sites in 2000 was ca. 15 kg/ha yr (**Table S1**), we chose a deposition change of 10 kg/ha yr increase or decrease (i.e. ca. 67% increase or decrease in deposition relative to the mean),

190 consistent across our study sites. From the past deposition levels in our study sites (Fig. S4), we
191 gathered that a decrease or increase of 10 kg/ha yr is realistic.

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