

1 **Spatiotemporal variability of dendroecological indicators in pedunculate oak (*Quercus***
2 ***robur* L.) tree-rings across Europe in relation to species distribution models**

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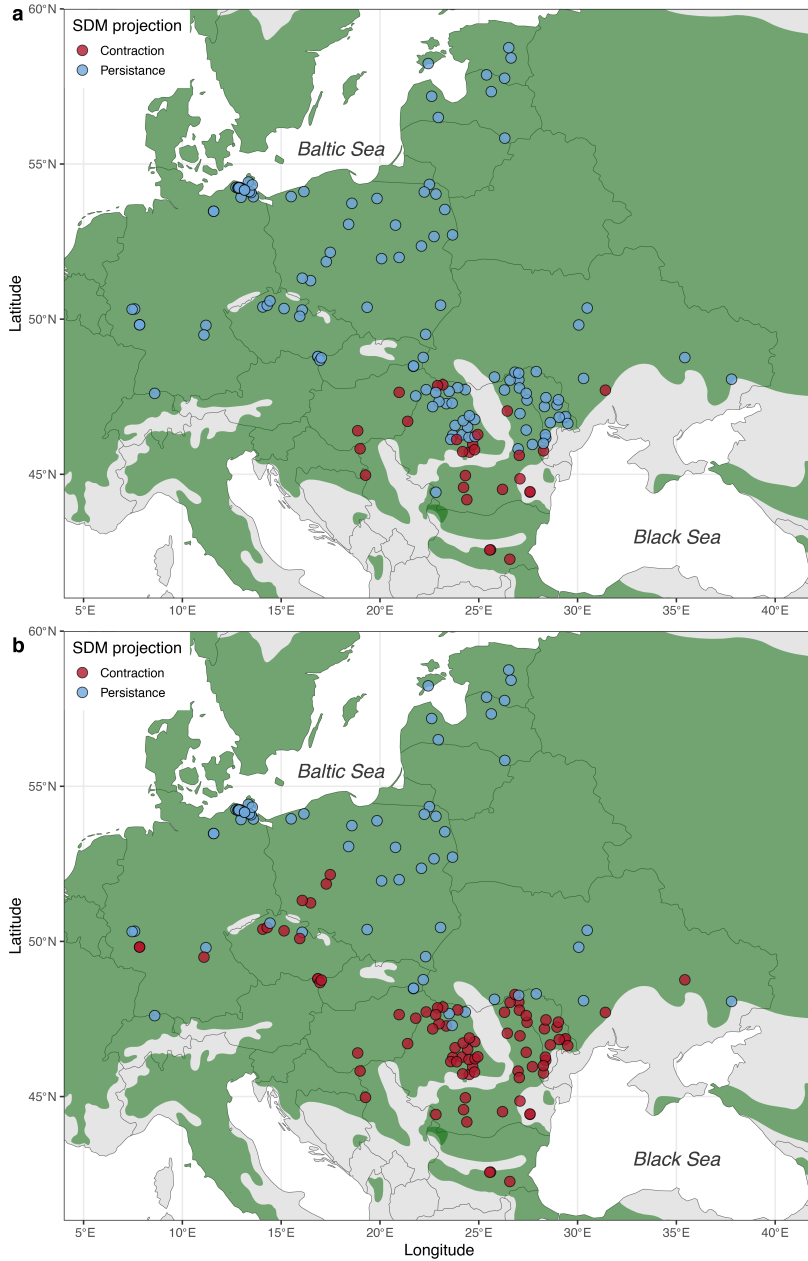
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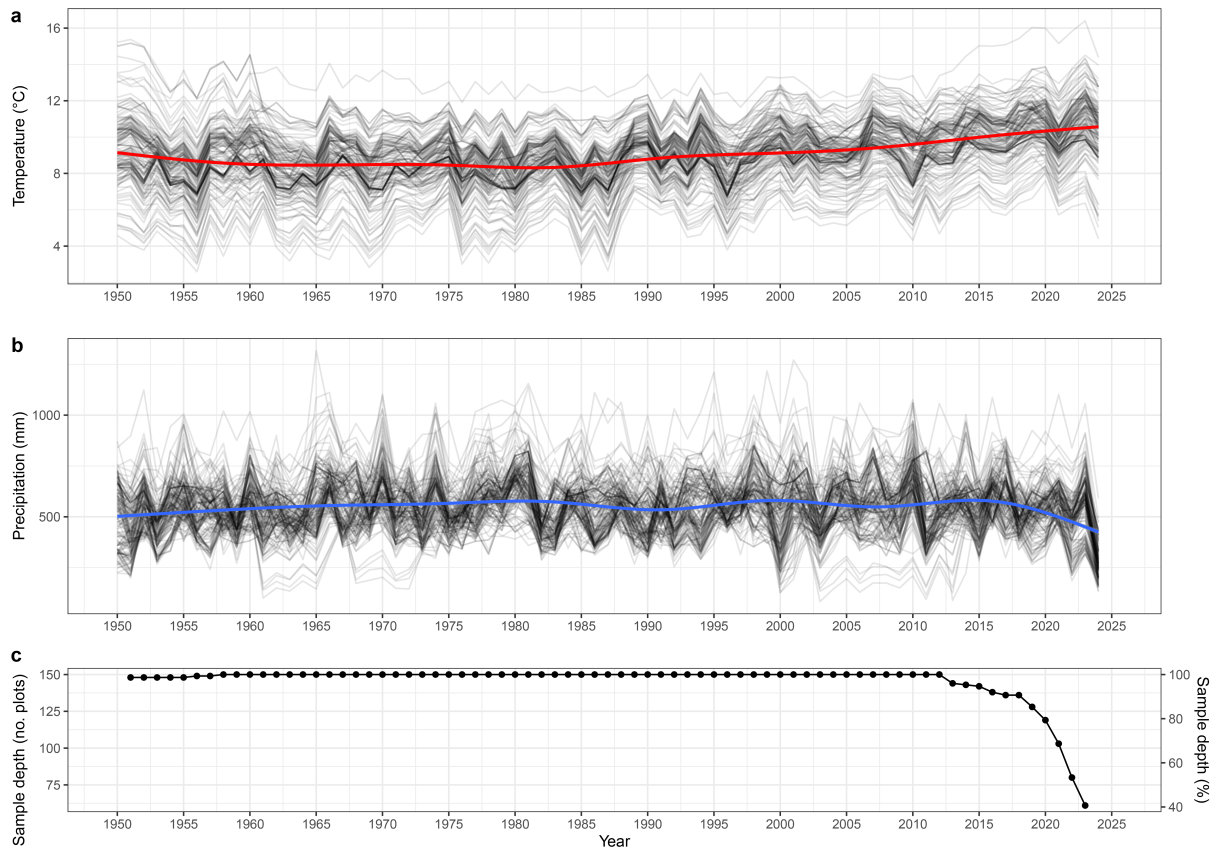
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 67 **Supplementary Material**



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 69 Figure S1 Map of the study area and points indicating study site locations; colors indicating
 70 the species distribution model (SDM) projection under the climate scenario SSP245 (a) and
 71 under the climate scenario SSP585 (b). The shaded green area depicts the distribution of
 72 *Quercus robur* L. in Europe (Caudullo et al., 2017).
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75 Figure S2 (a) Mean annual temperature at the plot level (black lines) and the overall trend

76 since 1950 (red). (b) Annual precipitation at the plot level (black lines) and the overall trend

77 since 1950 (blue). (c) Number of chronologies that cover the study period

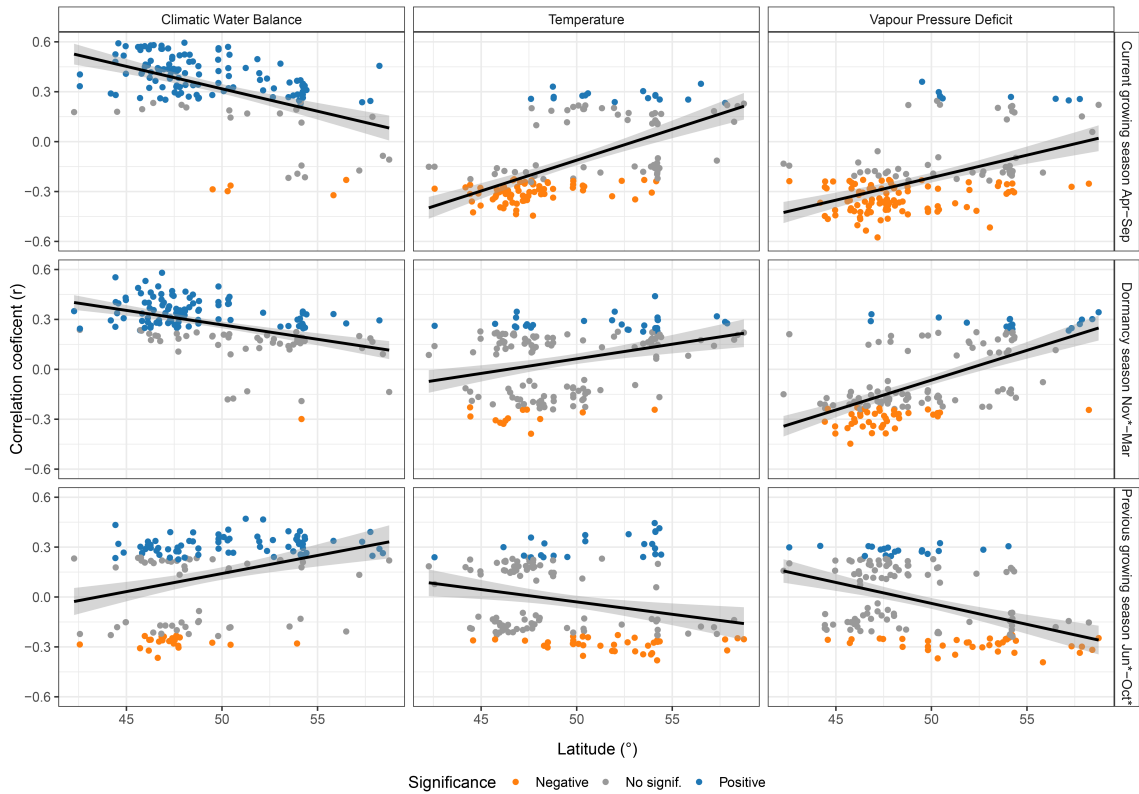


Figure S3 The geographic variability of oak's sensitivity to climate, the regressions of correlation coefficients \sim latitude. Abbreviated name of month with or without asterisk refers to the month in the year preceding and current year of ring formation, respectively.

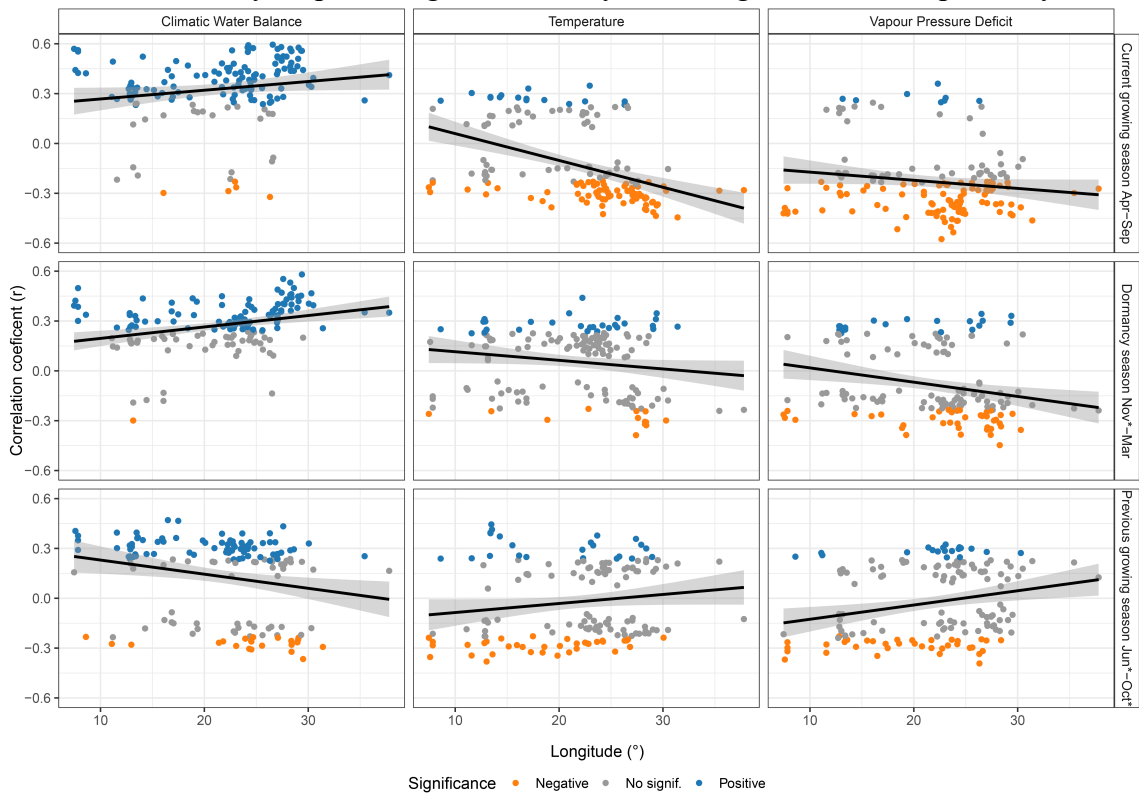


Figure S4 The geographic variability of oak's sensitivity to climate, the regressions of correlation coefficients \sim longitude. Abbreviated name of month with or without asterisk refers to the month in the year preceding and current year of ring formation, respectively.

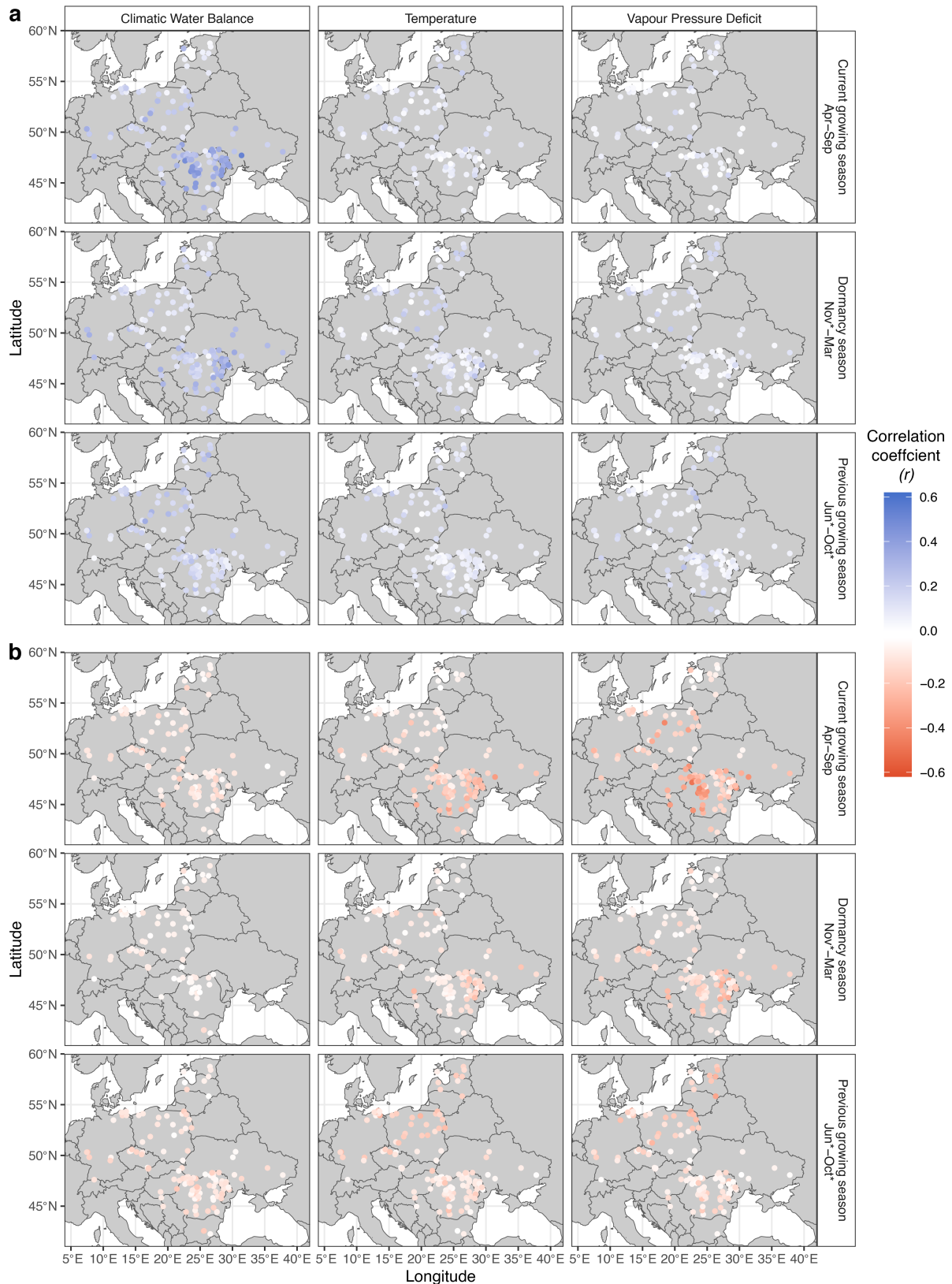


Figure S5 Median correlation of all seasons regardless of significance. **(a)** The upper 3 rows show the median of only positive correlations in relation to climate parameters and seasons. **(b)** The lower 3 rows show the median of only negative correlations in relation to climate parameters and seasons. Abbreviated name of month with or without asterisk refers to the month in the year preceding and current year of ring formation, respectively.

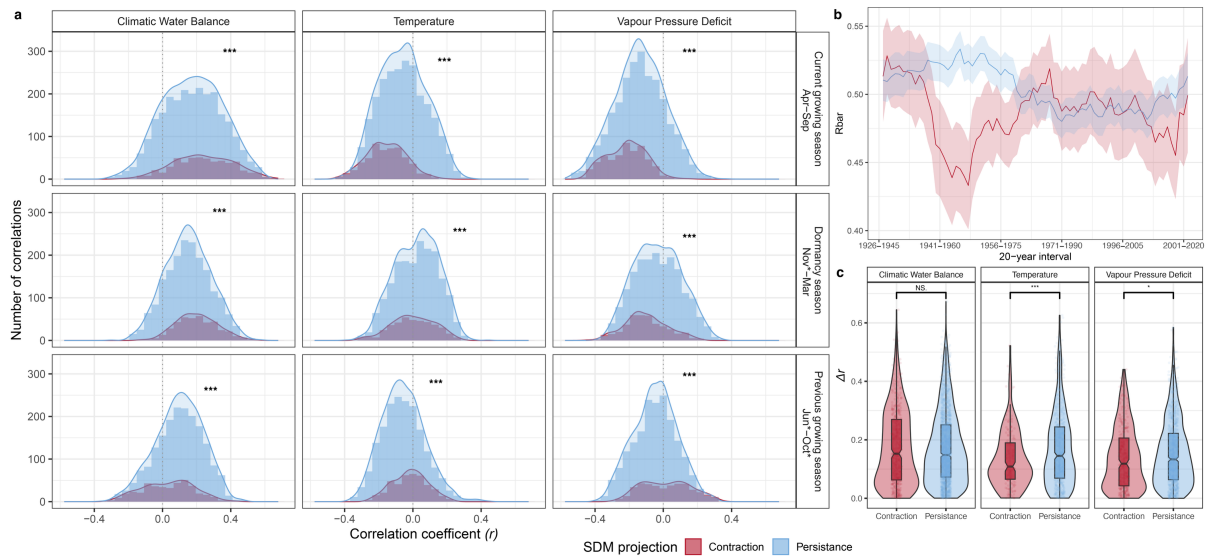


Figure S6 (a) Distributions of the correlation coefficients in areas of contraction and persistence across different seasons based on SDM under the SSP245 scenario. (b) Mean growth synchrony (r_{bar}) within the SDM projections. Shaded areas represent the standard error; the x-axis presents the interval for which the r_{bar} was calculated, indicated by the end of the reference window. (c) The temporal shift of climate sensitivity, where Δr depicts the absolute difference in the correlations between the late and early periods, respectively. In panel a abbreviated name of month with or without asterisk refers to the month in the year preceding and current year of ring formation, respectively.

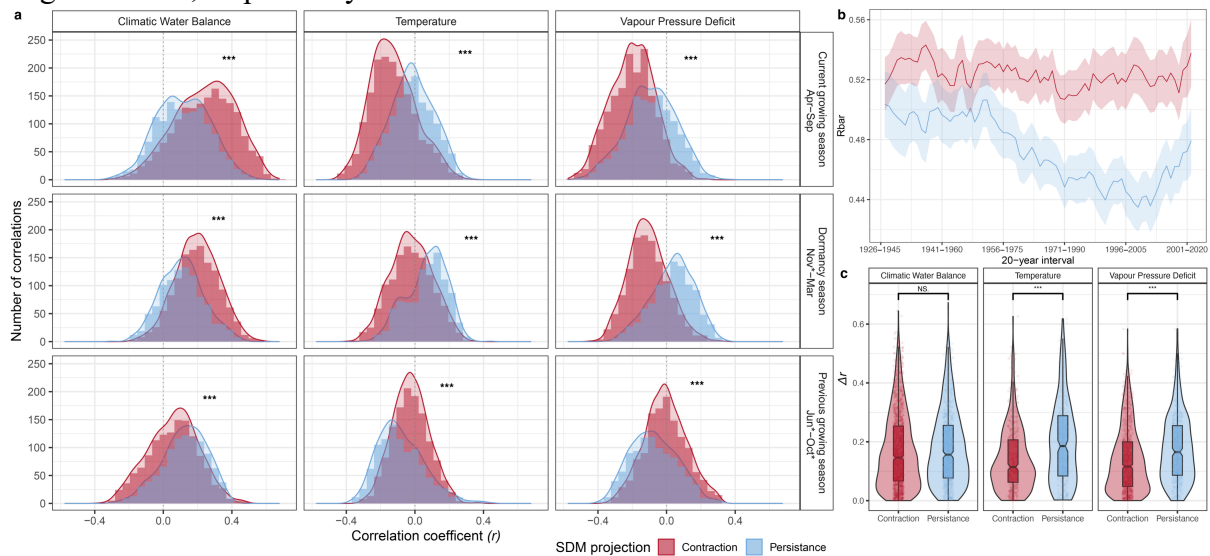


Figure S7 (a) Distributions of the correlation coefficients in areas of contraction and persistence across different seasons based on SDM under the SSP585 scenario. (b) Mean growth synchrony (r_{bar}) within the SDM projections. Shaded areas represent the standard error; the x-axis presents the interval for which the r_{bar} was calculated, indicated by the end of the reference window. (c) The temporal shift of climate sensitivity, where Δr depicts the absolute difference in the correlations between the late and early periods, respectively. In panel a abbreviated name of month with or without asterisk refers to the month in the year preceding and current year of ring formation, respectively.

Table S1 Summary of the fitted mixed-effects models for the sensitivity of oak to climatic water balance (CWB), mean temperature, and vapor pressure deficit (VPD).

Fixed effects	CWB				Temperature				VPD			
	β	CI	<i>t</i>	<i>p</i>	β	CI	<i>t</i>	<i>p</i>	β	CI	<i>t</i>	<i>p</i>
(Intercept)	0.052	-0.155, 0.258	0.488	0.625	0.220	0.032, 0.408	2.297	0.022	0.062	-0.162, 0.287	0.543	0.587
BIO18	-0.000	-0.001, -0.000	-2.574	0.010	0.000	-0.000, 0.001	1.753	0.080	0.000	-0.000, 0.001	0.917	0.359
BIO9	-0.006	-0.011, -0.001	-2.242	0.025	0.004	-0.001, 0.008	1.630	0.103	0.000	-0.009, 0.010	0.075	0.940
BIO10	0.011	0.003, 0.019	2.555	0.011	-0.019	-0.027, -0.011	-4.937	<0.001	0.005	-0.001, 0.010	1.658	0.097
BIO11	-0.002	-0.011, 0.007	-0.359	0.719	0.001	-0.007, 0.009	0.296	0.767	-0.012	-0.021, -0.003	-2.657	0.008
Period [late]	0.022	0.013, 0.030	4.848	<0.001	0.047	0.039, 0.055	11.607	<0.001	0.021	0.013, 0.029	4.967	<0.001
SDM projection [persistence]	0.003	-0.029, 0.035	0.179	0.858	-0.022	-0.051, 0.007	-1.470	0.142	0.021	-0.013, 0.056	1.202	0.229
age	0.000	-0.000, 0.000	0.006	0.995	0.000	-0.000, 0.000	0.689	0.491	0.000	-0.000, 0.000	0.409	0.682
Period [late] × SDM projection [persistence]	-0.032	-0.044, -0.020	-5.185	<0.001	0.018	0.007, 0.029	3.216	0.001	0.002	-0.009, 0.013	0.344	0.730
Random Effects												
σ^2	0.035				0.029				0.020			
$\tau_{0\text{ cod}}$	0.004				0.003				0.022			
ICC	0.102				0.101				0.691			
No. corr. / No. plots	15138 / 150				15138 / 150				15138 / 150			
R^2_m / R^2_c	0.031 / 0.130				0.062 / 0.156				0.038 / 0.164			

One model was fitted individually for each of the climate factors. The response variables are correlation coefficients between RWI and climatic factors. The fixed part of the model included BIO18 (mean monthly precipitation amount of the warmest quarter), BIO9 (mean daily mean air temperatures of the driest quarter), BIO10 (mean daily mean air temperatures of the warmest quarter), BIO11 (mean daily mean air temperatures of the coldest quarter), mean age of the stands (age), periods (early, late), and SDM projection (contraction, persistence) as categorical variables, and interaction between periods and SDM projections. The random part of the model included the site and the season. This model is based on all correlations regardless of significance; as a sensitivity analysis, we present in Table S2 similar models using only significant correlations in early or late periods, and in Table S3, a model in which we used climatic parameters as a fixed factor. Values represent the estimates of regression coefficients (β), 95% confidence intervals (CI), the *t* statistic, and the associated *p*-value of significance (bold values stand for significant fixed effects, $p < 0.05$). σ^2 represents the variance of residuals, τ variance caused by random effects, ICC intra-class correlation coefficient R^2_m is the marginal R^2 , and R^2_c is the conditional R^2 . The low marginal R^2 explained by the fixed effects of the optimized models might be a consequence of data heterogeneity.

Table S2 Summary of the fitted mixed-effects models for the sensitivity of oak to climatic water balance (CWB), mean temperature, and vapor pressure deficit (VPD) using only significant correlations.

Fixed effects	CWB				Temperature				VPD			
	β	CI	<i>t</i>	<i>p</i>	β	CI	<i>t</i>	<i>p</i>	β	CI	<i>t</i>	<i>p</i>
(Intercept)	0.333	0.218, 0.448	5.682	<0.001	0.706	-0.086, 1.499	1.749	0.081	0.087	-0.554, 0.727	0.265	0.791
BIO18	-0.000	-0.000, 0.000	-1.441	0.150	0.001	-0.001, 0.002	0.958	0.338	0.001	-0.000, 0.002	1.392	0.164
BIO9	-0.002	-0.004, 0.001	-1.109	0.268	0.009	-0.010, 0.029	0.918	0.359	0.029	0.001, 0.057	2.014	0.044
BIO10	0.007	0.002, 0.011	2.856	0.004	-0.057	-0.088, -0.025	-3.513	<0.001	0.002	-0.014, 0.018	0.224	0.823
BIO11	-0.002	-0.007, 0.003	-0.687	0.492	0.012	-0.021, 0.046	0.715	0.475	-0.028	-0.054, -0.003	-2.174	0.030
Period [late]	0.012	0.005, 0.020	3.382	0.001	0.114	0.061, 0.168	4.225	<0.001	0.078	0.052, 0.103	5.925	<0.001
SDM projection [persistence]	-0.003	-0.021, 0.015	-0.340	0.734	-0.163	-0.290, -0.036	-2.519	0.012	0.052	-0.048, 0.151	1.023	0.306
age	-0.000	-0.000, 0.000	-1.076	0.282	0.000	-0.001, 0.001	0.599	0.549	-0.000	-0.001, 0.000	-1.072	0.284
Period [late] × SDM projection [persistence]	0.000	-0.011, 0.012	0.082	0.935	0.180	0.111, 0.249	5.119	<0.001	0.056	0.018, 0.095	2.846	0.004
Random Effects												
σ^2	0.005				0.059				0.034			
$\tau_{0\text{ cod}}$	0.001				0.048				0.037			
ICC	0.157				0.450				0.522			
No. corr. / No. plots	2900 / 147				1221 / 140				2035 / 145			
R^2_m / R^2_c	0.047 / 0.197				0.170 / 0.543				0.142 / 0.590			

One model was fitted individually for each of the climate factors. The response variables are correlation coefficients between RWI and climatic factors. The fixed part of the model included BIO18 (mean monthly precipitation amount of the warmest quarter), BIO9 (mean daily mean air temperatures of the driest quarter), BIO10 (mean daily mean air temperatures of the warmest quarter), BIO11 (mean daily mean air temperatures of the coldest quarter), mean age of the stands (age), periods (early, late), and SDM projection (contraction, persistence) as categorical variables, and interaction between periods and SDM projections. The random part of the model included the site and the season. Values represent the estimates of regression coefficients (β), 95% confidence intervals (CI), the *t* statistic, and the associated *p*-value of significance (bold values stand for significant fixed effects, $p < 0.05$). σ^2 represents the variance of residuals, τ variance caused by random effects, ICC intra-class correlation coefficient R^2_m is the marginal R^2 , and R^2_c is the conditional R^2 . The low marginal R^2 explained by the fixed effects of the optimized models might be a consequence of data heterogeneity.

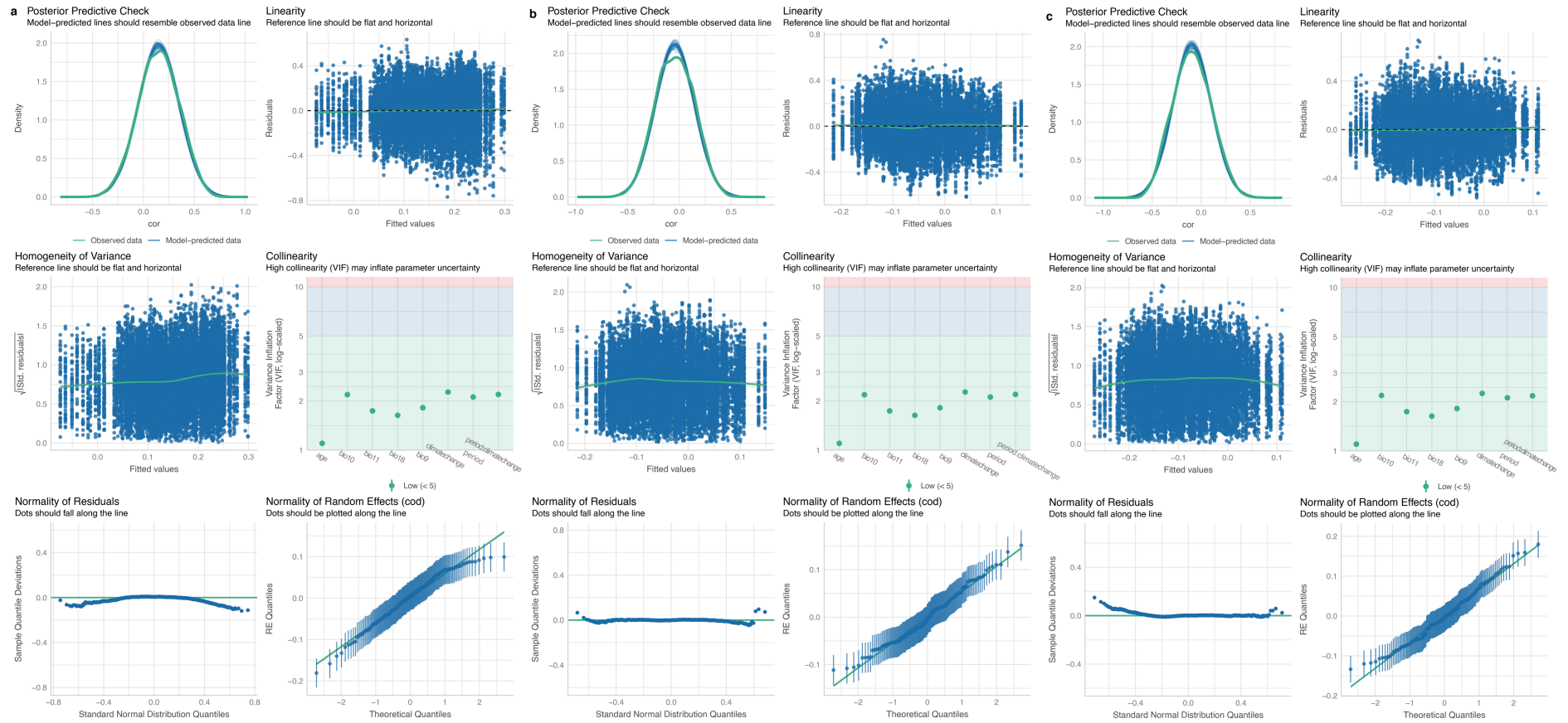


Figure S8 Diagnostic plots for the models presented in Table S1 for CWB (a), temperature (b), and VPD (c). Figures were generated using the `check_model()` function from ‘performance’ R package (Lüdtke et al., 2021)

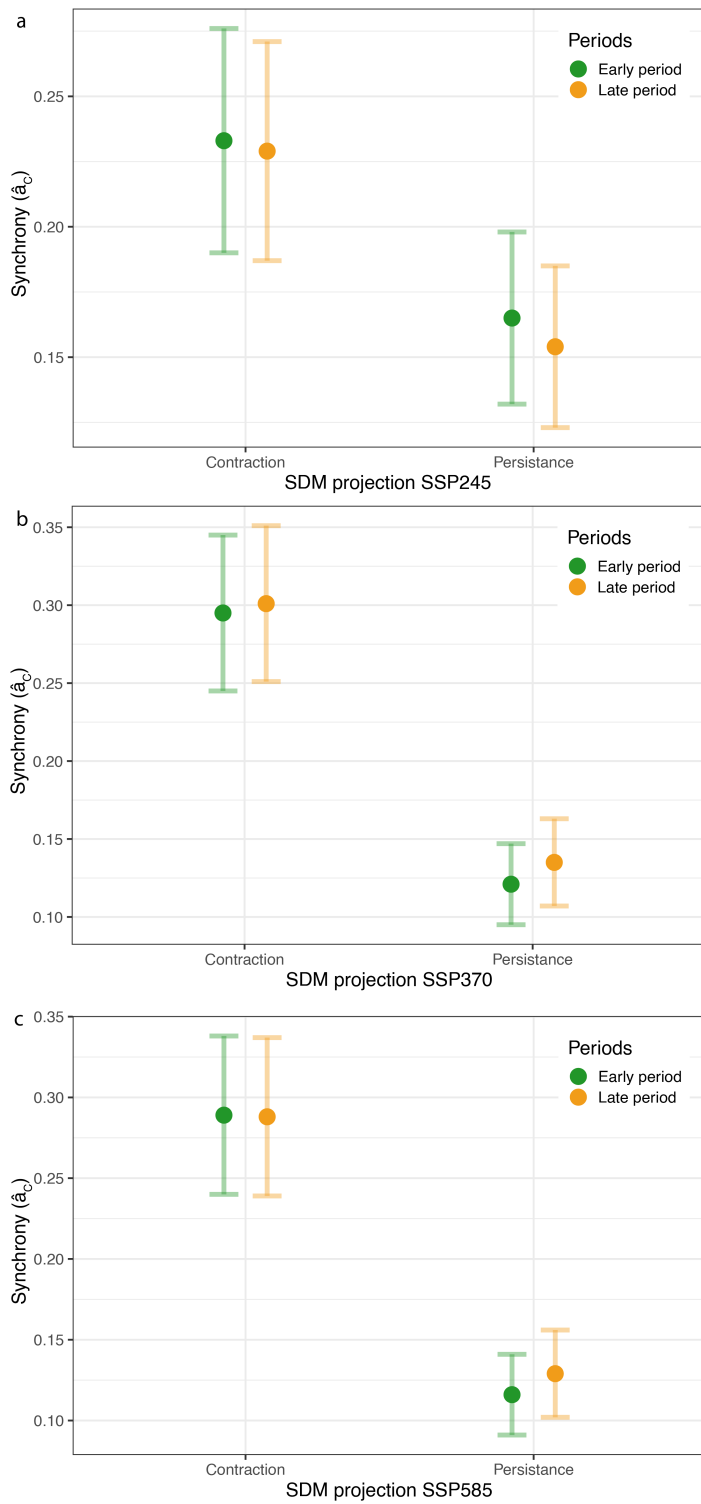


Figure S9 Regional growth synchrony within the SDM projections based on SSP245 scenarios (a), on SSP370 scenarios (b), and on SSP585 (c) using a variance-covariance model, the homoscedastic variant of the full model defined by (Shestakova et al., 2014)

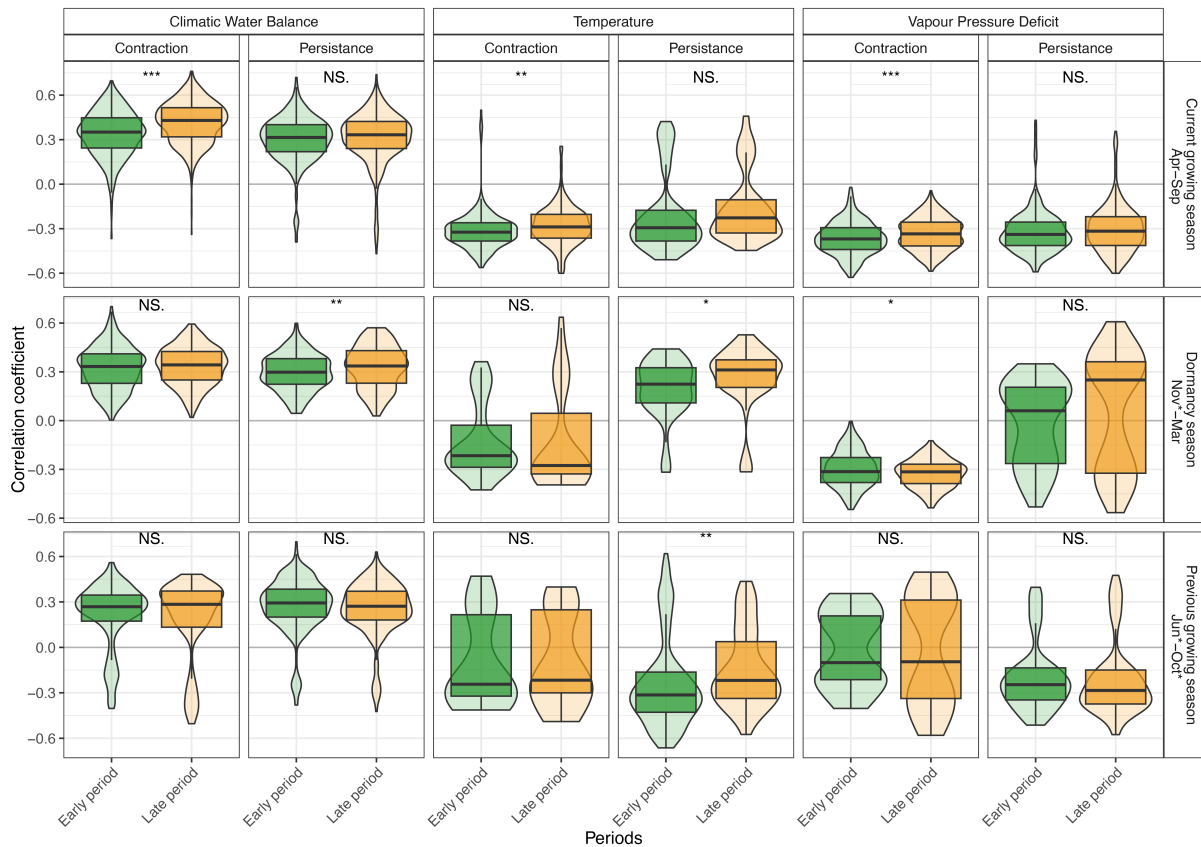


Figure S10 Correlation coefficients in early and late periods for intervals (months or cumulation of months) that recorded a significant correlation in the entire period; SDM projection related to the SSP370 scenario; annotation shows results from the Wilcoxon test, *** represents $p < 0.001$, ** represents $p < 0.01$, * represents $p < 0.05$, N.S. represents $p > 0.05$.

Table S3 Summary of the optimized mixed-effects model for the sensitivity of oak based on correlations in the early / late periods with the climate factor as a fixed effect

<i>Fixed effects</i>	β	<i>CI</i>	<i>t</i>	<i>p</i>
(Intercept)	0.296	0.197, 0.396	5.860	<0.001
bio18	-0.007	-0.011, -0.003	-3.611	<0.001
bio9	0.000	-0.004, 0.004	0.040	0.968
bio10	-0.243	-0.250, -0.237	-77.468	<0.001
bio11	-0.301	-0.307, -0.295	-95.772	<0.001
Climatic parameter [tmed]	0.029	0.024, 0.034	11.415	<0.001
Climatic parameter [vpd]	0.000	-0.000, 0.000	0.831	0.406
SDM projection [persistence]	0.098	0.090, 0.107	22.744	<0.001
period [late]	0.114	0.106, 0.123	26.412	<0.001
age	-0.004	-0.011, 0.003	-1.073	0.283
Climatic parameter [tmed] × SDM projection [persistence]	-0.007	-0.011, -0.003	-3.611	<0.001
Climatic parameter [vpd] × SDM projection [persistence]	0.000	-0.004, 0.004	0.040	0.968
period [late] × SDM projection [persistence]	-0.243	-0.250, -0.237	-77.468	<0.001
<i>Random Effects</i>				
σ^2	0.035			
τ_{00_cod}	0.001			
$\tau_{00_seasons}$	0.001			
ICC	0.047			
No. corr. / No. plots / No. seasons	45414 / 150 / 3			
R^2_m / R^2_c	0.241 / 0.277			

The response variables are correlation coefficients between RWI and climatic factors. The fixed part of the model included latitude (LAT), longitude (LON), BIO18 (mean monthly precipitation amount of the warmest quarter), BIO9 (mean daily mean air temperatures of the driest quarter), BIO10 (mean daily mean air temperatures of the warmest quarter), BIO11 (mean daily mean air temperatures of the coldest quarter), mean age of the stands (age), periods (early, late) and SDM projection

(contraction, persistence) as categorical variables, and interaction between periods and SDM projections. The random part of the model included the site and the month nested in the season. Values represent the estimates of regression coefficients (β), 95% confidence intervals (CI), the t statistic, and the associated p -value of significance (bold values stand for significant fixed effects, $p < 0.05$). σ^2 represents the variance of residuals, τ variance caused by random effects, ICC intra-class correlation coefficient R^2_m is the marginal R^2 , and R^2_c is the conditional R^2 .

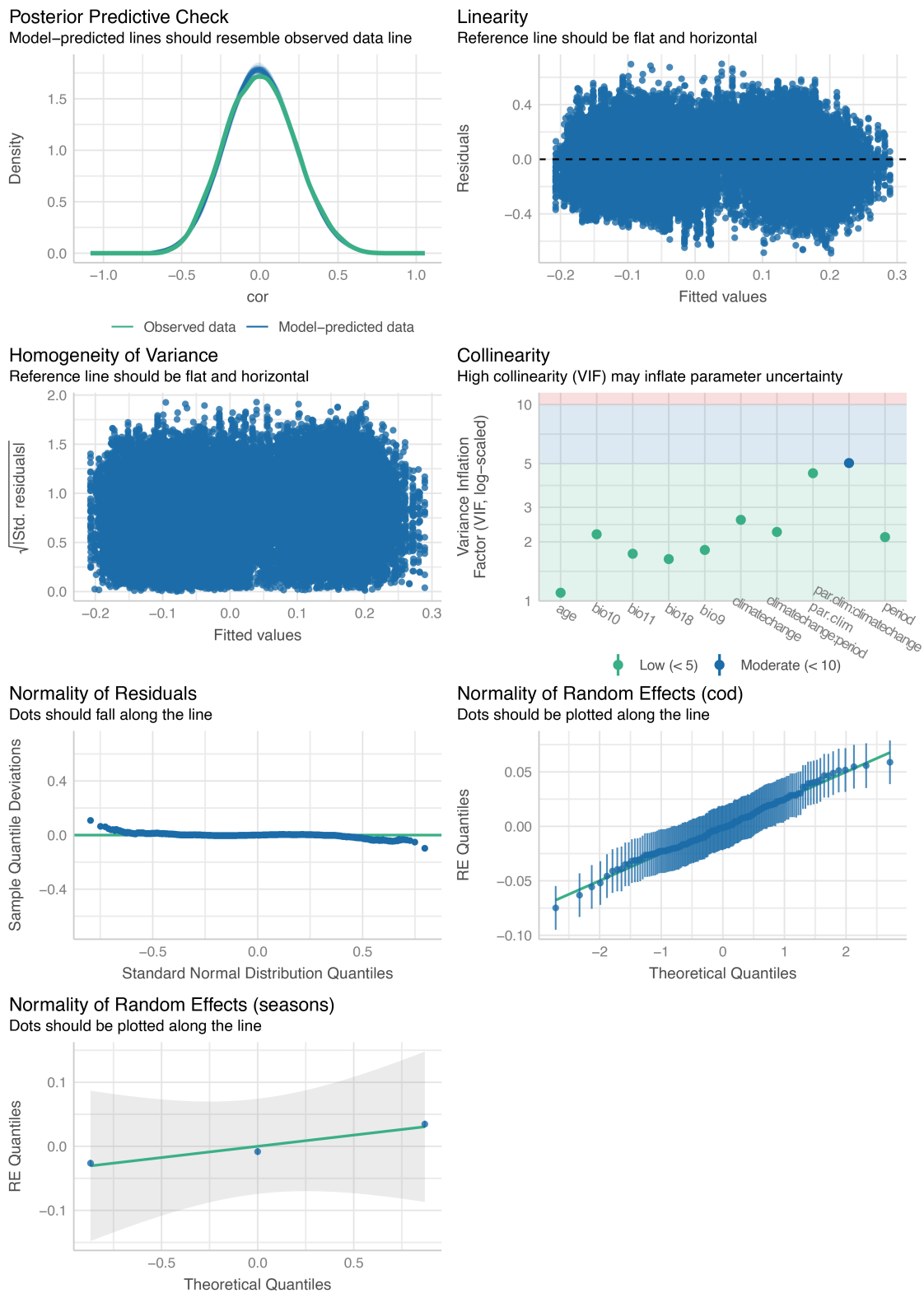


Figure S11 Diagnostic plots for the model presented in Table S3. Figure was generated using the `check_model()` function from 'performance' R package (Lüdtke et al., 2021)

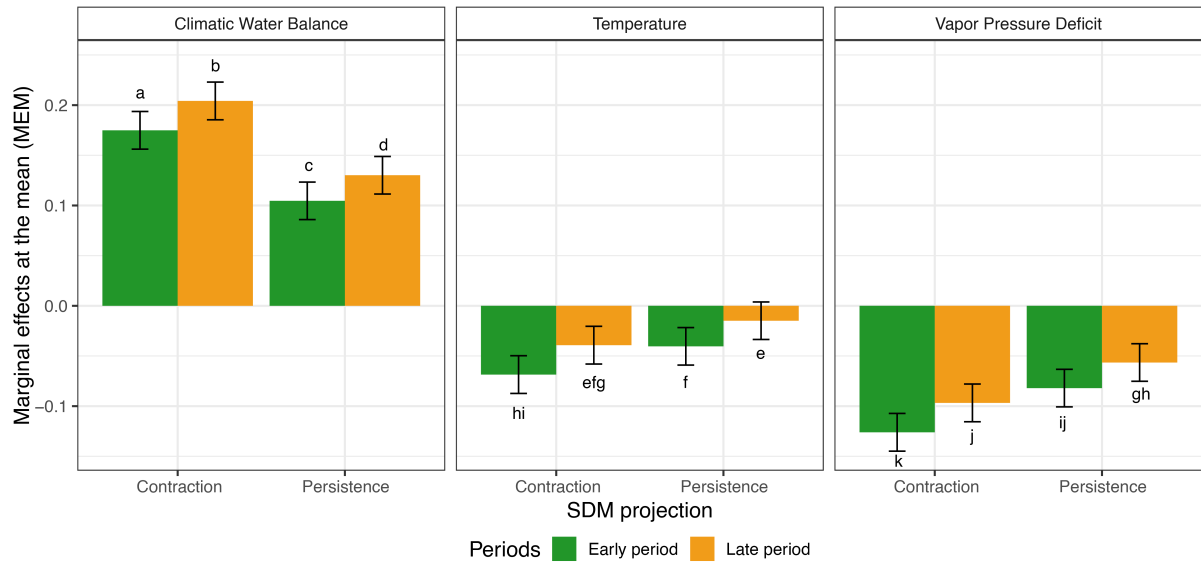


Figure S12 Marginal effects at the mean of study periods (i.e., early and late periods) on oak sensitivity to climate (Climatic Water Balance; Temperature; Vapor Pressure Deficit) in relation to SDM projection (potential range contraction or persistence); see Supplementary Table 3; error bars show \pm one standard deviation; the letters show the significant differences between the categorial predictors according to Tukey test