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ORIGINAL RESEARCH ARTICLE

Dendroclimatic analysis and cartographic modeling of the climatic response of *Fagus sylvatica* during growth in a sector of the central Cantabrian Mountains

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ABSTRACT

The wide distribution of the common beech (*Fagus sylvatica*) in Europe reveals its great adaptation to diverse conditions of temperature and humidity. This interesting aspect explains the context of the main objective of this work: to carry out a dendroclimatic analysis of the species *Fagus sylvatica* in the Polaciones valley (Cantabria), an area of transition with environmental conditions from a characteristic Atlantic type to more Mediterranean, at the southern limit of its growth. The methodology developed is based on the analysis of 25 local chronologies of growth rings sampled at different altitudes along the valley, generating a reference chronology for the study area. Subsequently, the patterns of growth and response to climatic variations are estimated through the response and correlation function, and the most significant monthly variables in the annual growth of the species are obtained. Finally, these are introduced into a Geographic Information System (GIS) where they are cartographically modeled in the altitudinal gradient through multivariate analysis, taking into account the different geographic and topographic variables that influence the zonal variability of the species response. The results of the analyses and cartographic models show which variables are most determinant in the annual growth of the species and the distribution of its climatic response according to the variables considered.

Keywords: *Fagus Sylvatica*; Dendrochronology; Dendroclimatology; Climate; Geographic Information Systems; R-Project; Multivariate Analysis; Mapping

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1. Introduction

Knowledge of the environmental factors that affect the growth of woody plants is essential not only for proper management of these resources, but also for observation of the possible effects that will occur in the future if these factors are modified. Variations in environmental conditions are evident in the analysis of spatial and temporal patterns of distribution and explanation of population dynamics[1-3].

The present work is framed in this context: taking into account the special sensitivity of *Fagus sylvatica* to the changes that occur in its environment (in particular drought stress situations), it is proposed as an initial hypothesis to use this species as a pattern of spatial modeling of the response to climatic variables, determining the incidence or extent of these in the altitudinal gradient. The main objective of this study is, therefore, to carry out a dendroclimatic analysis of the response of this species to climate in the Polaciones valley (Cantabria), one of its southern limits of distribution. From this, a series of secondary objectives are proposed, such as: (1) to create a primary chronology of growth rings for the study area that will be a reference dendrochronological observatory within the Cantabrian Mountains; (2) to characterize the climatic response of *Fagus sylvatica*, in the so-called growth-climate relationship and identify which monthly variables have the greatest influence on annual growth; (3) to model cartographically in a GIS the climatic variables of the growth-climate relationship in the whole beech forest area of the Polaciones Valley (Cantabria).

The use of a dendroclimatic methodology for the phenological knowledge of *Fagus sylvatica* and its behavior in relation to climate is based on the general principle that trees respond in a certain way to certain climatic parameters and variables that influence their annual growth[4,5]. However, there are other non-climatic perturbing effects that also affect the growth and formation of annual rings: the age of the tree, disturbances at the individual level (e.g., a change in competition) or fires or pests that may have affected the population in general[6,7]. These must be minimized if a useful climatic signal is to be obtained, so sample replication and site selection are key in this type of study.

The importance of applying this type of studies to the case of *Fagus sylvatica* in the Cantabrian Coast is due to the important extension that deciduous hardwoods acquire in this area and, in general, its wide distribution in European forests, in humid environments and with well-drained soils[8], since it is a species commonly known for its low tolerance to water deficit or summer drought[9,10], due to cavitation and loss of xylem conductivity caused by low precipitation. They form pure and mixed forests from altitudes close to sea level to formations that delimit the upper limit of the forest[11,12].

The study of this species is widely developed in the forests of central, southern, western and northern Europe[13–33]. In some of them, it presents certain common geographical patterns in the growth response of the rings with respect to climate, in which it shows modulating local environmental gradients such as altitude[23,27,33].

Finally, the integration of results obtained from climatic analyses in relation to the growth of *Fagus sylvatica* rings in a Geographic Information System (GIS) is interesting when it comes to understanding the response of forests of this species to the various environmental variables or gradients exposed. In this sense, these works are recent works in which information obtained through tree climate analysis and purely geographical and physical variables are integrated into a GIS and correlated with each other[34,35].

1.1 Study area

The area chosen for this study is the Polaciones valley in Cantabria (**Figure 2**). It constitutes an area of the southern limit of distribution of *Fagus sylvatica* in Europe and is, in turn, an ecotone between two very different bioclimatic environments in which climatic effects are manifested with greater intensity[18]. On the one hand, the Atlantic bioclimatic domain of the Cantabrian valleys (Saja, Nansa, Deva, Pas, etc.), which is generally characterized by abundant annual rainfall, between 1,000 and 1,300 mm[37], regularly distributed with maximums in spring and autumn and minimums in summer. Temperatures show mild summers and cool winters, which worsen as the altitude rises. The other major bioclimatic domain that separates the two, corresponds to conditions of greater continentality and transit towards a Mediterranean climate in the Castilian-Leonese basin.

From the standpoint of vegetation cover, the valley has three highly contrasting areas: the most developed area corresponds to the characteristics of a moderately mountainous area, which allows for the formation of large forests, with elevations ranging from 700 m above sea level to over 1,600 m.a.s.l. A second area, occupied by mixed shrub formations dotted with herbaceous pastures, covers the high slopes on the main mountainous alignments that contour the basin. Finally, there are the rocky outcrops with sparse vegetation that form the culminating areas, which in many points exceed 2,000 m.a.s.l., both in the Sierra de Peña Sagra, to the north, and in the Sierra de Peña Labra and the Cordel, to the south.

The tree species that characterize this area are mainly: *Fagus sylvatica*, which dominates the tree canopy from the lower slopes to the forest boundary; *Betula alba* var. *alba* is distributed in narrow strips in the culminating parts, which is a frugal and opportunistic species with a rapid adaptation to changing and harsh environmental conditions often forming the upper limit of the forest with *Fagus sylvatica*; and *Quercus petraea* subsp. *petraea* and *Quercus pyrenaica* in mixed formations with *Fagus sylvatica* or as young stands on slopes with sunny orientations, preferably in the south.

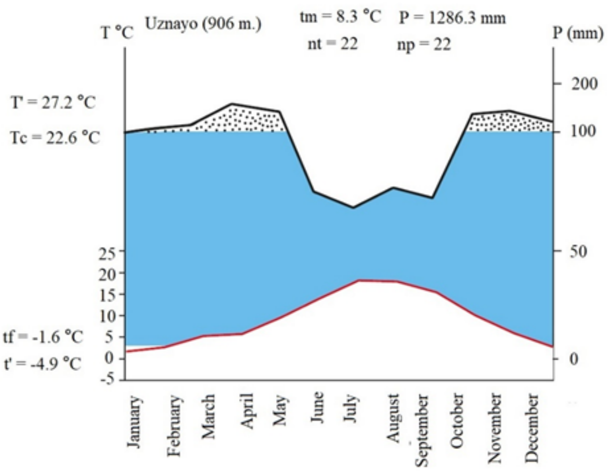


Figure 1. Walter Lieth climogram for the Uznayo weather station.
Red line: average temperatures; black line: monthly precipitation threshold; dotted area: excess precipitation.
Source: AEMET. Own elaboration.

Regarding the climatic characteristics of the Upper Nansa Valley (Boraciones Valley), it has a series of unique characteristics. Its high topography and elevation (the valley's lowest point at the Embalse de la Cohilla at 709 meters above sea level), both above 2,000 meters above sea level, defines a certain degree of continental. This is mainly observed in the winter thermal characteristics, with more pronounced minimum temperatures. At the same time, its distance from the sea and its configuration as a watershed (Nansa, Duero and Ebro), determines the appearance of Mediterranean nuances, such as a certain decrease in summer rainfall. It is because of these unique features and despite the existence of a network of observatories close to the valley under analysis, that the climatic data from the thermo-pluviometric station Uznayo (11590), located in the interior of the valley at 905 m.a.s.l., belonging to the State Meteorological Agency [AEMET][37], is taken as a reference for the characterization of the area. This provides a continuous daily record of thermopluviometric data for the period 1973–1996.

Based on the available data, the characteristics of the climate in the upper Nansa valley are defined by an average annual temperature of 8.2 ºC, with maximums in the summer months of July and August with annual averages between 14 ºC and 15 ºC. Winters in the interior of the valley register average temperatures between 3–4 ºC and minimum temperatures between –1 ºC and –2 ºC. Regarding precipitation values, 1,286 mm per year are regularly distributed, with maximums in spring and autumn and minimums in summer (**Figure 1**).

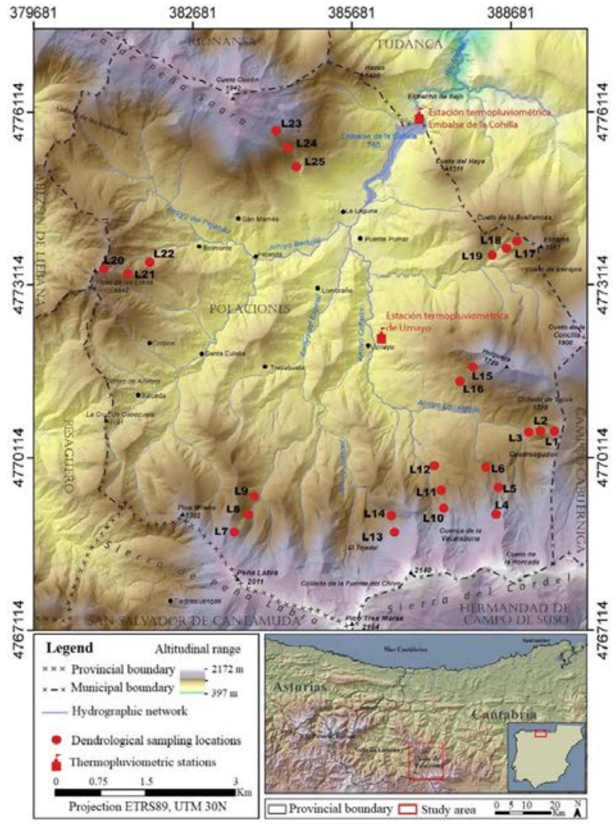


Figure 2. Location of the study area, reference climatic station and locations of the dendrochronological transects developed.
Source: National Center for Geographic Information (CNIG). Own elaboration.

In addition, it is observed, from the Viewer of the Climate Atlas of the Peninsula and Balearic Islands[38], that in the plant populations analyzed between 1,200 and 1,600 m.a.s.l., the average winter temperature for this interval is between 2.5 ºC and 5 ºC, dropping below 0 ºC between 80 and 100 days a year. Precipitation occurs more than 125–150 days per year, to which must be added a significant number of cloudy days, when fog covers the forest and adds additional humidity to the total precipitation. Lacking a measure of precipitation in the high sectors of the upper reaches of the Nansa, it is not easy to estimate the total annual volume that the headwaters receive in the altitude range we are considering, but in any case, it is high, above 1,400 mm.

The choice of the study area, therefore, is of great interest as it combines climatic, ecological and localization requirements, since it is an area of southern distribution of beech forests in Europe[39,40]. These characteristics, together with the possible strong relationship established between the annual growth of the species under analysis and climate, make this area a valuable observatory of climatic variability.

2. Methodology

The work was structured in four phases: (1) photo-interpretation and digitalization of the zonation occupied by *Fagus sylvatica* forest stands; (2) dendrochronological sampling and sample processing; (3) statistical treatment of samples and analysis of the growth-climate relationship and; (4) modeling and integration into a GIS.

2.1 Photointerpretation and digitization of the zonation occupied by Fagus sylvatica forest stands

In the first phase, field work and inventories were carried out to identify the dominant plant communities on the territory, focusing especially on the areas occupied by beech forest. These were delimited by photointerpretation on the images of the National Aerial Orthophotography Plan 2014 (PNOA)[41]. Thus, a vector cartographic database was obtained, which shows the area occupied by beech forests and was used for the delimitation of the final cartographic model.

2.2 Dendrochronological sampling and sample processing

In the second phase, dendrochronological sampling was carried out. To do this, we initially proceeded to the selection of the areas, for which we followed a criterion of maximum diversity of possible conditions[4,5]. This allowed the maximum territorial representativeness to be achieved with the smallest finite number of plots to be analyzed. In total, 25 locations were sampled, distributed in 9 slopes from the upper limit of the forest to the middle-lower areas of the valley. In the selection of the sampling sites, a first criterion of discrimination by species was used, based on field work and the Third National Forest Inventory [IFN3][42]. With this, we discarded those slopes where other species such as *Quercus petraea* subsp. *petraea* and *Quercus pyrenaica* dominate, mainly on the sunny side. The geoforms and lithologies found were also considered as criteria for the selection of areas and slopes, resorting to consultation sources of the Geological and Mining Institute of Spain [IGME], such as the Geological Map and Geomorphological Map of the Autonomous Community of Cantabria 1:25,000[43,44] and the geomorphological cartography elaborated by Frochoso[45]. This made it possible to consider the different geological and geomorphological characters present in the valley and to select spaces among the various types defined. On the other hand, the topographic variables orientation, slope and altitude were also considered, calculated directly or indirectly with the LIDAR Digital Terrain Model [DTM][46] as a starting reference, adapted to the criteria and characteristics in the creation and exploitation of the DTM[47,48] and the Soil Map at scale 1:50,000 of the Cartoteca Regional Agraria (CRA)[49]. The use of these data made it possible to select for sampling representative zones of the different orientations, slope range and soil formation and types present.

In the calculation of the 25 chronologies, a total of 249 trees were involved, extracting 402 cores, all of them healthy, dominant and co-dominant individuals of the target species *Fagus sylvatica*. From each selected tree, one or two cores were extracted at a height of approximately 1.30 m from the base. Sampling was carried out with a 40 cm long *Pressler* type auger with a 5 mm diameter of an inner tube. The cores were glued on supports, dried at room temperature and sanded until the annual growth rings could be seen with the naked eye. They were then treated statistically following the protocols established in dendrochronology[50].

2.3 Statistical treatment, development of chronologies and analysis of growth-climate relationship

Each individual ring series was previously validated visually by comparing it with the rest of the samples of the same series or location, following the method of Yamaguchi[51]. The ring thickness measurements were performed with a LINTAB6 semi-automatic measuring table and its associated software TSAPWIN with a measurement accuracy of 0.001 mm.

The statistical validation or crossdate was carried out using the COFECHA software[52]. The correlation between the samples that make up each chronology was calculated in 50-year segments, eliminating those that did not synchronize with a correlation coefficient higher than 0.32 because it was not considered significant[53]. Of the 402 cores analyzed, 376 were finally used.

The subsequent process of standardization and elaboration of growth index chronologies was carried out through the statistical program R[54] in its dplR function package[55]. This transformed each individual series of measured ring width to dimensionless indices, removing the effects of changes in tree growth resulting from aging and homogenizing the mean and variance to construct standardized chronologies for each location. All individual series were standardized by initially applying a downward linear or negative exponential model, which removed the trend due to age, and then a 53-year cubic spline model, suitable for reducing the variation due to disturbances in dense forests while preserving the high-frequency variability resulting from the climatic signal.

The main characteristics and statistics of the mean chronologies obtained are shown in **Table 1**. The quality and significance of the resulting chronologies was evaluated mainly through the EPS (Expressed Population Signal) statistic. This statistic was used as an indicator of the agreement between the variance of each chronology with the theoretical population, a good level of fidelity of the common signal between chronologies being a threshold above 0.85[2,56,57].

Other statistics considered in the chronologies were: the mean intercorrelation (Interc.) of all individuals with respect to the mean chronologies; the mean correlation coefficient (RBAR) of all individual ring series, calculated for a common time interval (50-year window with a 25-year overlap); the autocorrelation coefficient (A^1), indicative of the influence of the previous year on the growth of the coming year; and the mean sensitivity (MS), representative of the interannual variability of ring width[5]. This last statistic is highly significant if it exceeds 0.30, intermediate if it is between 0.20 and 0.29 and insignificant if it is below 0.19[53].

Once the average chronologies of growth rates for each sample (including at least five cores for each dated year) were elaborated, a general or master chronology for the valley as a whole was elaborated by averaging these average chronologies.

On the other hand, in order to know which variables and months have a determining influence on the growth of *Fagus sylvatica*, an analysis of the growth-climate relationships was carried out. For this purpose, correlation and response functions were calculated. By this procedure, the residual chronologies of indices obtained from the set of trees for each of the sampling locations were contrasted with the explanatory monthly climatic variables previously standardized (mean, maximum, minimum and precipitation temperature).

Regarding the use of reference climatic data for the analysis, the option of using data from the Uznayo thermopluviometric station was discarded. Although it shows a good climatic characterization of the study area, its short time span (1973–1996) does not provide robustness to the data series for a climatic analysis. Instead, it was decided to use monthly mean climate data from the Climatic Research Unit (CRU) network[58]. These data were chosen because they cover a wide period between 1901–2015, offer a spatial resolution of 0.5º and are widely contrasted in climatic and dendroclimatic research (such as McGuire *et al.*[59]; Shi, *et al.*[60]).

The calculation of the growth-climate relationship was performed for the common period 1901–2011 using R software, which calculates and tests the statistical significance and stability of the multiple regression coefficients[7,61]. In this work, only correlation analyses were considered to determine climatic responses. Thus, values greater or less than +/-0.24 were considered significant at the $p < 0.05$ significance level. The temporal amplitude of the function calculation covered a window of 16 months, from June of the year prior to growth ($n - 1$) to August of the current year (n), both included. This window was selected based on previous results and existing data from studies on both ring formation of the study species and growth-climate relationships[17,19,22,23].

Table 1. Main characteristics and statistics of the average chronologies analyzed

	Location features			Main statisticians									
	H	**O**	**P**	**N**	**L_t**	**A_5**	**L_5**	**RW**	**Int.**	**MS**	**A1**	**EPS**	**RBAR**
L1	1,480	W	>35º	18	114	1,913	99	1.43	0.62	0.32	0.43	0.92	0.45
L2	1,380	W	20–30º	21	292	1,871	141	1.26	0.71	0.29	0.27	0.94	0.47
L3	1,280	W	30–35º	26	435	1,864	148	0.88	0.60	0.31	0.20	0.93	0.41
L4	1,540	N	30–35º	15	136	1,899	113	1.19	0.70	0.35	0.48	0.93	0.52
L5	1,460	N	15–20º	21	408	1,814	198	0.84	0.64	0.36	0.27	0.94	0.49
L6	1,350	N	25–30º	17	309	1,763	249	0.67	0.66	0.31	0.32	0.94	0.55
L7	1,580	E	30–40º	20	294	1,900	112	0.94	0.73	0.36	0.43	0.94	0.54
L8	1,540	E	30–40º	16	291	1,781	231	0.89	0.69	0.38	0.34	0.91	0.47
L9	1,440	E	20–30º	16	272	1,759	253	1	0.63	0.32	0.34	0.95	0.53
L10	1,450	N	20–25º	18	240	1,872	140	0.83	0.71	0.38	0.41	0.95	0.55
L11	1,350	N	25–30º	16	180	1,852	160	0.97	0.71	0.29	0.34	0.95	0.60
L12	1,250	N	15–20º	18	220	1,836	176	1.04	0.61	0.27	0.35	0.92	0.44
L13	1,580	N	20–30º	14	145	1,887	125	0.99	0.78	0.36	0.47	0.91	0.72
L14	1,460	N	20–30º	14	229	1,803	209	1.05	0.67	0.30	0.37	0.92	0.50
L15	1,430	W	20–30º	15	330	1,809	203	1.06	0.59	0.32	0.28	0.90	0.46
L16	1,330	W	10–20º	16	187	1,858	154	1.70	0.62	0.26	0.26	0.91	0.43
L17	1,400	SE	25–30º	19	241	1,771	241	1.34	0.57	0.29	0.18	0.86	0.39
L18	1,250	SE	25–30º	19	211	1,836	176	1.12	0.68	0.28	0.21	0.92	0.44
L19	1,000	SE	20º	17	159	1,888	124	1.28	0.57	0.26	0.36	0.89	0.38
L20	1,310	W	>35º	18	250	1,876	136	1.17	0.62	0.32	0.39	0.93	0.45
L21	1,220	W	>35º	15	267	1,805	207	0.90	0.55	0.35	0.29	0.88	0.40
L22	1,110	W	30–35º	18	290	1,771	241	0.95	0.65	0.29	0.28	0.92	0.50
L23	1,500	E	>30º	7	275	1,902	110	1.12	0.53	0.25	0.19	0.63	0.19
L24	1,400	E	20–30º	18	266	1,853	159	0.87	0.54	0.23	0.20	0.85	0.29
L25	1,300	E	>35º	9	285	1,849	163	0.95	0.44	0.21	0.22	0.72	0.21

Abbreviations: (H) altitude in m.a.s.l.; (O) orientation; (P) slope; (N) total number of samples; (L_t) total length of the series; (A_5) starting year of the series (5cores/year); (L_5): total length of the series with 5 cores/year; (RW): average width of rings; (Int.): intercorrelation; (MS): mean sensitivity; (A^1): autocorrelation; (EPS): expressed population signal; (RBAR): mean correlation coefficient.
Own elaboration.

2.4 Modeling and Integration in a Geographic Information System

The cartographic representation of the climatic response of *Fagus sylvatica* in the valley was supported by a multiple regression model. This analysis established the functional relationship between a dependent variable to be explained (response of the beech forest to monthly climatic variables) and a series of independent or explanatory variables (physical and topographic variables considered). From these relationships, empirical models capable of predicting the values of beech response in unsampled locations by means of the values of the geographic and topographic variables were created.

The independent variables initially considered were altitude, slope, orientation and insolation. Most variables were generated from the digital elevation model [DEM], such as the digital slope model, the digital orientation model (quantified prior to its inclusion in the regression model) or the solar radiation received model (W/m^2).

The multiple regression analysis was performed with R software, using the stepwise regression method[62,63]. Only those variables that were significant in the analysis of the growth-climate relationship were modeled as dependent variables (July Tªmax, March Tªmax, precipitation in April, May, June, July and August) in relation to the topographic and geographic variables as predictors. The relationship and quality of these models was determined by the value of determination coefficients (r^2). Once the regression functions were calculated, the final maps were obtained using ArcGIS. For this purpose, a regression model interpolation process was carried out, calculated by means of map algebra on the different raster coverages that incorporated the models. The cartographic models were evaluated by means of statistics that indicate the degree of agreement between the models and reality. Following Willmott[64], the error between the predictions obtained by the different interpolation models and the real data recorded in the chronologies was determined using the Root-mean-square error (RMSE) statistic. In turn, a common legend was established for all the cartographic models with values between –1 and 1, reclassified in 40 intervals of amplitude 0.05.

3. Results

3.1 Development of average and reference chronologies for the Cantabrian valley of Polaciones

One of the objectives set at the beginning of this study is the creation of a chronology for the Polaciones valley as a whole to serve as a reference location to be considered in future research on this species within its Iberian and European distribution. For this purpose, we start from the high correlations between the different chronologies and average them to obtain a chronology of the study area composed of at least 5 records/year covering the period 1759–2011 (**Figure 3**). As can be seen, the sample depth maintains a high replication until the middle of the 19th century, always maintaining at least 10 samples/year until the last dated year.

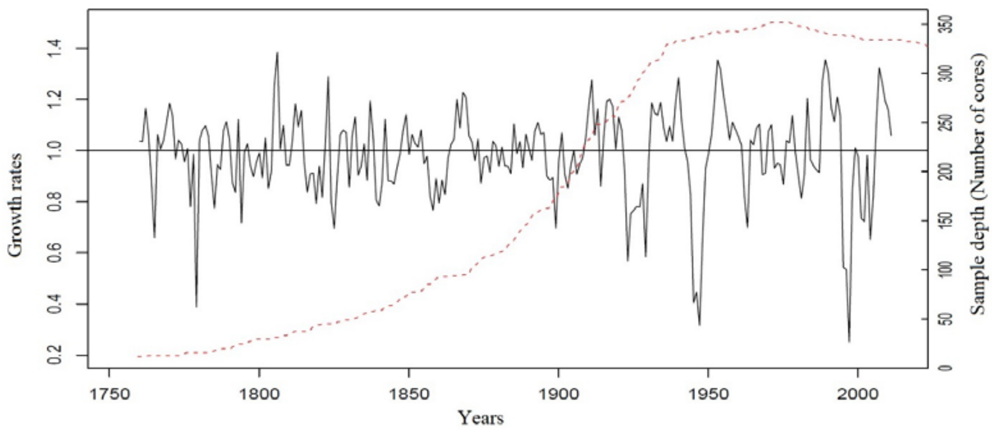


Figure 3. Master chronology of *Fagus sylvatica* in the headwaters of the Nansa valley (Polaciones, Cantabria). Black line: annual ring growth index value of the chronology; red line: depth of the sample. Own elaboration.

From the main statistics extracted from the 25 chronologies that make up this reference series (see **Table 1**), we can observe that two chronologies present long-lived individuals that exceed 400 years. The maximum length of the series generally shows an inverse relationship with altitude, with the youngest individuals being located in the samples taken at higher altitudes. The mean width of the rings in the different samplings is also greater in those carried out at higher altitudinal points (L1, L4, L9, L17, L20 and L23), with values exceeding 1 mm, which is associated with the youngest age chronologies in each transect. This data is corroborated by the longest chronologies with the highest number of older individuals in their composition (L3, L5 and L6), which have the smallest mean ring width of the series (0.67 and 0.88 mm).

As an exception, it is worth mentioning the transect carried out on the southern slope of Cueto de Helguera (L15 and L16), with average growth of the rings (1.06 and 1.7 mm) and chronologies of considerable length. In both points, L15 reaches 330 years and L16, in spite of registering only 187 years, six of its sampled specimens and a priori possibly older, could not be dated completely because the wood was deteriorated and it was impossible to extract the complete core.

The mean intercorrelation of all individuals with respect to the mean chronologies is high in all cases, with coefficients of determination r^2 between 0.6 and 0.7.

DM values are highly significant in all the sampled points. The chronologies located around the upper limit of the forest and elevated areas stand out, as opposed to those in lower altitudinal locations, where we found a less marked interannual variability.

As for the first order autocorrelation values, these are low (0.4 and 0.3), indicating a certain influence of the previous year on the growth of the coming year, although not in a determinant way. Finally, and taking into account the statistical values obtained in the HPS, chronologies L23 and L25 were discarded both for the elaboration of the reference chronology and for the climatic analysis, because they did not meet the minimum statistical criteria of reliability (0.85).

3.2 Analysis of the climatic response of ring growth using correlation functions and response function in *Fagus sylvatica*

Of the climatic variables of the CRU high resolution grid (precipitation, maximum temperature, minimum temperature and average temperature), only the precipitation and maximum temperature (> or < a ± 0.24; $p < 0.05$) show significant results, summarized in **Table 2** and **3**. The minimum and average temperature variables are not represented due to their low significance in the results of the functions.

Table 2. Summary of the climatic response in the growth of *Fagus sylvatica* chronologies to monthly precipitation values (only significant correlations are shown numerically (cells in gray correlation greater than ±0.24 at the $p < 0.05$ significance level)

	Precipitation														
Series	**months year *n* – 1**							**months year *n***							
	J	**J**	**A**	**S**	**O**	**N**	**D**	**E**	**F**	**M**	**A**	**M**	**J**	**J**	**A**
L1				–0.31		0.41		–0.26			0.62	0.48	0.55	0.63	0.53
L2	0.35					0.38		–0.25			0.51	0.46	0.51	0.60	0.51
L3	0.24	0.30							–0.34		0.46		0.46		0.46
L4		0.35						–0.29			0.57	0.51			0.60
L5						0.25					0.48	0.47	0.50	0.54	0.49
L6	0.26					0.29				0.29	0.47	0.43	0.41		0.38
L7		0.27									0.55		0.38	0.59	
L8	0.26							–0.35			0.51		0.51	0.48	0.55
L9								–0.29		0.24		0.44	0.48	0.56	0.52
L10	0.31				–0.26			–0.26			0.51	0.38	0.45		
L11	0.28				–0.31	0.35					0.39		0.39	0.54	0.46
L12	0.29								–0.30		0.37	0.39	0.36		
L13				–0.33											0.48
L14	0.30	0.26						–0.24			0.46	0.36			0.43
L15	0.36					0.26					0.49	0.42	0.47	0.45	0.56
L16												0.41		0.39	0.51
L17	0.33				–0.29				–0.26		0.63		0.42	058	
L18	0.31					0.29		–0.36			0.57		0.41	0.49	0.61
L19	0.25	0.35						–0.31			0.44	0.28	0.38	0.47	
L20								–0.26		–0.28		0.32	0.39	0.68	0.63
L21		0.28								–0.31	0.51	0.29	0.37		0.39
L22		0.31				0.26				–0.29	0.36		0.26	0.63	
L24	0.26	0.24						–0.28			0.58	0.27	0.42	0.61	0.57

Own elaboration.

The results obtained for this species in relation to monthly precipitation records show a positive response of growth to spring precipitation in April, May and June of the year of ring formation and June of the previous year, as well as to summer precipitation in July and August of the year of ring formation. In turn, the beech forest shows a negative response, although not marked in all the chronologies analyzed, to January rainfall.

Regarding the analysis of the maximum

temperature variable, all the localities analyzed showed a positive response to March temperatures, although it was not highly significant in four of them (L6, L10, L13, L19). Likewise, a negative response to growth in July of the year of ring formation is also outstanding, this relationship being highly significant in all cases except in chronologies L4, L12 and L21, repeating itself in many of them for the month of July of the previous year ($n - 1$).

Figure 4 shows the graphical representation of the growth-climate relationship through the correlation function and response function calculated for the master chronology of the valley.

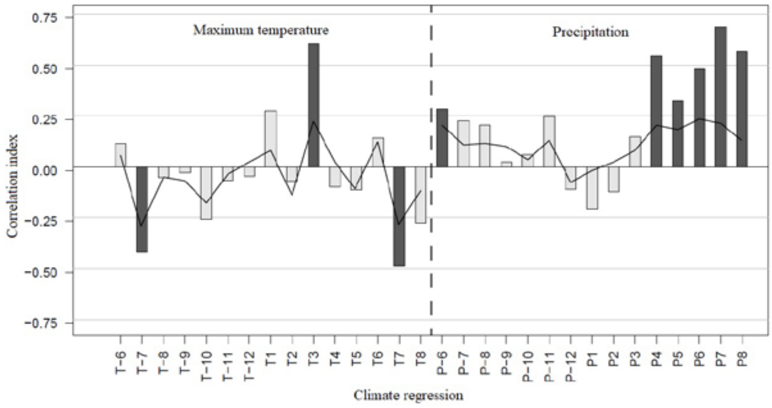


Figure 4. Correlation function (bars) and response function (lines) calculated for the master chronology of the 23 localities considered. The dark gray bars indicate correlations greater than ±0.24 at the significance level above 95% confidence ($p < 0.05$).
Own elaboration.

Table 3. Summary of the climatic response in the growth of *Fagus sylvatica* chronologies to monthly maximum temperature values (only significant correlations are shown numerically (cells in gray correlation greater than ±0.24 at the $p < 0.05$ significance level)

Series	**Maximum temperature**														
	months year $n - 1$							**months year n**							
	J	**J**	**A**	**S**	**O**	**N**	**D**	**E**	**F**	**M**	**A**	**M**	**J**	**J**	**A**
L1		–0.35					–0.33			0.55				–0.51	
L2		–0.32			–0.36					0.53				–0.48	
L3			–0.29	–0.31					0.28	0.43				–0.36	
L4		–0.38			–0.26			0.38		0.52			0.26		
L5										0.47		0.25		–0.50	
L6												0.32		–0.39	
L7		–0.32		–0.26						0.51				–0.46	
L8		–0.31								0.43				–0.40	
L9		–0.24								0.42			0.25	–0.39	
L10		–0.26									–0.25		0.31	–0.45	
L11		–0.25						0.26		0.47	–0.31			–0.46	
L12										0.36					
L13				0.29										–0.38	
L14		–0.27		0.27				0.39		0.39				–0.37	
L15		–0.37								0.46	–0.36			–0.48	
L16		–0.33						0.24		0.37			0.24	–0.42	
L17	–0.29									0.51	–0.29			–0.39	
L18										0.51				–0.33	
L19		–0.34						0.25	–0.22					–0.32	
L20		–0.3						0.29		0.38				–0.45	
L21	–0.27	–0.33	–0.32							0.45			0.27		
L22		–0.24	–0.30							0.36			0.26	–0.38	
L24		–0.37						0.25		0.48				–0.47	

Own elaboration.

3.3 Spatial modeling of the growth-climate relationship of beech in the Cantabrian valley of Polaciones

Based on the results of the 23 beech chronologies, the significant variables obtained from the growth-climate relationship are considered for cartographic modeling: rainfall in April, May, June, July and August. In the case of temperatures, only the maximum temperature in March and July is significant.

Correlations between growth responses to significant climatic variables and the different geographic and topographic variables that are candidates for implementation in the model are shown in **Table 4**.

Table 4. Correlation coefficient(r) between the response values to the monthly climatic variables and the different independent variables that are candidates for the model

Predictor variable	1	2	3	4	5	6	7
Altitude	0.76	0.64	0.70	0.71	0.55	0.81	0.85
Pending	0.22	0.51	0.35	0.29	0.48	0.13	0.18
Orientation	0.12	0.06	0.07	0.09	0.01	0.03	0.05
Radiation	–0.56	–0.55	–0.41	–0.57	–0.33	0.36	0.34

Note: 1: Precipitation in April; 2: Precipitation in May; 3: Precipitation in June; 4: Precipitation in July; 5: Precipitation in August; 6: Maximum temperature in March; 7: Maximum temperature in July.
Own elaboration.

As can be seen, the altitude variable is the one that initially offers the highest correlation values in the distribution of the beech response, both in monthly precipitation and maximum temperatures.

In the stepwise multiple regression analysis, the response to precipitation and monthly maximum temperature of *Fagus sylvatica* are used as dependent variables, while geographic and topographic variables act as predictor variables. The amount of variance explained and the variables that the analysis incorporates in each model are shown in **Table 5**. The rainfall response models explain a lower percentage of variance, between 42% and 67%, and implement between one and two independent variables. On the other hand, the temperature response models explain a higher percentage of the variance, 77% in the case of July and 83% in March, establishing a relationship with a single variable, altitude.

Table 5. Determination of the stepwise multiple regression models and coefficients of the independent variables calculated for the models

Calculated variables	r^2	Coefficients of the variables
April rainfall	0.61	(0.0058*Altitude)
May precipitation	0.42	(0.0044*Altitude)
Precipitation June	0.63	(0.0073*Altitude) + (–0.0016* radiation)
July precipitation	0.67	(0.0068*Altitude) + (–0.0008* radiation)
August precipitation	0.51	(0.0055*Altitude) + (–0.0023*radiation)
Temperature July	0.77	(0.0071*Altitude)
Temperature March	0.83	(0.0039*Altitude)

Source: Own elaboration.

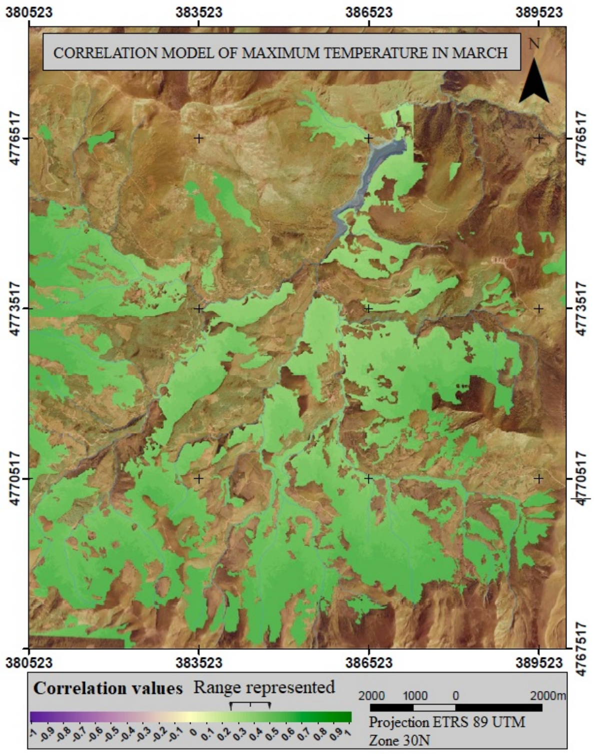
In the case of spring rainfall in April, May and June, the model shows moderate coefficients of 0.61, 0.42 and 0.63, respectively[65]. The cartographic distribution of the correlation values (**Figure 5**) shows lower correlations in the lower sectors of the valley (0.2) that progressively gain significance as the altitude rises and reach the upper limit of the forest around 0.5–0.6. The positive response throughout the altitudinal range demonstrates the importance of spring precipitation for the activation of metabolic functions of the tree. In the models generated for summer precipitation, the values are also moderate (July: 0.67 and August: 0.51). The spatial distribution of the modeled correlations follows a similar pattern in the two models, with positive values throughout the area, higher in the higher altitude zones, with this response decreasing as the elevation descends and move towards the bottom of the valley to values around 0.2.

Table 6. Validation statistics of the cartographic interpolation models

Interpolation models	RMSE
Precipitation in April	0.32
Precipitation in May	0.28
Precipitation in June	0.36
Precipitation in July	0.23
Precipitation in August	0.32
Temperature in July	0.24
Temperature in March	0.30

Source: Own elaboration.

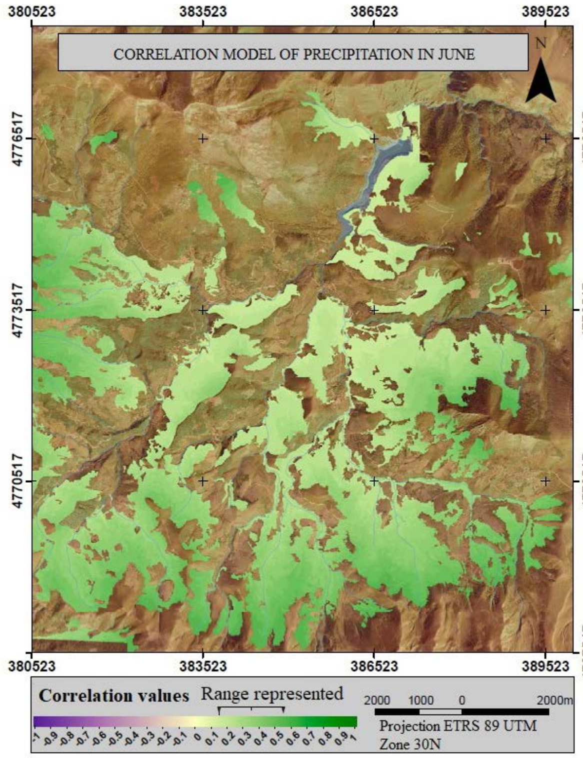
On the other hand, the cartographic modeling of the response to maximum temperatures in March and July has strong coefficients of determination (0.77 and 0.83). In the case of March temperatures, there are positive correlations from the upper limit of the forest (0.5) to the bottom of the valley (0.2). In the case of July there is an inverse response to the maximum temperatures of this month, which is the warmest month of the year. This response to July temperatures reflects coefficients of greater significance around the upper limit of the forest and high forest areas (–0.5), which progressively attenuates as we move into the interior and valley bottom (-0.2), being also considered in multiple studies as one of the monthly variables of greater impact on the growth of the annual ring, contributing to increasing the values of evapotranspiration. Finally, the validation statistics of the cartographic models (**Table 6**) show values close to zero, indicating the validity of the representation between real and estimated values.



4. Discussion of results

From the analyses and dendrochronological sampling carried out, we consider it important to elaborate a reference chronology for the whole Polaciones valley with a temporal amplitude that exceeds two centuries, reaching up to the year 1759. This is a considerable length if we take into account the increasing scarcity of long-lived individuals, as well as the strong deterioration and scarce validity for dendrochronological sampling that trees often show in areas of abundant humidity such as the Atlantic. In these environments, the infiltration of rain that generates trunk rot or human alterations of the longest-lived individuals (pollarding and pruning), make this work very difficult or completely impossible. This last fact can be corroborated from the results obtained in the sampled locations L15 and L16, where, in spite of preventing a correct sampling, the management and anthropic intervention of the forest positively discriminates the growth of the trees allowing the existence of large specimens, which otherwise would be subject to greater competition within the stand.

Regarding the climatic conditions of the study area, framed in the transit between the Atlantic mountain zone and the continental Mediterranean sector, they show a significant impact on the growth of *Fagus sylvatica* in the mountainous localities analyzed. In addition, the fact that the series or average chronologies located in higher altitudinal locations have the highest mean sensitivity values, responds to


CORRELATION MODEL OF PRECIPITATION IN JUNE
N
380523
383523
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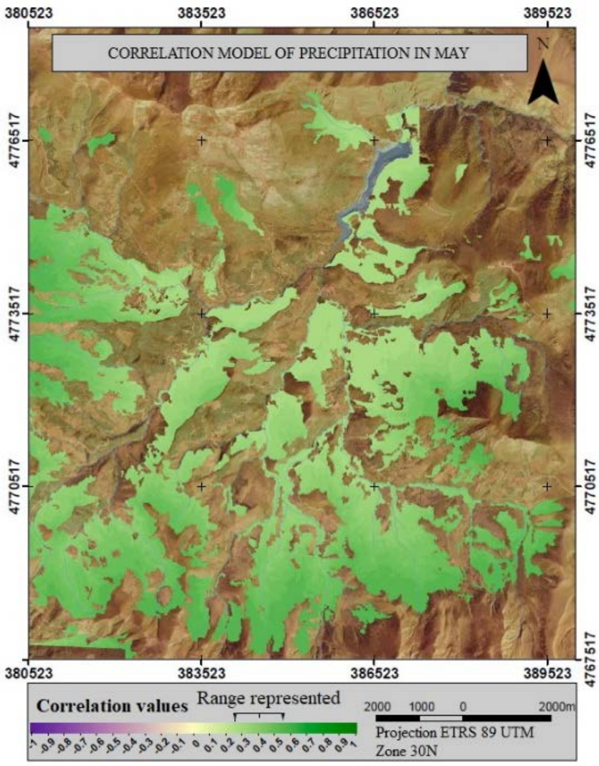
Correlation values
Range represented
-1 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
2000 1000 0 2000m
Projection ETRS 89 UTM
Zone 30N


CORRELATION MODEL OF PRECIPITATION IN MAY
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Correlation values
Range represented
-1 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
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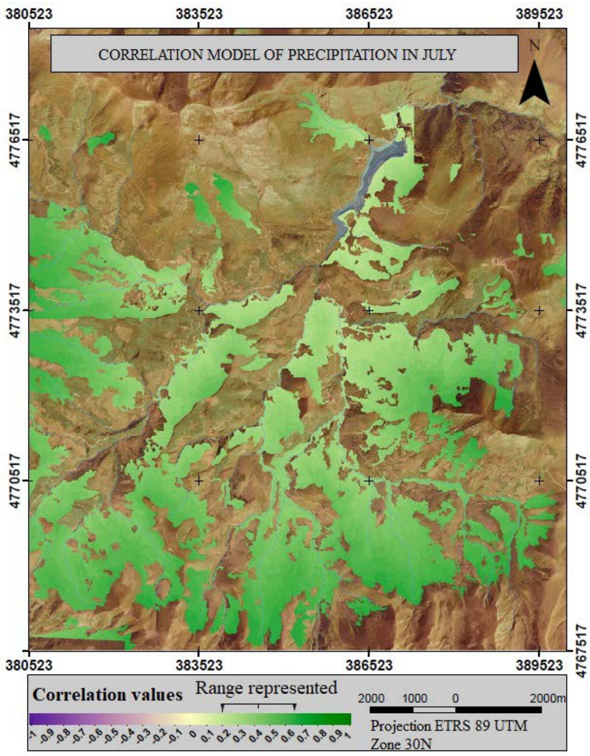
CORRELATION MODEL OF PRECIPITATION IN JULY
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Correlation values
Range represented
-1 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
2000 1000 0 2000m
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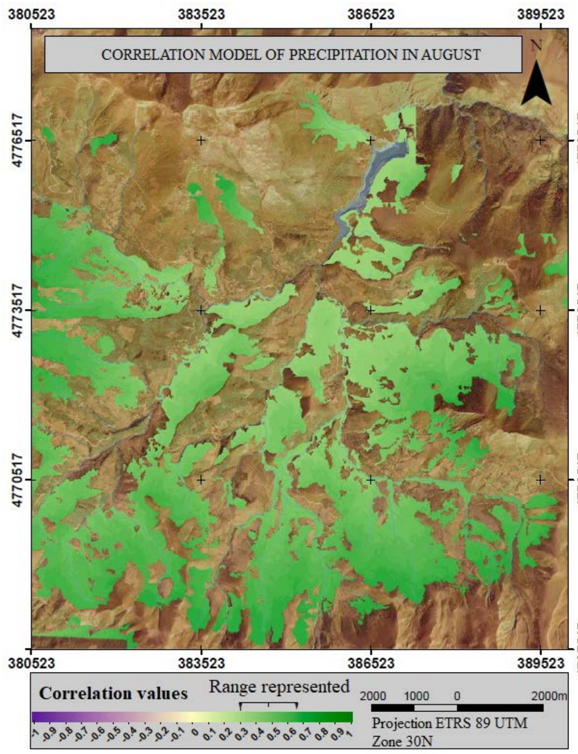

Figure 5. Cartographic models of correlation of climatic response to significant variables on the growth of *Fagus sylvatica*. Source: Own elaboration.

the fact that extreme climatic conditions leave more visible traces on the trees[66], establishing a certain altitudinal gradient.

In relation to the results of the analysis of the growth-climate relationship of *Fagus sylvatica*, a common climatic response in radial growth is observed. On the one hand, the response to thermal values (maximum temperatures in March and July) stands out. With respect to the high values in March, a period of inactivity of the species, this month could favor the start-up of the cellular functions of the tree prior to the germination of the spring shoots, as well as an improvement in the annual water distribution in the soil due to a greater snowmelt. On the other hand, the negative response to maximum temperatures in July may be related to the fact that it is the warmest and least rainy month of the year in this area and consequently the one with the highest evapotranspiration, which helps to understand the relationship established with growth. Both statements are only hypotheses and would require an in-depth study.

In relation to the response to monthly rainfall, the positive correlation with rainfall in the early spring months, April and May, is outstanding. Its main positive effects have to do with a prolongation of the growing season until the end of summer, producing wider tillers[67]. To this we must also add the positive relationships established between rainfall in late spring (June) and summer (July and August). In fact, the precipitation of this period as a whole (spring-summer) is shown to be an important factor promoting radial growth of beech. The positive response offered with respect to the precipitation of these months, is mainly explained by a start of the metabolic and cambial activity, evidenced in previous studies referred to the cambium activity and xylogenesis of the species[68–71], where a period of maximum cambial activity is established between April and July, and then declines rapidly thereafter.

We can highlight other values that, although not so outstanding, are worth considering. This is the case of the negative response to rainfall in January, which some authors associate with the intense cold and solid precipitation that can cause damage to the root system, affecting subsequent growth development[72,73].

In general terms, the climatic response pattern shown by *Fagus sylvatica* in this sector of the Cantabrian region confirms a drought-sensitive growth dynamic, both in spring and summer, widely supported by the literature throughout the natural distribution area of the species in Europe[16–20,23,25,29,30,74–76]. However, this sensitivity to the scarcity of summer and spring precipitation according to recent studies such as Rozas, *et al.*[33] in points of the Cantabrian and Tegel, *et al.*[32], support the hypothesis that drought stress is not as relevant as it seems in its limit of distribution if there are climatic conditions of cloudiness and fogs (concealed precipitation), which generate in the beech forest a behavior like a cloud forest with an immersion in the cloud for the improvement of growth and carbon gain.

Finally, although there are not a large number of works that have shown similar results, the combination of statistical tools and Geographic Information Systems facilitates the calculation and cartographic representation of the variations of the climatic response of *Fagus sylvatica* obtained from the dendroclimatic analysis, allowing the quantification and interpretation of the values expressed by means of correlation maps. The generated cartography is useful and reflects in a clear way the spatial relationships between the response of beech growth to climatic variables of certain months and the physical and topographic variables, with a clear gradation in altitude with respect to the climatic response, which confirms a better predisposition for this type of analysis in high mountainous areas, compared to growths less marked by the climatic influence in more favorable terrain located at lower altitudes.

5. Conclusions

The knowledge of the factors affecting the growth of *Fagus sylvatica* is essential for a correct monitoring of these forests. In this context, the use of dendrochronology is a solid and powerful tool to analyze the response of this species to climatic variables and to elaborate cartographic models of its geographic distribution.

The use of this technique in this work contributes to the scientific field by providing a new reference station in the central Cantabrian mountains, associated with the Polaciones valley. It is based on a series covering a period of 241 years (25 chronologies, local, 249 trees and 402 cores) that allows contrasting events, mainly climatic, beyond the extension of instrumental records.

It is shown how the patterns of climatic sensitivity of *Fagus sylvatica* in this sector of the central Cantabrian mountains, respond in a similar way to the analyses carried out in other studies in different geographical locations. We can affirm that drought stress is indeed a key factor in annual growth. In our case, and given the geographical conditions of the area, we can hypothesize that this climatic factor is mitigated by other factors such as cloudiness and fog (concealed precipitation), in which case a more in-depth study would be necessary to confirm this.

The results obtained by the cartographic models indicate the upper limit of the forest and its nearby slopes as ideal sampling points because they present stronger correlation values in all significant climatic variables. These upper limit areas indicate a more sensitive response to changing and extreme climatic conditions, as opposed to the more depressed sectors of the valley floor with more complacent and favorable growth for the species and less marked climatic response to the observed monthly variables. In turn, it can be seen how the altitude factor is of great importance in determining the climatic response of *Fagus sylvatica*, above the rest of the variables used in the modeling and of which hardly any incidence seems to be observed. This strong weight of the altitudinal gradient seems logical since it is also an important factor in the variations of both temperature and precipitation in any climatic environment.

However, this type of analysis is not without certain needs that are sometimes difficult to meet. In order to carry out a reliable and solid analysis and modeling, it is important to have a good replication in the set of dendrochronological series analyzed. For this, it is necessary to collect records in the greatest diversity of conditions and representative locations, and in view of the modeling, it seems that a better representation of the climatic variability in mountainous areas close to the upper limit of the forest can be achieved.

In addition, mountain areas are often lacking in spatially close instrumental climate measurements or these are often of very short temporal length, so that the results obtained from crossing with regional climate series such as the one used may be subject to some variation due to changes in climate at the local scale.

Conflict of interest

The author declared no conflict of interest.

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