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THE DENDROCHRONOLOGICAL SIGNAL OF PINE TREES (*PINUS* SPP.) IN SPAIN

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ABSTRACT

Thirty-one old-age pine stands in nine mountainous regions of Spain were studied in order to delineate dendrochronologically uniform areas. A country-wide cross-correlation analysis of the autoregressively standardized site chronologies showed the dendrochronological signal decreasing with distance so that beyond about 450 km crossdating becomes less reliable, but even over 630 km, the correlation coefficient is sometimes significantly high. A principal components analysis of the variance among the site chronologies segregated the chronologies into a northern and a southern group roughly along a line from Madrid to Barcelona. Two low-elevation northern sites were grouped with the southern sites. Moisture supply limits the growth of the pines in this group. In contrast, the high-elevation northern sites do not suffer from prolonged droughts. According to the uniform and extensive tree-ring signal in the south of the peninsula, the potential of dendrochronology for dating cultural objects is predicted to be favorable. Because of the greater variability between sites in the north, further studies are necessary to delineate uniform areas.

In neun Gebirgsregionen Spaniens wurden zur Abgrenzung dendrochronologisch homogener Räume 31 Kiefernaltbestände untersucht. Eine landesweite Korrelations-Entfernungsanalyse der autoregressiv standardisierten Standortindexchronologien ergab eine Abnahme des dendrochronologischen Signals zwischen den Standorten mit zunehmender Entfernung. Bei Distanzen von über 450 km wird die Synchronisation weniger zuverlässig, aber selbst bei 630 km Entfernung kann der Korrelationskoeffizient mitunter noch signifikant hoch sein. Eine Hauptkomponentenzerlegung der Varianz der Standortchronologien führte zu einer Gruppierung etwa entlang einer Linie von Madrid nach Barcelona in eine nördliche und eine südlich Region. Zwei der nördlichen Standorte, die zugleich Tieflagenstandorte darstellen, wurden dem südlichen Kollektiv zugeordnet. Als Ursache für diese Differenzierung kommt die Feuchtigkeitsverfügbarkeit in Betracht, die an allen südlichen Standorten sowie an den zwei nördlichen Tieflagenstandorten das Kiefernwachstum limitiert. Die Hochlagenstandorte im Norden sind keinem langanhaltenden Trockenstreß ausgesetzt. Das für den Süden der Halbinsel nachgewiesene einheitliche und weitreichende Jahrring-Signal läßt die

Möglichkeit für eine kulturhistorische Anwendung der Dendrochronologie günstig beurteilen. Im Norden sind wegen der größeren Standortvariabilität weitere Untersuchungen zur Abgrenzung homogener Räume nötig.

Trente et un sites de pins âgés provenant de neuf régions montagneuses d'Espagne, ont été étudiés en vue de délimiter des zones dendrochronologiques uniformes. Une analyse de corrélation portant sur des chronologies de sites standardisées par autorégression et realisée sur l'ensemble du pays a montré que le signal dendrochronologique diminuait avec la distance de telle maniére qu'au-delà de 450 km les datations croisées devenaient moins certaines même si à plus de 630 km le coefficient de corrélation demeure parfois significativement élevé. Une analyse en composante principale portant sur la variance entre les chronologies de sites, sépare celles ci en un groupe septentrional et un groupe méridional de part et d'autre d'une ligne reliant approximativement Madrid à Barcelone. Deux sites nordiques de basse altitude ont été groupés avec les pins de l'ensemble méridional. La disponibilité en humidité y limite la croissance, au contraire des sites de haute altitude du groupe septentrional qui ne subissent pas l'effet de sécheresses prolongées. En raison du signal largement homogène dans le sud de la péninsule, on peut envisager favorablement l'utilisation de la dendrochronologie pour dater des objets culturels. La plus grande variabilité existant entre les sites du nord, nécessitera de nouvelles études pour définir des zones uniformes.

INTRODUCTION

A spatially dense and temporally continuous network of tree-ring chronologies is needed for reconstructing climatic and environmental changes and for dating purposes (Hughes 1987). In the Mediterranean area, dendrochronology sometimes faces particular difficulties (e.g. Liphschitz 1986; Munaut and Serre-Bachet 1982). The location of the Iberian Peninsula in the westernmost part of the Mediterranean area between the Atlantic Ocean and the Mediterranean Sea has led to a great variety of and large contrasts in climate and vegetation (Lautensach 1964).

Dendrochronology in Spain started relatively late and concentrated on the northeastern part of the country (Creus and Puigdefábregas 1976; Génova 1986, 1987; Génova and Gracía 1984; Gutiérrez 1987, Tomás 1982). The first transregional comparisons of tree-ring series were done by Bräker and Schweingruber (1984) with pine and fir species from several temperature-sensitive sites in the Pyrenees and the Central Plateau. According to their study, latewood width and maximum density of the tree rings, but not ring width, were very similar both between regions and among species.

The objective of the present study was to establish a network of tree-ring chronologies for Spain using old trees of various pine species in numerous localities to delineate dendrochronologically uniform areas. Pines occur naturally in nearly every part of Spain and were used preferentially as building timber in historic and prehistoric times (Bauer 1980; Rábanos Faci et al. 1981). Long regional pine chronologies extended with timbers from old buildings have been used to reconstruct summer rainfall (Richter and Eckstein 1990) and to date buildings of cultural and ethnographic importance (Richter 1985/86; Richter and Eckstein 1986).

STUDY AREA

Twenty-four percent of Spain is covered by forests of coniferous and broadleaved trees in roughly equal proportions. Local distributions depend on the climate, soil, elevation, and exposure. The dendrochronological sampling reported here included 31 sites in nine forest areas (Figure 1) using information available on old-age pine stands (Ceballos 1966; Ceballos and Ruiz 1979; ICONA 1979). Pine sites were chosen at the upper treeline (Figures 2 and 3) as well as at medium and low elevations and along elevational transects. Altogether, four pine species (*Pinus sylvestris* L., *P. nigra* Arnold, *P. pinaster* Ait., *P. mugo* ssp. *uncinata* Turra) were sampled to compare intraspecies growth behavior. At 22 sites, at least 10 to 12 trees were sampled by taking two increment cores per tree. Due to local conditions, fewer than 10 trees were available for coring at 9 sites. All 348 sampled trees were dominant or codominant individuals without visible damage. The sites and sample depths are described in Table 1.

PROCEDURES

The tree-ring widths were measured with a mechanical, hand-driven Eklund measuring machine interfaced with a microcomputer. Data storage and retrieval and the crossdating of the tree-ring series were carried out using computer program CATRAS (Aniol 1983). The quality of crossdating was checked both visually and statistically using the nonparametric per-

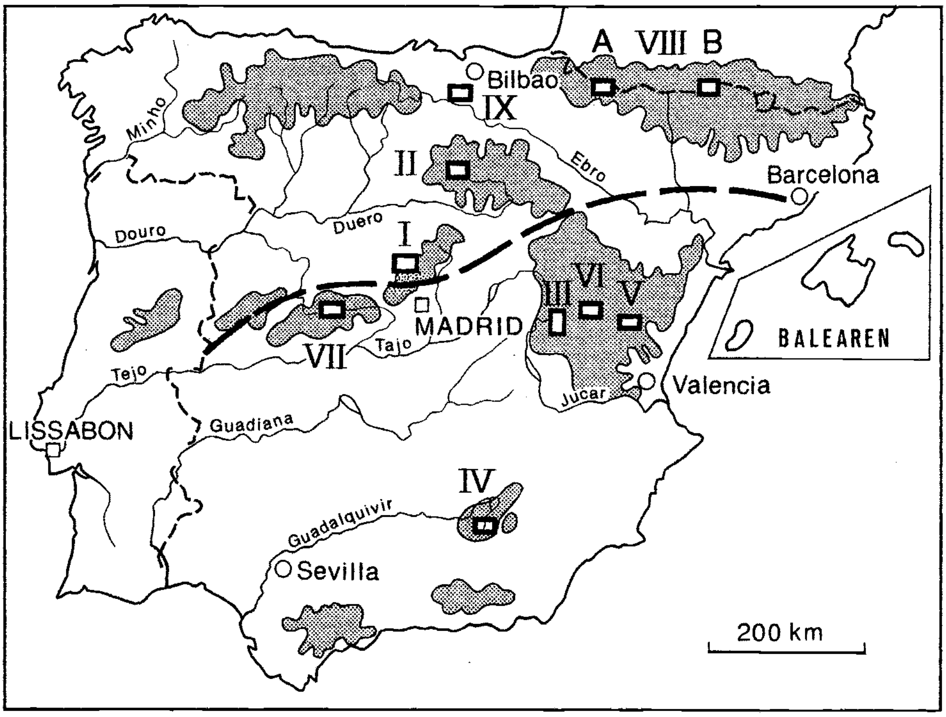

Figure 1. Map of the Iberian Peninsula showing mountainous regions (stippled) and areas sampled (rectangles). The dashed line separates the northern and southern regions as expressed in Figure 6. The regions indicated by Roman numerals are: I = Sierra de Guadarrama (Code GUA), II = Sierra de Urbión (URB), III = Serranía de Cuenca (CUE), IV = Sierra de Cazorla (CAZ), V = Sierra de Gudar (GUD), VI = Sierra de Albarracín (ALB), VII = Sierra de Gredos (GRE), VIII = Pirineos, IX = Montes de Burgos (ZAD).

Figure 2. *Pinus nigra* in the Serranía de Cuenca at 1400 m.

Figure 3. *Pinus sylvestris* at the upper tree line in the Sierra de Guadarrama at 2000 m.

Table 1. Descriptive statistics of 31 tree-ring site collections in Spain.

Site Name	Site Code (see Fig.1)	Region (see Fig.1)	Species	Latitude N	Longitude W	Elevation Meters	Exposure	Slope	Trees Sampled
Valsaín-Iniesto	GUA1	I	P. *syl.*	40°48'	3°59'	1625-2050	S-SW	15-25°	25
Valsaín-Camorca	GUA2	I	P. *syl.*	40°49'	4°03'	1300-1800	E	12-20°	17
Rascafría	GUA3	I	P. *syl.*	40°48'	3°57'	1780-1920	NE	15-35°	12
Navacerrada	GUA4	I	P. *syl.*	40°47'	3°48'	1850-2050	NW	25-45°	15
Vinuesa	URB1	II	P. *syl.*	42°00'	2°51'	1750	S-SE	-	4
Duruelo d.1.S	URB2	II	P. *syl.*	42°01'	2°54'	1800-1875	S	6°	9
Covaleda	URB3	II	P. *syl.*	41°59'	2°52'	1640-1850	S	10-15°	14
Quintenar d.1.S	URB4	II	P. *syl.*	42°02'	3°02'	1780-1900	S-SE	5-15°	13
Las Torcas	CUE1	III	P. *nigra*	40°00'	1°59'	1150-1300	-	-	3
Buenache	CUE2	III	P. *nigra*	40°09'	1°54'	1370-1400	-	-	5
Las Majadas	CUE3	III	P. *syl.*	40°20'	1°59'	1400	-	-	3
Uña I	CUE4	III	P. *nigra*	40°15'	1°56'	1360-1410	N	15-20°	12
Vega d. Cordono	CUE5	III	P. *nigra*	40°26'	1°54'	1400-1480	S-SE	20°	7
Uña II	CUE6	III	P. *nigra*	40°16'	1°56'	1400-1480	S-SW	5-10°	14
Las Bañas I	CAZ1	IV	P. *nigra*	37°57'	2°56'	1380-1430	S-SE	8-15°	14
Pto. Llano	CAZ2	IV	P. *nigra*	37°49'	2°57'	1800	W	-	12
Cañada d.1.F.	CAZ3	IV	P. *nigra*	37°50'	2°56'	1400-1500	N-NW	10-25°	17
Las Bañas II	CAZ4	IV	P. *pinaster*	37°58'	2°56'	1360-1400	W	25-40°	12
Fuentenarices	GUD1	V	P. *nigra*	40°18'	0°44'	1450	NW	10°	2
Pradillo	GUD2	V	P. *syl.*	40°18'	0°41'	1600-1700	SE	25-30°	5
Las Roquetas	GUD3	V	P. *nigra*	40°17'	0°42'	1450-1500	SE	15°	11
Cantavieja	GUD4	V	P. *syl.*	40°34'	0°29'	1750	W	no data	10
Villarluengo	GUD5	V	P. *nigra*	40°38'	0°29'	1500	SW	no data	11

Table 1. (cont.)

Site Name	Site Code (see Fig.1)	Region (see Fig.1)	Species	Latitude N	Longitude W	Elevation Meters	Exposure	Slope	Trees Sampled
Valdecuenca	ALB1	VI	P. *nigra* + P. *syl.*	40°17'	1°27'	1500-1600	E-NE	15°	10
Bezas	ALB2	VI	P. *pinaster*	40°18'	1°20'	1200-1250	S	10-15°	11
Navarredonda d.1.S.	GRE1	VII	P. *syl.*	40°20'	5°08'	1440-1500	W	10-25°	12
Hoyos d.Espino	GRE2	VII	P. *syl.*	40°20'	5°10'	1450-1480	N-E-S-W	10-20°	12
Puerto de Acher	PYR1	VIII A	P. *syl.* + P. *uncin.*	42°48'	0°42'	1550-1700	NW-SW	35-55°	12
Ansó-Zuriza	PYR2	VIII A	P. *syl.*	42°50'	0°47'	1250-1300	S-SE	25°	4
Viella	PYR3	VIII B	P. *syl.*	42°44'	0°47'E	1840-2000	S	30-45°	15
San Zadornil	ZAD	IX	P. *syl.*	42°50'	3°10'	810-950	S-SW	5°	14

centage of agreement (Eckstein and Bauch 1969) and the parametric t-value (Baillie and Pilcher 1973). After correction for missing and double rings, the tree-ring series were dated absolutely and rechecked using computer program COFECHA (Holmes 1983). The checking procedures eliminated the tree-ring series of 33 trees from further processing because of heavy disturbances, so that altogether 315 pines from 31 sites entered the final analysis. These tree-ring series were standardized and autoregressively transformed by program ARSTAN (Cook and Holmes 1986) to remove the age trend and nonclimatic disturbances and then assembled into site chronologies using robust estimation of the mean value function. These site chronologies were used in an analysis of correlation with distance and a principal components analysis.

RESULTS AND DISCUSSION

The raw ring-width data of the 31 sites are characterized by high first order autocorrelations (mean = 0.85, range = 0.64 to 0.96) and low mean sensitivities (mean = 0.19, range = 0.13 to 0.29). After being autoregressively modeled and transformed, the autocorrelations are zero, and the mean sensitivities increase slightly (mean = 0.23, range = 0.16 to 0.34). The variance accounted for by the first eigenvector of the transformed tree-ring series averages 48% and ranges from 35% to 64%, indicating good homogeneity within the sites. Thirty of the 31 site index chronologies were correlated with each other within a common time interval from 1861 to 1983. One of the chronologies (Valdecuenca) of the Sierra de Albarracín (Region VI) was removed from this analysis because of its short span of only 99 years. The average correlation coefficient of the 435 possible combinations equalled 0.31. The results (Figure 4) suggest a division of the sites into two regions, one including the Guadarrama, Urbi6n, and Pyrenees areas (Regions I, II and VIII), another including the Cuenca, Cazorla, Gudar, and Gredos areas (Regions III, IV, V and VII). Sites PYR2 (Region VIII) and ZAD (Region IX) fit somewhat better with the southern group. The similarity between the site chronologies is high within each of these groups, but often low or even missing between the

Site-Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1 GUA1	***																													
2 GUA2	.70	***																												
3 GUA3	.59	.37	***																											
4 GUA4	.70	.58	.76	***																										
5 URB1	.38	.28	.51	.52	***																									
6 URB2	.47	.37	.48	.55	.50	***																								
7 URB3	.48	.38	.54	.51	.65	.66	***																							
8 URB4	.38	.30	.50	.54	.57	.60	.72	***																						
9 CUE1	.27	.13	.13	.08	-.00	.11	.16	.23	***																					
10 CUE2	.37	.19	.29	.23	.22	.20	.35	.30	.50	***																				
11 CUE3	.25	.19	.18	.10	.20	.17	.31	.30	.39	.43	***																			
12 CUE4	.33	.19	.25	.19	.15	.15	.34	.36	.59	.60	.55	***																		
13 CUE5	.37	.14	.36	.23	.26	.24	.47	.37	.49	.58	.46	.58	***																	
14 CUE6	.39	.22	.33	.23	.23	.20	.41	.36	.57	.57	.49	.81	.67	***																
15 CAZ1	.31	.27	.17	.16	.14	.13	.28	.25	.43	.37	.40	.51	.40	.52	***															
16 CAZ2	.45	.27	.29	.28	.16	.32	.37	.33	.37	.49	.32	.54	.54	.53	.50	***														
17 CAZ3	.34	.19	.23	.19	.09	.23	.29	.24	.48	.50	.36	.59	.52	.55	.59	.68	***													
18 CAZ4	.31	.23	.11	.12	.05	-.00	.24	.14	.33	.28	.39	.48	.41	.50	.62	.40	.42	***												
19 GUD1	.26	.04	.16	.14	.07	.07	.25	.17	.28	.25	.25	.33	.35	.33	.22	.24	.28	.20	***											
20 GUD2	.27	.07	.17	.07	.08	.19	.24	.23	.35	.29	.31	.36	.35	.29	.22	.24	.25	.27	.44	***										
21 GUD3	.08	-.06	.11	-.02	-.05	.09	.15	.13	.36	.19	.31	.42	.37	.37	.31	.32	.40	.13	.53	.46	***									
22 GUD4	.39	.27	.30	.30	.32	.19	.37	.43	.27	.36	.43	.47	.38	.40	.39	.28	.38	.28	.26	.38	.31	***								
23 GUD5	.23	.04	.22	.15	.16	.10	.24	.31	.40	.33	.40	.48	.46	.40	.30	.24	.50	.30	.34	.44	.59	.70	***							
24 ALB2	-.10	-.12	-.03	-.10	-.17	-.07	-.10	.07	.35	.12	.35	.35	.24	.23	.13	.07	.24	.15	.34	.41	.54	.17	.47	***						
25 GRE1	.36	.32	.18	.11	.06	.17	.30	.24	.41	.48	.40	.40	.48	.50	.42	.40	.38	.23	.28	.15	.25	.32	.22	.03	***					
26 GRE2	.26	.20	.15	.08	.08	.10	.17	.23	.38	.33	.29	.34	.40	.42	.34	.32	.38	.20	.22	.06	.29	.23	.22	.14	.76	***				
27 PYR1	.33	.16	.46	.36	.58	.36	.52	.56	.19	.27	.21	.22	.40	.25	.24	.24	.26	.10	.20	.25	.18	.38	.28	.01	.32	.25	***			
28 PYR2	.27	.17	.19	.15	.17	.16	.37	.32	.37	.33	.45	.43	.40	.39	.36	.34	.40	.35	.42	.30	.32	.43	.37	.12	.37	.22	.47	***		
29 PYR3	.33	.22	.37	.26	.45	.38	.49	.53	.30	.25	.23	.31	.30	.32	.21	.33	.32	.09	.16	.28	.15	.31	.24	-.07	.25	.13	.70	.41	***	
30 ZAD	.21	.21	.01	.01	.11	.17	.28	.36	.39	.35	.40	.37	.44	.39	.23	.27	.34	.23	.16	.19	.11	.29	.22	.04	.30	.29	.14	.45	.27	***

Figure 4. Correlation matrix for 30 site index chronologies from 1861 to 1983; the heavy lines enclose northern sites, the light line encloses the southern sites.

groups. In Figure 5, all 435 correlation coefficients are plotted against distance from each site. As expected, similarity between sites decreases with distance. In some cases, however, wide variation in the correlation coefficients is evident between sites equidistant from one other. Between 220 and 320 km, the low or even absent similarity (expressed by negative correlation coefficients) is obvious for specific sites such as Las Roquetas (Region V) and Bezas (Region VI). The linear negative relationship (r = -0.49) is of the same order as those reported, for example, by Ahmed and Ogden (1985) for 11 *Nothofagus* chronologies in New Zealand and by Briffa (1984) for 36 oak chronologies in Great Britain and France. In western North America, 65 conifer chronologies correlate at the 99% level over distances of 992 km (Cropper and Fritts 1982). In Spain, sufficient crossdating quality between pine chronologies can be expected within an average range of some 450 km.

To derive the contours of dendrochronologically uniform regions more clearly, a principal components analysis was performed (Figure 6). The first eigenvector accounts for 34% of

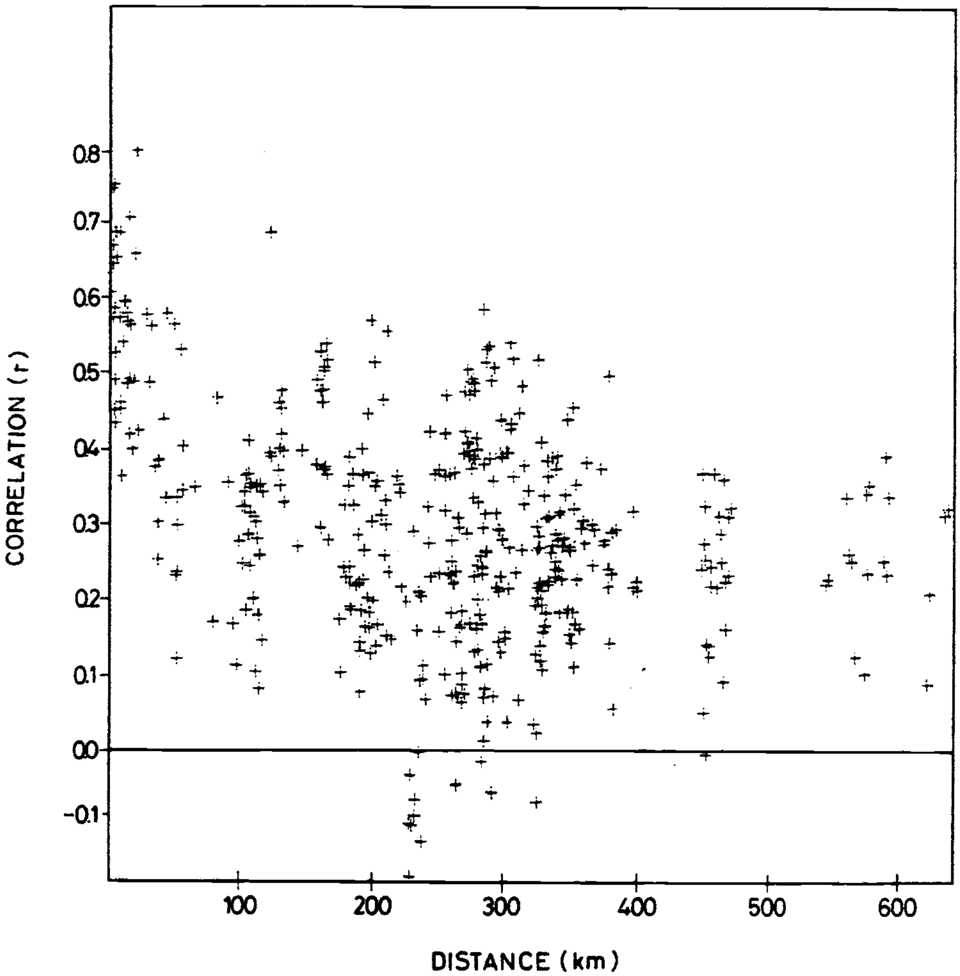

Figure 5. Correlation-by-distance plot of 30 site index chronologies for the common interval from 1861 to 1983.

the variance among all chronologies. Since 29 of the 30 site chronologies cluster tightly, a high common variance all over Spain is indicated. Presumably the cause of this clustering is the overall temperature, which varies less over wide areas than precipitation. The second eigenvector accounts for 13% of the variance among chronologies and divides the chronologies into two groups. At first sight, this grouping seems to express the northern and southern locations of the sites, but two northern sites (PYR2, ZAD) — the same sites as in the cross correlation analysis — are included with the southern sites. This grouping becomes more understandable, however, when the elevations of the sites are considered (Figure 6). North of the Cordillera Central, the upper treeline sites (1600-2000 m) can be distinguished from medium and low elevation sites, which are similar to the southern sites. This apparent elevational influence is indirect; the real cause of the grouping is rather precipitation. Summer drought is one of the growth-limiting factors on the semiarid southern sites (Richter 1988). The two northern sites grouped with the southern sites are located in the rain shadow of the mountains so that summer droughts may occur here as well. Figure 7 illustrates the climate-growth relationship for the pines in southeastern Spain derived by a response function analysis from a transregional climatic record and a ring chronology made of nine sites (Regions III, IV and V) for a calibration period from 1902 to 1984. In addition to summer rainfall, winter temperature is beneficial to the growth of the pines. The variance of tree-ring widths explained by climate amounts to 67%.

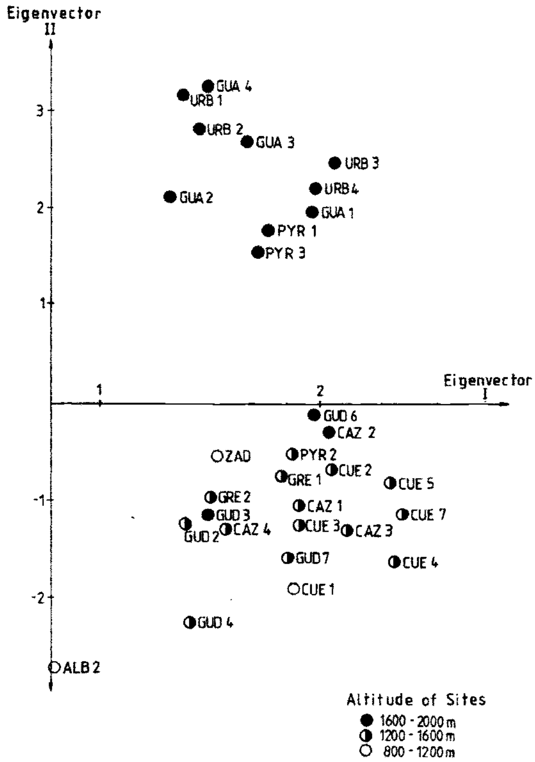

Figure 6. Comparison of the weights of the first and second eigenvectors of 30 site index chronologies.

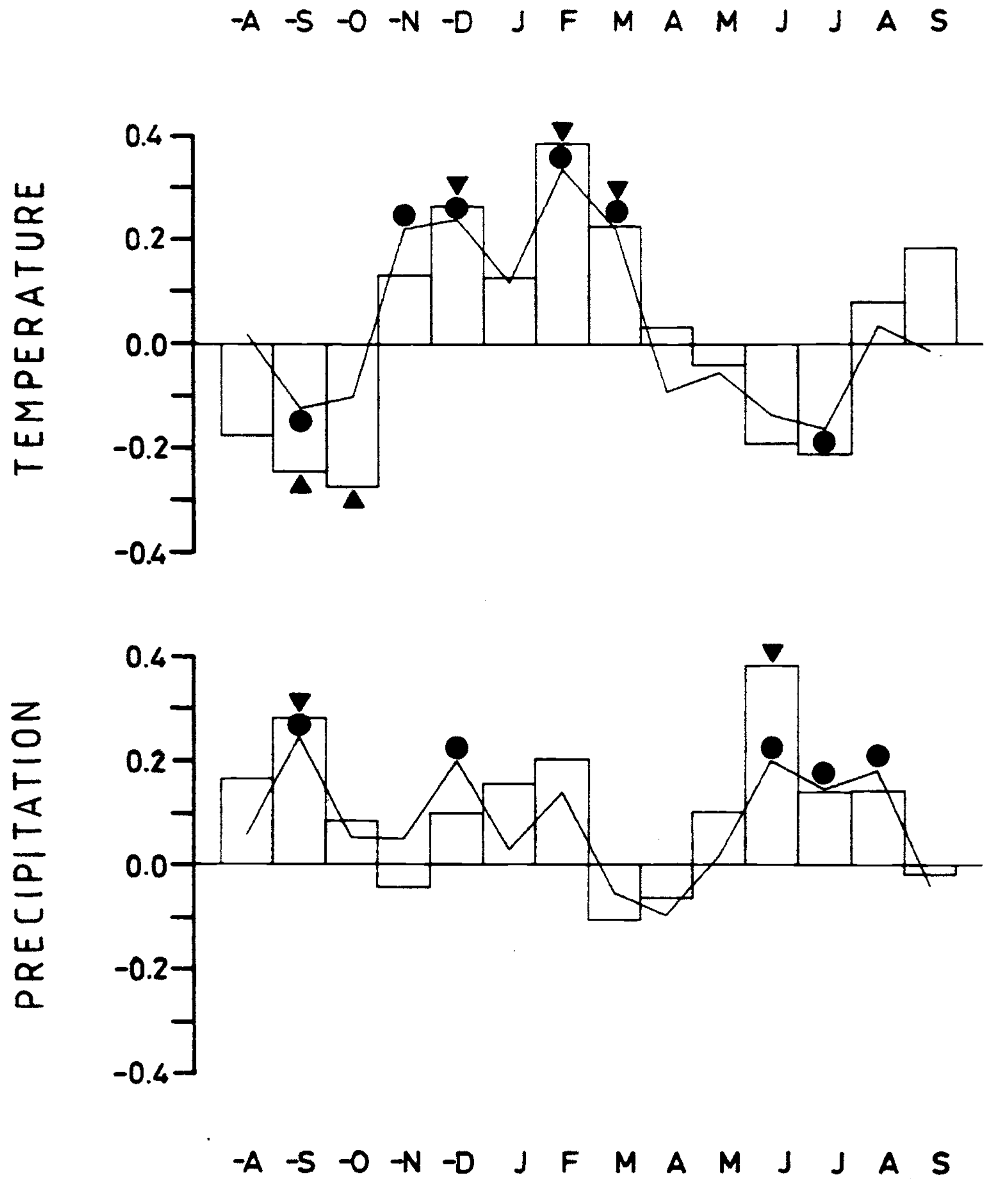

Figure 7. Response function (line) and correlation function (bars) for pines in nine sites in Regions III, IV and V, for monthly temperature and precipitation from previous August to current September; the dots and triangles indicate significance at the 95% level.

For further investigations, it is worth mentioning that correlations between sites of different species are as high as those between sites of the same species. Therefore, the four pine species studied can dendrochronologically be treated together. Bräker and Schweingruber (1984), Génova (1986) and Gutiérrez (1987) found a fairly high correlation between *Pinus sylvestris* and *P. uncinata* in the northeast of the peninsula. Kuniholm and Striker (1983) reported a great similarity between *P. sylvestris* and *P. nigra* in the Aegean area even over great distances. The correlative behavior of *P. sylvestris/nigra* and *P. pinaster* has not been studied so far. Groups of both pines occur in the Sierra de Cazorla (Region IV) and Sierra de Gudar (Region V). They are different in their ecological demands but crossdate with each other, so that, at least for dating purposes, chronologies of mixed species can be used. Regional climate obviously influences the cambial activity more than genetic differences.

A further practical aspect is that, if the site chronologies in an area are merged into chronologies with sample depths of some 20 trees, reasonable similarities are evident at distances up to 630 km, even between climatically different areas. However, distance is not the only relevant aspect, since, for example, the Sierra de Gredos (Region VII) *P. sylvestris* chronology is more similar to the regional *P. nigra* chronologies of the Sierra de Cuenca (Region III) and Sierra de Cazorla (Region IV) than to the regional *P. sylvestris* chronology of the much nearer Sierra de Guadarrama (Region I). The reason for this behavior is the different elevations of the sites, as can be seen in Figure 6.

CONCLUSIONS

The present study demonstrates that the four pine species studied, *Pinus sylvestris, P. uncinata, P. nigra* and *P. pinaster*, do not show growth differences within the same forest region and therefore can be considered to be dendrochronologically homogeneous. The correlation of the ring-width signal decreases with distance. Fairly good crossdating, however, can be expected up to distances of 450 km. The delineation of northern and southern areas is important for future dendrochronological work. This purely geographical criterion does not sufficiently explain the grouping of the sites, because some of the northern site chronologies correspond better with the southern group. Therefore, climatic factors, elevation, and topography also need to be considered. In the south, the common tree-ring signal covers a wider area than in the north. This is because moisture is more uniformly limiting to tree growth throughout the southern area, whereas local growing conditions and elevation are more influential on tree growth in the north. Consequently, the potential for dendrochronological dating of wooden objects and the extension of chronologies into the past is considered to be better in the south than in the north. Greater variability between sites in the north calls for further study, concentrating on medium and low elevation sites to delineate areas of coherent dendrochronological signal.

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