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DENDROCLIMATOLOGICAL STUDY OF *PINUS SYLVESTRIS* L. IN SOUTHERN CATALONIA (SPAIN).

EMILIA GUTIÉRREZ

Departamento d'Ecologia
Facultat de Biologia
Universitat de Barcelona
Avgda. Diagonal, 645
Barcelona 08028

ABSTRACT

Two modern tree-ring width chronologies of *Pinus sylvestris* L. have been established in an area near the southern limit of the species' distribution. Trees were sampled in the South of Catalonia in northeastern Spain where Mediterranean climatic conditions are of primary influence. To better understand climate ring-width relationships, tree-ring index series have been studied in relation to local climate. Ring-widths are strongly related to low precipitation at the beginning of the growing season in March, in June of the current growth year, and in September prior to tree-ring growth. High temperatures mainly affect growth in summer during the growing season and in autumn of the year prior to growth. During the winter, mainly in December, mean monthly temperatures show a significant positive correlation with growth. Major factors controlling the southern distribution of *P. sylvestris* may be related not only to water stress in summer but also to the amount of precipitation at the beginning of the growing season and in autumn, even in mild winters.

Es wurden zwei rezente Jahrringchronologien von *Pinus sylvestris* L. für eine Region nahe der südlichen Grenze ihrer Verbreitung aufgebaut. Die Probenbäume wachsen in Süd-Katalonien in Nordost-Spanien, wo mediterrane Klimabedingungen von vorrangiger Bedeutung sind. Um die Klima-Wachstums-Beziehungen besser zu verstehen, wurden die Jahrring-Index-Chronologien mit dem lokalen Klima verglichen. Die Jahrringbreiten sind stark korreliert mit geringen Niederschlägen am Beginn der Vegetationsperiode im März, im Juni des laufenden Jahres sowie im September des Vorjahres. Hohe Temperaturen beeinflussen überwiegend das Wachstum im Sommer des laufenden Jahres und im Herbst des Vorjahres. Im Winter, besonders im Dezember, zeigt die Temperatur eine signifikant positive Korrelation zum Jahrringwachstum. Die Hauptfaktoren für die Einregelung der südlichen Verbreitungsgrenze von *P. sylvestris* sind somit wohl nicht nur Wasserstreß im Sommer, sondern auch die Niederschläge zu Beginn des Wachstums und im Herbst, sogar bei milden Wintern.

Deux chronologies modernes basées sur l'épaisseur des cernes de *Pinus sylvestris* L. ont été établies dans une région voisine de la limite méridionale de la distribution de cette espèce. Les arbres ont été échantillonnés dans le Sud de la Catalogne au Nord-Est de l'Espagne, dans une aire où les conditions climatiques méditérranéennes sont d'importance primordiale. Afin de comprendre plus aisément les relations existant entre le climat et les épaisseurs des cernes, des séries d'indices dendrochronologiques ont été étudiées en liaison avec le climat local. L'épaisseur des cernes est fortement dépendante des basses précipitations au début de la saison de végétation (mars), durant celle-ci (juin), ainsi que de celle de septembre de l'année qui précède la croissance. Les températures élevées affectent principalement la croissance au cours de l'été correspondant à la saison de croissance et durant l'automne qui la précède. En hiver et principalement en décembre, les températures moyennes mensuelles montrent une corrélation positive significative avec la coissance. Les facteurs principaux qui contrôlent la distribution sud de *Pinus sylvestris*, peuvent être mis en relation non seulement avec un manque d'eau estival, mais aussi avec la quantité de précipitation au début de la saison de croissance ainsi qu'en automne même si les hivers sont doux.

INTRODUCTION

The potential species for dendrochronological studies in Spain are of interest because many species here are at or near the limit of their world distribution. Most grow under a Mediterranean climate, or at least the Mediterranean influence remains strong even at high altitudes (Serre 1978; Génova 1986; Gutiérrez 1987). Climate-tree growth relationships are poorly understood, and climatic records in the mountainous regions of Spain are scarce. During the last few years, however, dendroclimatological studies have been carried out in some parts of Spain (Génova 1986; Creus and Puigdefabregas 1978; Martínez *et al.* 1980; Gutiérrez 1987). This paper presents two modern chronologies of *Pinus sylvestris* L. and the results of the response function analysis of growth in relation to local climate in the Mountains of Prades and is part of a broader dendrochronological study in the Catalonian region (Gutiérrez 1987).

One of the aims of dendroclimatology is to identify possible responses of tree growth to climatic factors through the analysis of ring widths or other variables. In this paper I analyze such climate-ring width relationships for *Pinus sylvestris*, the most widespread species of the *Pinaceae*. If low temperatures are the most limiting factor for *P. sylvestris* growth in the northern regions of its distribution, it is to be expected that in the area considered in this study the most limiting factors will be the low precipitation and high temperatures of the growing season. Dendroclimatological analysis, by means of multiple regression after extracting the principal components of the climatic variables, identifies the response function pattern of this species in an area near the southern limit of its world distribution.

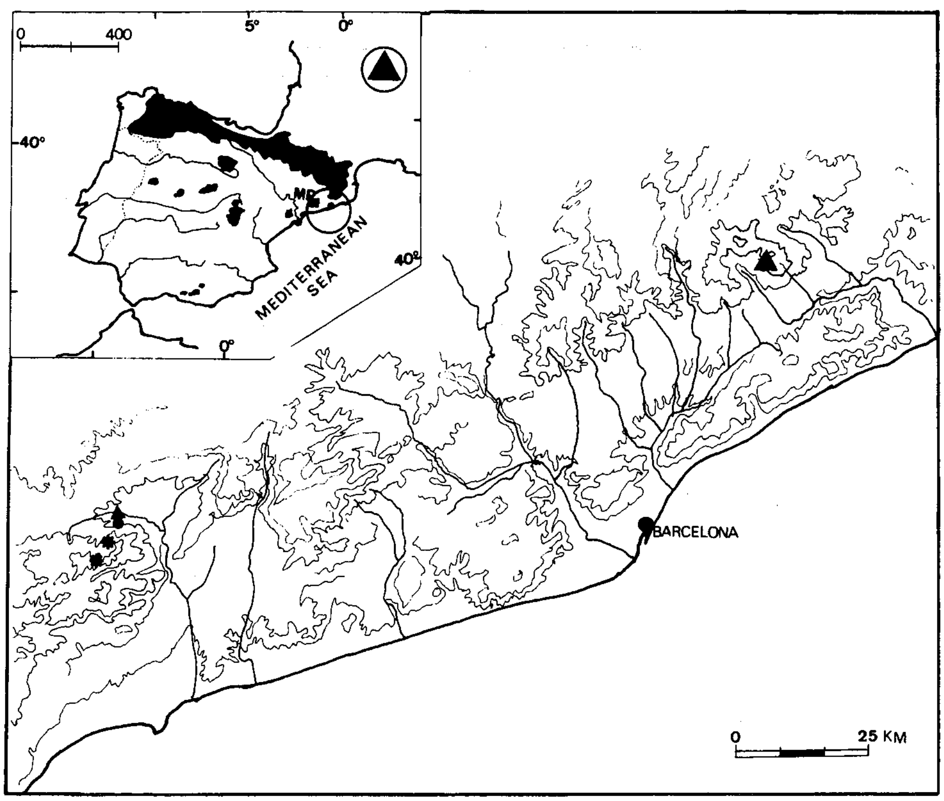

FIGURE 1. The study area: the Mountains of Prades (MP); the distribution of *Pinus sylvestris* in Spain (shading); the chronology sites (stars); the weather stations of Riudabella 590 m (triangle/circle) the Turó de l'Home 1,707 m (triangle).

MATERIAL AND METHODS

Location

Pinus sylvestris was sampled in the Mountains of Prades (Fig. 1). These mountains form part of a chain of prelittoral mountains parallel to the Mediterranean coastline. Elevations decrease from north to south, and in the Mountains of Prades the highest elevation is 1,201 m. The climate of the area is Mediterranean up to 800 m and at higher elevations becomes sub-Mediterranean, which means a slight increase in precipitation, especially in summer, though summer droughts persist for a high percentage of years. The *Pinus sylvestris* forests grow from 800 m to the top, escaping the harshness of summer droughts, which decreases with increasing elevation. Vegetation follows the climatic gradient, and the lower parts are occupied by *Quercus ilex* and other characteristic Mediterranean species.

Sites

Two sites were sampled, both located on north facing slopes. Trees growing on south facing slopes presented crossdating problems and are not discussed here. Site 1, NTOPS, is located almost on the top of the mountain at 1,100 m, and site 2, NPBPS, is at 880 m on the same mountain (Fig. 1). The criteria for tree selection were those usually followed in dendroclimatology: trees growing on undisturbed sites with steep slopes and rocky soils. A total of 42 trees was sampled, and at least two cores per tree were taken.

Tree-Ring Data

Cores were examined under a binocular microscope and measured twice. The synchronism, or crossdating, of the sequences of tree-ring widths was determined by visual and statistical methods (pointer years, coincidence coefficients, cross-correlations), and the patterns of wide and narrow rings were compared. Cross-correlation between cores and trees was also used to find the lag at which the correlation coefficient was highest. If it occurred at lag zero, cores and trees were considered well crossdated. Otherwise, samples were examined again. Of the 104 cores, 28 from 11 different trees were rejected due to lack of synchronism. The large number of multiple rings (2.75%) made crossdating difficult and accounts for the number of cores that had to be rejected.

Growth series were standardized by fitting the growth function described in Prodan (1968)

$$Y(t) = a\ t^{**}(b)\ \exp(-ct)$$

where Y(t) is the observed growth for the year t, and a, b, and c are parameters that are estimated for each tree. When tree-ring series exhibit a negative exponential distribution, parameter b is not significant and the function takes the form of a negative exponential curve. Indices were calculated by dividing the observed by the expected growth predicted by the function.

Once tree-ring series were crossdated and standardized, two chronologies of indices, named NPBPS and NTOPS, were established for the two sampled sites. Chronology characteristics are given in Tables 1 and 2, and plots are presented in Figure 2. The longer chronology, NTOPS, accounts for 161 years, while NPBPS is 124 years long. There are 17 and 15 trees and 42 and 34 averaged cores for, respectively, NPBPS and NTOPS. The standard deviations (SD) and mean sensitivities (MS) of the series are high (Table 1, Figure 2). The average correlations between radii in each tree, between trees in each chronology, and between the two chronologies are high (Table 2). The mean coefficient of coincidence is 76% and 79% for NTOPS and NPBPS respectively. Values of 55% are considered sufficient according to Polge (1971). The first serial autocorrelation (rl) is higher for the longer chronology (NTOPS); long-term fluctuations can be observed in Figure

2. The two series are long enough if climatic reconstruction is carried out for the last hundred years as climate is now considered to be anomalous to some extent in the Northern Hemisphere (Lamb 1972; Budyko 1982).

Climatic Data

The climatic data used for the calibration period are the average of two weather stations. The available climatic records, data series 1955-1982, from the weather station of Riudabella at 590 m in the Mountains of Prades are not representative of the climatic conditions under which *Pinus sylvestris* forests develop (Folch and Velasco 1974; Walter 1976). Thus, climatic data from Turó de l'Home in the same prelittoral mountain chain at 1707 m and 120 km north of the Mountains of Prades (Figure 1) were averaged with climatic data from Riudabella after a study of the two complete sets of data. Between-station correlation coefficients (r) were 0.76 for temperature and 0.60 ($p<0.01$) for precipitation for the 1955 to 1982 interval.

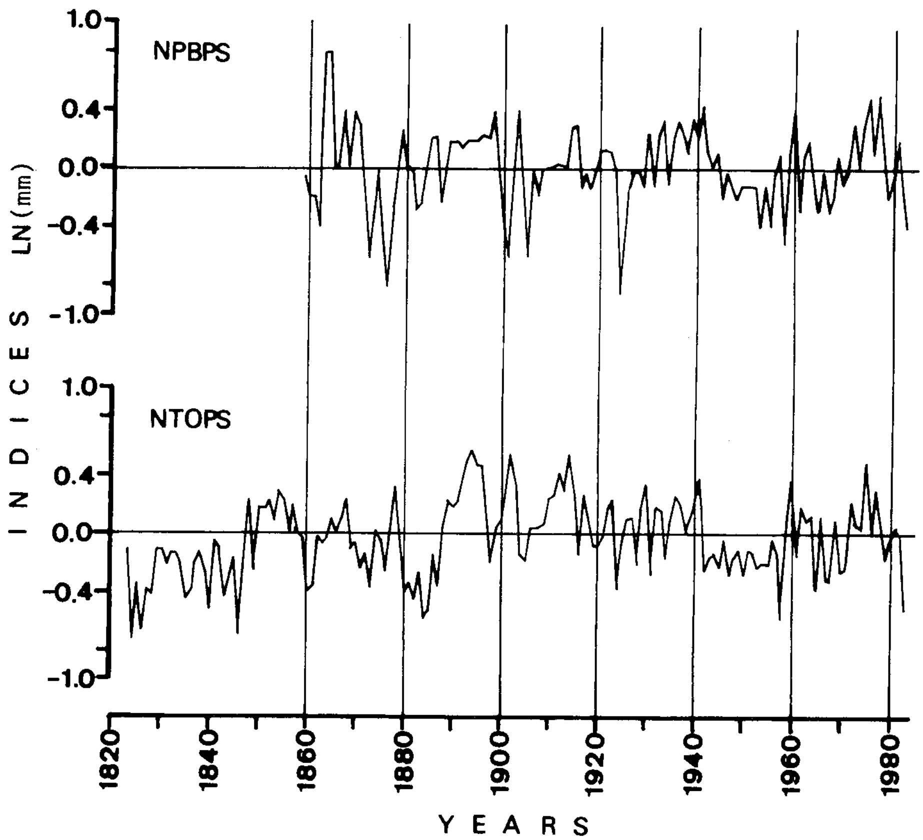

FIGURE 2. *Pinus sylvestris* chronologies for the Mountains of Prades.

Table 1. Site and statistical characteristics of *Pinus sylvestris* chronologies.

CHARACTERISTICS	NTOPS	NPBPS
Altitude (m)	1,100	890
No. trees	15	17
No. cores	34	42
Total years	161	124
Mean index	1.003	1.042
Mean sensitivity	.20	.21
Std. Deviation	.27	.29
Skew	.61	-.27
Kurtosis	.03	.81
Partial Autocorr.		
1st Order	.51	.35
2nd Order	.37	.00
3rd Order	.40	.14

Table 2. Correlation coefficients between cores, trees, and chronologies.

NAME	CORES	TREES	NPBPS	NTOPS
NPBPS	0.83	0.61	1.00	0.53
NTOPS	0.81	0.58		1.00

Response Functions

To study the influence of climatic variables on growth, multivariate regression analysis on principal components was performed. This type of regression has proved to be one of the most accurate methods for studying multivariate relationships between two sets of variables, i.e. growth and climate (Fritts and Wu 1986). The method is fully described elsewhere (Draper and Smith 1981; Fritts *et al.* 1971; Fritts 1974; 1976). The analysis was carried out using 28 climatic variables (14 monthly precipitation and 14 monthly mean temperature values) as predictors, and the ring-width index series as predictans. The analysis computes a regression for the dependent variable (tree-ring indices) on a set of principal components calculated from the 28 climatic variables. The climatic data were standardized and the correlation matrix was used to compute the principal components. The order of entry of components in the regression was done in a stepwise manner using the criteria of the highest correlation between the component and the indices.

The calibration period runs from 1955 to 1982. For this period, the index series were detrended by fitting a linear first order regression model

$$Yt = a + bt; \text{ from } t=1955 \text{ to } t = 1982$$

In this way, the serial correlation of the indices was not significant, and previous growth was not included when the response functions were calculated. For the two *Pinus sylvestris* chronologies, 10 eigenvectors (components) were entered in the regression to obtain the response function coefficients. The F-ratio limit to enter a new component was $F > 0.7$. The regression coefficients were then multiplied by the principal components to obtain a new set of regression coefficients related to the original climatic variables. These new coefficients were standardized and their confidence intervals ($p < 0.05$) calculated.

RESULTS AND DISCUSSION

Response function results are shown in Figure 3. The R^2 values are quite high, which means that in this type of analysis climatic factors explain 61% of the total variance in ring width in each chronology.

The response functions for the two chronologies are very similar. In fact, the two sampled sites are very close to each other, and differences in some coefficients are probably due to microhabitat differences. The results clearly show the type of relationships that can be expected under a Mediterranean climate in the sense that the trend is for the temperature coefficients to be negative and the precipitation coefficients to be positive during the growing season (from March to June). However, the response functions also exhibit greater complexity. Accordingly, it can be inferred that in situations of high temperatures and low precipitation during the growing season, water stress is the main limiting tree growth factor. Furthermore, while the number of significant coefficients for temperature follows a seasonal pattern, almost all of the significant precipitation coefficients have a positive effect on growth. Precipitation during three months is especially significant for radial growth: prior September and March and June of the current growth year. In warm sites like the mountains of Prades, cell division is likely to begin in March; thus, the climate for this month can have a major effect on ring width. During the rest of the spring months, neither temperature nor precipitation seems to have a significant effect on growth (Figure 3). Spring is the second most rainy season after autumn, and mean temperature is not as high as in June. Actually, in this month, when the mitotic rate is maximum (Wodzicki 1971), both precipitation and temperature limit growth (Figure 3). This result, together with the large number of multiple rings, leads me to think that the species stops growing when water in summer is not available. In the Mountains of Prades, as in the Mediterranean regions, decreasing precipitation and increasing temperature cause a rapid depletion of soil moisture when growth rate is highest. High temperatures and low precipitation in late summer, possibly after radial growth has finished, may control tree growth, which means a possible decrease in the reserve of assimilates.

Direct relationships to precipitation are evident in prior August and September, and a negative relationship prevails in prior October. Inverse relationships to temperature also occur in prior August and September and in the autumn prior to growth, while in winter the relationship is direct. Ring widths of *Pinus sylvestris*, like other conifers growing in arid sites, also correlate with climate during the autumn prior to growth. This is the season with more significant coefficients for the NTOPS chronology near the top of the mountain (Figure 3) where climatic conditions may be harsher.

It has been suggested by some researchers that correlations for prior late summer and autumn could only be the result of water stored in the ground (Zahner 1968) or in the trees. Since autumn is the rainiest season in the Mediterranean region, the first is possible, but the second is highly unlikely because water stored in trees is insignificant (Roberts 1976). The large number of multiple rings leads me to think that *Pinus sylvestris* does not store water; otherwise the species would regulate its growth rate under summer drought conditions, and fewer false rings would be formed. As can be deduced from the type of habitat and the response functions, this species has the properties of a pioneer species (Major 1963) able to colonize harsh habitats. Tessier (1986) suggests the name "durable pioneer" to describe *P. sylvestris*' strategy of colonizing and remaining in this type of habitat.

December temperature is the most important winter temperature effect (Figure 3). As mean temperatures below 0° C are seldom reached in this area, high December temperatures may lead to higher rates of respiration but also to higher photosynthesis rates. Nevertheless, the positive relationship between ring widths and December temperatures cannot support the inference of a direct relationship between photosynthetic rate and growth. This relationship is not quite exact because, among other things, the photosynthetic process operates at a lower rate than can be reached under optimal conditions. The "laziness" of this process is attributed to a low demand of assimilates (Kramer and Kozlowski 1979). The issue, according to these authors, is whether photosynthesis controls growth or growth controls the photosynthetic rate. However, it may not be possible to deduce that increased photosynthesis leads to increased growth, i.e. reserves of assimilates. Wardlaw (1968) points out that the effect of external factors on growth is more critical to assimilation of food than to its translocation. Therefore, if food reserves are accumulated in winter, mainly in December, they could be used during spring growth and, thus, in the formation of the new tree-ring.

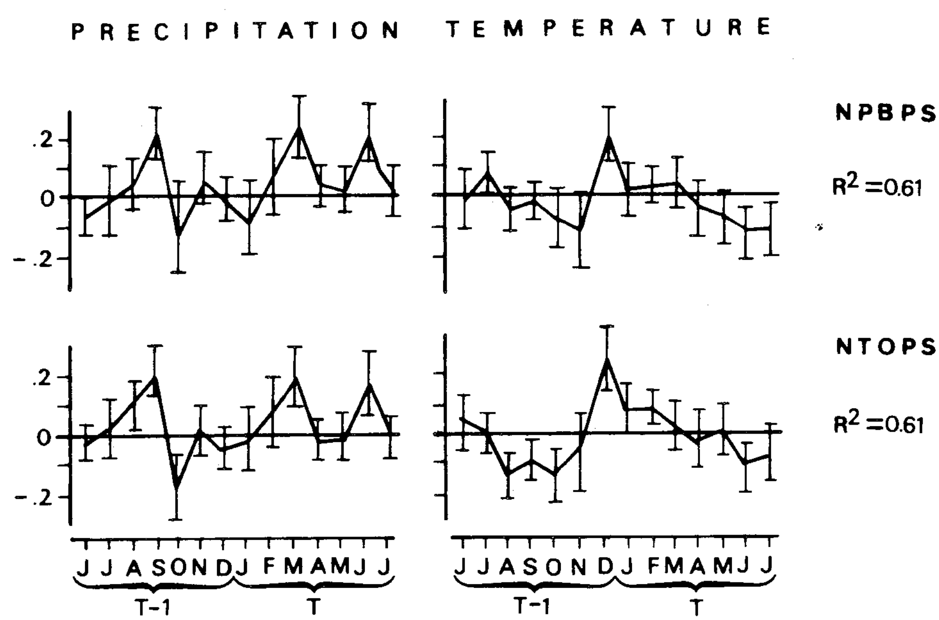

FIGURE 3. Response functions for each chronology obtained by performing multiple regression analysis on principal components. Vertical bars designate 0.95 confidence intervals.

CONCLUSIONS

Two modern chronologies of *Pinus sylvestris* L. have been established and related to local sub-Mediterranean climate in the South of Catalonia, Spain. The scarcity of dendroclimatological studies in Spain makes these first results of special value in understanding climate-tree growth relationships of the species in an area near the southern limit of its world distribution. According to the results of response function analysis, in the Mountains of Prades this species is especially sensitive to water stress in summer. However, the response functions indicate greater complexity as precipitation during three months (March and June of the current year of growth and September of the year prior to growth) are major limiting factors in *P. sylvestris* growth. From the high positive and significant effect of winter temperatures, it can be inferred that the accumulation of food reserves during this period could be used in the growth of new rings in the following spring.

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