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

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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 méditerranéennes 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.

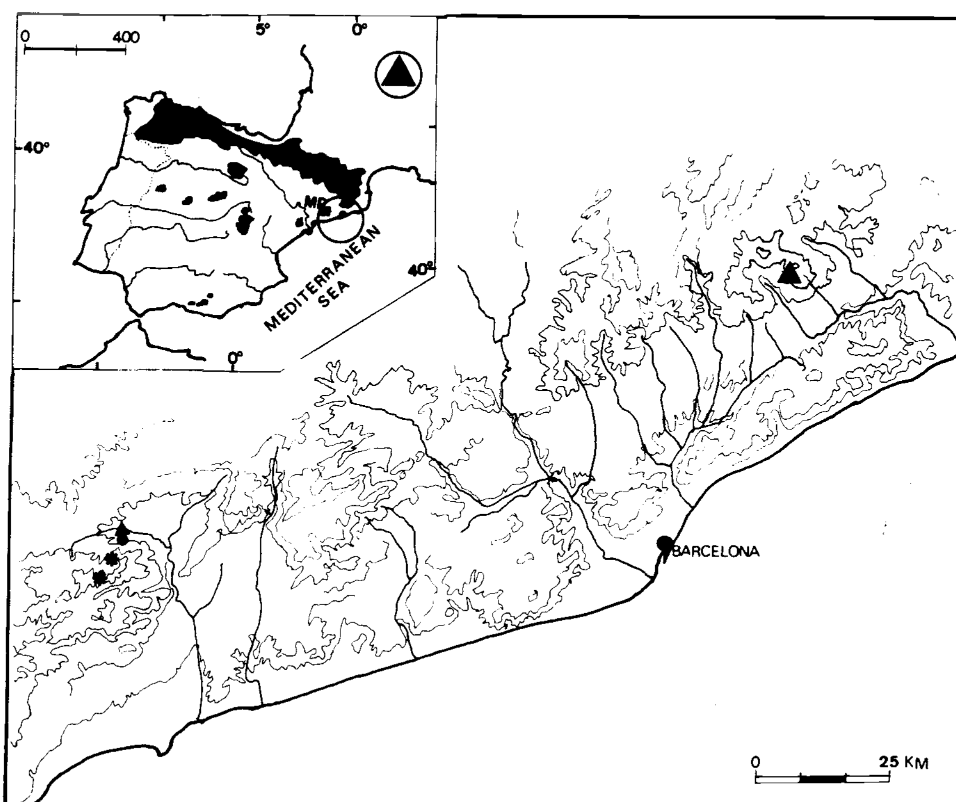

FIGURE 1. The study area: the Mountains of Prades (MP); the distribution of *Pinus sylvestris* in Spain (shading); the chronology sites (stars); the weather stations of Riudabella 590 m (triangle/circle) the Turó de l'Home 1,707 m (triangle).

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.

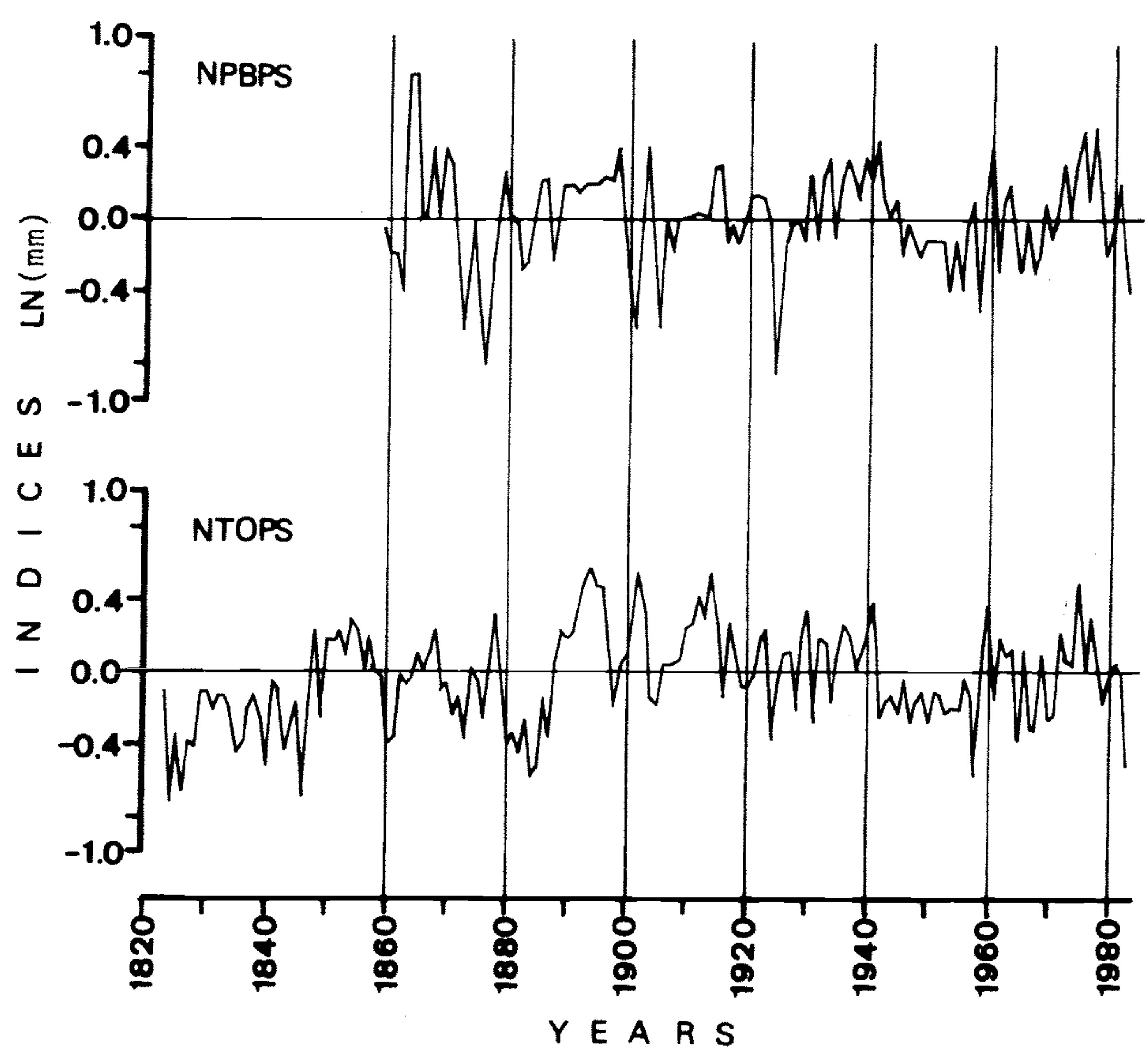

FIGURE 2. *Pinus sylvestris* chronologies for the Mountains of Prades.

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.

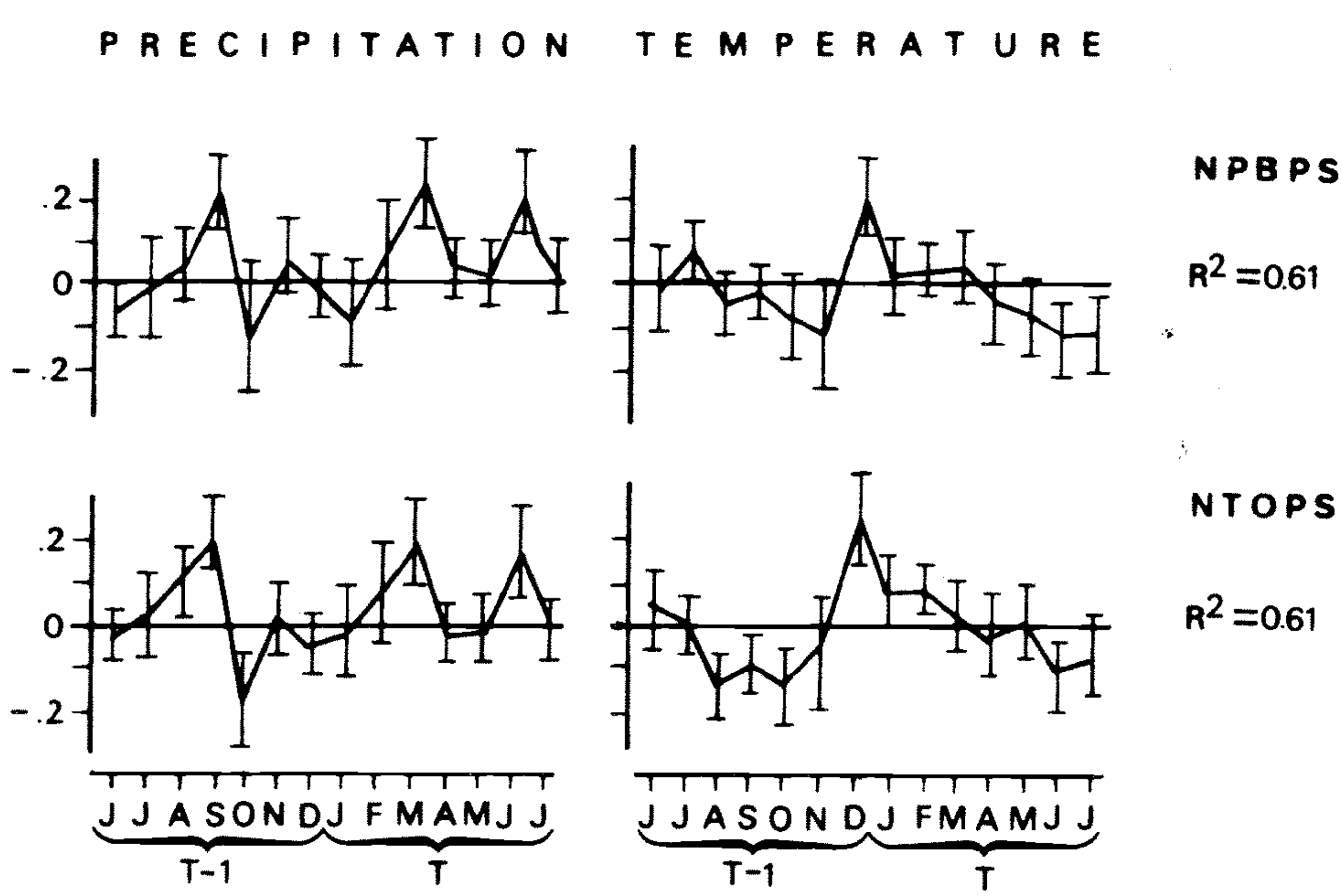

FIGURE 3. Response functions for each chronology obtained by performing multiple regression analysis on principal components. Vertical bars designate 0.95 confidence intervals.

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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DETECTION OF ATYPICAL YEARS IN TREE-RING SERIES BY CONSTRUCTION OF A TEMPORAL WALK IN THE PRINCIPAL COMPONENTS PLANES

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ABSTRACT

The purpose of this paper is to introduce a method for identifying years of anomalous radial growth, which are called atypical years and are characterized by particularly narrow rings for certain trees or sites, and wide for the others. With this aim, we use principal components analysis (PCA) of tree-ring series, where years are the variables and trees or sites are the individuals, even though in classical dendrochronological applications of PCA, the trees or sites are considered as variables and the years as cases. The relevant method is explained and results are given for five cedar forests (*Cedrus atlantica* (Endl.) Carrière) in Morocco.

In der vorliegenden Arbeit wird ein Verfahren vorgestellt, das es ermöglicht, Jahre mit anomalem Dickenwachstum zu identifizieren. Derartige Jahre werden als atypisch bezeichnet und fallen durch besonders enge Jahrringe für bestimmte Bäume oder Standorte und besonders breite Jahrringe für andere Bäume oder Standorte auf. Zur Indentifikation wird eine Hauptkomponentenzerlegung der Jahrringfolgen eingesetzt. Hierbei gelten die Jahre als Variable, und die Bäume oder Standorte sind die Individuen, obwohl bei der klassischen Anwendung der Hauptkomponentenzerlegung in der Dendrochronologie die Bäume oder Standorte als Variable und die Jahre als Beobachtungsfälle behandelt werden. Die angewandte Methode wird erklärt, und Ergebnisse für fünf Cedern-Wälder (*Cedrus atlantica* (Endl.) Carrière) in Marokko werden dargestellt.

L'objectif de cet article est d'introduire une méthodologie permettant d'identifier les années de croissance radiale anormale, qualifiées d'atypiques et caractérisées par des épaisseurs de cernes particulièrement petites pour certains arbres ou sites, et larges pour les autres. Nous appliquons dans ce but l'analyse en composantes principales (ACP) sur des chronologies d'épaisseurs de cernes, où les années sont les variables et les arbres ou sites sont les individus, alors que dans les applications dendrochronologiques classiques de l'ACP, les arbres ou sites sont considérés comme variables et les années comme observations. La méthodologie est expliquée et des résultats sont donnés pour cinq cédraies (*Cedrus atlantica* (Endl.) Carrière) au Maroc.

INTRODUCTION

Principal components analysis (PCA) is a classical method for data analysis (e.g., see Lebart and Fénelon 1975; Lebart *et al.* 1977, 1979). In dendrochronology, PCA has been applied directly to tree-ring series (Jacoby and Cook 1981; Peters *et al.* 1981) but has more generally been used in order to summarize meteorological data before computing response functions (Fritts 1976; Guiot 1981; Guiot *et al.* 1982).

In classical PCA of tree-ring series, trees or sites are considered as variables and years, as observations. Here, we analyze the transpose of such tree-ring series data arrays, *i.e.* years are taken as variables. The purpose is to detect years of anomalous radial growth, which are called *atypical years*. We define a year as atypical when tree rings are particularly narrow for certain trees or sites, and wide for the others. According to this definition, a year with generally narrow rings or a year with generally wide rings will not be considered atypical. In a discriminant analysis of 44 Moroccan cedar forests (Dutilleul and Till 1988), these atypical years contributed heavily to the construction of the two first canonical axes, which in turn clearly reproduced the geographical location of the forests and in particular, the proximity of the Rif and Western Middle Atlas sites.

TREE-RING DATA

Forty-four sites have been sampled across the whole natural area of the cedar forest (*Cedrus atlantica* (Endl.) Carrière) in Morocco. Five sites have been selected for the period 1860-1976 to perform the present analysis. These sites have been chosen according to their geographic locations and their tree-ring characteristics. Only five sites have been retained in order to allow easier interpretation of the PCA results. These sites are marked on the map (Figure 1). Sites 22 and 40 are from the Rif mountains, sites 34 and 47 from the Middle Atlas and site 5 from the Eastern High Atlas. Site 22 has been classified as complacent with mean sensitivity s=0.08 and first-order autocorrelation coefficient r=0.71; site 5 (s=0.27, r=0.50), site 40 (s=0.21, r=0.36) and site 47 (s=0.18, r=0.21) as intermediate; site 34 (s=0.30, r=0.09) as sensitive (Till 1987b).

According to the woody material available, 10 to 20 trees have been sampled in each site; 2 to 4 cores have been extracted from each tree. After measuring ring widths to the nearest hundredth of a millimeter and crossdating the ring-width series for all sites, trees were classified as young-adult stage or old-adult stage (Till 1985, 1987a, 1987b). Individual chronologies and master chronologies have been computed. An individual chronology is a mean chronology summarizing synchronized cores of an individual tree. A master chronology is an average of the chronologies relative to synchronized cores from the same site. For the present paper, only five or six old-adult stage trees (10 to 12 synchronized cores) have been randomly retained for each site, and the mean chronologies (individual and master chronologies) concern these trees only, extending over the period 1860-1976.

METHOD

Data Arrays and Data Transformations

Tree-ring width series relative to the sites under study may be arranged in data arrays

$$X = (X_{it})$$

where i denotes the site or the individual (i=1, ..., I) and t denotes the year (t=1860, ..., 1976); X_{it} is the ring-width of the ith individual or site for year t.

PCA is performed on the raw data arrays, and two transformations are studied for their effects on PCA results. These transformations are the following:

1. centering of the tree-ring series (X rows):

$$X^c = (X^c_{it})$$

where:

$X^c_{it} = X_{it} - X_{.t}$

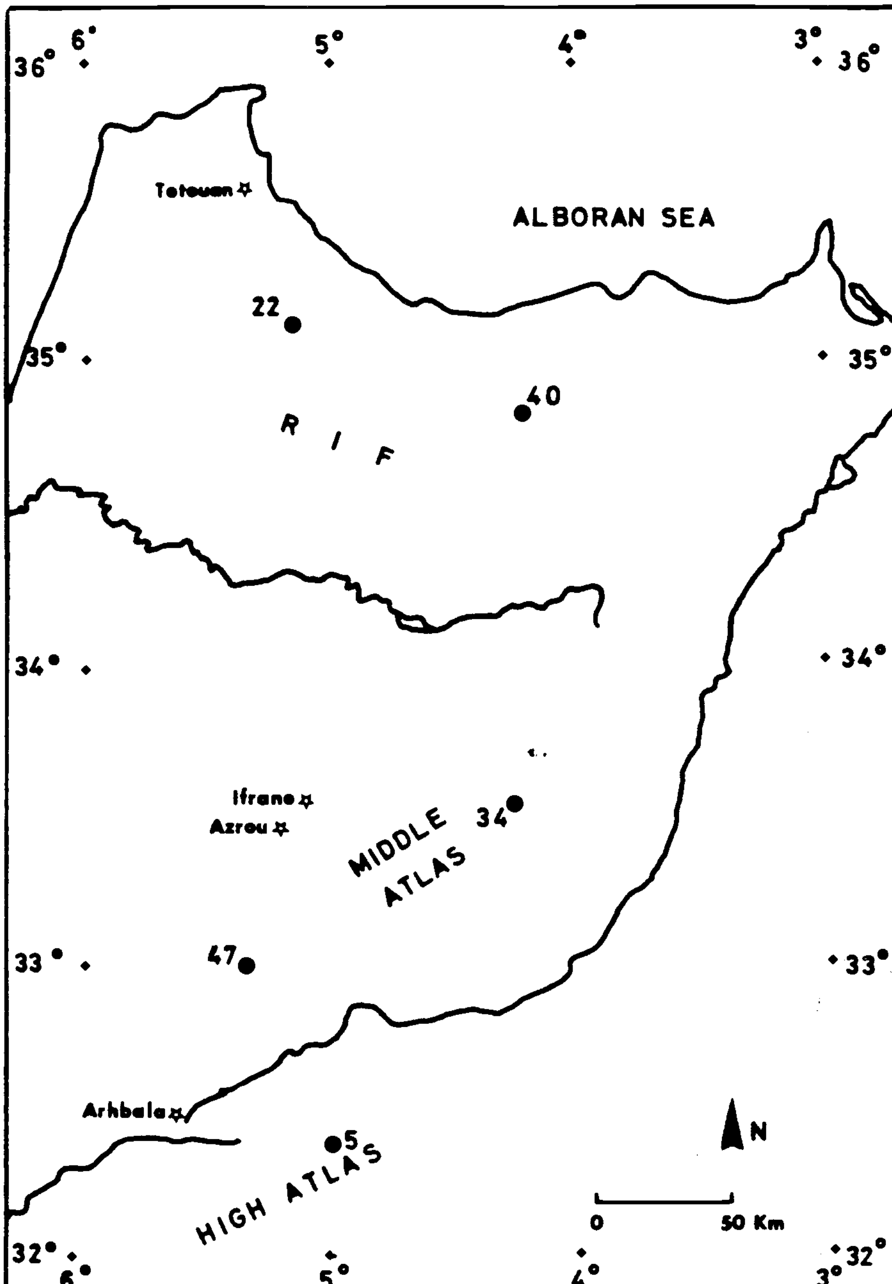

Figure 1. Location of tree-growth sites studied: 5 Afraskou (3050-Lv), 22 Jbel Lakrâa (3280-Lv), 34 Immouzer des Marmoucha (3420-Lv), 40 Tizi Ifri (3550-Lv), 47 Jbel Irhoud (3620-Lv).

$$X_{i.} = (\sum_{t=1860}^{1976} X_{it})/117$$

This centering of the data is performed in order to obtain a symmetrical projection of the variable-points in the principal components planes of the individuals in a way similar to the factorial correspondence analysis (FCA).

2. standardization of the tree-ring series (X rows):

$$X^s = (X^s_{it})$$

where:

$$X^s_{it} = X^c_{it}/S_i = (X_{it} - X_{i.})/S_i$$

$$S_i^2 = \sum_{t=1860}^{1976} (X_{it} - X_{i.})^2/116$$

Standardization of the tree-ring series scales their variance so they are more homogeneous than is normally the case.

The choice of these transformations instead of log transformation or first-differencing is justified as follows. Transformations should be applied to all tree-ring width series to achieve comparable results. This is the case for centering and standardization as defined above because of, respectively, the similarity with FCA and the heterogeneity of variances among tree-ring series. Log transformation is particularly recommended for removing exponential trends, but such trends are not present in the ring-width series of the old-adult stage trees selected for the present analysis. First-differencing, on the other hand, reduces first-order autocorrelation in the presence of trend but introduces autocorrelation in the case of absence of dependence over time or white noise. The autocorrelation of certain tree-ring series (sites 22 and 40 in particular) being much stronger than in the others, the effect of first-differencing would not be constant when applied to all sites. Both log transformation and first-differencing reduce the size component of tree-ring series, on which the definition of atypical years is based. As we observe below, the centering and standardization of the years never facilitate the interpretation of results, and the best graphical representation of atypical years provided by PCA is obtained with raw data.

Construction of the Temporal Walk

The PCA is carried out on the correlation matrix of either the raw or the transformed tree-ring series. Thus, yearly tree-ring widths are considered as the variables and trees or sites as the individuals in the PCA. The correlation matrix instead of the covariance matrix is used to perform PCA in order to avoid possible heterogeneity through time of the yearly tree-ring widths although they are variables of the same nature and defined on the same experimental unit.

The analysis is first carried out on all sites together by using the master chronologies and then by using all individual chronologies together. The analysis is also carried out on the individual chronologies for each site. When PCA is performed on master or individual chronologies of the 5 sites together, atypical years eventually detected concern the whole set of sites. Applied site by site, PCA detects atypical years for individual sites. The presence or absence of an individual in PCA sense -- *i.e.* a tree or a site -- with wide rings may influence the outcome of the analysis. However, in the case of a homogeneous set of individual tree-ring series, results are essentially the same whether PCA is carried out on the whole set or on a representative subset of the chronologies. This remark is valid for the data arrays under study.

By the correlation structure of a data array, we mean the structure of the corresponding correlation matrix in terms of its eigenvalues. Considering the individual chronologies of all sites, it must be pointed out that the between-sites correlation structure is altered by the within-site correlations, *i.e.* by the correlations between individual chronologies of the same site. This alteration will have repercussions in PCA performed on the variables, *i.e.* the yearly tree-ring

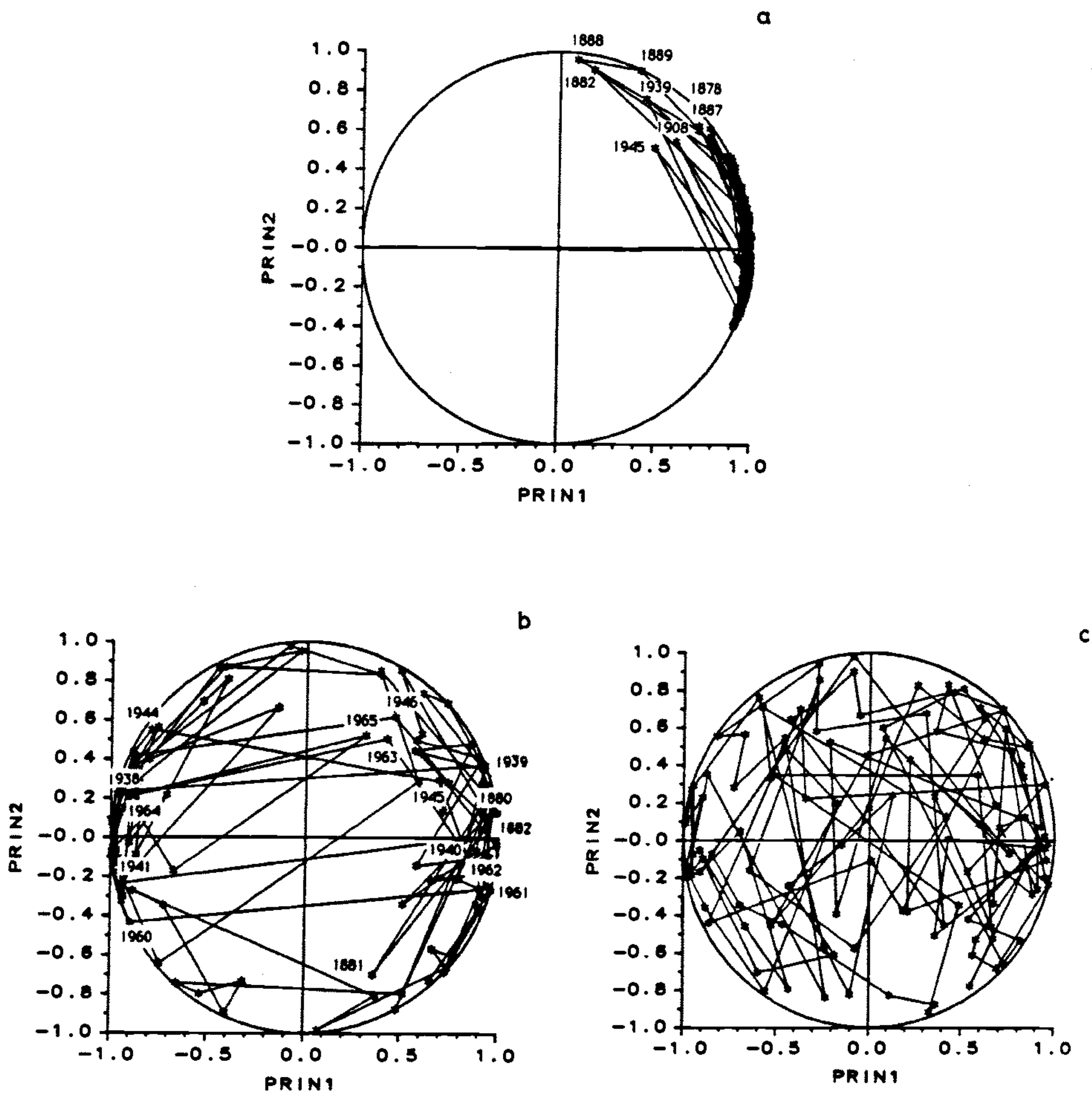

Figure 2. Principal components analysis performed on master chronologies: projection of the years in the plane of the two first principal components, PRIN1 and PRIN2, for raw data (a), centered data (b), and standardized data (c). The temporal walk is obtained by joining the years in chronological order in the plane supported by PRIN1 and PRIN2.

widths. In fact, it must be remembered that, from a mathematical viewpoint, all the positive eigenvalues relative to the variables in PCA differ only by a multiplicative constant from those relative to the individuals. This perturbing effect does not appear when master chronologies of all sites together are considered or, site by site, when individual chronologies are considered in sufficient numbers to reduce the influence of a single individual.

The construction of the *temporal walk*, which permits the detection of atypical years, is carried out by joining the variable-points (years) in chronological order in the plane supported by the two first principal components of the individuals (trees or sites). As a time series represents a temporal walk in the space of observations, the temporal walk provided by PCA is built in the space of

Table 1. Principal components analysis of sites 5, 22, 34, 40, and 47.

Chronologies	Eigenvalue (%) λ_1	λ_2	λ_3	Cumulative Proportion (%)
Master 5 sites				
raw data	86.13	9.90	3.03	99.06
centered data	64.64	20.80	10.18	95.62
standardized data	39.82	25.33	18.04	83.19
Individual 5 sites				
raw data	62.51	9.62	6.67	78.89
centered data	30.78	17.15	13.05	60.98
standardized data	17.22	13.11	11.55	41.88
Individual site 5				
raw data	61.41	15.67	11.99	89.07
centered data	37.35	26.03	19.82	83.23
standardized data	34.50	26.60	21.08	82.18
Individual site 22				
raw data	55.18	18.90	11.84	85.92
centered data	37.71	23.44	16.16	77.31
standardized data	37.88	20.79	18.11	76.78
Individual site 34				
raw data	74.87	11.63	8.53	95.03
entered data	33.59	30.46	20.22	84.27
standardized data	34.01	26.12	20.87	81.27
Individual site 40				
raw data	35.04	25.45	20.02	80.51
centered data	35.85	25.40	16.30	77.55
standardized data	31.83	25.63	19.67	77.13
Individual site 47				
raw data	48.38	26.60	13.57	88.55
centered data	42.03	25.04	15.84	82.91
standardized data	33.43	30.53	15.33	79.29

principal components. The latter temporal walk, as the former, may be characterized by a strong first-order autocorrelation, which implies that a year can sometimes be detected as atypical only because the previous one is. This must be taken into account in the interpretation.

Table 2. Atypical years detected by principal components analysis carried out on raw data.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
1878	1882	1867	1860	1880	1878	1860
1882	1888	1868	1868	1882	1880	1861
1887	1889	1879	1869	1883	1882	1862
1888	1890	1888	1882	1884	1932	1863
1889	1908	1893	1885	1886	1933	1864
1908	1939	1894	1886	1887	1934	1865
1939	1945	1898	1887	1889	1935	1866
1945		1899	1890	1904	1936	1867
		1900	1893	1905	1937	1868
		1901	1905	1906	1938	1869
		1905	1907	1907	1939	1870
		1906	1917	1908	1940	1871
		1908	1924	1910	1945	1872
		1929	1965	1943	1950	1873
		1934	1967	1945	1955	1875
		1939		1946	1959	1876
		1941		1966	1960	1879
		1944			1968	1884
		1946			1969	1885
		1947				1886
		1968				1918
		1976				1919
						1923
						1924
						1925
						1926
						1941
						1942

1. Master chronologies of all sites.
2. Individual chronologies of all sites.
3. Individual chronologies of site 5.
4. Individual chronologies of site 22.
5. Individual chronologies of site 34.
6. Individual chronologies of site 40.
7. Individual chronologies of site 47.

RESULTS AND DISCUSSION

The interpretation of the PCA is carried out on the basis of Table 1 and Figures 2 and 3. Table 1 describes the numerical results of the PCA. The eigenvalues (%) represent the proportion of the dispersion explained by the corresponding principal components. Those figures represent the temporal walk provided by PCA performed on the correlation matrix of either the raw or the transformed tree-ring data.

For raw data, the first principal component is easy to interpret for the master chronologies (Figure 2a) and, to a lesser degree, for the individual chronologies (Figure 3a). In fact, all scores being positive and almost equal, the first principal component is obviously a size component,

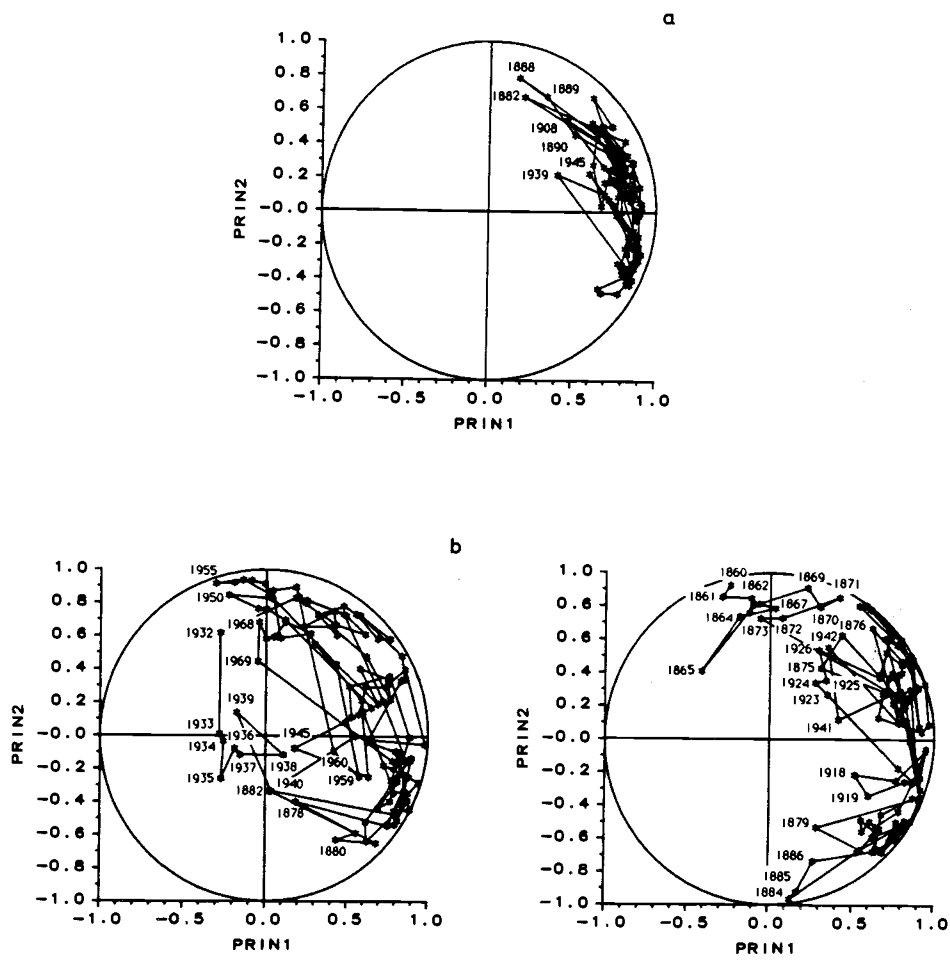

Figure 3. Principal components analysis performed on individual chronologies: temporal walk and atypical years are represented for all sites (a) and for two sites in particular, 40 (b) and 47 (c).

ranging from 86% of the dispersion for the master chronologies to 35% of the within-site dispersion for site 40 (Table 1). Low values of yearly ring-width projections onto this size component correspond to years of anomalous growth, *i.e.* to atypical years as defined in the introduction. The temporal walk allows the detection of these years because they are out of the sequence of normal years in the principal components planes of the individuals. The second principal component is supported by atypical years for raw master chronologies (Figure 2a). The atypical years are detailed in Table 2 for each site and for all sites together.

Most of the atypical years detected for the five sites on the basis of their master chronologies correspond to narrow rings for sites 5 and 40, to wide rings for site 22, and to mixed ones for sites 34 and 47 (Figure 4). The repartition of narrow and wide tree rings at atypical years has to be linked to the sensitivity of the five sites. The detection of atypical years for each site in particular is more difficult through the correlation structure among individuals, which reflects the high level of noise in the system. This fact is particularly verified for site 40 (Figure 3b), whose individual chronologies vary in their major part in a nonconcordant manner, reflecting a hardly satisfactory synchronization. This problem does not exist when PCA is performed on master chronologies (Figure 2a) for which the parallelism is usually broken only at atypical years. The high number of atypical years detected for site 47 (Figure 3c) may be attributed to age differences among trees and the autocorrelation of the individual chronologies. In fact, their nonconcordance begins at their first year (1860) and extends up to 1873.

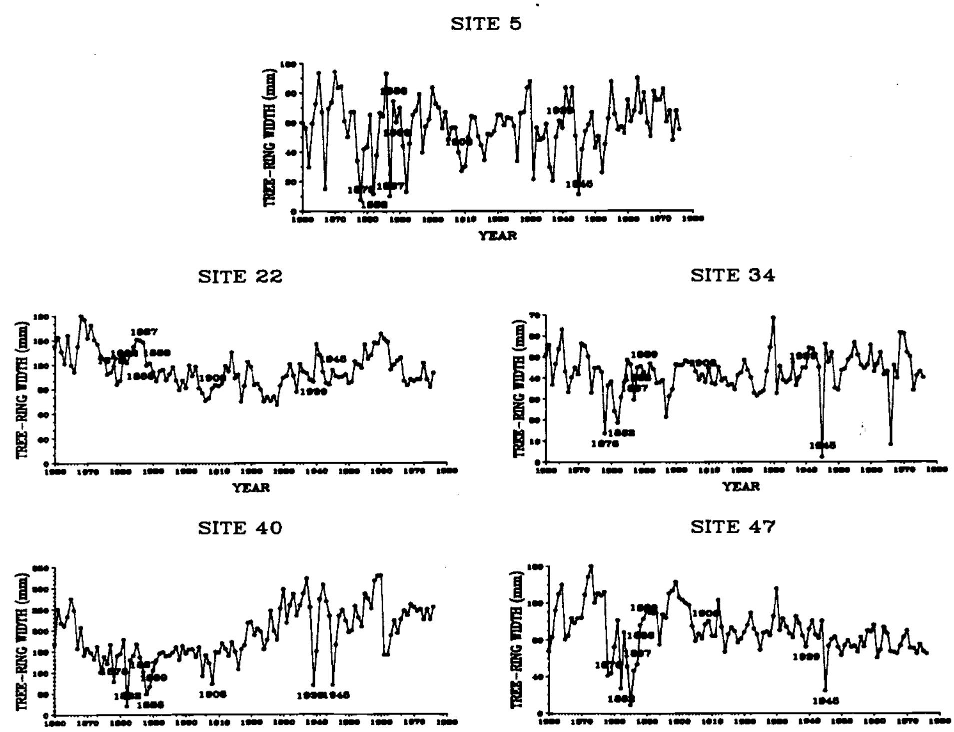

Figure 4. Master chronologies of sites 5, 22, 34, 40 and 47: they evolve in a quasiparallel way and differ by a constant, except at atypical years.

The first principal component on the centered data (Figure 2b) is a sort of size component in which an atypical year is characterized by a right-left-right movement or its reciprocal. A nonimmediate return in this movement may be attributed to the strong autocorrelation of the chronologies.

Interpretation of the standardized data (Figure 3c) is impossible, although the third principal component takes important values for all atypical years (Dutilleul and Till 1988).

CONCLUSIONS

PCA is a powerful method to synthesize data arrays of time series and of tree-ring series in particular. By the construction of a temporal walk in the plane supported by the two first principal components, PCA of tree-ring series provides a pertinent graphical representation with easy detection of atypical years for raw data when master chronologies are considered. PCA may be performed on individual chronologies for each site only if a sufficient number of individuals is available. The number acceptable depends on the length of the chronologies, five individuals appearing to be a minimum in our case. The atypical years obtained in this analysis are specific to the five cedar forests studied. Ecological interpretation will be possible only if the method is applied to the whole set of chronologies available for Morocco.

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RESEARCH REPORT

PRESERVING DECAYED WOOD SAMPLES FOR TREE-RING MEASUREMENT

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ABSTRACT

Wood disks in various states of decay can be inexpensively preserved and prepared for accurate crossdating and precise tree-ring measurement by impregnation with commercial wood glue. The technique does not affect the dimensions or physiological features of samples preserved in this manner. Dead red spruce trees on Mt. Washington, New Hampshire, remain available for dendrochronological examination as long as 29 years after their last year of stem growth.

Holzscheiben mit unterschiedlich intensiver Fäulnis können mit einem handelsüblichen Holzleim imprägniert und auf diese Weise kostengünstig geschützt und zur Datierung und genauen Jahrringmessung vorbereitet werden. Dadurch werden die Dimensionen physiologischen Merkmale des Holzes nicht verändert. Tote Fichten (*Picea rubens* Sarg.) am Mt. Washington in New Hampshire bleiben so noch 29 Jahre, nachdem sie ihren letzten Jahrring gebildet haben, für eine dendrochronologische Untersuchung verfügbar.

Les disques de bois en divers états de décomposition peuvent être préservés de façon peu coûteuse et préparés pour effectuer des datations croisées fiables ainsi que des mesures de cernes précises, par imprégnation à l'aide de la colle à bois commerciale. La technique n'affecte pas les dimensions ou les caractéristiques physiologiques des échantillons préparés de cette manière. Des épicéas morts (*Picea rubens* Sarg.) provenant du Mont Washington dans le New Hampshire, sont restés disponibles pour un examen dendrochronologique au moins 29 ans après la formation du dernier cerne de croissance.

INTRODUCTION

Dendrochronologists often are confronted with samples in various states of decay. Decayed wood is not easily handled, and important cellular features can be difficult to discern. This paper reports a method for stabilizing and obtaining ring-width information from dead and decaying red spruce (*Picea rubens* Sarg.).

METHODS

In the autumn of 1986, a study site was selected on the eastern slope of Mt. Washington, New Hampshire, at an elevation of 800 m. Three sample types were selected from 20 dead red spruce trees. The first type included eight standing, whole stems with complete boles and branches that retained fine branchlets. The second type included eight standing snags, or trees broken at varying heights. The third type consisted of partially decayed stems lying on the ground.

Whole-stem disks 5- to 7-cm thick were sawed from each tree at 1.4 m above the base. To prevent breakage of disks cut from the more severely decayed trees, masking tape was wrapped several times around the circumferences. The disks were then labeled and bagged in plastic for transportation. Samples were refrigerated to curb the growth of fungi.

Prior to any treatment, all disks were rated by a decay class ranging from 0 to 4 (C.A. Federer, USDA Forest Service Durham, New Hampshire, personal communication) (Table 1). Preparation differed by the decay classification given to each disk. Samples from decay classes 0 to 2, generally sound wood with little or no decay, required the least preparation. These were smoothed with a hand-held motorized planer, and then sanded (Krusic et al. 1987). Samples from decay classes 3 and 4, containing advanced decay, were secured with adjustable metal retaining bands placed around the circumferences then impregnated with a solution of 70% water and 30% commercial wood glue, the main ingredient of which is polyvinyl acetate.

Sample disks <24 cm in diameter were impregnated with the wood glue solution under reduced pressure in a vacuum chamber. Disks were kept submerged by weights throughout the treatment process. Impregnation continued until unweighted samples no longer floated high on the surface of the impregnant. This process was generally completed within 48 hours. Samples that exceeded the size limit of the vacuum chamber were treated by submersion in the wood glue solution without vacuum for a longer period, usually two weeks. Disks treated in this manner were deemed sufficiently impregnated when they demonstrated a loss of buoyancy. Once removed from the vacuum chamber or soak, each treated disk was dried slowly at 36°C and then surfaced by the standard methods of planing and sanding.

Prior to the vacuum impregnation of three decayed disks, randomly selected radial segments from near-pith, middle, and near-bark regions were marked and measured. These same segments were remeasured after impregnation of the disks to evaluate dimensional changes that may have occurred as a result of the preservation treatment.

In dating the samples, two to four selected radii were first compared to each other using skeleton plots, then compared to a master chronology. The master chronology used for initial dating was provided by the Appalachian Mountain Club and was compiled from living trees on an adjacent site (Keifer 1985). Dating was aided by comparison to the Nancy Brook, New Hampshire, chronology (DeWitt and Ames 1978), a site 20 km southeast of Mt. Washington. After nine trees were dated in this manner, a new site-specific master chronology was developed for all future dating. At this point, five of the 20 samples were rejected because of problems in dating, species identification, or due to damage while handling.

The remaining samples were measured on a digital micrometer accurate to 0.01 mm. Choosing the radii for measurement was based on three criteria. Foremost consideration was given to the radius with the greatest number of rings (highest ring recovery), second to the even spatial distribution of all potentially selectable radii about the disk, and finally to those radii traversing the fewest areas of severe decay. All selected radii were measured outward from the pith. Average

TABLE 1. Decay classes.

0	Sound wood
1	Slight sapwood discoloration
2	Sapwood decay
3	Sapwood and some heartwood decay
4	All decayed sapwood and heartwood

radial increments were then computed for two radii from each disk and plotted. The average raw ring-width series for one tree that stopped growing in 1957, 29 years before sampling, is shown in Figure 1.

RESULTS

In a comparison of linear distances on disks before and after preparation, changes due to impregnation were minimal. Radial shrinkage due to impregnation and drying ranged from 1 to 3% over measured radial segments of 1, 3, and 5 cm. Segments remeasured from the near bark region changed the most while near pith segments changed the least.

The dating of these dead trees, and particularly the last years of growth, is facilitated by the trees' continued sensitivity to environmental factors until death. Not more than one completely missing ring was found in any single disk. However, locally absent rings (incomplete growth rings) became increasingly common within the last years of xylem production as the trees approached death.

Table 2 summarizes the age information from the 15 measured trees, and shows the first and last year of growth, decay class of each sample, and sample type. A range of years under the last year of growth in Table 2 is an indication of missing and locally absent rings found in the last few years of growth within the disk. The age distribution of dead trees from this area ranged from 133 to 321 years. Sampled trees grew into the stand between the years of 1648 and 1848. The last measurable ring ranged from 1955 to 1984.

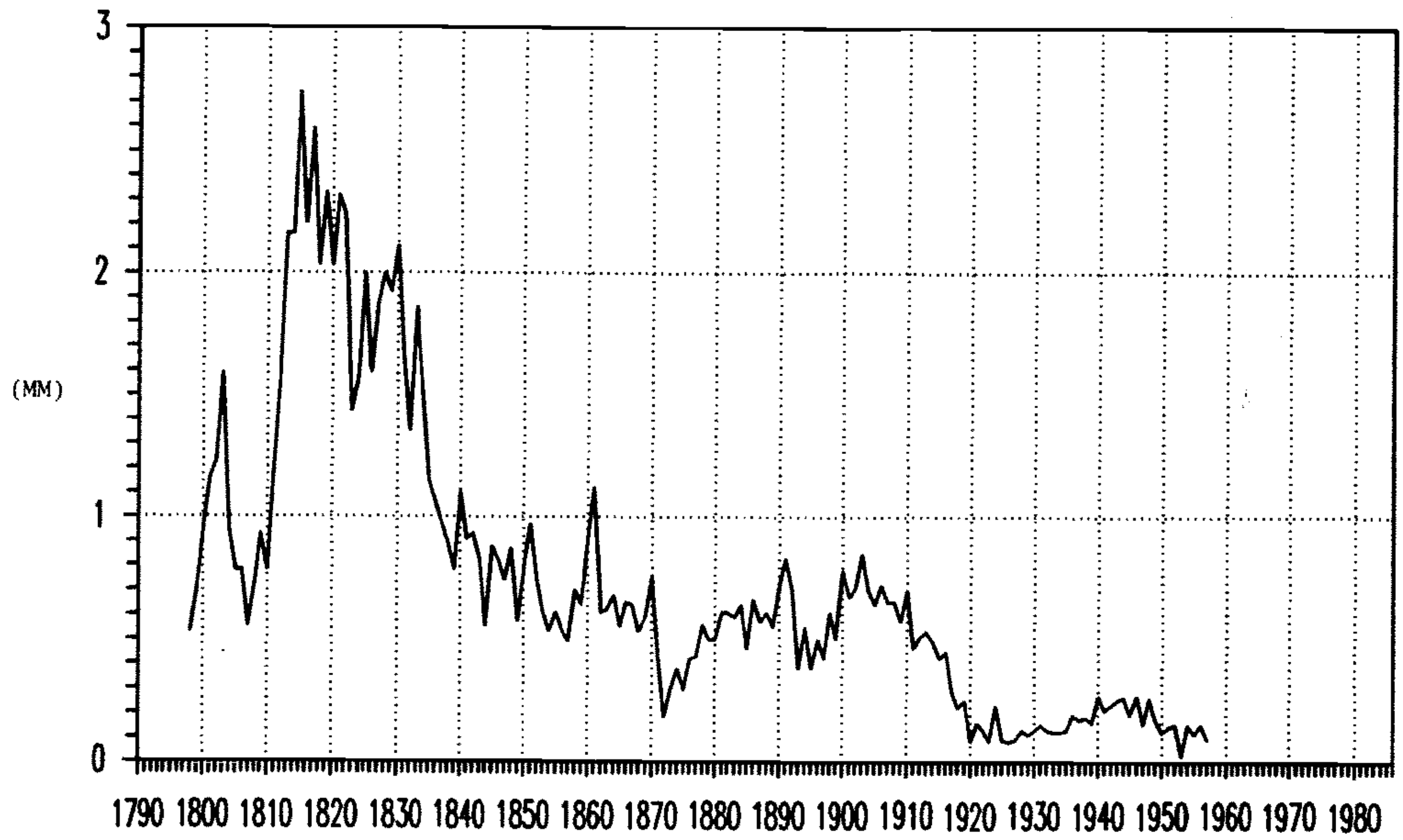

Figure 1. Average raw ring widths (mm) for tree 8, a fallen tree dead 29 years prior to sampling.

TABLE 2. Age and sample type information. All samples taken at 1.4 m, N = 15.

Age	Diameter (cm)	First Year of Growth	Last Year of Growth	Decay Class	Sample Type*
321	32	1648	1968-65	4	SS
312	27	1662	1973-68	2	SW
292	35	1691	1982-81	2	SS
253	52	1731	1984-81	4	SS
248	38	1726	1973-70	1	SS
233	39	1752	1984-83	0	SW
222	41	1760	1981	1	SW
212	22	1767	1978-77	2	SW
208	45	1772	1979	2	SS
160	23	1798	1957-55	3	F
159	18	1815	1973	4	SS
162	27	1821	1982	1	SW
161	22	1822	1982	3	SW
156	19	1823	1978	2	SS
133	22	1832	1964-63	4	F

CONCLUSIONS

Tree-ring information can be obtained from fallen and standing dead trees for at least 29 years after death in northern New England forests. Treating decayed woody material by impregnation with wood glue renders samples strong enough to be surfaced and polished. Ring-width measurements as small as 0.01 mm can be made by the greatly improved visibility of individual xylem cells. Decayed red spruce disks treated by impregnation did not appreciably change in dimension.

The use of this technique may be valuable to researchers looking to extend the length of existing chronologies, to study patterns of tree growth prior to death, and to date deteriorating architectural structures.

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CONTENTS

PAGE

Dendroclimatological Study of *Pinus Sylvestris* L.
in Southern Catalonia (Spain) .... *Emilia Gutiérrez* 1

Detection of Atypical Years in Tree-Ring Series by
Construction of a Temporal Walk in the Principal
Components Planes .... *Pierre Dutilleul, Claudine Till* 11

RESEARCH REPORT

Preserving Decayed Wood Samples
for Tree-Ring Measurement .... *Paul J. Krusic, Jr., James W. Hornbeck* 23