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Original article

Spatial and altitudinal bioclimatic zones of the Italian peninsula identified from a beech (*Fagus sylvatica* L.) tree-ring network

Gianluca Piovesan [a,*], Franco Biondi [b], Mauro Bernabei [c], Alfredo Di Filippo [a], Bartolomeo Schirone [a]

[a] *DAF (Department of Technologies, Engineering, Sciences of the Environment and Forests), University of Tuscia, Via S. C. de Lellis, I-01100 Viterbo, Italy*
[b] *Department of Geography, University of Nevada, Reno, NV 89557-0048, USA*
[c] *CNR-IVALSA/PAT, Via Biasi 75, I-38010 San Michele All'Adige (Trento), Italy*

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Abstract

A network of 24 beech (*Fagus sylvatica* L.) tree-ring chronologies has been developed for the Italian peninsula. Principal component and cluster analyses were used to identify geographical and altitudinal patterns of tree growth. Correlations and response functions were then applied to the main modes of tree-ring variability to uncover climatic signals. In a landscape occupied by humans for millennia, this approach provided a detailed quantitative ecological characterization of forest types. Altitude was significantly correlated with dendrochronological parameters. The Alps and northern Apennines could be distinguished from the central-southern Apennines. In central Italy, we recognized three different vegetation belts occupied by beech forests, from low- to high-elevation sites. Summer drought impacted beech growth with different intensity at different elevations, depending on the onset and duration of the growing season. Moreover, low-elevation beech forests showed a distinct late spring climate signal, which was opposite to that of high-elevation sites. The coherent geographical and ecological patterns of tree-ring variability suggest that dendrochronological networks help define bioclimatic zones and forest types.

Keywords: Dendroecology; Dendroclimatology; Tree growth; Phytoclimate; Italy; European beech

1. Introduction

The prediction of long-term climate effects on ecosystems requires a deep historical understanding because Earth's surface features are products of the natural and cultural processes that have shaped them over time (Jackson et al., 2001). Dendrochronology is most useful for defining the historical range of variability of tree growth-climate relationships at multiple temporal and spatial scales (Swetnam et al., 1999). Indeed, fine-scale networks of multi-century tree-ring chronologies based on climatically sensitive species have been used to disentangle local, regional, and global phenomena (Briffa et al., 2002a; 2002b). In addition, common growth patterns between forest stands reflect ecologically and climatologically homogeneous territories, and can be used to characterize vegetation types along horizontal and vertical gradients (Cook et al., 2001). Dendroclimatic studies reveal not only the main climatic signals embedded in xylem layers, but also the temporal stability of climate-tree growth relationships (Briffa et al., 1998; Biondi, 2000). Because tree-ring records can disclose trends in growth due to environmental driving forces, they should also be considered powerful tools for assessing changes in productivity of both coniferous (Biondi, 1999; Mäkinen et al., 2002) and deciduous (Cullen et al., 2001; Dittmar et al., 2003) tree species.

Numerous studies have revealed the sensitivity of European beech (*Fagus sylvatica* L.) to climatic variations in terms

* Corresponding author.
E-mail address: piovesan@unitus.it (G. Piovesan).

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of growth and reproduction responses (Eckstein and Frisse, 1982; Biondi, 1993; Power, 1994; Piovesan and Adams, 2001; Stribleya and Ashmore, 2002; Nielsen and Jørgensen, 2003). Beech is a late-successional species widely distributed in European temperate forests, growing in environments little affected by wildfires. Its broad geographical range, which spans more than 20° latitude, 30° longitude, and 1500 m altitude (Fenaroli and Gambi, 1976), presents an interesting opportunity to examine the growth response of this species to a range of climatic regimes. Beech stands in Europe have commonly been managed following high-forest silvicultural systems so that stands with trees older than a century are not uncommon over the landscape (Dittmar et al., 2003). Even in areas of intense, millennia-long human presence, nuclei of old-growth beeches still remain today, and such stands have allowed the construction of multi-century tree-ring chronologies (Biondi, 1992; Bourquin-Mignot and Girardclos, 2001; Piovesan et al., 2003). Because of its longevity, widespread distribution, and climatic sensitivity, beech is a most promising species not only for tree-ring networks, but also for biomonitoring programmes on the status of European temperate forests. Beech growth patterns at the continental scale have already been used to identify distinct regional and altitude-dependent growth-limiting factors (Ellenberg, 1988; Dittmar et al., 2003). In the Italian peninsula, previous research revealed a latitudinal gradient in beech tree-ring records consistent with climatic features (Biondi and Visani, 1996).

Italian beech forests are present over several phytoclimatic regions, from the Mediterranean region, at the southern latitudinal limit of the species, to the beginning of boreal forests (Pignatti, 1998). The ecological gradients present in cold temperate (Alps) and Mediterranean climates (Apennines and Mount Etna) offer the possibility to study growth-controlling factors of beech, and to use its response to climate for identifying latitudinal and altitudinal zones of vegetation. For instance, in the Apennines beech extends over a 1400-1500 m altitudinal interval, from hilly lowlands (300-400 m a.s.l.) to high-elevation forests (1800-2000 m a.s.l.). Using phytosociological analysis, beech forests in the Alps and northern Apennines have been described as *Abieti-Fagion*, *Eu-Fagion*, *Cephalanthero-Fagion*, and *Luzulo-Fagion*, whereas the syntaxonomic unit *Geranio versicoloris-Fagion* was proposed for southern Italy (Pignatti, 1998). However, beech ecological patterns and processes (such as productivity) need to be examined within a quantitative regional framework in order to describe their forcing factors. Tree-ring networks can offer an accurate ecological characterization of beech forests, providing useful information towards a sustainable, science-based management of these natural resources. In this article, we analyse an Italian network of 24 *Fagus sylvatica* tree-ring chronologies with the objective to uncover the principal modes of growth variability. Such modes are then used to identify latitudinal and altitudinal zones depending on climate and geographic location.

2. Materials and methods

2.1. Beech tree-ring network

The tree-ring network is a combination of beech chronologies developed over the past 15 years (Biondi, 1992; Schirone et al., 2002). Sampling sites are distributed throughout Italy (beech is absent in Sardinia), from 39.9° to 46.1° N and from 9.3° to 16.2° E (Fig. 1, Table 1). The main network features are: a) distribution over the entire peninsula, with higher density in central Italy; b) broad elevational range, from low hills to high mountains; c) presence of old trees within forest stands with no intense human disturbance in the recent past. A total of 24 chronologies are distributed from the Alps to the southern Apennines, at elevations ranging between about 450 m and 1900 m a.s.l. Although sampled sites are more numerous in central Italy (17 chronologies), site conditions vary in terms of topography, substrate, soil, and associated species. Sampled stands could not be considered free from past human influence, although several of them show no signs of logging. Numerous sites were also located in forested areas not easily accessible or set aside several decades ago for conservation purposes as parks and natural reserves. At least one location (Val Cervara, which includes VCL and VCH; Fig. 1 and Table 1) is representative of old-growth patterns and processes in Apennine beech forests (Piovesan et al., 2005), and sampled trees reach the maximum age reported for the species, up to 500 years (Biondi and Visani, 1996; Piovesan et al., 2003).

The tree-ring network covers climate regimes from cold temperate to Mediterranean (Essenwanger, 2001). Each site was catalogued according to Mayr-Pavari's classification (De Philippis, 1937), which identifies five phytoclimatic zones by means of the dominant tree species. Every zone is climatically defined, and further divided into sub-zones and types, as shown in Table 2 for northern, central, and southern Italy. The stands we sampled belong to the *Castanetum* and *Fagetum* zones. Tree selection focused on predominant, dominant or codominant trees, either isolated or grouped, with the best combination of old age and trunk health. Trees were sampled at breast height (about 1.3 m from the ground) using increment borers. A few samples were taken from downed trees either with an increment borer or with a chainsaw. Maximum age, stem diameter and height of trees were used as indicators of forest structure. Maximum age computed from the number of visible rings underestimates beech longevity because increment cores were taken at breast height and most cores did not include the stem pith. Also, if stands have not reached old-growth status, such structural indicators do not describe species potential in relation to the environment, but only actual stand conditions (Peterken, 1996).

Tree-ring chronologies were developed from wood samples using standard dendrochronological procedures (Stokes and Smiley, 1996). After surfacing and crossdating, tree-ring widths were measured to the nearest 0.01 mm using a sliding stage micrometer interfaced with a personal computer. After

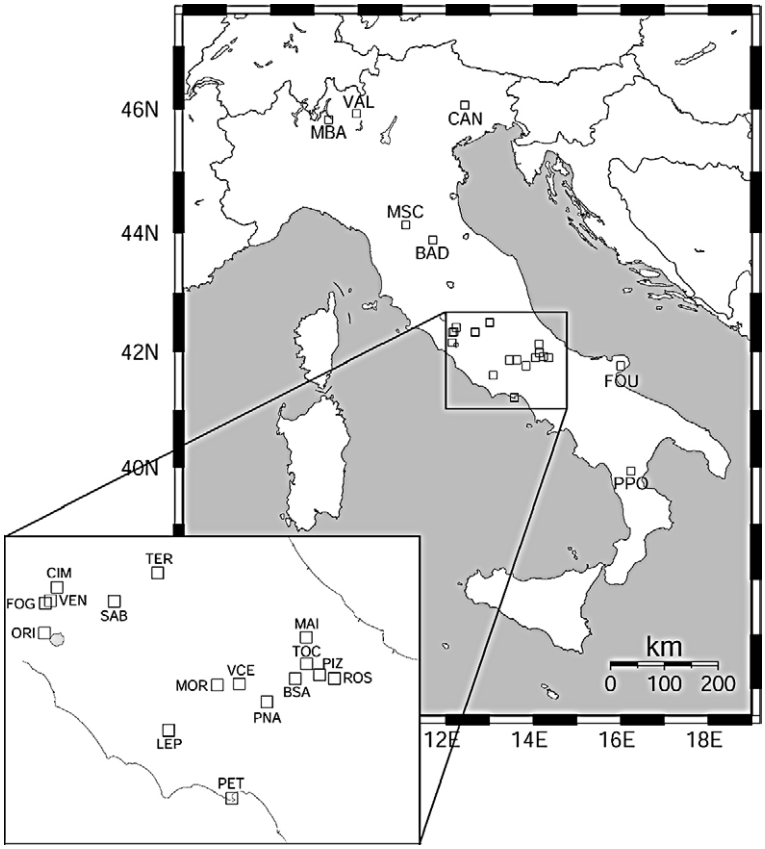

Fig. 1. Map of collection sites. Site codes are the same as in Table 1, the only difference being that VCE includes both VCL and VCH. The enlarged area shows the location of central Italy sites (called L-A in the text).

measuring, tree-ring series were statistically compared with each other to ensure accuracy of crossdating and measurement (Holmes, 1983). Locally absent rings, when detected, were given ring-width equal to zero. The dated ring-width series were standardized and averaged to produce a tree-ring chronology for each site (Fritts, 1976), as follows:

$$\bar{I}_t = \frac{\sum_{i=1}^{i=n_t} \left(w^{0.5} - y \right)_{it}}{n_t} + c_{it}$$

with $\bar{I}_t$ = chronology value at year t; n_t = number of samples for year t; w = crossdated ring width of sample i in year t; y = value of sample i in year t computed by fitting a modified negative exponential with asymptote ≥ 0 or a straight line with slope ≤ 0 to the i ring-width series; c_{it} = constant added to sample i in year t so that the standardized chronology has mean equal to 1. The standardized chronologies were then prewhitened by fitting autoregressive (AR) models (Box and Jenkins, 1976) to the period 1925-1988, which represents the common overlap among chronologies. The order of the AR model was chosen according to a combination of criteria, including the partial autocorrelation function, significance of AR model parameters, Akaike Information Criterion, and residual autocorrelation function (Biondi and Swetnam, 1987; SAS Institute Inc., 2000).

The level of common growth variation among different trees of the same site was quantified by the mean correlation, first principal component, percentage of agreement coefficient or GLK for "Gleichläufigkeitswert" (Eckstein and Bauch, 1969), and Baillie-Pilcher's t-test (Baillie and Pilcher, 1973) over the period 1925-1988. Hierarchical cluster analysis (Ludwig and Reynolds, 1988) was used for detecting subdivisions among the 24 prewhitened site chronologies. Distance between variables was based on the Pearson product-moment correlation coefficient; clusters were then identified by means of the average distance between all pairs of variables contained in them (Wilkinson, 1997).

Principal components analysis, or PCA (Jolliffe, 1986) was performed on the correlation matrix of the 24 prewhitened beech site chronologies for the period 1925-1988. Principal component loadings (or eigenvectors), which display the pattern of association between chronologies, were employed to detect groupings in the tree-ring network. Principal component scores (or amplitudes) were used to represent growth fluctuations over time, and to investigate their relationship with synoptic climate data (see section 2.2. on "Climate-growth relationships"). The PCA was then similarly applied to the sub-set of 17 chronologies from central Italy (called L-A for Latium-Abruzzi), where the higher density of the network (Fig. 1) allows for finer spatial (i.e., latitudinal and altitudinal) detail. Selection of principal components was

Table 1
Summary information on sampled sites and tree-ring chronologies for each region [1]

REGION	SITE	ID	LATITUDE (°)	LONGITUDE (°)	ELEVATION (m a.s.l.)	SLOPE %	TREE	CORE	DBH (cm)	H (m)	PERIOD*	LENGTH* years	N_{max}
A - Southern Italy	Foresta Umbra	FOU	41.7667	16.0000	750 (720-770)	0-15	3	6	108-151	31	1852-1988	137	184
	Parco del Pollino	PPO	39.9333	16.2333	1900 (1800-2000)	20-40	4	8	74-121	25	1783-1988	206	299
B - Central Italy (Latium)	Oriolo Romano	ORI	42.1583	12.1392	450 (400-500)	5-45	26	26	45-90	35	1905-2002	98	106
	Monte Fogliano	FOG	42.3285	12.1440	750	5-30	20	26	45-95	35	1869-2002	134	198
	Monte Venere	VEN	42.3434	121851	800	5-35	36	37	30-85	32	1871-1996	126	133
	Monte Cimino	CIM	42.4181	12.2350	950	0-35	70	101	35-100	41	1813-2000	188	193
	Sabina	SAB	42.3383	12.6697	1050	5-40	25	45	40-65	32	1784-1995	212	227
	Monti Lepini	LEP	42.6047	13.0839	1250	20-35	21	21	44-65	30	1827-2001	175	181
	Monte Petrella	PET	41.2178	13.5681	1375	0-30	22	23	41-73	27	1925-2000	76	84
	Monte Terminillo	TER	42.5000	13.0000	1650 (1550-1750)	5-60	20	20	42-69	32	1697-2000	304	307
C - Central Italy (Abruzzi)	Rosello	ROS	41.9008	14.3497	1000	10-55	11	11	30-61	28	1876-1997	122	136
	Majella	MAI	42.1333	14.1333	1150 (1110-1190)	65-70	4	7	62-64	13	1901-1988	88	140
	Morino	MOR	41.8639	13.4581	1250	0-50	20	25	40-70	37	1766-1997	232	288
	Bosco S. Antonio	BSA	41.9000	14.0500	1350 (1320-1375)	0-20	9	17	59-123	30	1879-1988	110	210
	Monti Pizi	PIZ	41.9214	14.2372	1400 (1350-1450)	0-60	32	32	40-83	30	1901-2001	101	107
	Valle Cervara low	VCL	41.8690	13.6230	1350 (1200-1500)	0-55	21	21	55-102	32	1581-2001	421	435
	Tocchito	TOC	41.9842	14.1381	1600	5-30	21	21	41-71	24	1875-2001	127	138
	Parco d'abruzzo	PNA	41.7667	13.8333	1600 (1290-1895)	0-53	22	48	69-261	34	1670-1988	319	319
	Valle Cervara high	VCH	41.8690	13.6230	1725 (1600-1850)	5-55	32	37	55-100	32	1523-2002	480	503
D - Northern Apennines	Badia Prataglia	BAD	43.8833	11.7000	1150 (991-1316)	20-80	13	25	43-136	30	1785-1988	204	335
	Monte Scoperta	MSC	44.1333	11.0833	1200 (1185-1215)	44-68	8	17	40-63	21	1901-1989	89	90
E - Alps	Monte Barro	MBA	45.8333	9.3333	750 (750-765)	22-71	12	26	67-126	35	1855-1988	134	191
	Cansiglio	CAN	46.0667	12.4333	1200 (1160-1265)	40-48	5	12	58-63	28	1885-1988	104	122
	Valzurio	VAL	45.9333	9.9667	1450 (1430-1480)	20-27	8	16	82-139	24	1810-1988	179	197

* Site chronologies are made up of at least 3 trees-6 radii; [1]**DBH**: Diameter at breast height; **H**: Mean height of the 3-4 tallest trees in the stand (stature); $\mathbf{N_{max}}$: Maximum number of rings counted on a single specimen.

Table 2
Pavari's phytoclimatic belts with related climatic features and altitudinal ranges in different regions. Tc: mean temperature of the coldest month, m: mean of the absolute minimum temperatures (modified from De Philippis, 1937)

Zone	Subzone	Tmed °C	Tc °C	m °C	Southern Italy (A) m a.s.l	Central Italy (B-C) m a.s.l.	Northern Apennines (D) m a.s.l.	Alps (E) m a.s.l.
Castanetum	Warm	10-15	> 0	> -12	600 to 800-900	300-500 to 600-800	200-300 to 500-600	up to 300-400
	Cold	10-15	> -1	> -15	800-900 to 1000-1200	600-800 to 800-1000	500-600 to 700-900	300-400 to 700-900
Fagetum	Warm	7-12	> -2	> -20	1000-1200 to 1700	800-1000 to 1500	700-900 to 1200	700-900 to 800-1200
	Cold	6-12	> -4	> -25	1700 to 2000	1500 to 1800	1200 to 1600	800-1200 to 1500-1600

guided by the Kaiser-Guttman rule (Guttman, 1954; Kaiser, 1992).

2.2. Climate-growth relationships

Climate-growth relationships were determined using both dendroclimatic (Fritts, 1976) and synoptic (Barry and Carleton, 2001) procedures. Dendroclimatic correlation and response functions (Blasing et al., 1984) were calculated between principal component scores of prewhitened tree-ring chronologies and monthly climate variables. The bootstrap method (Efron and Tibshirani, 1986; Guiot, 1991) was used for computing and significance testing (Biondi and Waikul, 2004). Explanatory climate variables spanned a 14-month window, from October of the current growth year to September of the previous year. Since tree-ring chronologies had been prewhitened to remove time-series autocorrelation, possible vegetative lag effects from previous growing seasons were not considered. Because of the higher density of sites in central Italy, this dendroclimatic analysis was performed on the PCs of the 17 L-A chronologies. Climate was quantified by monthly total precipitation (P) and monthly mean air temperature data for the period 1928-1995 published by the Italian "Servizio Idrografico di Stato". Thermal variables consisted of mean temperature (Tmed), mean maximum temperature (Tmax), and mean minimum temperature (Tmin). A total of 13 meteorological stations distributed throughout the Latium and Abruzzi regions (latitude range: 41.20-42.57°N; longitude range: 11.87-14.37°E) were averaged to compute the monthly climate variables (Table 3). Each station had records from 1928 to 1995, which also passed data homogeneity tests (Fritts, 1976).

Synoptic analysis relied on correlation maps between principal component scores and gridded climate data (precipitation and temperature) available from the NCEP/NCAR reanalysis for the period 1948-1988 (Kalnay et al., 1996). Temperature signals at different elevations were studied by means of correlation maps for three different atmospheric pressure levels, i.e. 1000 mb, 925 mb, and 850 mb. Correlation maps were drawn for the region covering 6-19°E longitude and 36-48°N latitude when studying the climate significance of the entire tree-ring network. Such area includes all of Italy, the surrounding seas, and nearby Mediterranean environments (Fig. 1). Correlation maps were also drawn for the central Italy region when principal component scores were particularly relevant for the Latium-Abruzzi (L-A) area.

3. Results

3.1. Characteristics of the tree-ring network

A total of 465 trees and 628 cores were used to compute tree-ring chronologies (Table 1). The 24 site chronologies are from 76 to 480 years in length, with maximum tree ages ranging from 84 years at Monte Petrella to 503 years at Valle Cervara. Numerical features of tree-ring chronologies are summarized in Table 4. Significant correlations were found between key dendrochronological parameters and the main site and stand features (Table 5). Mean tree-ring width (MW) is negatively influenced by elevation and chronology length, which is determined by maximum tree age. Elevation and chronology length are also negatively correlated to the standard deviation (SD) and to the first-order serial correlation (A_1) of the site chronology. Mean sensitivity (MS) is positively correlated to longitude over the whole network, and positively to both elevation and maximum age when considering central Italy. Note that, in dendrochronology, sensitivity is the absolute difference between two adjacent tree-ring values, scaled over their mean; mean sensitivity is the arithmetic average of sensitivity computed for an entire tree-ring series. Mean sensitivity was originally defined by Douglass (1920), and has been used as a synthetic measure of the year-to-year variability in a tree-ring series (Fritts 1976).

Elevation is related to chronology statistics because in Italy the oldest beech trees are often found in the highest portion of its altitudinal range, where tree rings tend to be narrower

Table 3
Geographical coordinates of the 13 meteorological stations that were averaged to compute monthly precipitation and temperature for the Latium-Abruzzi (L-A) region

		Latitude (°)	**Longitude (°)**	**Elevation (m.a.s.l.**
Latium (L)	Gaeta	41.20	13.58	50
	Latina	41.45	13.10	21
	Roma C.R.	41.90	12.48	51
	Tuscania	42.42	11.87	165
	Poggio Mirteto	42.27	12.68	346
	Viterbo	42.42	12.10	327
	Subiaco	41.92	13.10	458
	Leonessa	42.57	12.97	975
	Sulmona	42.05	13.92	420
	Avezzano	42.03	13.43	700
Abruzzi (A)	Palena	41.98	14.13	767
	Agnone	41.80	14.37	806
	Pescasseroli	41.80	13.78	1150

Table 4
Statistics (mean followed by range in parentheses) for tree-ring chronologies [1]

CHRONOLOGY	MW (0.01 mm)	SD (0.01 mm)	MS	A_1	LAR %	N	ACBT	PC1 %	GLK %	t BP	*p*	VAR
Foresta Umbra	177(164-192)	51.7 (61.1-73.8)	0.31 (0.25-044)	0.26 (0.13-0.72	0	3	0.41	63.2	70.3	6.68	4 (neg. 2nd)	35.6
Parco del Pollino	135(64-226)	30.6 (22.0-65.8)	0.20 (0.22-0.32)	0.41 (0.36-0.64)	0	3	0.32	54.2	65.0	3.25	2 (neg. 2nd)	24.0
Oriolo Romano	458(232-790)	101.5 (91.9-349.7)	0.16 (0.17-0.35)	0.64 (0.49-0.84)	0	24	0.50	53.0	66.3	5.07	3 (neg. 2nd)	38.6
Monte Fogliano	289(154-442)	59.7 (49.0-213.9)	0.18 (0.16-0.41	0.53 (0.40-0.83	0	19	0.21	28.66	62.7	4.62	3 (neg. 2nd)	40.2
Monte Venere	198(57-368)	54.6 (18.8-183.4)	0.20 (0.23-0.56)	0.63 (0.39-0.88)	0.164	34	0.31	43.6	65.4	4.28	1	45.0
Monte Cimino	183(58-530)	42.9 (35.7-168.7)	0.21 (0.22-0.62)	0.43 (0.15-0.84)	0.067	59	0.35	42.0	64.1	4.92	3 (neg. 2nd)	29.4
Sabina	196(73-444)	62.7 (45.4-296.2)	0.23 (0.19-0.52)	0.65 (0.37-0.85)	0.071	11	0.47	50.4	68.9	4.986	3 (neg. 2nd)	58.6
Monti Lepini	179(61-318)	65.5 (37.8-166.9)	0.21 (0.21-0.42)	0.74 (0.44-0.94)	0.149	21	0.44	50.4	69.9	3.45	3 (neg. 2nd)	66.5
Monte Petrella	382(290-556)	111.5 (79.6-202.0)	0.14 (0.11-0.28)	0.78 (0.42-0.90)	0	22	0.56	63.8	63.3	3.67	1	69.3
Monte Terminillo	108(42-173)	33.4 (14.0-84.0)	0.31 (0.25-0.59)	0.43 (0.13-0.78)	0.313	20	0.53	50.2	71.9	7.12	1	20.9
Rosello	226(91-281)	52.5 (29.4-197.0)	0.20 (0.21-0.43)	0.53 (0.14-0.80)	0.145	25	0.24	37.5	67.9	3.44	3 (neg. 2nd)	44.7
Majella	132(81-212)	41.4 (24.1-89.8)	0.28 (0.25-0.51)	0.39 (0.37-0.59)	0	3	0.18	61.9	67.5	3.48	1	23.6
Morino	209(137-523)	42.0 (42.8-258.8)	0.18 (0.19-0.42)	0.46 (0.25-0.77)	0.066	18	0.39	40.5	69.8	4.05	3 (neg. 2nd)	39.0
Bosco S. Antonio	211(92-292)	73.3 (33.0-118.9)	0.27 (0.22-0.41)	0.56 (0.34-0.85)	0	9	0.61	78.1	77.8	7.21	3 (neg. 2nd)	28.5
Monti Pizi	254(140-366)	52.0 (50.8-190.1)	0.21 (0.17-0.43)	0.22 (0.17-0.68)	0	32	0.28	35.5	70.4	5.14	1	7.1
Valle Cervara low	138(92-226)	33.7 (30.2-134)	0.27 (0.17-0.42)	0.19 (0.18-0.76)	0.074	21	0.37	47.3	74.5	5.42	2 (neg. 2nd)	7.6
Tocchito	184(107-329)	45.0(32.5-92.2)	0.26 (0.23-0.45)	0.26 (0.17-0.68)	0.074	21	0.49	52.8	73.3	6.75	1	18.0
Parco d'Abruzzo	138(58-227)	34.7 (21.5-97.0)	0.24 (0.15-0.43)	0.33 (0.20-0.74)	0.081	17	0.30	42.1	64.9	3.91	4 (neg. 2nd)	23.1
Valle Cervara high	119(49-182)	29.0 (15.3-75.5)	0.28 (0.23-0.51)	0.12 (0.08-0.65)	0.338	32	0.41	45.5	68.9	5.06	3 (neg. 2nd)	18.3
Badia Prataglia	241(84-372)	45.9 (20.1-137.4)	0.14 (0.15-0.33)	0.49 (0.33-0.73)	0.067	12	0.29	45.9	61.3	3.84	1	19.1
Monte Scoperta	279(205-332)	68.0 (68.0-108.3)	0.23 (0.22-0.35)	0.29 (0.10-0.57)	0.099	8	0.52	61.7	66.9	7.90	2	17.5
Monte Barro	226(123-323)	44.1 (39.9-105.8)	0.15 (0.17-0.28)	0.60 (0.43-0.80)	0.068	12	0.31	36.8	60.7	2.97	1	41.5
Cansiglio	268 (199-320)	74.3 (72.6-111.2)	0.15 (0.17-0.28)	0.66 (0.55-0.73)	0	5	0.62	46.2	61.0	4.70	1	43.5
Valzurio	185 (114-308)	41.1 (44.8-120.6)	0.22 (0.23-0.46)	0.28 (0.03-0.56)	0.439	8	0.27	42.3	61.7	4.39	2 (neg.2nd)	21.6

[1] **MW**: mean ring-width; **SD**: standard deviation; **MS**: mean sensitivity; **A_1**: autocorrelation of first order; **LAR**: percent of the measured local absent rings; **N**: number of trees considered for the common period analyses; **ACBT**: average correlation between trees; **PC1**: amount of variance explained by first principal component of the ring-width measures; **GLK**: mean percentage of agreement coefficient between trees; **t BP**: mean value of Baillie-Pilcher t test between trees; **p**: order of the autoregressive model used to obtain the pre-whitened chronology; **VAR**: % of variance explained by AR model (period 1925-1988).

Table 5
Correlation coefficients between chronology statistics (see Tables 1 and 3 for acronyms) and forest site features for (A) the 24 beech chronologies of the Italian peninsula, and (B) the 17 chronologies of central Italy (bold: p <0.01; italic: p <0.05)

	Latitude	Longitude	Elevation	DBH_{max}	H	LENGTH	N_{max}
A							
MW	0.15	-0.29	**-0.55**	-0.23	0.11	**-0.59**	**-0.59**
SD	0.02	-0.13	*-0.43*	-0.31	-0.02	**-0.61**	**-0.64**
MS	-0.32	*0.44*	0.35	0.09	-0.21	0.41	0.34
A1	0.07	-0.24	*-0.43*	-0.29	0.17	*-0.49*	*-0.46*
LAR	0.28	-0.35	0.34	0.03	-0.02	*0.49*	0.37
ACBT	0.05	0.04	0.14	-0.26	0.06	-0.09	-0.13
PC1	-0.24	0.35	0.15	-0.06	*-0.46*	-0.22	-0.16
GLK	**-0.52**	**0.53**	0.27	-0.18	-0.04	0.23	0.20
t BP	0.01	0.09	0.09	-0.11	-0.05	0.02	-0.04
p	-0.35	0.27	-0.17	0.40	*0.43*	0.27	0.24
B							
MW	-0.22	-0.31	**-0.60**	-0.17	0.15	*-0.59*	**-0.60**
SD	-0.36	-0.24	-0.47	-0.21	-0.02	**-0.63**	**-0.63**
MS	0.29	0.35	**0.61**	0.11	-0.31	*0.53*	*0.55*
A1	-0.11	-0.45	*-0.54*	-0.26	0.06	*-0.59*	*-0.59*
LAR	0.18	-0.04	0.43	-0.07	0.14	**0.65**	*0.58*
ACBT	-0.23	-0.05	0.27	-0.10	0.15	-0.13	0.05
PC1	-0.28	0.26	0.20	-0.06	-0.46	-0.22	-0.14
GLK	-0.06	*0.50*	0.47	-0.13	-0.19	0.22	0.29
t BP	0.36	0.03	0.32	-0.01	0.12	0.16	0.21
p	-0.04	-0.18	-0.19	*0.49*	*0.55*	0.29	0.34

(Piovesan et al., 2005). Maximum age of beech trees almost doubles going from low- to high-elevation stands (Table 1), even though anthropic influences and management practices probably contribute to this difference. Since old trees have smaller ring widths, and MW is positively correlated to SD ($r = 0.87, p < 0.001$), higher sites also tend to have lower year-to-year variability (Table 5). Locally absent rings were frequently observed at higher elevations and in older stands, but significant correlation occurs with maximum age considering the central Italy chronologies.

Indices of common variability in tree-ring chronologies were also correlated with measures of forest structure and spatial location (Table 5). The amount of variance explained by the first principal component of each site chronology was negatively correlated with maximum tree height (H), possibly because in fertile sites climate becomes less limiting for radial growth, and the among-trees coherence of ring-width variability decreases. The GLK is correlated negatively to latitude and positively to longitude, suggesting that climate affects beech growth to a greater extent going from north to south and from west to east within the Italian peninsula. Finally, a positive correlation exists between the order of the fitted AR model and indicators of forest structure, i.e. maximum tree diameter and, especially, maximum tree height. This is consistent with a similar relationship previously found between order of the autoregressive model and tree age (Biondi and Visani, 1996). For AR models of order > 1, the second-order parameter estimate was negative in almost all chronologies (Table 4), confirming the inverse link between increments at 2-year intervals uncovered in other studies of beech tree-ring records (Biondi, 1993; Biondi and Visani, 1996). Because flower primordia develop the year before seeds are produced, and mast production can reduce radial increment in mature beech trees (Holmsgaard, 1955; 1962), the observed negative biennial autocorrelation is most likely related to the interplay among tree growth, climate, and mast production (Piovesan and Adams, 2001).

Groupings among tree-ring chronologies identified by cluster analysis were mainly consistent with geographic location, so that sites near one another and at a similar elevation were placed in the same group (Fig. 2). For instance, chronologies ORI, FOG, and VEN were clustered together, with FOG and VEN showing major affinity. These three sites belong to the warm sub-zone of the *Castanetum* in northern Latium (Table 2), and MBA, a northern Italy hilly site of the cold *Castanetum*, shows more affinity with this cluster than with any other one. Another cluster comprises PPO, TOC, TER, PNA, and VCH, which belong to the cold *Fagetum* in central and southern Italy. Major similarities were found between PNA and VCH, and between PPO and TOC. The VCL is also included in this group, although it is classified as warm *Fagetum*. A third cluster is the most numerous, and comprises mainly chronologies from the warm sub-zone of *Fagetum* in central Italy (CIM, SAB, BSA, PIZ, MOR, ROS, LEP, MAI and PET). In this group, major affinity is found between BSA, PIZ, MOR, ROS and LEP. The PET is slightly different, probably because of its proximity to the Tyrrhenian Sea (Fig. 1). The FOU site, even if within the *Castanetum* zone, is linked to this group. The FOU is located on Monte Gargano promontory, an isolated mountain descending to the Adriatic Sea (Fig. 1) and characterized by altitudinally compressed vegetation belts (Falinski and Pedrotti, 1990). The MSC, BAD and CAN constitute a fourth cluster made of stands of the

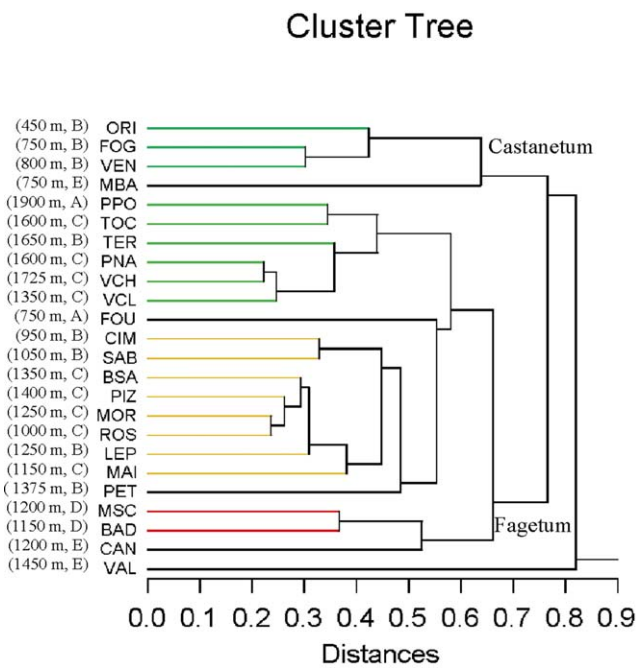

Fig. 2. Hierarchical clustering dendrogram of the 24 beech prewhitened chronologies over the common period 1925-1988 (see Table 1 for explanation of letter codes).

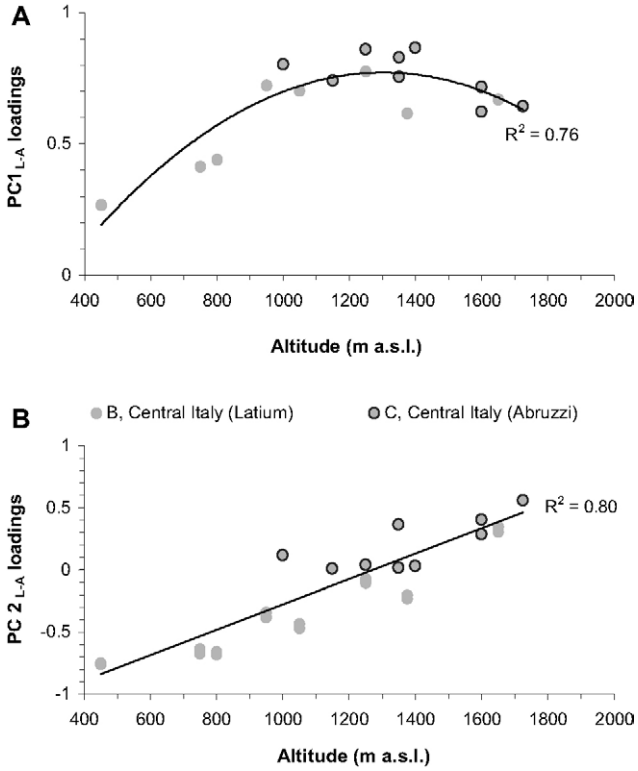

Fig. 4. $PC1_{L\text{-}A}$ (A) and $PC2_{L\text{-}A}$ (B) loadings plotted against altitude. Grey scales refer to the regions in Table 1.

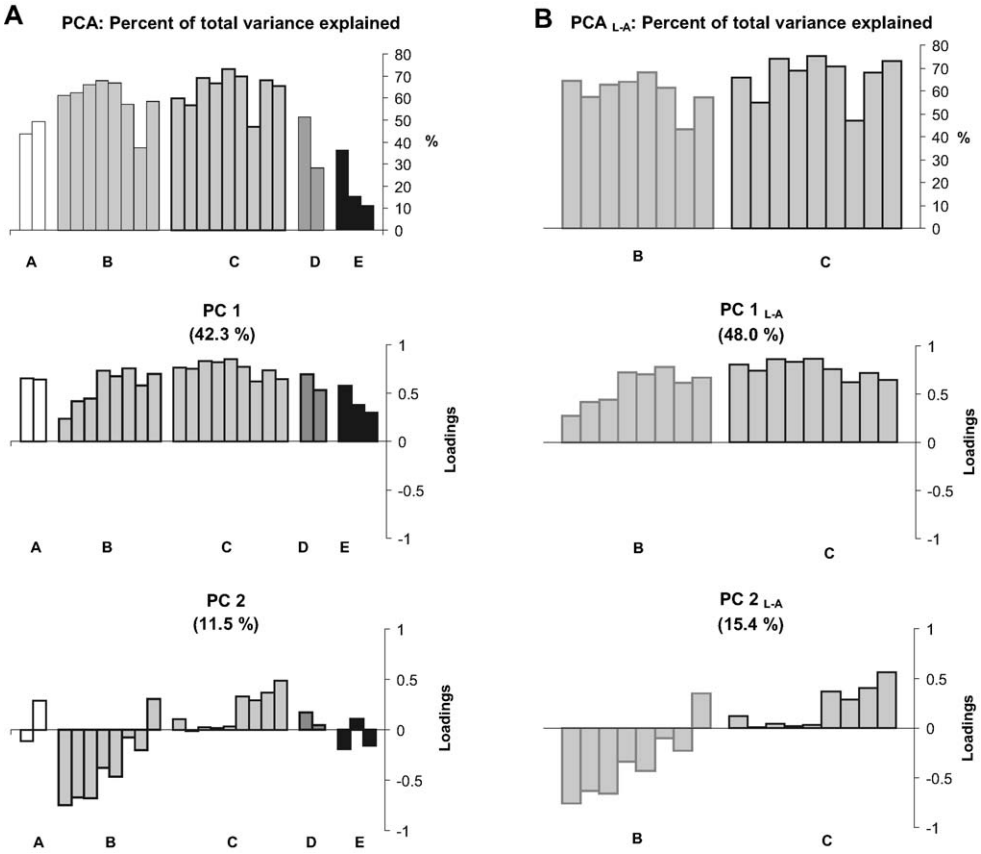

Fig. 3. Eigenvalues (% of explained variance) and eigenvectors (loadings) of the first two principal components for (A) the 24 beech chronologies, and (B) the 17 central Italy chronologies. Data are grouped in regions (see Table 1 for explanation of letter codes) from south (left) to north (right), and ordered inside each group from lower (left) to higher (right) elevation.

warm *Fagetum* in the northern Apennines and the Alps. The VAL, which belongs to the cold *Fagetum* in the Alps, is isolated from any other cluster, showing no particular affinity with the rest of the network.

For the common interval 1925-1988, the first two principal components accounted for 53.8% of the total variance in the 24-chronology network (PC1 and PC2; Fig. 3A), and for 63.4% of the variance in the 17 chronologies from Latium-Abruzzi ($PC1_{L\text{-}A}$ and $PC2_{L\text{-}A}$; Fig. 3B). The PC1 and $PC1_{L\text{-}A}$ loadings are always positive, and reach the highest values for mountainous sites in the central Apennines (Figs. 3 and 4A). The PC2 and $PC2_{L\text{-}A}$ mainly separate the low-elevation sites from the high-elevation ones (Figs. 3 and 4B). Principal component scores are almost identical for PC1 and $PC1_{L\text{-}A}$, as well as for PC2 and $PC2_{L\text{-}A}$, with a linear correlation of 0.99 and overlapping time-series patterns (Fig. 5).

3.2. Radial growth-climate relationship

Dendroclimatic analyses focused on the Latium-Abruzzi (L-A) region. The $PC1_{L\text{-}A}$ is correlated with current summer, directly with precipitation and inversely with temperature, especially maximum temperature (Table 6A). Another significant positive correlation exists with previous winter (December) precipitation. Response functions confirmed the central role of summer climate, especially during June and July (Table 6B). The $PC2_{L\text{-}A}$, which contrasted low- and high-elevation sites (Fig. 4B), was negatively correlated with late spring precipitation (May-June) and positively correlated with May-August temperature (Table 6A). Response functions pointed to May temperature as the main climate signal (Table 6B).

Synoptic analysis of the correlations between summer climate (precipitation and temperature) and PC1 scores showed that central-southern Italy is the region most influenced by summer climate (Figs. 6A and 7). December precipitation was correlated to PC1 especially over the central-northern Apennines (Fig. 6B). Correlation maps drawn separately for different pressure levels (Fig. 7) indicated a stronger summer temperature signal at 925 mb (~760 m a.s.l.) and 850 mb (~1460 m a.s.l.), in agreement with the average elevation (1200 m a.s.l.) of the network. Correlation between $PC2_{L\text{-}A}$ and May temperature extends over the Italian peninsula, and reaches its maximum in northern Latium (Fig. 8), where several low-elevation chronologies are located.

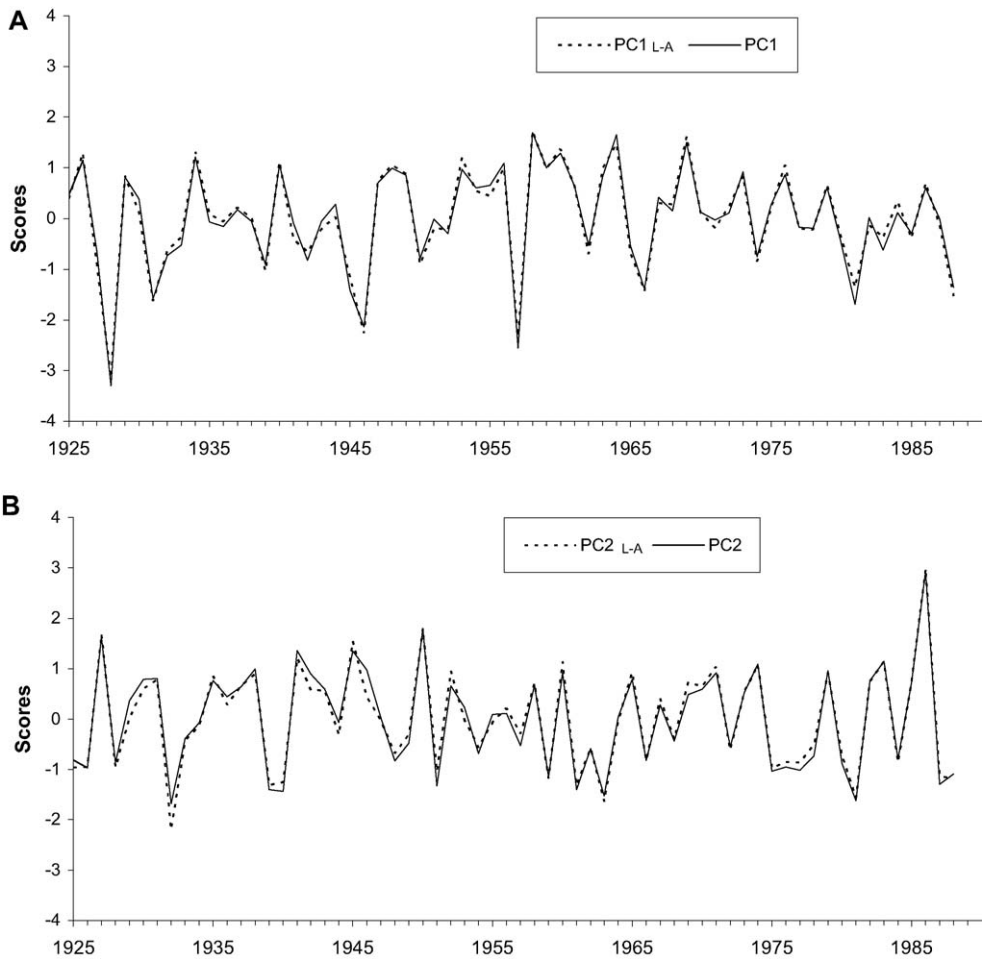

Fig. 5. Time series plot of the first two principal component scores for the whole Italian tree-ring network (24 chronologies, PC1 and PC2) and for the central Italy sub-set (17 chronologies, $PC1_{L\text{-}A}$ and $PC2_{L\text{-}A}$). (A) First principal component scores; (B) Second principal component scores.

Table 6
Significant values (p <0.05) of bootstrapped (A) correlation, (B) response functions calculated between principal component scores of the chronologies of central Italy and the regional climatology (period 1929-1988)

A

		Year preceding growth				Year of growth									
		SEP	OCT	NOV	DEC	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
$PC1_{L-A}$	P				0.31						0.40	0.31	0.28		
	Tmed										-0.26	-0.30	-0.35		
	Tmax										-0.28	-0.29	-0.36		
	Tmin											-0.29	-0.30		
$PC2_{L-A}$	P								0.22	-0.29	-0.27				-0.25
	Tmed									0.41	0.38	0.36	0.31		
	Tmax									0.42	0.36	0.31	0.26		
	Tmin									0.34	0.37	0.39	0.34		

B

		Year preceding growth				Year of growth									
		SEP	OCT	NOV	DEC	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
$PC1_{L-A}$	P				0.20						0.21	0.23			
	Tmed									0.27					
	P				0.22						0.20	0.21			
	Tmax									0.26					
	P				0.27						0.22	0.26			
	Tmin									0.22					
$PC2_{L-A}$	P														
	Tmed									0.20					
	P														
	Tmax									0.22					
	P														
	Tmin														

4. Discussion

Despite the ecological complexity of Italian beech forests (Pignatti, 1998), a number of patterns identified in the beech tree-ring network are clearly related to geographical differences in climatic regimes. Hierarchical clustering and principal component analysis of tree-ring chronologies generated distinct beech forest types. For each of those types, correlation between principal component scores and climate data revealed the most important climatic signals and their spatial extension. In agreement with previous studies (Biondi, 1992; Biondi and Visani, 1996; Dittmar et al., 2003), distinctive radial growth-climate relationships uncovered in the tree-ring network are organized along altitudinal and latitudinal gradients. With regard to latitude, central and southern forests were clearly separated from northern ones.

In central Italy, bioclimatic zones (Fig. 2) are distributed along an elevation gradient, and agree with those (*Castanetum* and *Fagetum*) proposed by Mayr-Pavari (De Philippis, 1937). Three major types of beech forests could be distinguished: low-elevation, mountainous, and high-elevation. Low-elevation beech forests (400-800 m a.s.l.) are typically located on fertile (e.g., volcanic) soils, in foggy areas near lakes (Vico and Bracciano). These stands can be ascribed to the *Castanetum* belt, and to the phytosociological unit *Aquifolio-Fagetum* (Pignatti, 1998). This association, with abundant *Ruscus aculeatus* in the understory, has structural and floristic affinities with other warm-temperate beech forests (Peters, 1997). In these environments, beech trees leaf out early in the spring, and are favoured by a wetter and cooler May. Deciduous oak species in the Latium region display similar climatic controls (Romagnoli and Codipietro, 1996). The cardinal role of May climate on low-elevation beech forests has also been reported for central and eastern Europe (Dittmar et al., 2003). This may help explain the significant correlations between Alpine and central Apennine low-elevation chronologies.

Mountainous beech forests (from 1000 to 1400 m a.s.l.), which are enclosed in the warm *Fagetum* belt of Mayr-Pavari, belong to different syntaxa (e.g., *Aquifolio-Fagetum*, *Polysticho-Fagetum*). In some cases, the vegetation is characterized by the occurrence of the evergreen *Taxus baccata* (for instance, at sites LEP, MOR, ROS, PIZ; Fig. 1) and *Abies alba* (e.g., site ROS) (see Laurent et al., 2004). In the cluster analysis, those stands are grouped together (Fig. 2). Considering the limited geographic distance between them (Fig. 1), it follows that patterns of tree-ring variability separated beech vegetation types at a fine spatial scale. In this altitudinal belt, trees leaf out at the beginning of May, when they are susceptible to the occurrence of late spring frost. However, the main factor limiting radial growth is water deficit during the summer, especially June and July (Biondi, 1993; Piovesan and Schirone, 2000). In the Apennines, this beech forest type extends north, reaching the limit of the Mediterranean region (Pignatti, 1998). Mountainous northern Apennines chronologies have greater affinities with the Alpine mountainous ones

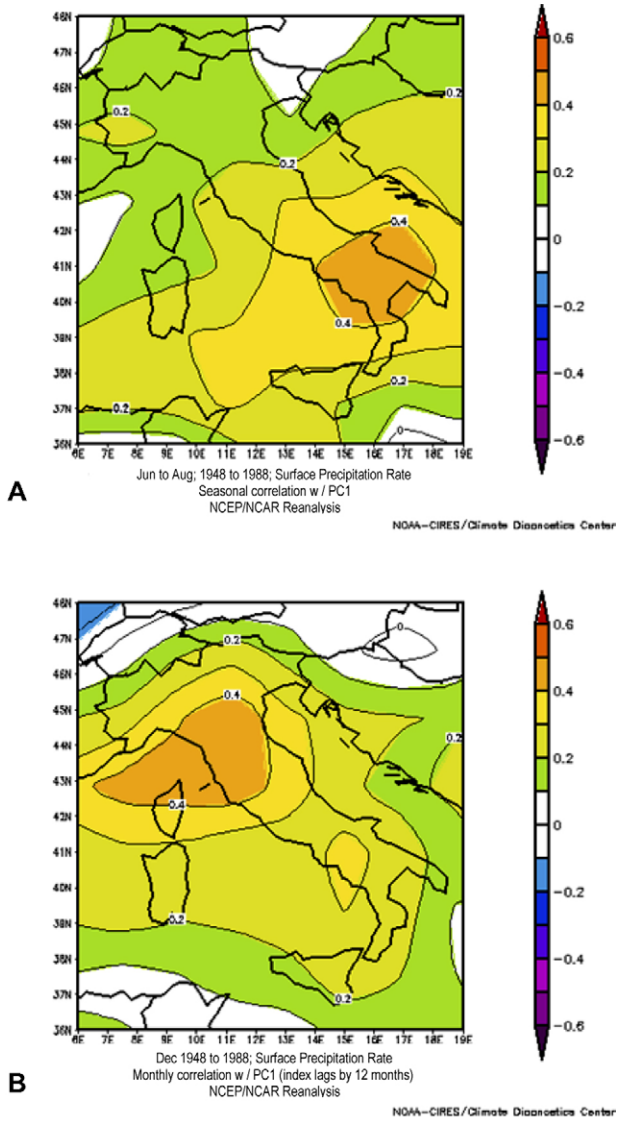

Fig. 6. Interpolated correlation maps between PC1 scores and (A) gridded summer precipitation, (B) previous December precipitation.

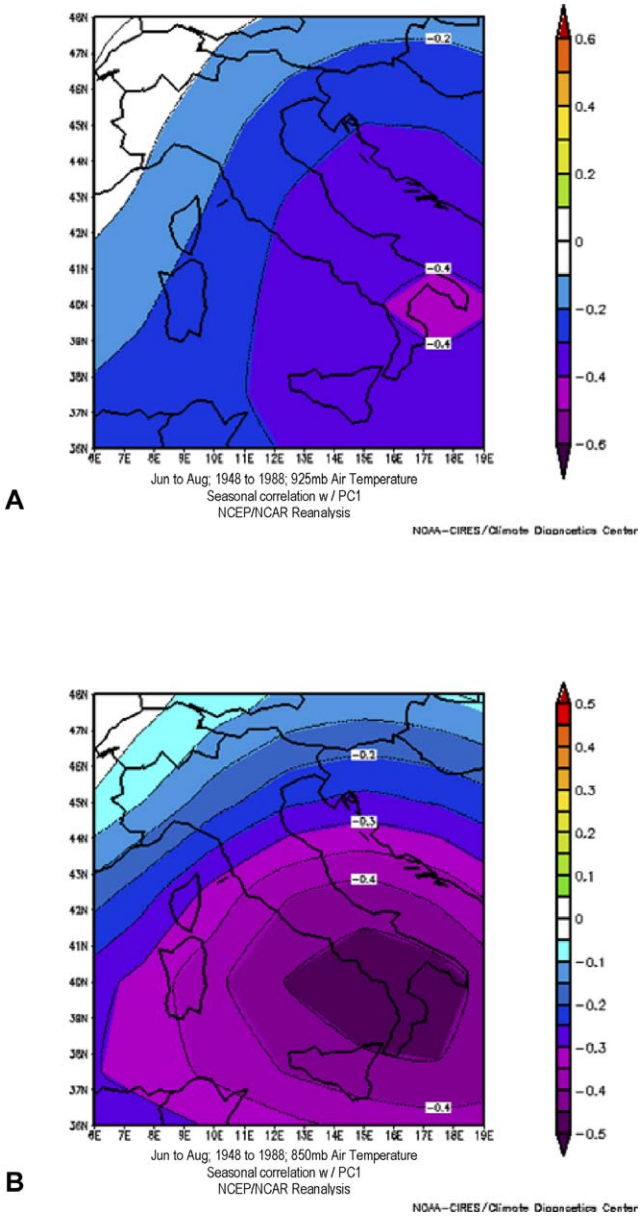

Fig. 7. Interpolated correlation maps between PC1 scores and gridded summer temperature at (A) 925 mb, (B) 850 mb.

than with those in central Italy. This result is consistent with the phytosociological characters of beech forests in the northern Apennines and Alps (Pignatti, 1998). High-elevation beech forests of central-southern Italy (from 1550 to 1800-2000 m a.s.l.) can be ascribed to the cold *Fagetum*. This vegetation type reaches elevations in excess of 2000 m a.s.l. on Mount Etna in Sicily (Piovesan et al., unpublished data). These stands are characterized by beech dominance in the overstory, and by an impoverishment of herbaceous species (Schirone et al., in press). In southern Italy, PPO is well within the high-mountain vegetation type.

The beech network, currently dominated by Apennine mountainous beech forests, exhibits strong common variability of annual growth. As pointed out by other authors (Biondi, 1993; Biondi and Visani, 1996; Piovesan and Schirone, 2000; Dittmar et al., 2003; Piovesan et al., 2003), summer drought is the key climatic factor that affects beech growth, especially in central-southern Italy. The importance of summer drought as a bioclimatic indicator means that mountainous sites in the central-southern Apennines fall within the Mediterranean region, although their climate is often classified as temperate, as was recently done by Blasi et al. 1999. The correlation maps between PC1 scores and summer temperature or precipitation delineated two regions, one Northern or Continental, the other Central-Southern or Peninsular. This is in agreement with vegetation (Pignatti, 1979) and climatic studies (Brunetti et al., 2004), which draw a boundary approximately at the latitude of Monte Conero, near Ancona, where the border between the Mediterranean and the temperate cold region is also located (Daget, 1977; Pignatti, 1979). Our results have therefore confirmed the northern Apennines as a zone of transition between two bioclimatic types. In that region, the positive response to December precipitation could have an important role in synchronizing tree-ring variability.

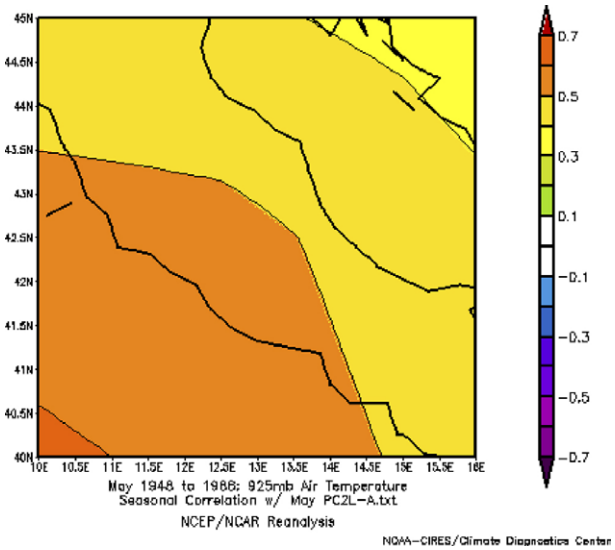

Fig. 8. Interpolated correlation maps between PC2 $_{L\text{-}A}$ scores and gridded May temperature at 925 mb.

Winter precipitation, mediated by the NAO, contributes to water availability during the growing season through soil water recharging (Biondi, 1993), and may also affect the low frequency component of tree-ring chronologies (Piovesan and Schirone, 2000). Since network density is greatest in central Italy, a more articulate analysis of climate relationships can be provided for the Latium-Abruzzi (L-A) area.

In central Italy, $PC2_{L\text{-}A}$ revealed a gradual transition of forest types along the altitudinal gradient, which spans 1275 m. This is consistent with published relationships between climate and vegetation in the same region (Blasi et al., 1999). Temperature is a key factor for explaining the differences between hilly and mountainous sites. Low-elevation beech forests have a distinct late spring climate signal, which is opposite to that of high-elevation sites. This opposite dendroecological behavior between low and high altitude beech stands was previously observed in central Europe, where it extends to summer months (Dittmar et al., 2003). Phenological observations have shown that beech growing season decreases with increasing elevation (Lausi and Pignatti, 1972), so that the role of May as the turning point between dormant-bud bursting and growing period changes with elevation. During May at the lower-elevation sites, thanks to a higher temperature regime, trees have the crown completely developed, so that a warm-dry late spring can cause water stress, while at the upper-elevation sites mild temperatures are needed to protect the bud burst and foliage from late spring frost. Since Italian climate is becoming warmer and drier (Brunetti et al., 2004), future climatic influences on beech physiology could be predicted using sophisticated phenological models (Schaber and Badeck, 2003).

Genetic control has been proposed for time of leaf formation in beech (Borghetti and Giannini, 1982). However, a study on genetic variability of 21 Italian populations of beech found no association between allele frequencies and altitude (Leonardi and Menozzi, 1995). In central Europe, beech genetic diversity is indeed related to elevation (Sander et al., 2000). During the last Ice Age, central-southern Italy was a centre of refugia for temperate forest species (Tallis, 1990), but the size of such refugia is not completely known, especially in relation to altitudinal gradients. Divergent occupation of space should affect the genetic diversity of populations, especially since the last Ice Age (Comps et al., 2001). Further research is needed to clarify if the reported altitudinal pattern identified by our dendroecological approach has a genetic component or if it is an expression of phenotypic plasticity of the species. In the latter case, beech could then be considered an ideal bioindicator. In other words, tree-ring networks would result in a classification of forest types based on quantitative ecology and life history parameters, and this classification would become the starting point for the selection of material used in genetic and provenance studies.

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