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Climate Effect on Radial Growth of *Pinus sylvestris* at Its Southern and Western Distribution Limits

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The associations between tree-ring width and climatic variables, the tree age effect on climate-growth relationship and the drought index impact on radial growth of Scots pine (*Pinus sylvestris* L.) were studied in Mediterranean environments in the Iberian Peninsula. Dendrochronological techniques were applied to construct six tree-ring width chronologies for *P. sylvestris*. The association between tree growth and climate was analysed with correlation coefficients and bootstrapped response functions. Drought index (DRI) was used to detect the effects of aridity. Tree-ring width was positively correlated with rainfall in the growing season but this association stated earlier at the lowest altitudinal sites. The effects of temperature varied according to the site. The response to climatic variables depended on the age of the trees: more of the variability was explained by climatic variables in young stands than in old stands. The significant association between radial growth and DRI suggests that drought is a determining factor in the radial growth of *P. sylvestris.* Climate forecast scenarios show an increase in rainfall irregularity in the Mediterranean region so the differential tree response to rainfall at different elevations can be used to predict tree growth for determining silvicultural treatments.

Keywords dendroclimatology, Scots pine, tree ring, pulse and interpulse
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1 Introduction

Growth-climate relationships are crucial in understanding and modelling the carbon sequestration process in forests and in developing forestry strategies to mitigate the impact of climate change. Different methodological approaches can be used to explore tree growth-climate relationships, but dendroclimatological studies are valuable tools in detecting long-term changes in radial growth in woody species in association with variable climatic responses, as a result of warmer conditions and variable precipitation (Andreu et al. 2007). Extreme sites, such as the upper tree line or dry sites, are considered the most valuable for dendroclimatological studies because there are fewer determining factors, which enables a better interpretation of growth patterns (Fritts 1976).

In arid and semi-arid ecosystems, where water is a limiting resource, water availability undergoes two different phases: pulse, when the resource is available, and interpulse, when water availability is too low for plant use (Noy-Meir 1973, Goldberg and Novoplansky 1997). Mediterranean environments in the Iberian Peninsula, which are water limited ecosystems, are characterised by summer droughts and high interannual variability in precipitation and temperature. In summer months, when temperature is favourable for growth, moisture is limiting; whereas in winter, when moisture is available, low temperature limits further growth (Mooney and Dunn 1970).

Scots pine (*Pinus sylvestris* L.) is the most widely distributed pine species throughout the world (Blanco et al. 1997) and represents one of the most important dendroecological species in Europe (Schweingruber 1996). *P. sylvestris* is one of the most important tree species in Spain in terms of both, the covered area (1 280 000 ha) and the diverse functions of stands of species (Montero et al. 2008). Forests of *P. sylvestris* in Spain occupy the southern and western limits of the worldwide distribution of the species (Barbéro et al. 1998), in assessing the impact of global warming on ecosystems, any changes in tree growth are likely to occur first in those tree stands located at the ecological boundary of the species (Tessier et al. 1997).

The forecasted impact of climate change on the diversity and distribution of European higher plants for the year 2050 indicates that Spain could be one of the most vulnerable areas in terms of species loss, mainly because of the expected variability in climatic conditions (Bakkenes et al. 2002). Previous studies in the Iberian Peninsula concluded that, under severe dry conditions, shrub species that evolve under Mediterranean climate conditions, are more severely damaged by drought than the earlier evolved pre-Mediterranean genera, mainly trees (Peñuelas et al. 2001); furthermore among pine species, *P. sylvestris* displayed the highest mortality rate under severe droughts in the 1990s (Martínez-Vilalta and Piñol 2002).

On the other hand, age-related ecophysiological changes in trees (Bond 2000, Bond and Franklin 2002) also indicate the importance of considering tree age in climate-growth response analysis. Contradictory results have been reported for tree age and growth-climate responses, for different species analysed: for example, no differences were found between young and old specimens of *Pinus aristata* Engelm (Fritts 1976) or *Larix lyalii* Parl. (Colenutt and Luckman 1991), but climate effect was found to have a greater effect on old specimens of *Larix decidua* Mill. and *Pinus cembra* L. in the Italian Alps (Carrer and Urbinati 2004) and of *Abies lasiocarpa* (Hook.) Nutt. in North America (Peterson and Peterson 1994), than on young specimens. Previous dendroclimatological studies of *P. sylvestris* in the Iberian Peninsula concluded that this species is vulnerable to variation in rainfall during the growing season (Guttierrez 1990, Richter et al. 1991, Fernández et al. 1996), although the authors did not establish the effect of age on climate response.

Although predictions obtained with climate models are not wholly accurate, it is clear that future climate conditions may be characterised by greater extremes and perhaps more erratic fluctuations, with potentially strong effects on interannual to intraseasonal variability in rainfall (Schiwinning et al. 2004). It is therefore essential to understand how different species may be affected by temporal variations in water supply (Easterling et al. 2000). Furthermore, in arid and semiarid environments, it is essential to interpret short-term responses of individuals and populations to precipitation (Chesson et al. 2004). Different responses of species to changes in intra-season recharge have been reported for grasses and shrubs (Jobbágy and Salas 2000, Oesterheld et al. 2001) and for annual species that grow in Mediterranean environments (Sher et al. 2004), but to our knowledge, no studies have been carried out to investigate the effects of pulse-interpulse events on the growth of woody species in Mediterranean environments in the Iberian Peninsula.

The objectives of this paper were to analyse on *P. sylvestris* a) the relationship between *P. sylvestris* tree-ring width and climatic variables (precipitation and temperature), b) the association between climate and cambial age and c) the effects of the drought and the interannual water availability (pulse and interpulse) on radial growth.

2 Material and Methods

2.1 Study Sites, Field Work and Laboratory Methods

Six sites along the natural distribution area of *Pinus sylvestris* in the Iberian Peninsula were selected (Fig. 1, Table 1). Individuals older than 100 years old were present at three sites, and individuals younger than 100 years old at the other three sites. Usually, Scots pine trees in Mediterranean environments are harvested at 120 years (maximum) so it is not easy to find trees over 140 years in the studied area.

In the summer of 2006, two cores were extracted at 1.30 m above ground level from fifteen dominant and co-dominant trees at each sampling site. Cores were glued onto channelled wood, dried for two weeks and polished with progressively finer grade sandpaper. Tree rings were dated, in order to establish the calendar year in which a tree ring was formed, by analysis of samples under a binocular microscope by standard dendrochronological techniques (Stokes and Smiley 1968, Fritts 1976, Cook and Kairiukstis 1990). The transverse sections (cores) were scanned at high resolution (2000 dpi) with an Epson Expression 1640 XL scanner (precision, 0.01 mm) and rings were measured with WinDENDRO software (Regent Instrument Inc. 2002). The v6.06P COFECHA program (Holmes 2001, Grissino-Mayer 2001, available at www.ltrr.arizona.edu) was applied to

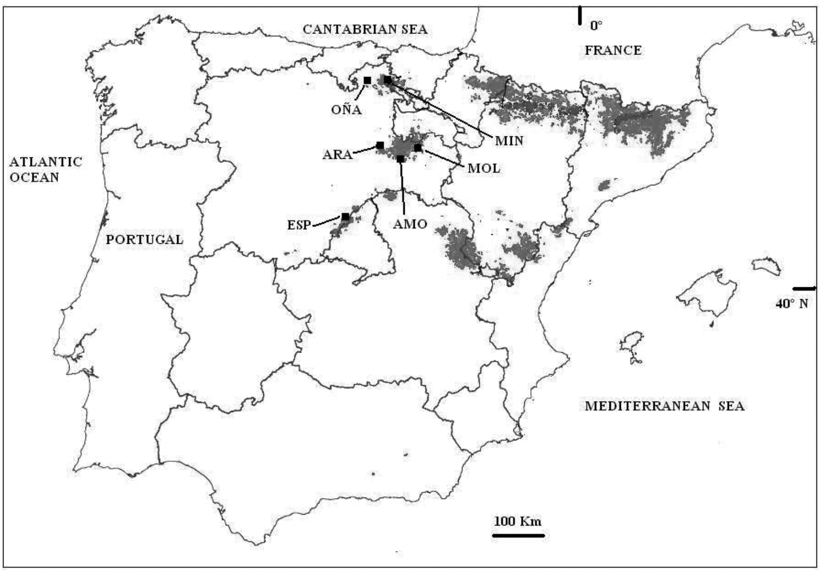

Fig. 1. Sampling sites set up across the natural distribution area of *Pinus sylvestris* woodlands in Spain [Shaded area (Catalán 1991)]. Site codes: MIN: *Miñón*; OÑA: *Oña*; ESP: *El Espinar*; MOL: *Molinos Piqueras*; AMO: *Amogable*; ARA: *Arauzo*.

Table 1. Geographical position of six sampling sites of *Pinus sylvestris* in the Iberian Peninsula.

Site name	Code	Latitude N	Longitude W	Altitude (m.a.s.l.)
Miñón	MIN	42°54´46˝	03°21´27˝	860
Oña	OÑA	42°58´22˝	03°18´12˝	760
El Espinar	ESP	40°38´58˝	04°12´07˝	1426
Molino Piqueras	MOL	42°04´36˝	02°30´18˝	1676
El Amogable	AMO	41°50´44˝	02°55´48˝	1134
Arauzo de Miel	ARA	41°53´04˝	03°21´32˝	1081

assess the accuracy of measurement and dating. This program calculates the Pearson's correlation indices between the indexed tree-ring series and a master reference chronology in a series of consecutive, partially overlapping segments of a length specified by the user.

The v6.05P ARSTAN program (Cook and Holmes 1984, Holmes 2001; available at www.ltrr.arizona.edu) was used to eliminate biological trends in tree-ring series and to minimize variations in growth that are not shared by most trees (Fritts 1976). Standardisation removes geometrical and ecological trends while preserving inter-annual high-frequency variations that are presumably related to climate. Each tree-ring chronology was standardised in two-steps by fitting first, to a negative exponential or straight line, and then to a cubic smoothing spline with a 50% frequency response of 64 years, which was flexible enough to reduce considerably any non-climatic variance (Cook and Peters 1981). The standardised series were averaged to obtain a master chronology for each study site by applying a biweight robust estimation of the mean value function (Cook et al. 1990). Finally, the chronologies were prewhitened by autoregressive modelling. Raw chronology conversion to a ring-width indices expressed the annual variations in radial growth of *P. sylvestris* at the population level in each sampling site. The quality of the chronology was evaluated by mean sensitivity (MS), signal-to-noise ratio (SNR), and expressed population signal (EPS), (Wigley et al. 1984, Fritts and Swetnam 1989, Briffa 1995, Schweingruber 1996). The tree-ring index was used to be compared with climatic variables.

2.2 Climatic Data

Monthly precipitation and mean monthly temperature, provided by the Agencia Estatal de Meteorología (National Meteorological Agency, Spain) were selected to assess the climate-growth relationship. Recorded meteorological data, that varied from 61 to 71 years, pertain to four meteorological stations placed at less than 30 km from the sampling sites: Miranda del Ebro (Burgos), Villafría (Burgos), Observatorio (Soria) and Aldea del Rey Niño (Avila) (Table 2, Fig. 2). Climatic series were considered homogeneous after applying the HOM (Homogeneity of Meteorological Data) routine of the DPL [Dendrochronology Programme Library (Holmes 1983; available at www.ltrr.arizona.edu)].

2.3 Growth-Climate Relationship Analysis

To determine the climatic variables that control the radial growth of *P. sylvestris*, mean monthly temperature and monthly rainfall were compared with the local chronologies for each sampling site. The local chronologies were compared with the meteorological station closest to the analysed site. The period explored was from June prior to the current growth year to September of the current growth year. The v 5.17 PRECON program (Fritts 1999; available at www.ltrr.arizona.edu) was used to compute the response of tree growth to climate, by means of a multiple stepwise regression. Coefficients were considered significant at $^*p<0.05$ and $^{**}p<0.01$. A bootstrap analysis, that estimates the error of the dataset by repeated random

Table 2. Meteorological data used in this study. Rainfall: annual precipitation; Temp.: mean annual temperature; Site: code of the sampling sites related to the meteorological station; Period: time with data available (Agencia Estatal de Meteorología, Spain).

Meterological station	Latitude	Longitude	Altitude) (m)	Rainfall (mm)	Temp. (°C)	Site	Period
Miranda del Ebro (Burgos)	42°40´42˝	02°57´20˝	520	529.97	12.08	MIN-OÑA	1936–2005
Villafría (Burgos)	42°21´22˝	03°37´57˝	890	564.67	10.15	ARA	1943–2005
Observatorio (Soria)	41°46´00˝	02°28´00˝	1082	529.85	10.59	MOL-AMO	1944–2005
Aldea del rey Niño (Avila)	41°34´35˝	04°42´02˝	1160	522.24	9.17	ESP	1935–2005

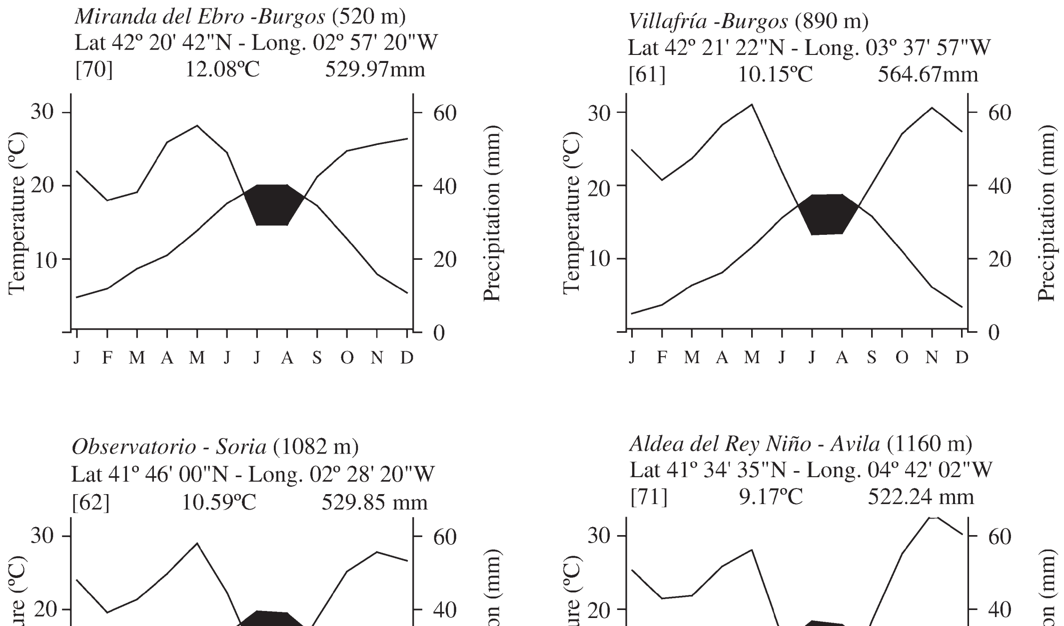

Fig. 2. Climate diagrams of Miranda del Ebro (Burgos), Villafría (Burgos), Observatorio (Soria) and Aldea del Rey Niño (Avila) meteorological stations.

sampling of the data as to increase the sample size artificially, was also applied to improve the robustness of the correlation coefficients. A total of 1000 bootstrap interactions were considered in the analysis (Mooney and Duval 1993).

2.4 Drought Index Effect and Pulse and Interpulse Analysis

The drought index (DRI) of Thornthwaite (1948) was applied to detect the pulse-interpulse effect on radial growth of *Pinus sylvestris*. The DRI at each sampling site was calculated from the months where the response function analysis showed a significant association between precipitation and radial growth (May and June at *Miñon*, *Oña* and *Arauzo de Miel* sites; June and July at *El Espinal* site; July at *Amogable* site and July and August at *Molino Piqueras* site).

The monthly DRI was calculated by the formula (Eq. 1):

$$DRI = P - PET \quad (1)$$

Where DRI is the drought index, P = monthly precipitation and PET = the potential evapotranspiration estimated from the monthly mean temperature and the geographical position of the meteorological station. The Pearson's correlation coefficient was calculated for DRI and tree-ring width (Sokal and Rohlf 1995).

3 Results

All six chronologies analysed (Fig. 3) displayed high SNR (10.67 – 24.74) and EPS values (0.91–0.96), while the variance accounted for the first eigenvector was over 35 % (Table 3). The mean sensitivity varied from 0.15 to 0.26 and the standard deviation from 0.18 to 0.35, depending on the sampling site.

The association between radial growth and climatic variables (mean monthly temperature and monthly precipitation) at the *Miñón* and *Oña* sites showed that rainfall in the growing season (May

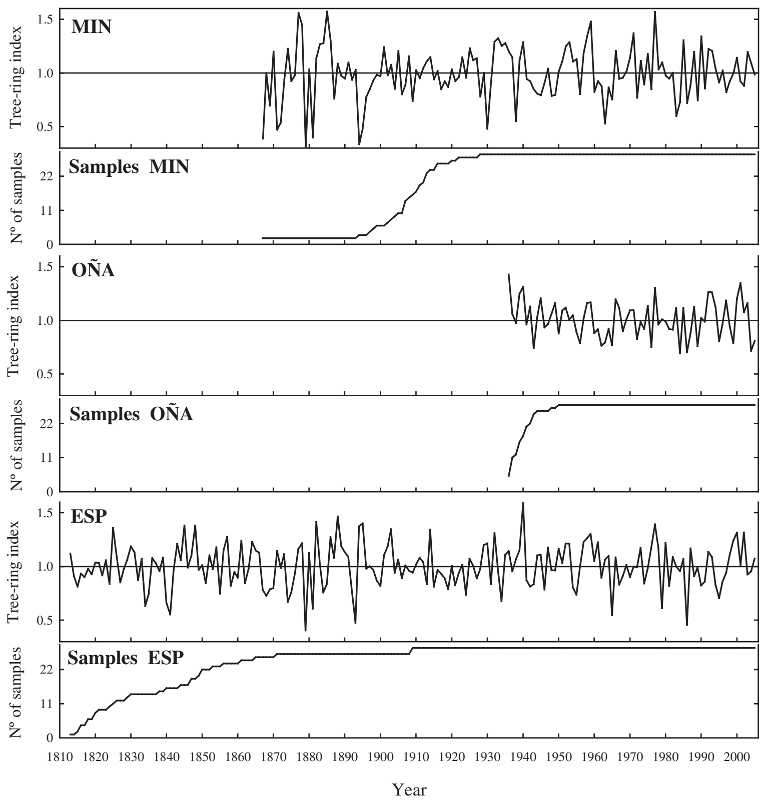

Fig. 3. Standardised chronologies of *Pinus sylvestris* along the natural distribution area in Central Spain. The upper part of each figure show the tree-ring indexes through time and the bottom part the number of samples used in each chronology.

Table 3. Descriptive statistic of the six chronologies of *Pinus sylvestris* in Spain. SD: standard deviation; MS: mean sensitivity; SNR: signal to noise ratio; EPS: expressed population signals. Var.: variance in first eigenvector and Mean. Corr.: mean correlation among trees.

	MIN	OÑA	ESP	MOL	AMO	ARA
Time span	1867–2005	1932–2005	1811–2005	1945–2005	1949–2005	1846–2005
Core number	29	28	29	30	30	24
Ring number	2956	1845	4803	1528	1538	4490
Age range	81–140	55–74	99–195	40–61	46–57	127–160
SD	0.28	0.18	0.24	0.35	0.19	0.30
MS	0.26	0.20	0.19	0.25	0.15	0.18
SNR	18.82	20.13	19.89	24.74	15.30	10.67
EPS	0.95	0.95	0.95	0.96	0.93	0.91
Var.	43.17	46.41	45.95	54.99	38.23	35.88
Cor.	0.40	0.43	0.43	0.51	0.34	0.30

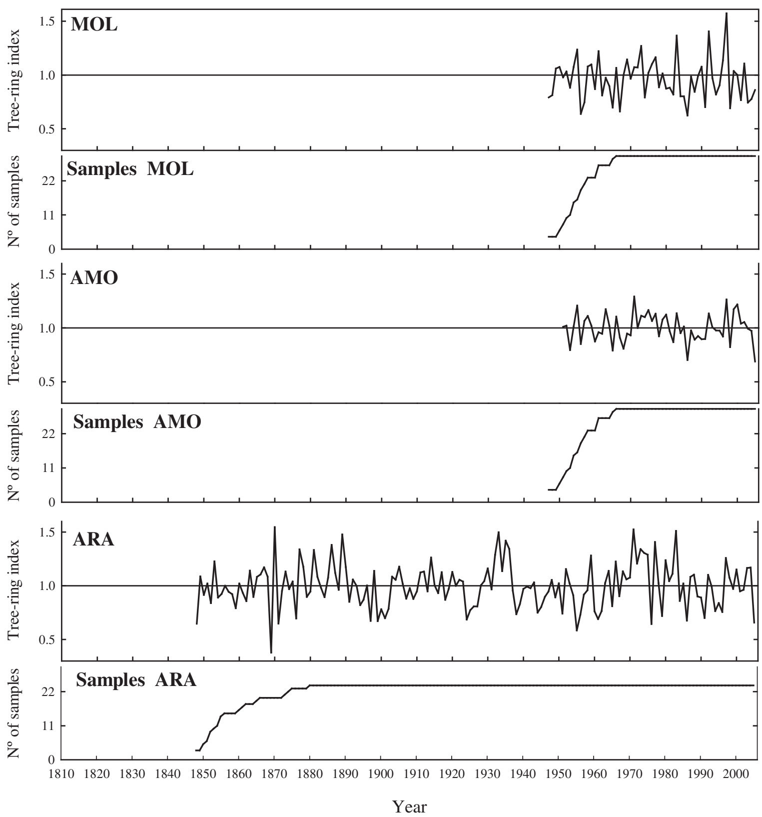

Fig. 3 continued.

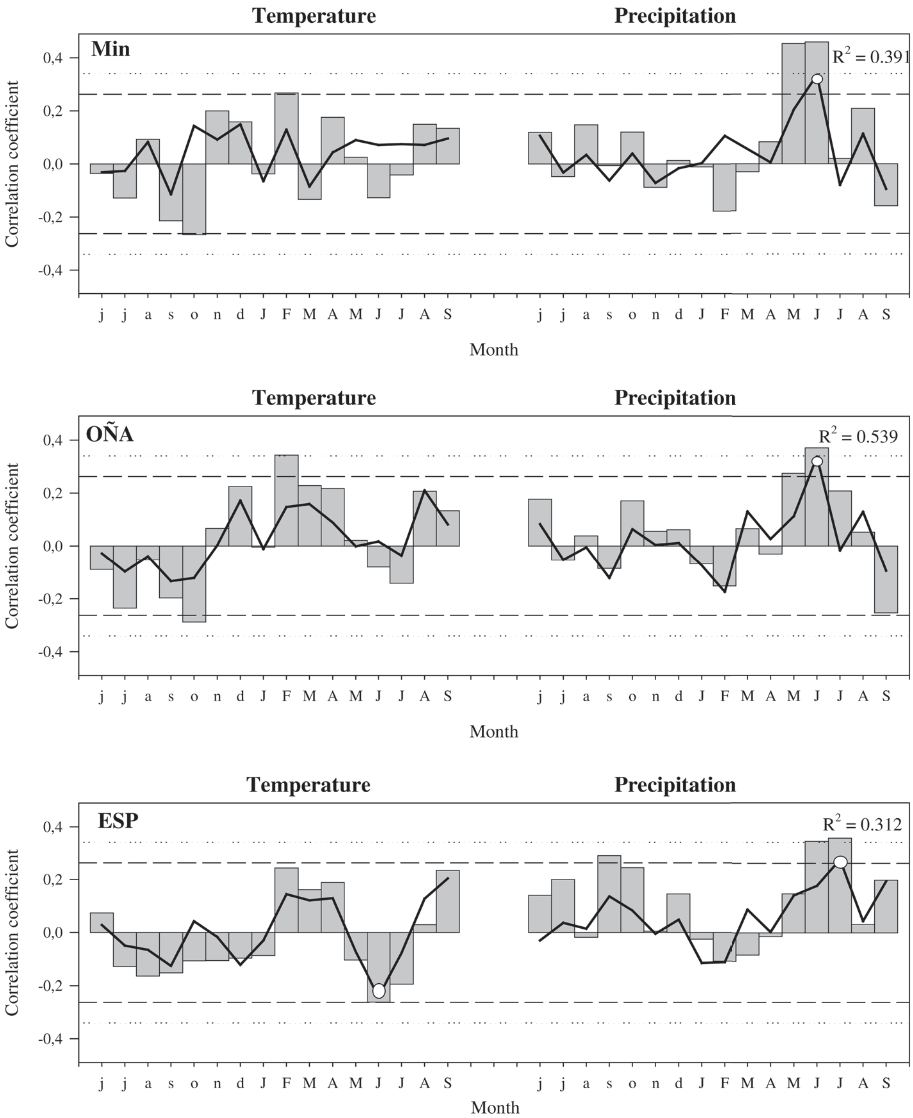

Fig. 4. Correlation coefficients (bars) and bootstrapped response function (lines) that relate the effect of regional climatic variables (mean monthly temperature – monthly precipitation) and growth of *Pinus sylvestris* during the 1950–2005 period at *Miñon, Oña; El Espinar, Molino Piqueras and Arauzo de Miel* sites. *Amogable* site was analysed from 1960–2005. The analysed period is from June of the previous growing season to September of the current growing season. Bars higher than the dashed lines show a significant coefficient at $p<0.05$. Bars higher than the dotted lines show a significant coefficient at $p<0.01$. White circles indicate the months where the bootstrapped response function coefficients are significant at $p<0.05$. R^2 values show the total variance explained by both variables. Lower case letters indicate the months prior to the growing season. Upper case letters indicate the growing season months.

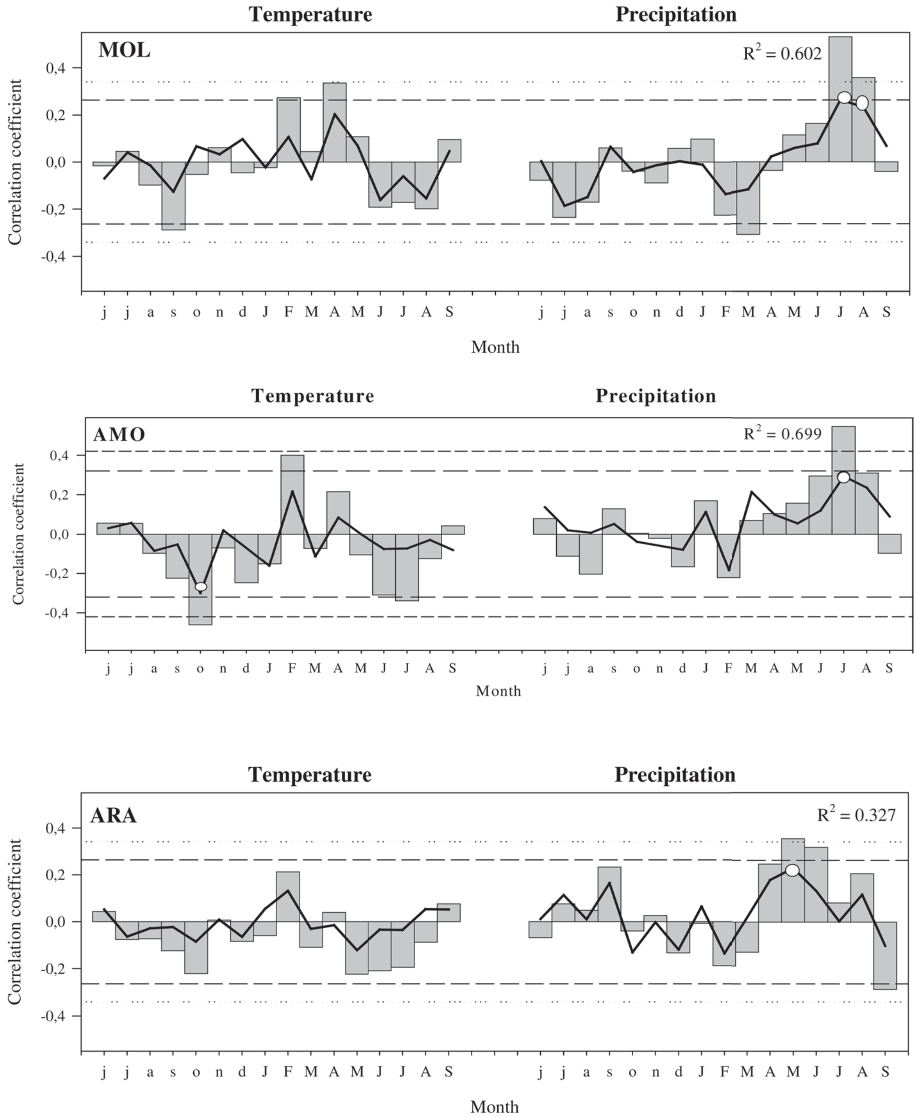

Fig. 4 continued.

and June) had a positive effect on growth of this species. On the other hand, temperature was positively correlated with radial growth in February and negatively in the October prior to the growing season (Fig. 4). The association between radial growth and climatic variables at the *El Espinar* site showed that rainfall during the growing season (June and July) had a positive effect on growth of this species. High temperatures during the growing season limited growth (Fig. 4). At the *Molino Piqueras* site, a positive relationship between growth and rainfall during the growing season (July and August) was observed; temperature was significantly, negatively related to growth in September, and positively in February and April prior to the growing season (Fig. 4). At the *Amogable* site there was also a positive relationship between growth and rainfall in the growing season (July), and between growth and mean temperature in February. Temperature limited growth in October prior to the growing season (Fig. 4). Finally, rainfall in May and June had a significant effect on growth at the *Arauzo de Miel* site (Fig. 4). The total variance explained by both variables ranged from 31.2% to 60.2%, according to the sampling site and the tree age (Fig. 4). The variance for the *Amogable* site was higher compare to the other sites analysed, although the study period was shorter than at the other sites [from 1960 to 2005 (Fig. 4)].

The age-dependent response to climate in the response function analysis indicated that young stands have higher variability explained by climatic variables (from 53 to 69%) than old stands [from 31 to 39% (Table 3, Fig. 4)]. The Pearson's correlation coefficient between tree-ring index and DRI revealed a significant association for all sampling sites [* $p<0.05$; ** $p<0.01$; *** $p<0.001$ (Table 4)]. By mean of an example, two chronologies from an old stand (*Miñon* site) and

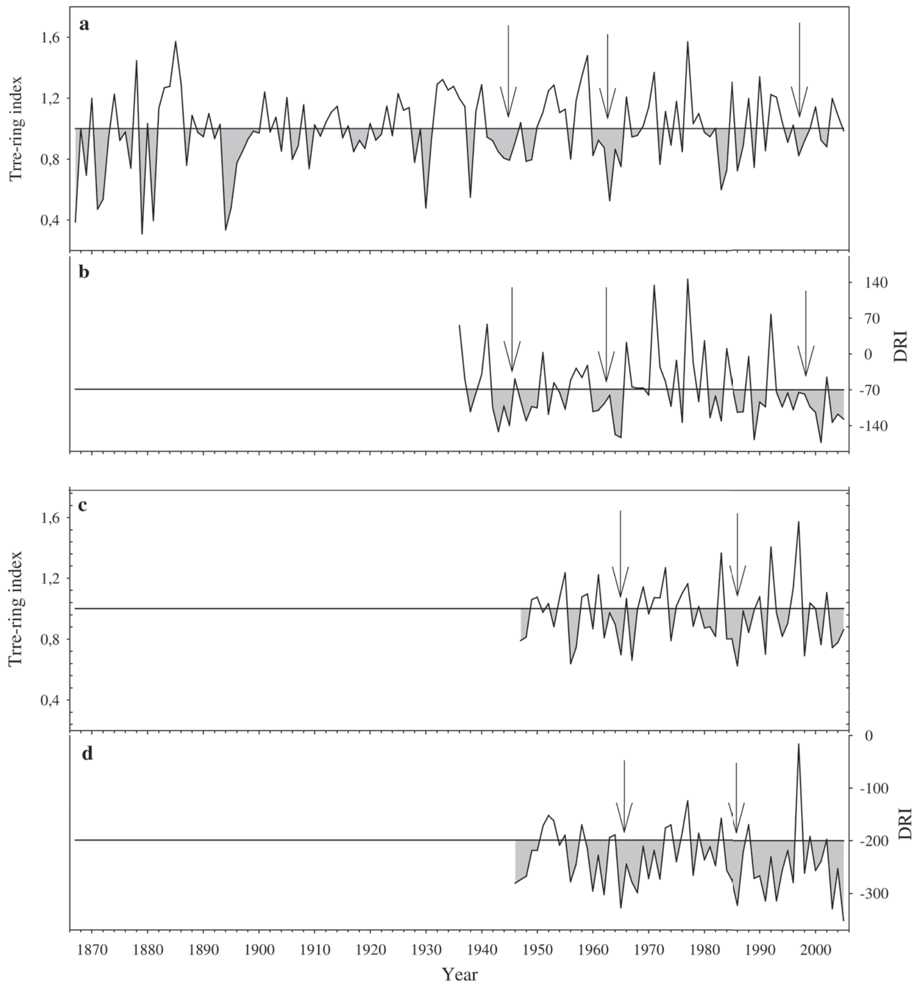

Fig. 5. Radial growth index of *Pinus sylvestris* at the *Miñon* site (a); May and June DRI from the Miranda del Ebro meteorological station (b) and radial growth index at the *Molino Piqueras* site (c); and July and August DRI from Observatorio, Soria meterological station (d). Arrows indicates low tree-ring growth that coincides with low DRI values.

Table 4. Pearson's correlation coefficient between tree-ring index of *Pinus sylvestris* and DRI (May and June at *Miñon*, *Oña* and *Arauzo de Miel* sites; June and July at *El Espinal* site and July and August at *Molino Piqueras* and *Amogable* sites) (* p<0.05; **p<0.01;***p<0.001).

	Period	Correlation
MIN	1936–2005	0.47***
OÑA	1936–2005	0.31**
ESP	1944–2005	0.31*
MOL	1944–2005	0.56***
AMO	1935–2005	0.46**
ARA	1935–2005	0.43***

a young stand (*Molino Piqueras* site) are represented (Fig. 5), illustrating how small tree-ring width coincided with negative DRI values.

4 Discussion

Pinus sylvestris is a useful species in dendrochronological studies since accurate statistical values are obtained indicating clear responses to environmental causal factors. In the present study, the relationship between climatic variables and radial growth was identified in *P. sylvestris* stands in Spain by dendrochronological methods. The six studied chronologies showed high mean sensitivity (MS), signal-to-noise-ratio (SNR), expressed population signal (EPS) and percentage of the variance accounted by the first eigenvector, suggesting a strong common signal for related-climatic environmental factors. The mean sensitivity values are comparable with the range (0.16 to 0.34) observed for four different pine species growing in the Iberian peninsula (Richter et al. 1991) and for two stands of *P. sylvestris* growing on the Central Mountains System in Spain (MS from 0.13 to 0.20; Fernández et al. 1996).

Expressed population signal (EPS) values were higher than 0.85, which suggests that the chronologies describe well enough the infinite, hypothetical population of *P. sylvestris* at each sampling site (Wigley et al. 1984). High signal-to-noise ratio (SNR) values suggest that the proportion of explainable variation due to climate or other causal factors is high enough for all the sampling sites. The first eigenvector variance indicated good homogeneity within each site, which is comparable to the 35 to 64% values calculated for four pines species in Spain (Richter et al. 1991).

The association between growth and climate shows that rainfall in the growing season had a significant positive effect on radial growth at all sites, no matter of the altitudinal location, geographical position or cambial age. Rainfall had different effects on growth within the growing season: at sites located at the lowest altitudinal positions (*Miñon*, *Oña* and *Arauzo de Miel*), a positive effect was observed in spring (May and June), in contrast with sites located at a higher altitudinal positions where the positive association occurred in late spring and early summer [June and July (*El Espinar* site)] and in summer [July and August (*Molino Piqueras* and *Amogable* sites)]. These differences may be due to temperature. Sites located at the lowest altitudinal positions are warmer, the growing season starts early, and thus spring rainfall is a driving factor that affects growth. However, sites located at the highest altitudinal position are colder, the growing season starts later and growth depends on summer rainfall. These results indicated the importance of the within-season precipitation dynamics, which may be as or more important than the seasonal or annual total for plant growth (Fay et al. 2000, Knapp et al. 2002).

These results also complement those of previous studies that highlighted the essential effect of precipitation on radial growth of different pine species growing in the Iberian Peninsula under Mediterranean climatic conditions, such as, for example, *Pinus nigra* Arnold, *P. halepensis* Mill. and *P. pinaster* Ait. (Génova 1994, Fernández et al. 1996, Raventós et al. 2001, Martín-Benito et al. 2008, Bogino and Bravo 2008).

Previous studies in Spain suggest that both, the decrease in rainfall and the increase in mean temperature must be considered as the most important factors that affect growth of the Scots pine (Gutierrez 1989); previous studies on four pine species, including *P. sylvestris*, analysed together also showed the positive impact of winter temperatures (December and February) on radial growth (Richter et al. 1991). Moreover, a study in the Central

Pyrenees corresponding to the period 1952–1993 also indicated the positive impact of temperatures (in November and in May) on radial growth of *P. sylvestris* (Tardif et al. 2002). In this study, rainfall was found to be important at all sites analysed, but the effect of temperature varied depending on the site considered: from positive in the winter prior to the growing season (*Miñón, Oña, Molino Piqueras* and *Amogable* sites) to negative in the autumn prior to the growing season (*Miñón, Oña, Molino Piqueras* and *Amogable* sites) as well as in the summer in the growing season (*El Espinar* and *Amogable* sites). It was thus concluded that the local growth pattern of this species is the result of a changing association with mean temperature, which varies according to the site analysed. Previous studies suggest that species growing in temperate areas (Tessier et al. 1994, Dittmar et al. 2003, Pederson et al. 2004) do not show a common response to climatic variables, and that the response of *P. sylvestris* in Spain to climatic variables varies depending on the sampling site (Gutierrez 1989).

The age-dependent response to climate indicate that young stands have higher variability explained by climatic variables than old stands. Ecophysiological changes related to tree age indicated a reduction in photosynthesis and in stomatal conductance, changes in leaf structure and in canopy structure (Bond 2002, Bond and Franklin 2002), which may imply a variable association between radial growth and climate according to age. A study of *Pinus ponderosa* Douglas ex. C. Lawson in Oregon showed that as trees become older, the water storage capacity in the stems increases, which provides a buffer against short-term water stress (Anthoni et al. 2002) and may imply, as in the present study, a lower vulnerability to climatic conditions in old trees.

The significant association between radial growth and DRI in the growing season suggests that this index is an accurate tool for predicting restrictions in radial growth of *P. sylvestris*. The DRI provides accurate estimates of growth restrictions and mortality of *P. sylvestris* and has been applied in Switzerland, with a similar correlation coefficient as in the present sampling sites (Bigler et al. 2006).

Estimation of the impact of drought events on growth of *P. sylvestris* becomes important considering that previous studies in Spain demonstrated that among all pine species, *P. sylvestris* displays the highest mortality rate under severe droughts (Martínez-Vilalta and Piñol 2002), and that in Switzerland drought processes are considered as a major factor in death of *P. sylvestris* (Eilmman et al. 2006). Considering the predicted higher variability in precipitation in the future and that the mean annual temperature has increased by 1.6 °C in the last century in the Iberian Peninsula (IPCC 2007), the applications of these results in models to predict future growth may be essential to corroborate the forecast of climate change, which suggest that Spain could be one of the areas most vulnerable to species loss due to climatic variability (Bakkenes et al. 2002).

5 Conclusion

The relationship between climate and radial growth of *Pinus sylvestris* varied depending on the climatic variable analysed: rainfall in the growing season was the main climatic variable that determined growth at all the sites analysed, while the association with temperature varied depending on the site, and was positive or negative. The relationship between cambial age and climate suggests the importance of considering this variable during analysis of the relationship between growth and climate. Drought was found to be a determining factor for tree growth and should be considered in models that forecast the impact of climate change in Mediterranean environments.

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Total of 59 references