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Master Oficial de Investigación en Conservación y Uso Sostenible de Sistemas Forestales

Growth dynamics and responses of intra-annual density fluctuations to climate in Aleppo pine (*Pinus halepensis* Mill.) trees of different crown classes identifying strongly related climatic variables

by

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Resumen

Entender las respuestas del crecimiento forestal a variaciones en el clima es un elemento clave para profundizar en el entendimiento de las dinámicas de los bosques en un nuevo entorno. Además, la región mediterránea, como zona de transición climática entre zonas áridas y húmedas del mundo, es un área donde los cambios climáticos pueden afectar en mayor medida. El objetivo de éste estudio es analizar el crecimiento radial del pino carrasco (*Pinus halepensis* Mill.) atendiendo a las diferencias entre clases sociales (árboles dominantes y dominados), especificar las diferencias en la frecuencia de fluctuaciones intra-anuales de densidad (IADFs) dependiendo de la clase social y de la edad e identificar las variables climáticas más influyentes para integrarlas en un modelo empírico. Se seleccionaron ocho parcelas dentro de la distribución natural del pino carrasco en la Península Ibérica. La calidad de las cronologías fue evaluada utilizando la sensibilidad media (MS), la desviación estándar (SD), la relación señal-ruido (SNR), la señal de la población (EPS), la varianza en el primer vector y la correlación entre los individuos. Las precipitaciones y las temperaturas medias mensuales durante la primavera están positivamente correlacionadas con la aparición de IADFs. Se ha detectado un aumento en la frecuencia de IADFs durante los últimos cincuenta años.

Abstract

Understanding how forest growth responds to climate is a key element for a deeper knowledge of forest dynamics in a new environment. Moreover, Mediterranean regions, as transitional climate zones between arid and humid regions of the world, are areas where climatic changes may have the greatest effects. The objectives of this paper are to analyze radial growth of Aleppo pine (*Pinus halepensis* Mill.) trees of different crown classes, to specify the differences in frequency of intra-annual density fluctuations (IADFs) according to crown class and cambial age and to identify strongly related climatic variables to be integrated in empiric growth models. Eight sampling sites were selected throughout the natural distribution area of *Pinus halepensis* in the Iberian Peninsula. Chronology quality was evaluated using mean sensitivity (MS), standard deviation (SD), signal-to-noise ratio (SNR), expressed population signal (EPS), the percentage of the variance accounted for the first eigenvector and the correlation between individuals. Precipitation and mean monthly temperatures in spring were positively correlated to the occurrence of IADFs. A higher frequency in IADFs occurred in the last fifty years.

Key words

Mediterranean ecosystem, dendrochronology, climatic change, dominant, suppressed, annual growth.

Introduction

The future development and the potential of European forests as renewable resources for wood, energy, water and other goods and services (e.g. carbon sequestration, soil protection, biodiversity) as well as the impacts of climate change on forests ecology come to the forefront of scientific research. Since alterations in wood density due to climate may affect wood quality and consequently wood price and forest income, rural development would also be affected in the long term.

Mediterranean regions, as transitional climate zones between arid and humid regions of the world, are areas where climatic changes may have the greatest effects. Fritts *et al.* (1965) suggested that trees growing in extreme conditions respond strongly to climate variations. Understanding how forest growth responds to climate is a key element for a deeper knowledge of forest dynamics in a changing environment.

Wood anatomical features in tree rings have been interpreted as indicators of environmental change (Glock and Agerter, 1966; Tessier et al., 1997; Hughes, 2002; Briffa et al., 2003; Cherubini et al., 2003; Helle and Schleser, 2004). Different Mediterranean pine species have been analyzed to detect relationship between climatic trends and tree growth. Gutiérrez (1989) and Bogino and Bravo (2008a) studied *Pinus sylvestris* L., Martin-Benito et al (2008) studied *Pinus nigra* Arnold, Bogino and Bravo (2008b) and Vieira et al. (2009) studied *Pinus pinaster* Ait., Campelo et al (2007) studied *Pinus pinea*, Attolini et al. (1990) and Rathgeber et al. (2005) studied *Pinus halepensis* Mill.

Species growing under Mediterranean climate, with summer droughts and high inter-annual variability in precipitation and temperature, commonly show special anatomical characteristics in tree rings (Schweingruber, 1993). Besides the normal transition between earlywood and latewood in tree rings, intra-annual density fluctuations (IADFs) can be present. Intra-annual density fluctuations are characterized by latewoodlike cells within the earlywood and earlywoodlike cells within the latewood (Fritts, 2001). These structures are formed in response to changing climatic conditions during the growing season (Masiokas and Villalba, 2004) and their radial position within the ring is determined by the time the triggering factor occurred (Campelo et al., 2007; Vieira et al., 2009).

The Aleppo Pine (*Pinus halepensis* Mill.) is a pine native of the Mediterranean region, where is one of the main species in the present landscape. Therefore, the study of the impact of climatic variables (temperature and precipitation) on its radial growth becomes of major interest.

The objectives of the present study were a) to analyze radial growth of Aleppo pine (*Pinus halepensis* Mill.) trees of different crown classes, b) to specify the differences in frequency of IADFs according to crown class, site and cambial age and c) to identify strongly related climatic variables to be integrated in an empiric model. In order to accomplish these objectives, tree-ring chronologies of dominant and suppressed trees will be examined using dendrochronological techniques to analyze their differences on radial growth. In addition, IADFs will be measured and strongly related climatic variables will be identified.

Materials and Methods

Eight sampling sites were selected from different bioclimatological ecoregions throughout the natural distribution area of *Pinus halepensis* in the Iberian Peninsula. Each ecoregion has common physiographic, climatic and lithological characteristics (Elena-Roselló et al., 1997; Figure 1; Table 1).

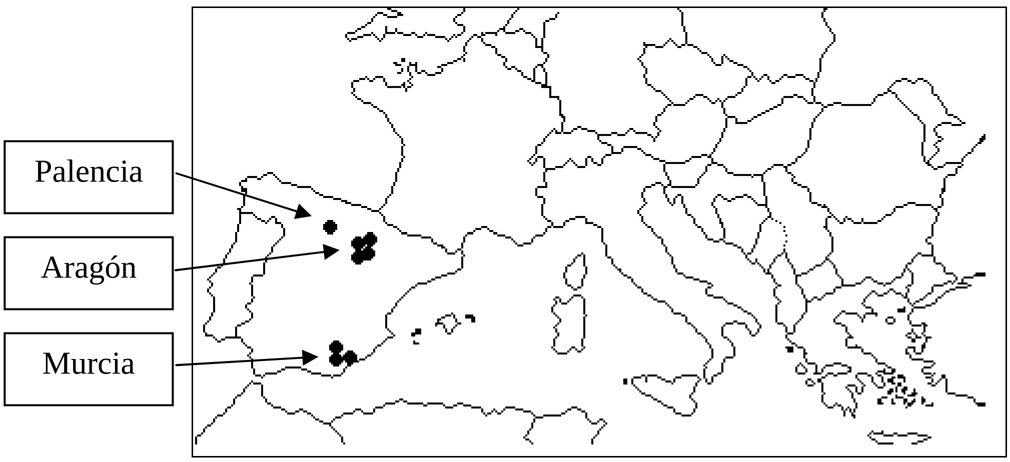


Figure 1: *Study areas.*

Table 1: *Ecoregion classification and geographical position of eight Pinus halepensis sampling sites across its natural distribution area in Spain.*

Site	Code	Location	Ecoregion	Latitude	Longitude	Altitude (m)	Site Index
H34001	Am	Palencia	Duriense	41°51´36´´	4°45´36´´	849	Q17
H50009	Ca	Aragón	Catalano-Aragonesa	41°18´16´´	1°44´52´´	976	Q14
H50001	Ta	Aragón	Catalano-Aragonesa	41°59´31´´	1°50´09´´	695	Q20
H50101	Za1	Aragón	Catalano-Aragonesa	41°48´58´´	0°32´15´´	535	Q11
H50102	Za2	Aragón	Catalano-Aragonesa	41°56´04´´	0°56´25´´	706	Q11
H30101	M1	Murcia	Litoral-Mediterránea	37°52´51´´	1°30´36´´	811	Q11
H30102	M2	Murcia	Litoral-Mediterránea	37°52´50´´	1°32´15´´	957	Q20
H30103	M3	Murcia	Litoral-Mediterránea	37°51´13´´	1°32´34´´	1118	Q17

The site index was determined by using site index curves. The site index was defined as the top height at age 80 (Montero et al., 2001).

Fifteen trees from each social status, i.e. crown class (dominant and suppressed) were selected on each sampling site. In sampling sites Za1 and Za2 only dominant trees were sampled. Therefore, a total of fourteen series (eight dominant and six suppressed) were analyzed. On each tree two cores were extracted at 1.30 m above ground. The increment cores were air dried and mounted on wooden supports and dated according to standard dendrochronological techniques (Stokes and Smiley, 1968). The preparation of the samples was done by use of the diamond flycutter (Kugler F500). This machine was designed specifically for single point diamond flycutting of plan surfaces requiring an optical quality surface finish, precise flatness and exacting parallelism.

The v6.06P COFECHA program (Holmes, 2001; Grissino-Mayer, 2001; available at www.ltrr.arizona.edu) was applied to assess measurement and dating accuracy. This program calculates the Pearson correlation indices between the indexed tree-ring series and a master reference chronology in a series of consecutive, partially overlapped segments of a length specified by the user. Absolute dating is essential for any dendroclimatological study, and it is impossible to compare climatic variables in one specific year with tree-ring growth if the individual tree-ring series are not dated correctly. According with standard methods in dendrochronology (Vieira et al., 2009) trees exhibiting correlation values with the master chronology below 0.4 were excluded.

To eliminate biological trends in tree-ring series and to minimize growth variations that are not shared by most trees, the v6.05P ARSTAN program (Cook and Holmes, 1984;

Holmes, 2001; available at www.ltrr.arizona.edu) was used. Standardization removes geometrical and ecological trends while preserving inter-annual high-frequency variations that are presumably related to climate. To obtain a master chronology at each study site and crown class, the standardized series will be averaged.

Chronology quality was evaluated using mean sensitivity (MS), which is a measure of the mean relative changes between adjacent ring widths (Fritts, 1976); signal-to-noise ratio (SNR), the proportion of the variability explained by climate or other casual factors divided by the residual or unexplained variability (Fritts and Swetnam, 1989); and expressed population signal (EPS), which indicates the degree to which the particular sample chronology portrays a hypothetically perfect chronology (Wigley et al., 1984).

The correctly dated cores were visually examined for IADFs. IADFs showed a non-sharp transition in opposite to the annual rings boundary (Fritts, 2001). Because of the variability of IADFs tangentially and vertically within the tree ring along the stem the IADFs were only considered when present in both the cores, in the same tree ring (Kuo and McGinnes, 1973).

As the number of samples changed over time, the relative frequency was calculated with the following formula [1]:

[1] $F = n/N$

where F is the number of IADFs per year; n the number of trees that formed the IADF and N the total number of trees analyzed. As the number of samples changed over time, the bias in the frequency was assessed by calculating the stabilized IADF frequency (f), according to the formula of Osborn et al (1997) [2]:

[2] $f = F^{0.5}$

The nonlinear logistic equation form was chosen to model the probability of occurrence of IADFs [3]:

[3] $P = (1.0 + e^{(-z)})^{-1}$

where P is the probability of IADFs and $Z = b0+b1(x1)+b2(x2)+\ldots\ldots+bk(xk) + \varepsilon$; where x1; x2..... xk are the climatic variables and b0; b1; b2 ….. bk are unknown parameters of the model and ε is a normal random error N (0,1); and *e* is the exponential operator. The logistic equation can be formulated to accept a binary variable such as occurrence of IADFs, and the parameters can be estimated by maximum-likelihood methods. The resulting prediction is bounded by 0 and 1. Monthly rainfall and mean monthly temperature were used as explanatory variables. A stepwise selection method was used to find the best model.

The alternative fits were evaluated on the basis of Akaike information criterion (AIC), the –2*Log Likelihood, the area under the receiver operating characteristic (ROC) curve and the expected behavior - as indicated by the signs of the estimated parameters. ROC curve is displayed for the models and the area underneath was calculated as a value of the accuracy of the model. Value over 0.80 indicates an excellent discrimination (Hosmer and Lemeshow, 2000). This curve relies on false/true positive/negative tests, and the sensitivity is indicated by the proportion of correctly classified events and the specificity by the proportion of correctly classified non-events (Hair et al., 1998). This model was previously used to estimate the probability of occurrence of IADFs in *Pinus pinaster* subsp. *mesogenesis* in the Iberian Peninsula (Bogino and Bravo, 2008b). PROC LOGISTIC of SAS 9.1 (SAS Institute Inc. 2004) was used to fit the model.

Monthly rainfalls and mean monthly temperature recorded at the closest meteorological stations (Agencia Estatal de Meteorología, Spain) were used to assess the relationships between IADFs and climatic variables (Table 2).

Table 2: *Description of the meteorological stations.*

Site	Code	Location	Station	Longitude	Latitude	Altitude (m)
H34001	Am	Palencia	Palencia escl cap agraria	42º00’30’’	4º33’27’’	760
H50009	Ca	Aragón	Calatayud aguas	41º19’51’’	1º38’49’’	600
H50101	Ta	Aragón	Tarazona	41º54’28’’	1º43’54’’	480
H50103	Za1	Aragón	Sos del rey catolico	42º29’34’’	1º12’52’’	630
H50002	Za2	Aragón	Sos del rey catolico	42º29’34’’	1º12’52’’	630
H30101	M1	Murcia	Moratalla "benizar"	38º16’25’’	1º58’59’’	899
H30102	M2	Murcia	Moratalla "benizar"	38º16’25’’	1º58’59’’	899
H30103	M3	Murcia	Moratalla "benizar"	38º16’25’’	1º58’59’’	899

Results

Each chronology is calculated with a maximum of 30 core series per site (some were broken during the preparation process). Chronology quality was evaluated using mean sensitivity (MS), signal-to-noise ratio (SNR) and expressed population signal (EPS) (Table 3).

Table 3: *Descriptive statistics of the chronologies of Pinus halepensis. SD: standard deviation; MS: mean sensitivity; SNR: signal to noise ratio; EPS: expressed population signal; Var: variance in first eigenvector; and Mean corr.: mean correlation among trees.*

Code	Crown class	Location	Time span	Core num.	SD	MS	SNR	EPS	Var.	Mean corr.
AmD	Dom.	Palencia	1974-2008	27	0.32	0.40	66.08	0.98	74.82%	0.860
Ams	Suppr.	Palencia	1976-2008	30	0.24	0.26	7.31	0.88	40.84%	0.555
CaD	Dom.	Aragón	1977-2008	30	0.25	0.33	28.70	0.96	70.28%	0.819
Cas	Suppr.	Aragón	1981-2008	30	0.24	0.28	17.48	0.95	50.01%	0.610
TaD	Dom.	Aragón	1976-2008	30	0.27	0.32	32.01	0.97	67.36%	0.796
Tas	Suppr.	Aragón	1979-2008	30	0.28	0.30	10.31	0.91	51.98%	0.642
Z1	Dom.	Aragón	1919-2007	28	0.18	0.19	9.53	0.91	36.26%	0.522
Z2	Dom.	Aragón	1926-2007	25	0.18	0.19	3.85	0.79	29.31%	0.437
MD1	Dom.	Murcia	1931-2008	30	0.10	0.11	3.50	0.78	16.55%	0.582
Ms1	Suppr.	Murcia	1939-2008	30	0.17	0.16	3.53	0.78	19.98%	0.365
MD2	Dom.	Murcia	1916-2008	30	0.19	0.18	13.12	0.93	40.09%	0.596
Ms2	Suppr.	Murcia	1921-2008	29	0.33	0.31	8.10	0.96	57.25%	0.751
MD3	Dom.	Murcia	1915-2008	28	0.25	0.26	13.39	0.93	45.57%	0.615
Ms3	Suppr.	Murcia	1917-2008	30	0.17	0.17	5.56	0.85	25.22%	0.400

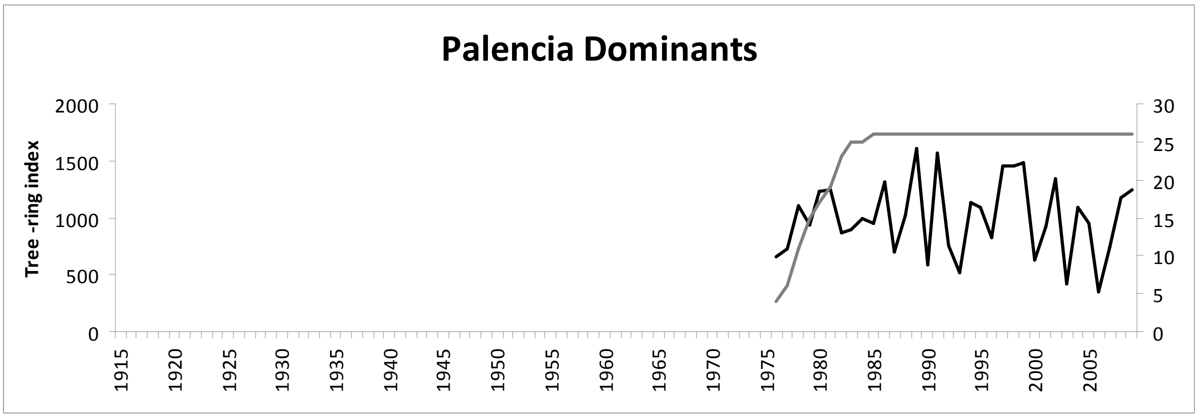
The AmD chronology showed the highest mean sensitivity values (0.40) while MD1 showed the lowest (0.11). AmD also showed higher SNR and EPS values (66.08 and 0.98 respectively) than the rest of the chronologies. To obtain a master chronology at each study site, the core series with correlation values under 0.4 were removed and the new chronologies were re-calculated (Table 4).

Table 4: *Descriptive statistics of the master chronologies of Pinus halepensis. SD: standard deviation; MS: mean sensitivity; SNR: signal to noise ratio; EPS: expressed population signal; Var: variance in first eigenvector; and Mean corr.: mean correlation among trees.*

Code	Crown class	Location	Time span	Core num.	SD	MS	SNR	EPS	Var.	Mean corr.
AmD	Dom.	Palencia	1974-2008	27	0.32	0.40	66.08	0.98	74.82%	0.861
Ams	Suppr.	Palencia	1976-2008	19	0.32	0.37	14.30	0.93	57.34%	0.722
CaD	Dom.	Aragón	1977-2008	30	0.25	0.33	28.70	0.96	70.28%	0.819
Cas	Suppr.	Aragón	1981-2008	29	0.31	0.36	15.57	0.94	63.16%	0.755
TaD	Dom.	Aragón	1976-2008	28	0.29	0.33	39.87	0.97	71.00%	0.831
Tas	Suppr.	Aragón	1979-2008	25	0.34	0.35	20.33	0.95	64.38%	0.784
Z1	Dom.	Aragón	1919-2007	15	0.24	0.25	8.94	0.90	48.40%	0.679
Z2	Dom.	Aragón	1926-2007	11	0.28	0.30	8.31	0.89	55.18%	0.724
MD1	Dom.	Murcia	1932-2008	19	0.20	0.21	12.86	0.93	44.45%	0.656
Ms1	Suppr.	Murcia	1939-2008	10	0.25	0.28	3.94	0.98	39.90%	0.596
MD2	Dom.	Murcia	1915-2008	21	0.24	0.25	18.20	0.95	51.00%	0.707
Ms2	Suppr.	Murcia	1921-2008	18	0.33	0.31	8.10	0.96	57.25%	0.751
MD3	Dom.	Murcia	1915-2008	23	0.30	0.32	30.20	0.97	62.68%	0.778
Ms3	Suppr.	Murcia	1917-2008	15	0.34	0.32	14.35	0.94	55.35%	0.731

The master chronologies from Palencia showed higher mean sensitivity values (0.40 for dominants and 0.37 for suppressed) than the other two locations. The master chronology of the dominant trees in Palencia also showed higher SNR and EPS (66.08 and 0.98 respectively) than the rest of the locations.

The fourteen master chronologies of *Pinus halepensis* were divided in three groups (Palencia, Aragón and Murcia), according to their location since they were located more than 450 km apart, a figure previously considered as too long a distance to guarantee a good cross-dating among different pine chronologies (Richter and Eckstein, 1990; Bogino and Bravo, 2008a). On each group, the master chronologies of the dominant and the suppressed trees were analyzed separately (Figure 1).


Palencia Dominants
Tree -ring index
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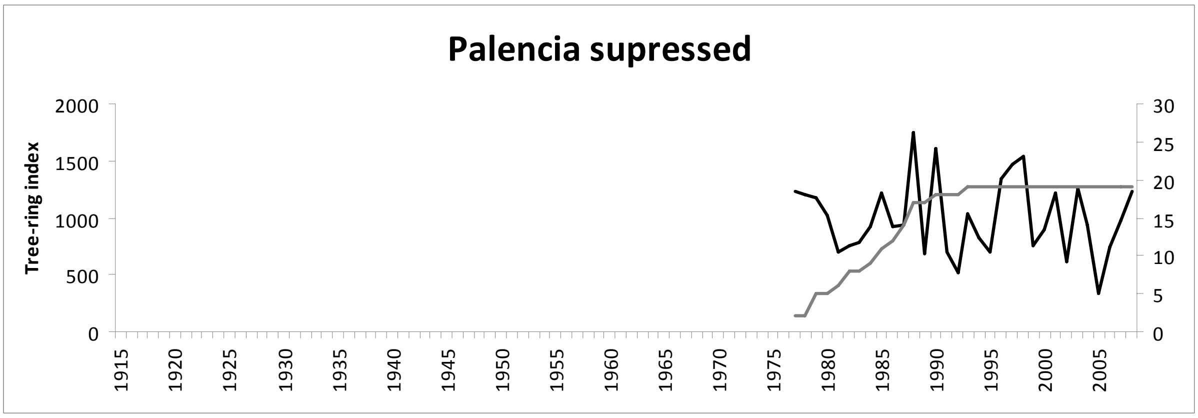
Palencia supressed
Tree-ring index
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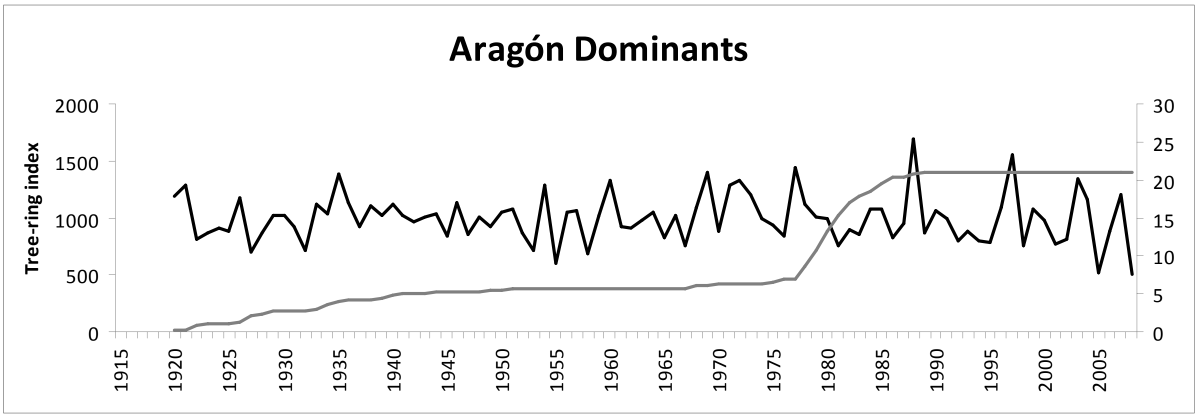
Aragón Dominants
Tree-ring index
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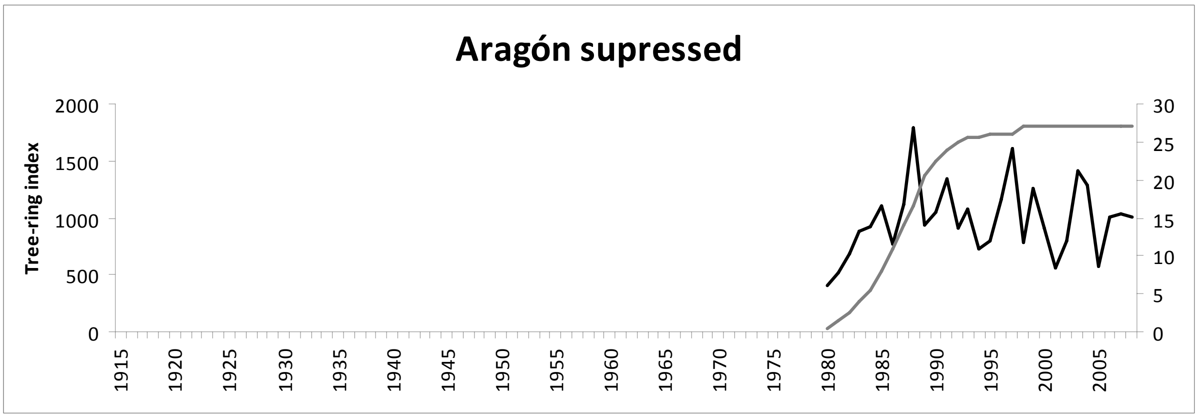
Aragón supressed
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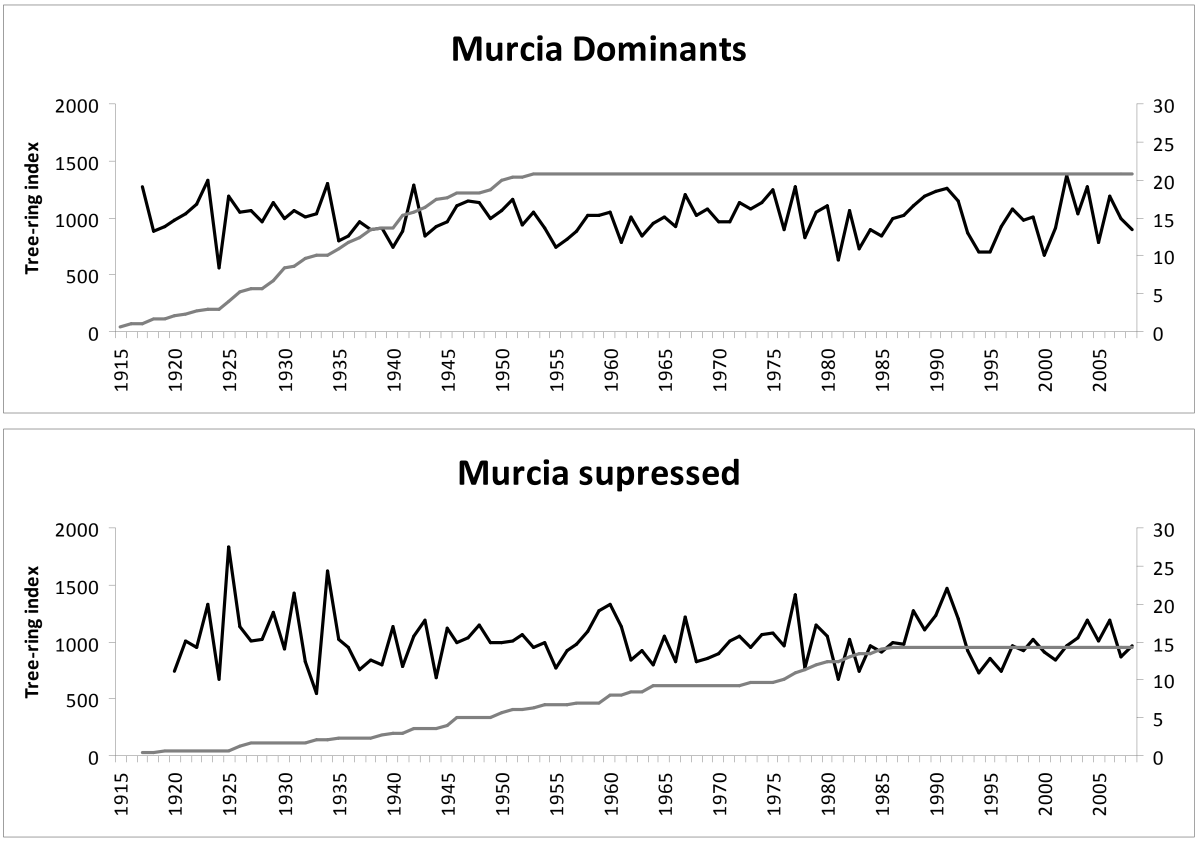

Figure 2: *Standardized chronologies of Pinus halepensis along the natural distribution in Spain. The black line shows the tree-ring index through time and the grey line shows the number of samples used in each chronology.*

Series from dominant and suppressed trees were averaged in two separate general chronologies and analyzed using mean sensitivity (MS), signal-to-noise ratio (SNR) and expressed population signal (EPS) (Table 5).

Table 5: *Descriptive statistics of the mean dominant and suppressed chronologies. SD: standard deviation; MS: mean sensitivity; SNR: signal to noise ratio; EPS: expressed population signal; Var: variance in first eigenvector; and Mean corr.: mean correlation among trees.*

Social class	Time span	Av.core num.	Av.ring num.	Age range	SD	MS	SNR	EPS	Var.	Mean corr.
Dom.	1915-2008	22	1139	95-27	0.27	0.30	26.64	0.94	0.60	0.70
Suppr.	1917-2008	19	732	92-20	0.32	0.33	12.77	0.95	0.56	0.63

The mean chronology of the suppressed trees showed slightly higher mean sensitivity values (0.30 for dominants and 0.33 for suppressed) and higher SNR values (26.64 for dominants and 12.77 for suppressed) than the mean chronology of the dominant trees. The mean chronology of the dominant trees also showed higher variance and mean correlation values than the mean chronology of the suppressed trees. The mean chronologies were normalized by subtracting the mean and dividing by the standard deviation. Values far from cero mean higher reactions (Figure 2).

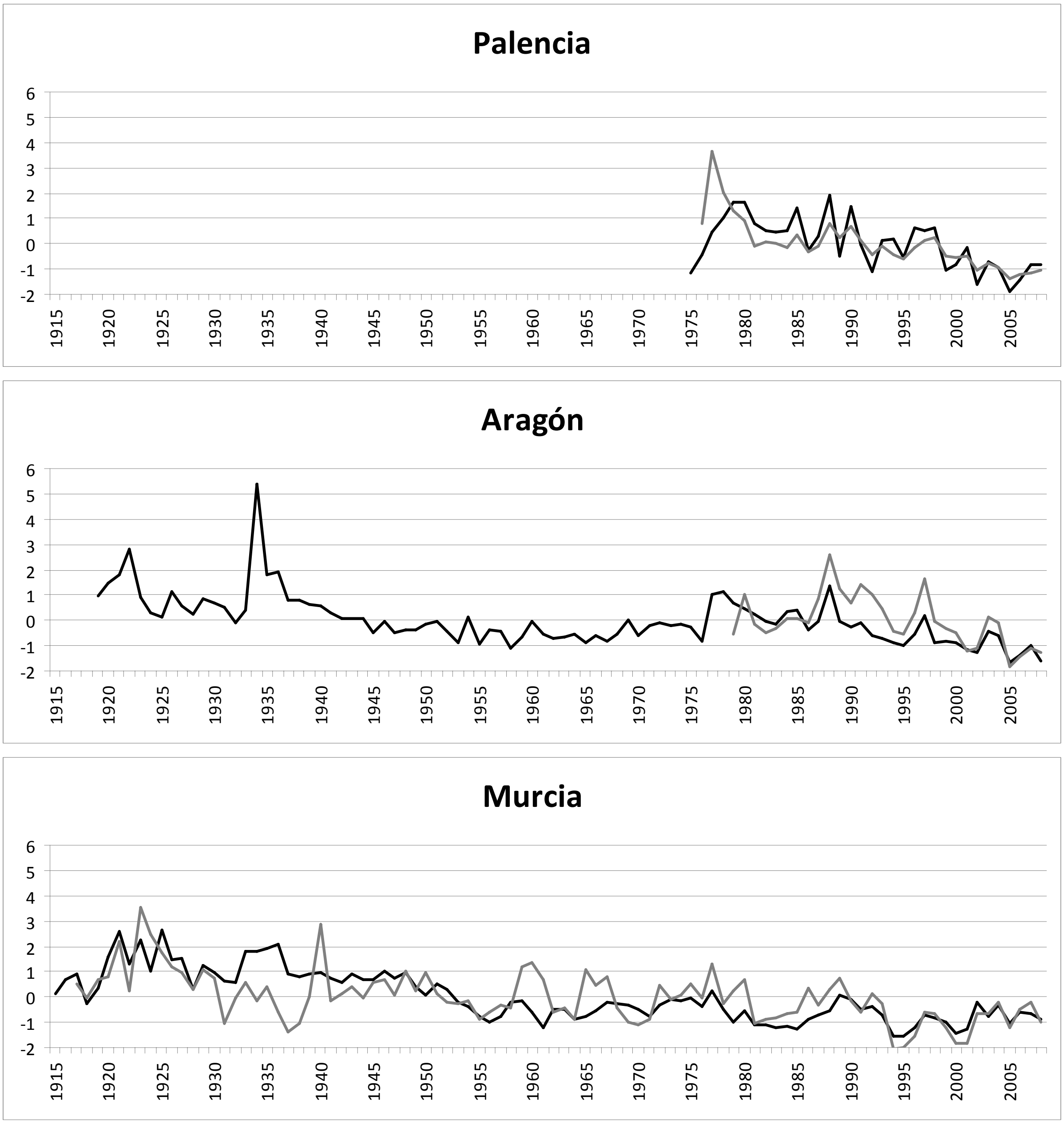

Figure 3: *Normalized chronologies of Pinus halepensis. The black line shows the mean dominant series and the grey line shows the mean suppressed series.*

Looking at the normalized curves it can be observed that, in the region of Palencia, dominant trees react stronger in favourable years while in the regions of Aragón and Murcia suppressed trees react stronger in favourable years.

The Normalized Difference Index is calculated by subtracting the normalized values of the suppressed trees to the normalized values of the dominant trees. If the values of the NDI are positive, then the dominant trees react stronger; if the values of the NDI are negative, then the suppressed trees react stronger (Figure 3). From 1980 to 2000 suppressed trees react stronger in Murcia and Aragón, while since 2000 no clear tendency is found.

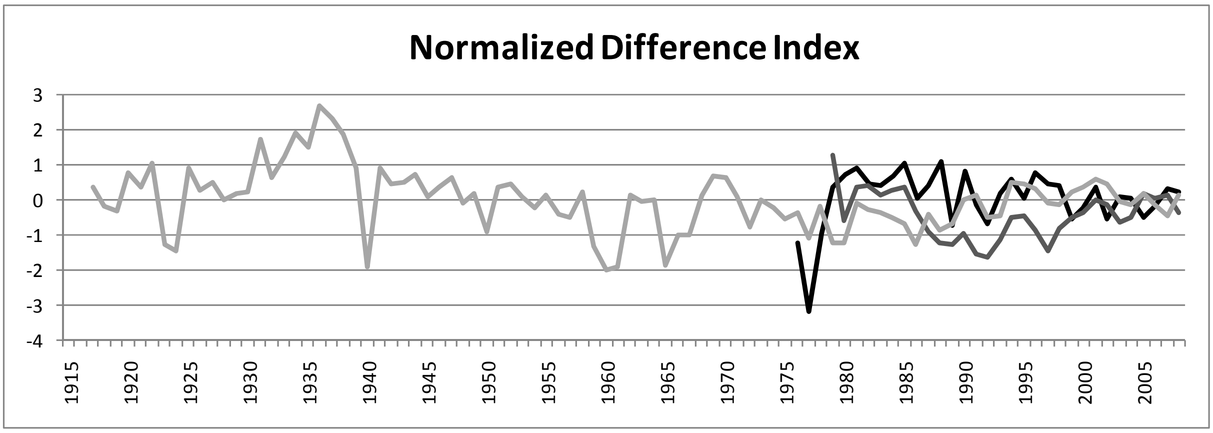

Figure 4: *Normalized Difference Index of Palencia (black line), Aragón (dark grey line) and Murcia (light grey line).*

A total of 13502 tree rings were analyzed from trees from the eight sampling sites and a total of 107 IADFs were found. Samples were first grouped according to site location (Palencia, Aragón and Murcia) (Table 6), age (younger than 80 years and older than 80 years) (Table 7) and crown class (dominant and suppressed) (Table 8).

Table 6: *Descriptive statistics of the IADFs in Pinus halepensis according to site location (Palencia, Zaragoza and Murcia).*

Site	Palencia	Zaragoza	Murcia
Number of trees	23	69	53
Period	1974-2008	1919-2007	1914-2008
Trees with IADF	4	30	28
Trees with IADF (%)	17,39	43,48	52,83
Tree rings in total	1342	4722	7438
Tree rings with IADFs	4	64	39
Percentage of IADF	0.003	0.014	0.005
Mean stabilized IADF	0.30	0.68	0.61

The percentage of trees with IADFs, the percentage of IADF and the mean stabilized IADF was higher in Zaragoza and Murcia than in Palencia.

Table 7: *Descriptive statistics of the IADFs in Pinus halepensis according to age (younger than 80 years and older than 80 years).*

Age	**Young**	**Old**
Number of trees	79	66
Period	1974-2008	1915-2008
Trees with IADF	28	33
Trees with IADF (%)	41,77	43,94
Tree rings in total	4183	9319
Tree rings with IADFs	67	40
Percentage of IADF	0.016	0.004
Mean stabilized IADF	0.65	0.55

The percentage of trees with IADFs was rather similar for young and old stands. However, the percentage of IADFs and the mean stabilized IADF was higher for young stands than for old stands.

Table 8: *Descriptive statistics of the IADFs in Pinus halepensis according to crown class (dominant and suppressed).*

Age	**Dominant**	**Suppressed**
Number of trees	87	58
Period	1915-2008	1917-2008
Trees with IADF	32	30
Trees with IADF (%)	36,78	51,72
Tree rings in total	9112	4390
Tree rings with IADFs	64	43
Percentage of IADF	0.007	0.010
Mean stabilized IADF	0.61	0.61

On the one hand, the percentage of trees with IADFs was higher for suppressed than dominant trees. On the other hand, the percentage of IADFs was higher for suppressed trees. Mean stabilized IADF was the same for both crown classes. IADF frequency was analyzed according to calendar year (Figure 4).

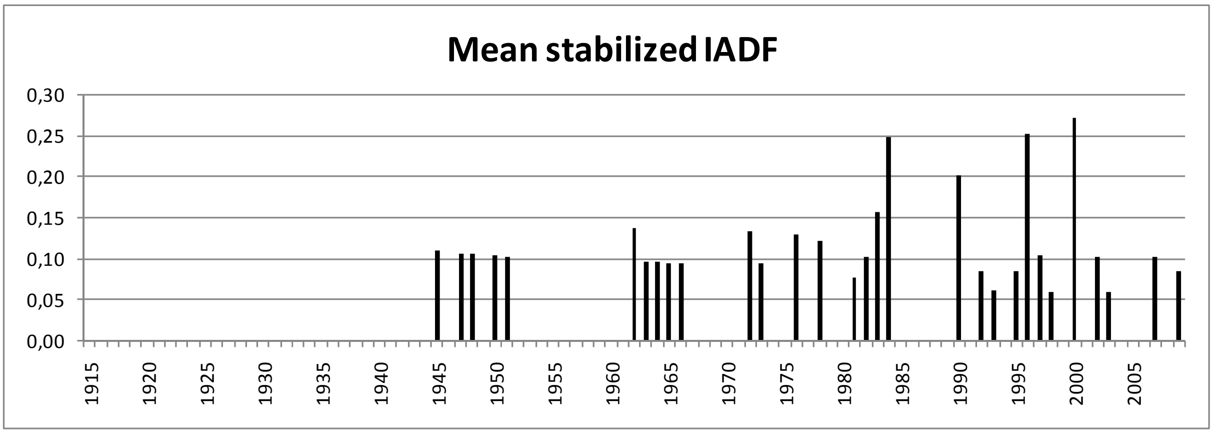

Figure 5: *Mean stabilized IADF.*

IADF frequency in relation to calendar year showed an increase in IADFs from the 1980s to the present. 1983, 1989, 1995 and 1998 were the years with more IADFs, with a stabilized frequency higher than 0.2. The nonlinear logistic equation form was chosen to model the probability of occurrence of IADFs. The alternative fits were evaluated on the basis of Akaike information criterion (AIC) and -2*Log Likelihood (Table 9).

Table 9: *Stepwise selection (pp:monthly precipitation; tt:mean monthly temperature; AIC: Akaike's Information Criterion ; L: likelihood).*

Variables included in the model	AIC	-2*Log L
pp-October	578.501	574.501
pp-June, pp-October	548.423	542.423
tt-May, pp-June, pp-October	528.541	520.541
pp-March, tt-May, pp-June, pp-October	523.212	513.212
pp-April, pp-March, tt-May, pp-June, pp-October	514.850	502.850
pp-September, pp-April, pp-March, tt-May, pp-June, pp-October	503.057	489.057
pp-September, pp-April, tt-May, pp-June, pp-October	501.225	489.225
tt-December, pp-September, pp-April, pp-March, tt-May, pp-June, pp-October	488.521	474.521
tt-August, tt-December, pp-September, pp-April, pp-March, tt-May, pp-June, pp-October	477.266	528.266
tt-July, tt-August, tt-December, pp-September, pp-April, pp-March, tt-May, pp-June, pp-October	472.794	454.794
tt-October, tt-July, tt-August, tt-December, pp-September, pp-April, pp-March, tt-May, pp-June, pp-October	464.042	444.042
tt-April, tt-October, tt-July, tt-August, tt-December, pp-September, pp-April, pp-March, tt-May, pp-June, pp-October	459.310	437.310
pp-February, tt-April, tt-October, tt-July, tt-August, tt-December, pp-September, pp-April, pp-March, tt-May, pp-June, pp-October	456.695	432.695

The logistic function estimated that 11 monthly climatic variables out of 24 had a significant effect on predicting future IADFs (Table 10).

Table 10: *Climatic variables with a significant effect on the probability of IADFs in Pinus halepensis (pp:monthly precipitation; tt:mean monthly temperature).*

Parameter	Estimate	Standard error	Chi-square de Wald	Pr>ChiSq
Intercept	-0.4471	2.7709	0.0260	0.8718
pp-February	-0.0136	0.00641	4.5010	0.0339
pp-April	-0.0433	0.00954	20.5821	<.001
pp-June	-0.0594	0.0113	27.8067	<.001
pp-September	0.0317	0.00587	29.1684	<.001
pp-October	-0.0458	0.00904	25.6452	<.001
tt-April	-0.3613	0.1243	8.4531	0.0036
tt-May	0.6082	0.1233	24.3519	<.001
tt-July	0.6542	0.1702	14.7810	0.001
tt-August	-0.8745	0.2229	15.3873	<.001
tt-October	-0.3778	0.1271	8.8307	0.0030
tt-December	0.6605	0.1853	12.7049	0.0004

The model showed that precipitations in February, April, June and October and mean monthly temperatures in April, August and October had a positive impact on the formation of IADFs, while precipitations in September and mean monthly temperatures in May, July and December had a negative impact on the formation of IADFs. ROC curve is displayed for the models and the area underneath was calculated as a value of the accuracy of the model (Fig 5).

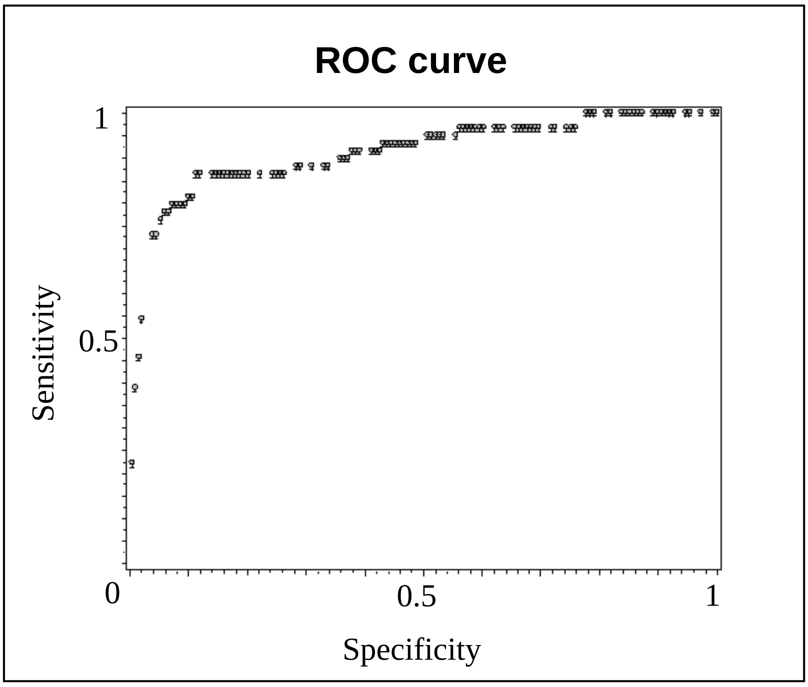

Figure 6: *ROC curve for all trees.*

The area underneath the ROC curve (0.904) shows that the accuracy of the model is good enough to use it to predict occurrence of IADFs (Hosmer and Lemeshow, 2000). The nonlinear logistic equation form was applied to model the probability of occurrence of IADFs in dominant trees (Table 11).

Table 11: *Climatic variables with a significant effect on the probability of IADFs in dominant trees (pp:monthly precipitation; tt:mean monthly temperature).*

Parameter	**Dominant**				**Suppressed**			
	Estimate	**St. Error**	**Wald Chi-square**	**Pr>ChiSq**	**Estimate**	**St. Error**	**Wald Chi-square**	**Pr>ChiSq**
Intercept	-4.4672	0.8424	16.9396	<.0001	-2.0265	3.7849	0.2867	0.5924
pp-April	-0.0274	0.00804	11.6271	0.0006	-0.0448	0.0161	7.7648	0.0053
pp-May					0.0339	0.0139	5.9574	0.0147
pp-June	-0.0342	0.0109	9.8465	0.0017				
pp-Sept.					0.0501	0.00918	29.7552	<.0001
pp-Oct.	-0.0309	0.00755	16.7628	<.0001	-0.0780	0.0156	24.9418	<.0001
tt-May					1.1591	0.2807	17.0486	<.0001
tt-Dec.	0.4017	0.1318	9.2938	0.0023	-1.1724	0.2780	17.7808	<.0001

Precipitations in April and October had a positive impact on the formation of IADFs in both dominant and suppressed trees, while mean monthly temperatures in December had a positive impact in dominant trees and negative in suppressed trees. The area underneath ROC curve was 0.825 for dominant trees and 0.933 for suppressed trees. The accuracy of the model is also sufficient to use it to predict occurrence of IADFs

Discussion

Pinus halepensis appears as a reliable species for dendrochronological studies, showing good correlations between trees growing at the same site, high expressed population signals and accurate statistical values meaning a clear response to environmental factors. In addition, confirm the tendency of Mediterranean species, and this species in particular, to develop special anatomical structures (Schweingruber, 1993), as it was also observed in *Pinus pinaster* in Spain (Bogino and Bravo, 2008b) and Portugal (Vieira et al., 2009) and *Pinus pinea* L. from a dry Mediterranean area in Portugal (Campelo et al., 2006).

The descriptive statistics of the chronologies suggest that the tree-ring series reflects one or more associated factors (including climate), shown by the mean sensitivity values (MS) from 0.21 to 0.40 that are higher than the 0.16 to 0.34 values found in previous studies on pine species (*Pinus sylvestris* L., *Pinus nigra* Arnold, *Pinus pinaster* Ait. and *Pinus mugo* ssp. *uncinata* Turra.) in the Iberian Peninsula (Richter et al., 1991; Bogino and Bravo, 2008a).

Signal to noise ratio (SNR) values vary from 3.94 at the sites with lower samples availability to 66.08 at the sites with higher samples availability. Expressed population signal (EPS) ranging from 0.89 to 0.98 is in all cases higher than the critical level of 0.85 suggested by Wigley et al. (1984), meaning that the chronologies are representative of tree growth in the stands. First eigenvector variance ranges from 39.90 to 74.82%, indicating good homogeneity within the same site. It can be concluded that the fourteen mean chronologies have high MS, SNR, EPS and percentage of the variance accounted for by the first eigenvector, suggesting a strong common signal to related-climatic environmental factors. Suppressed trees showed slightly higher mean sensitivity values and higher SNR values than the dominant trees.

Common radial growth patterns among dominant and suppressed series in the same site were found. These results agree with previous studies in the Iberian Peninsula suggesting that pine species growing in the southern dendroecological section could have a common growth response to environmental factors (Richter et al., 1991; Bogino and Bravo, 2008a) and, in our case, without differences between social classes (dominant and suppressed).

Chronology from Palencia showed higher mean sensitivity values than the other two locations, specially the dominant trees (0.40). However, in the regions of Aragón and Murcia the mean suppressed series showed a higher sensitivity than the mean dominant series.

There is evidence that suppressed trees suffer greater drought stress because of greater root competition for soil (Kloeppel et al., 1993). However, understory trees receive lower solar radiation and higher wind protection by the influence of neighbouring crowns reducing transpiration rates. Therefore, climatic sensitivity may be reduced (Bréda et al., 2006; Martin-Benito et al., 2008). In Mediterranean forests tree density is low and suppressed trees get relatively abundant light, so it is no appropriate to draw a general conclusion.

The significant association between IADFs and radial growth or climatic variables provides a useful proxy for complementing and enhancing the dendroclimatological data (Bogino and Bravo, 2008a). Latewood is initiated by photoperiod and water stress (Vaganov et al., 2006). The efficiency of water translocation through a tree declines with increasing age and/or height, due to a nonoptimal network of xylem conduits with a tapered structure (Anfodillo et al., 2006; Ryan et al., 2006; West et al., 1999). As a result, water deficits may become more pronounced with age, as observed in older trees of *P. pinaster* (Vieira et al., 2009). Several studies of pine species in the Iberian Peninsula showed a good correlation between IADF formation and climate (Campelo et al., 2007; Bogino and Bravo, 2008b; Vieira et al., 2009).

Mean stabilized IADF was higher for young stands than for old *P. halepensis* trees and similar according to crown classes. Several studies have also shown that IADFs were more frequent in wider and younger tree rings (Copenheaver et al., 2006; Rigling et al., 2001; Villalba and Veblen, 1994; Vieira et al., 2009; Bogino and Bravo, 2008b). This could be due to a faster response of young trees to changing factors (Villalba and Veblen, 1994) and/or to a longer growing season of young trees (Rossi et al., 2008).

A higher tendency in young stands for developing IADFs presumably related to physiological changes due to changes in stomatal structure and photosynthesis efficiency (Bond, 2002) corroborates previous dendroecological studies which suggested the incorporation of the age in any dendrochronological study since young trees have a different response to environmental factors than old ones (Carrer and Urbinati, 2004; Bogino and Bravo, 2008b).

An increase in the mean temperature in spring increases the probability of IADFs. These results are consistent with those of previous studies in *P.pinea* in Portugal (Campelo et al., 2006) and *P.pinaster* in Spain (Bogino and Bravo, 2008b). In addition, mean monthly temperatures in December had a positive impact in dominant trees and negative in suppressed trees.

Previous models associated IADFs of *P.pinaster* to precipitation in autumn (Vieira et al., 2009). The probability model used showed a positive correlation between precipitation in April and October and the occurrence of IADFs. As it was previously reported (Bogino and Bravo, 2008b) a higher frequency in IADFs occurred in the last fifty years. The increase in drought events in the Iberian Peninsula (IPCC 2007), may explain the higher IADF frequency during this period.

Conclusions

Pinus halepensis is an accurate species for tree-ring analysis with good correlations between trees growing at the same site and a clear response to environmental factors. Suppressed trees showed higher sensitivity than dominant trees in Aragón and Murcia, with greater growth rates during favourable years while dominant trees showed higher sensitivity than suppressed trees in Palencia. IADFs were more frequent in young than in old stands with no clear differences according to crown classes. The probability model used, showed that high mean monthly temperatures in spring lead to increase the probability of occurrence of IADFs in Aleppo pine trees growing under Mediterranean climate conditions. Dominant trees showed a negative correlation with mean monthly temperatures in December while suppressed trees showed a positive correlation. Precipitation was positively correlated to the occurrence of IADFs in April and October. A higher frequency in IADFs occurred in the last fifty years, which coincides with the increase in drought events in the Iberian Peninsula.

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