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An empirical mixed model to quantify climate influence on the growth of *Pinus halepensis* Mill. stands in South-Eastern Spain

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ABSTRACT

The influence of climate on forest stand composition, development and growth is undeniable. Many studies have tried to quantify the effect of climatic variables on forest growth and yield. These works become especially important because there is a need to predict the effects of climate change on the development of forest ecosystems. One of the ways of facing this problem is the inclusion of climatic variables into the classic empirical growth models. The work has a double objective: (i) to identify the indicators which best describe the effect of climate on *Pinus halepensis* growth and (ii) to quantify such effect in several scenarios of rainfall decrease which are likely to occur in the Mediterranean area.

A growth mixed model for *P. halepensis* including climatic variables is presented in this work. Growth estimates are based on data from the Spanish National Forest Inventory (SNFI). The best results are obtained for the indices including rainfall, or rainfall and temperature together, with annual precipitation, precipitation effectiveness, Emberger's index or free bioclimatic intensity standing out among them. The final model includes Emberger's index, free bioclimatic intensity and interactions between competition and climate indices. The results obtained show that a rainfall decrease about 5% leads to a decrease in volume growth of 5.5–7.5% depending on site quality.

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1. Introduction

The influence of climate on forest stand composition, development and growth is undeniable. Many studies have proven the sensitivity of forests to climate conditions and have tried to quantify their effect on forest growth and yield, mostly in Central and Northern Europe (Hasenauer et al., 1999; Bergh et al., 2003; Matala et al., 2005; Briceno-Elizondo et al., 2006; Laubhann et al., 2009). In the Mediterranean region, still few studies analyzing the species response to climate change have been developed (Sabaté et al., 2002; Vicente-Serrano et al., 2010).

However, there is an important difference between the phenology of the boreal forest, which is mainly driven by temperature, and the phenology of the Mediterranean coniferous forest which is mainly driven by water availability (Kramer et al., 2000). In Southern Europe, temperature increase and the resulting rise in potential evapotranspiration could lead to a decrease in soil moisture content and an aggravation of drought conditions, with the resulting negative effect on volume growth (Moreno et al., 2005).

As a consequence, there is a clear need to modify current management practices to adapt them to climate change and avoid the risks associated with it as much as possible (Linder, 2000; Garcia-Gonzalo et al., 2007; Kellomäki et al., 2008). Therefore, the development of adaptive management strategies should be based on the knowledge on the sensitivity of forest dynamics to climate change. As climate change may have different impacts on different forest ecosystems, a regional assessment taking into account the consequences of both climate change and management options on forest growth is a useful first step in outlining proper management alternatives under different climate change scenarios (Lasch et al., 2002).

Traditionally, empirical models are widely used to support decision making in forestry. However, in these models it has been assumed that the future environmental conditions will be similar to those in the past. As these models excluded the impacts of any changes in environment on forest growth, they were not suitable for use under changing environmental conditions (Matala et al., 2006).

In recent years, forest growth models based on physiological processes with hydrological and nutrient cycles controlled by climatic factors, as well as hybrid models which combine these ones with empirical models, have been developed to predict stand productivity in a changing environment (i.e. Sabaté et al., 2002; Bergh et al., 2003; Kellomäki et al., 2008). Although statistical models are

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more accurate under stable conditions, the results of physiological models confirm the need to develop new empirical models that can be applied under changing climatic conditions, for instance, including bioclimatic variables in the future predictive statistical models (Fontes et al., 2010; Matala et al., 2005; Laubhann et al., 2009).

In the Spanish region of Murcia, Aleppo pine (*Pinus halepensis* Mill.) is the most important tree species. The forest area of this region is about 189,000 ha, nearly 87% of which is covered by Aleppo pine in pure stands or mixed with broadleaf Mediterranean species such as *Quercus ilex* L. or other pines like *Pinus nigra* Arn. The main management objective for the silviculture of this species is environmental conservation (soil protection or biodiversity maintenance) but it could also supply wood for particle board industries and saw logs to produce pallets (Condés and Sterba, 2008).

The objectives of the present work are (i) to develop an empirical growth model for *P. halepensis* stands in the Murcia province that can be applied under changing climatic conditions and (ii) to analyze the effect of short-term climate change (temperature and precipitation) on the growth of this species. In order to achieve this goal, we first developed an empirical growth model for stand volume increment depending on stand and stocking variables, we then added climate indices and checked if they contributed significantly to the model, identifying on the one hand the climatic indicators which best capture the effect and, on the other hand, quantifying such effect in several scenarios of climate change which are likely to occur in the study area.

This kind of work may contribute to clarify the relationship between climate and growth in particular stands, providing a tool to analyze growth variations in different climate scenarios.

2. Materials and methods

2.1. Study area and data sources

The study area is located in the region of Murcia (South-Eastern Spain). For stand volume increment estimation, 809 sample plots from the Spanish National Forest Inventory (SNFI) have been used. These are permanent plots located in pure *P. halepensis* stands in the province of Murcia which were remeasured during inventories 2, 3 and 4, carried out in 1987, 1999 and 2010 respectively. The periods between inventories are 12 and 11 years. These plots are located in even-aged stands that came from natural or artificial regeneration, but their age is not known because it has not been recorded during the inventories.

The plots of the SNFI are spread over the Spanish forest area, located at the nodes of a 1 km square grid. The plots consist of four concentric sample circles of 5, 10, 15 and 25 meter radius, where diameters and heights of all trees over 7.5, 12.5, 22.5 and 42.5 cm dbh respectively are measured.

On the other hand, the climatic indices have been calculated from data provided by the Spanish National Meteorological Agency, which has over 150 meteorological stations spread throughout the Murcia province. Out of the 150 stations, only 82 of them have almost complete series of monthly mean temperature and precipitation data during the study period, that is, between 1987 and 2010.

In most cases, it has been necessary to fill in some of the temperature and precipitation data, a task which has been done as usual, by interpolating from data that are available at nearby meteorological stations (de Vries et al., 2003), finding linear relationships with determination coefficients over 95% for temperature and over 90% for precipitation.

Fig. 1 shows a map of Murcia depicting the location of the SNFI plots together with the location of the meteorological stations considered in this work.

2.2. Stand volume increment

Being concentric, the SNFI sample plots require the use of a specific methodology to calculate the stand volume increment. An adaptation of the method proposed by Hébert et al. (2005) has been used in this work. The stand volume growth has been calculated as:

$$\mathrm{IV} = \frac{\Delta V_s + \Delta V_m + \Delta V_c + \Delta V_i}{t_2 - t_1}$$

where IV is the mean periodic volume growth measured in $\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$, and ΔV_s, ΔV_m, ΔV_c y ΔV_i are volume increments corresponding to survival, mortality, harvest and ingrowth during the period between inventories respectively, while t_1 and t_2 are the years in which the initial and final inventories are carried out.

In the case of trees that either died or were cut between inventories, given the lack of precise data as to the date at which the harvest took place or the dbh at that time, it has been assumed that the trees were cut at the midpoint of the period between inventories, the dbh at that time being calculated from the initial dbh and the estimated growth. All tree volumes have been calculated using the volume equations published for this species and study area (DGCONA, 2002).

Together with these data, and for the subsequent model fit, a set of classical stand variables have been estimated at the beginning of each growth period. These variables are number of stems per hectare N, basal area G, quadratic mean diameter d_g, dominant height h_{dom} (Assmann, 1961) and Reineke's stand density index (SDI) defined as the stem number of an equally dense stand with a quadratic mean diameter of 25 cm (Reineke, 1933b):

$$\mathrm{SDI} = N\left(\frac{25}{d_g}\right)^{-1.605}$$

Mean values of the stand variables from 809 sample plots used in this work, at the beginning of the 2nd and 3rd SNFI, are shown in Table 1.

2.3. Bioclimatic indices

From the monthly series of mean temperature and precipitation, the bioclimatic indices described in Table 2 have been calculated for each one of the 82 meteorological stations considered in the study.

In addition, the free bioclimatic intensity (IBL) has been calculated (Montero de Burgos and González-Rebollar, 1974). The inputs needed to calculate this index are potential evapotranspiration, which is shown in Table 2, runoff and water retention capacity. Given the lack of data on soil analysis, runoff and water retention capacity have been estimated as a function of terrain slope and soil texture respectively. An example of calculation of this index can be found in López-Serrano et al. (2005).

All these indexes can be understood as different approaches in attempting to define climate conditions (Wallén, 1967) and particularly aridity which is perhaps the most important factor involved in forest growth as water scarcity is the main factor limiting biological processes in this region. A first approach includes simple climate parameters that have been used to quantify and determine the influence of climate on plants and vegetation: temperature or precipitation; as well as the evapotranspiration factor (the amount of water that would be lost from water-saturated soil by plant transpiration and direct evaporation from the ground) although this one was included later because it is much more difficult to calculate. However, it has been pointed out that just these parameters do not give enough information (Gavilán, 2005). The second approach involves the combination of simple climate parameters in

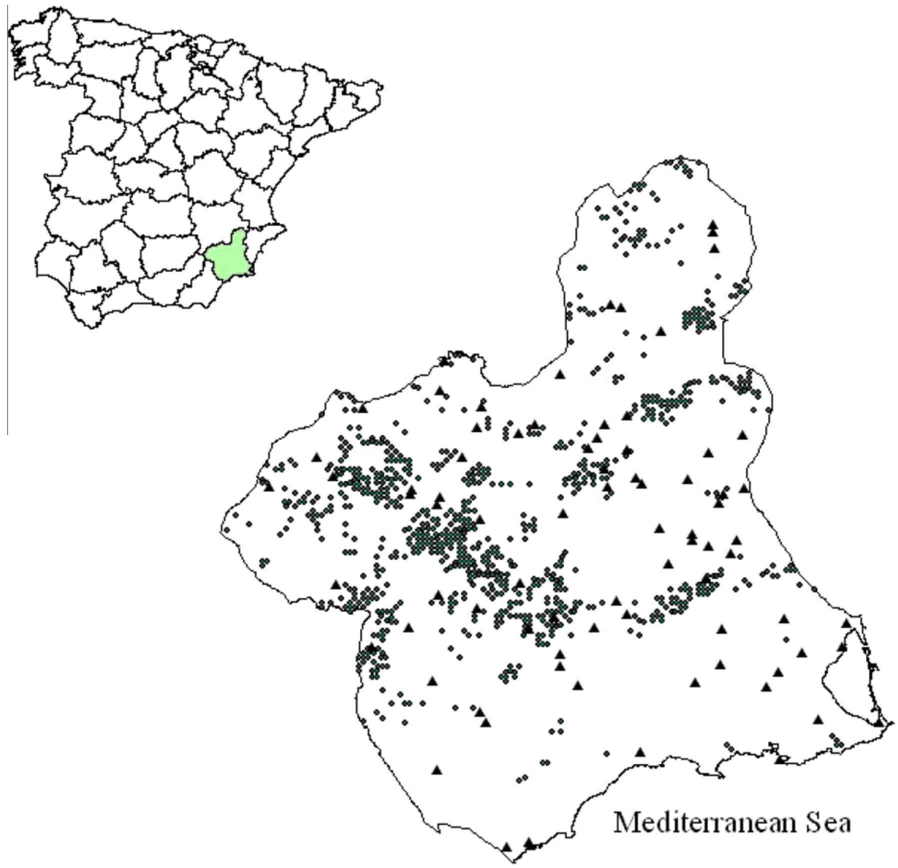

Fig. 1. Location of NFI plots and meteorological stations considered in the study (marked with a triangle).

Table 1
Mean values of stand variables from 809 sample plots on 2nd and 3rd National Forest Inventory (variables are in the same units used in the models).

NFI	Variable	Average	Standard deviation	Minimum	Maximum
2	N (stem/ha)	262.49	278.70	5.09	1973.52
	G (m^2/ha)	4.78	4.34	0.39	26.51
	d_g (cm)	17.52	6.58	7.60	54.00
	H_{dom} (m)	6.74	2.19	2.00	17.21
	V (m^3/ha)	18.15	17.64	1.12	110.97
	SDI (stem/ha)	114.95	103.30	10.53	578.36
2–3	IV (m^3 ha^{-1} $year^{-1}$)	0.74	0.66	0.01	4.26
3	N (stem/ha)	318.89	301.04	5.09	2132.68
	G (m^2/ha)	7.03	5.31	0.46	32.48
	d_g (cm)	19.35	6.44	8.92	54.15
	H_{dom} (m)	7.94	2.26	2.50	18.44
	V (m^3/ha)	27.50	22.62	1.36	128.76
	SDI (stem/ha)	163.81	124.65	11.91	715.95
3–4	IV (m^3 ha^{-1} $year^{-1}$)	0.80	0.62	0.00	3.43
	Elevation (hm)	7.48	2.53	0.74	14.31
	Slope (%)	16.44	10.74	0.78	61.34
	Aspect (°)	186.91	111.84	–	–

the form of phytoclimatic indices (index approach). This group includes Martonne's, Emberger's and UNEP aridity indexes together with the Thermicity index defined by Rivas-Martinez (1983).

A final approach is the water-balance approach which includes Precipitation effectiveness, Temperature efficiency and the Moisture index defined by (Thornthwaite, 1948, 1931), and the free bioclimatic intensity that quantifies the capacity of a climate to produce plant biomass, and may thus be considered as a measurement of potential productivity.

The values of the indices are calculated year by year within the period between the second and the fourth SNFI, and the average values of the indices in the two periods between inventories, that is, between 1987 and 1999, and between 1999 and 2010, are calculated afterwards. Then they have been spatially interpolated with the kriging method by means of a geographic information system, and maps of iso-values have been obtained for the Murcia province. From these maps, the values corresponding to the SNFI plots are extracted taking into account their UTM (Universal Transverse Mercator) coordinates. In the case of the IBL, the values of soil texture and slope for the SNFI plots are obtained from topographic and soil maps respectively.

Some common statistics of the values of bioclimatic indices obtained for the inventory plots during the periods between inventories are shown in Table 3.

Table 2
Bioclimatic indices used in the study.

Index	Equation	Climate
Mean annual temperature	$\Sigma_{12}\ T_i/12$	–
Annual precipitation	$\Sigma_{12}\ P_i$	<200 Arid >1600 Extremely humid
UNEP aridity (Middleton and Thomas, 1992)	P/PET	<0.05 Extremely arid >0.65 Humid
Emberger (Emberger, 1932)	$100P/((M+m)(M-m))$	0–30 Arid >90 Humid
Precipitation effectiveness (Thornthwaite, 1931)	$10\Sigma_{12}11.5\ [P_{Pi}/(T_{Fi}-10)]^{10/9}$ if $11.5[P_{Pi}/(T_{Fi}-10)]^{10/9} > 40$ then $11.5\ [P_{Pi}/(T_{Fi}-10)]^{10/9} = 40$	<16 Arid >128 Humid
Temperature efficiency (Thornthwaite, 1948)	$10\Sigma_{12}\ [(T_{Fi}-32)/4]$ if $T_{Fi} < 32$ then $T_{Fi} = 32$	<142 Ice climate >1440 Megathermic
Moisture index (Thornthwaite, 1948)	$(P-\mathrm{PET}/\mathrm{PET}) * 100$	<−60 Dry >100 Extremly humid
Martonne aridity (Martonne, 1926)	$P/(T+10)$	0–5 Extremely arid >60 Perhumid
Thermicity (Rivas-Martinez, 1983)	$10(T+m+M)$	<−30 Crioromediterranean >350 Termomediterranean
PET (Thornthwaite, 1948)	$112\ \Sigma_{12}\ (L_i \cdot 16\ (10T_i/I)^a)$ where $I = \Sigma\ (T_i/5)^{1514}$ and $a = 675$ $(I^*10^{-3})^3 - 77.1(I*10^{-3})^2 + 1792(I*10^{-5}) + 0.49329$	<11.875 Ice climate >95 Megathermic

where P annual precipitation (mm), T mean annual temperature (°C), M mean warmest month temperature (°C), m mean coldest month temperature (°C), P_{Pi} monthly precipitation (in.), T_{Fi} mean monthly temperature (°F), P_i monthly precipitation (mm), T_i mean monthly temperature (°C), L_i correction factor depending on month and latitude, PET mean annual potential evapotranspiration (mm).

Table 3
Statistics of bioclimatic indices in inventory plots during periods between inventories.

	Average	Standard deviation	Minimum	Maximum
NFI 2–NFI 3 (1987–1999)				
Mean annual temperature	16.16	1.39	12.42	18.99
Annual precipitation	366.22	54.70	248.78	575.64
UNEP aridity index	0.44	0.09	0.26	0.74
Emberger's index	62.17	13.10	39.24	100.21
Precipitation effectiveness	25.61	5.45	15.16	45.52
Temperature efficiency	872.80	74.89	670.50	1025.62
Moisture index	−55.92	9.14	−74.46	−25.90
Martonne aridity index	14.18	2.69	8.69	23.52
Thermicity index	337.44	26.13	268.33	393.02
PET	70.73	5.29	58.49	87.60
IBL	4.23	0.94	1.75	6.83
NFI 3–4 (1999–2010)				
Mean annual temperature	16.31	1.30	12.46	19.79
Annual precipitation	347.02	50.54	237.87	501.86
UNEP aridity index	0.41	0.08	0.24	0.67
Emberger's index	57.15	11.80	33.82	94.00
Precipitation effectiveness	24.24	5.09	14.85	39.58
Temperature efficiency	880.73	70.15	672.57	1068.78
Moisture index	−59.10	8.34	−75.96	−33.25
Martonne aridity index	13.33	2.47	8.47	21.05
Thermicity index	337.27	24.26	266.39	399.65
PET	72.03	5.12	59.17	93.15
IBL	3.82	1.03	1.11	6.27

2.4. Growth models

Since data come from a hierarchical structure (same sample units remeasured on repeated occasions) the observations could be correlated. To alleviate this, a mixed model was proposed.

At first, a stand growth model was estimated from the fitting dataset. The variables allowed in this model were stand density variables (stems per hectare N and basal area G), structure variables (dominant height H_{dom}, cuadratic mean diameter d_g, diameter distribution standard deviation s_d), stocking variables (Hart-Becking index (Hart, 1928; Becking, 1954) and stand density index SDI (Reineke, 1933) and static site variables (elevation, slope aspect and the transformations of these variables (Stage, 1973), which are not related to climate conditions, as fixed effects, and the intercept of the model varies randomly between periods. To select the variables included in this first model a mix of procedures of stepwise regression and manual insertion and/or deletion of variables in the model was used. An inspection of the variance inflation factors (VIFs) was carried out to remove variables with variance inflation larger than 10, and finally the biological and ecological sensitivity of the model was checked. The resulting model included the variables number of stems per hectare, dominant height and Stand Density Index (Reineke, 1933). As site variables, the model included elevation and the transformations of slope and aspect proposed by (Stage, 1973):

$$\log(\mathrm{IV}) = a_0 + a_1 \cdot \log(N) + a_2 \cdot \log(H_{\mathrm{dom}}) + a_3 \cdot \mathrm{SDI} + a_4 \cdot \mathrm{Elevation}^2 + a_5 \cdot \mathrm{Slope} \cdot \cos(\mathrm{aspect})$$

In subsequent steps, bioclimatic indices were included as explanatory variables, one by one, to avoid the existing multicollinearity between them. Although an intercorrelation of bioclimatic index and static site characteristics could be expected, the p value shows that all independent variables in the models are significant ($p < 0.05$) and no high inter-correlation among independent variables is observed (VIF < 10). In order to assess the model improvement, Akaike criterion, statistic logarithm of the likelihood function, and pseudo R^2 were considered. The models were fitted and compared using maximum likelihood methods.

Once the influence of the studied bioclimatic indices was analyzed, a final non linear mixed model, to avoid the bias of logarithm, was fitted using the RMLE (restricted maximum likelihood estimation) method. This final model includes most suitable bioclimatic indices, avoiding variance inflation larger than 10, and variables interaction:

$$\mathrm{IV} = \exp(a_0 + a_1 \cdot \log(N) + a_2 \cdot \log(H_{\mathrm{dom}}) + a_3 \cdot \mathrm{Elevation}^2 + a_4 \cdot \mathrm{Slope} \cdot \cos(\mathrm{aspect}) + a_5 \cdot \mathrm{Emberger} + a_6 \cdot \mathrm{IBL} + a_7 \cdot \mathrm{IBL} \cdot \mathrm{SDI})$$

2.5. Climate change scenarios

Finally, using the latter model, three climate scenarios were proposed to quantify the climate change influence on stand volume increment of *P. halepensis*. The proposed scenarios are compatible with observed climatic variations during the study period from 1987 to 2010.

The first scenario is a slight decrease in precipitation, about 2%, which, assuming no changes in the difference between the maximum and the minimum monthly temperature, results in an Emberger's index decrease of about 3. In the second and third scenarios the assumptions were becoming stronger, with a precipitation reduction of 5% and 10% respectively. Due to the difficulty of planning scenarios to assess changes in IBL, we decided to assess the actual changes in that value, so reductions of 0.25, 0.5 and 0.75 were considered respectively.

The effect of climate change has been tested over four different stand types. Each one is defined by a different dominant height (7–11.5 m), a different stand density index (between SDI = 100 and SDI = 400), and different site conditions. In all of these areas average conditions for static site variables have been considered (elevation 750 m, slope 17% and aspect 180°).

The model was also used to assess climate and stocking interaction.

3. Results

A comparison between mean values of stand and climatic variables for the Aleppo pine sample plots during the two studied periods is shown in Tables 1 and 3, respectively.

Stand characteristics of the sample plots show that Aleppo pine in Murcia is growing in low-density stands with an average density around 250 stems/ha, and basal areas close to 5 m^2/ha. Stand density index is also poor showing that the individuals of this species cover a small proportion of the total area. Dominant height is moderate, probably describing only medium to poor site qualities. These results agree with the low volume growth in *P. halepensis* sample plots. Comparing values from the two studied periods, it can be concluded that density, basal area and dominant height have increased, while this is not clearly resulting in an increment of stand volume growth.

The bioclimatic indices show that the climate of the study area is semi-arid Mediterranean, which implies extremely dry and hot summers, although some plots are located in sub-humid or rarely arid climates. The average annual precipitation is about 360 mm, occurring mostly in autumn and spring. The mean annual temperature is about 16 °C, and the potential evapotranspiration reaches 70 mm per month. There are not big differences between mean annual temperatures registered during the two study periods. However, annual rainfall has decreased about 5%, reaching more than 10% in some areas, which would result in a reduction of 25% of the soil water reserve (Gracia et al., 2002), with the subsequent impact on stand growth.

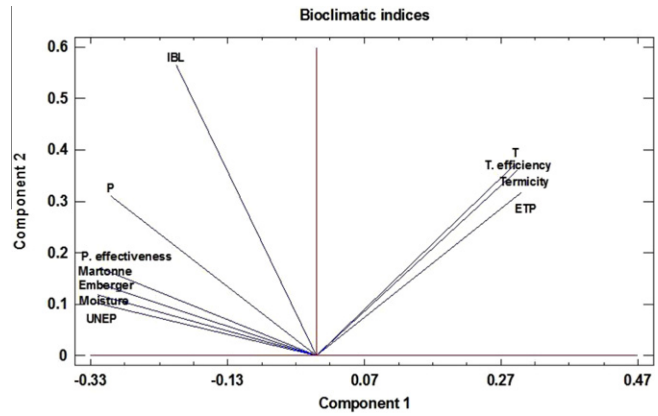

Fig. 2. Principal component analysis between bioclimatic indices.

Table 4
Basic model without bioclimatic indices for the natural logarithm of stand volume increment: log(IV) in m^3 ha^{-1} year^{-1}. The independent variables units are described in Table 1.

	Value	Std.Error	DF	t-Value	p-Value
(Intercept)	−6.7443	0.2159	1611	−31.2433	0.0000
log(N)	0.6141	0.0252	1611	24.3863	0.0000
log(H_{dom})	1.4035	0.0687	1611	20.4335	0.0000
SDI	−0.000905	0.000286	1611	−3.1634	0.0016
Elevation^2	0.004632	0.000456	1611	10.1484	0.0000
Slope·cos(aspect)	0.004532	0.00117	1611	3.8712	0.0001

A principal component analysis, as presented in Fig. 2, indicates that there are strong correlations between climatic indices. According to this, the indices have been grouped into four categories: temperature based (mean annual temperature, temperature efficiency, thermicity index and potential evapotranspiration), precipitation based (annual precipitation), temperature and precipitation based (UNEP aridity index, Emberger's index, precipitation effectiveness, moisture index and Martonne's aridity index) and those including some other variables such as slope or soil type (free bioclimatic intensity IBL).

This last result must be taken into account when the stand growth models are fitted because, if two or more indices from the same category are included in the model, variance inflations will be too high.

3.1. Growth models

The coefficients of the stand growth model were estimated using all data from sample plots measured on three different occasions. The estimated parameters for the basic model without the inclusion of bioclimatic variables, when evaluated by a mixed model approach, are shown in Table 4. All of them are significant at the 0.05 level.

Tables 5 and 6 respectively show the model coefficients and the improvement on Akaike criterion (AIC), logarithm of the likelihood

Table 5
Coefficients of growth models including bioclimatic indices: $\log(IV) = a_0 + a_1\log(N) + a_2\log(H_{dom}) + a_3SDI + a_4Elevation^2 + a_5Slope\cdot\cos(aspect) + a_6\cdot index$. The independent variables units are described in Table 1.

Group	Bioclimatic index	a_0	a_1	a_2	a_3	a_4	a_5	a_6
Without climatic indices	Without climatic indices	−6.74	0.6141	1.4035	−0.00091	0.0046	0.0045	–
Temperature based	Mean annual temperature	−4.73	0.6184	1.3794	−0.00085	0.0019	0.0051	−0.1122
	Thermicity	−4.56	0.6184	1.3816	−0.00086	0.0019	0.0050	−0.0059
	Temperature efficiency	−4.73	0.6184	1.3794	−0.00085	0.0019	0.0051	−0.0021
	PET	−4.22	0.6191	1.3738	−0.00087	0.0016	0.0052	−0.0323
Precipitation based	Annual precipitation	−7.82	0.6137	1.2879	−0.00089	0.0028	0.0060	0.0040
Temperature and precipitation based	Precipitation effectiveness	−7.43	0.6138	1.2890	−0.00088	0.0019	0.0061	0.0431
	Martonne aridity index	−7.53	0.6146	1.2973	−0.00086	0.0019	0.0060	0.0834
	Moisture index	−4.93	0.6148	1.2989	−0.00086	0.0017	0.0060	0.0251
	UNEP aridity index	−7.44	0.6148	1.2989	−0.00086	0.0017	0.0060	2.5137
	Emberger	−7.45	0.6136	1.2905	−0.00086	0.0017	0.0062	0.0185
Other variables	IBL	−7.39	0.6106	1.3145	−0.00089	0.0051	0.0067	0.2000

Table 6
Comparison of growth models including bioclimatic indices.

Group	Bioclimatic index	DF	AIC	LogLik	Pseudo-R^2
Without climatic indices	Without climatic indices	8	3190.52	−1587.26	0.6141
Temperature based	Mean annual temperature	9	3148.12	−1565.06	0.6245
	Thermicity	9	3147.71	−1564.85	0.6247
	Temperature efficiency	9	3148.12	−1565.06	0.6245
	PET	9	3133.84	−1557.92	0.6277
Precipitation based	Annual precipitation	9	3044.26	−1513.13	0.6475
Temperature and precipitation based	Precipitation effectiveness	9	3035.21	−1508.60	0.6496
	Martonne aridity index	9	3056.50	−1519.25	0.6449
	Moisture index	9	3055.63	−1518.82	0.6451
	UNEP aridity index	9	3055.63	−1518.82	0.6451
	Emberger	9	3038.95	−1510.47	0.6486
Other variables	IBL	9	3041.10	−1511.55	0.6482

function (LogLik) and pseudo R^2, when different bioclimatic variables are included. All the new models include the same variables as the basic model and the bioclimatic index as well, and they are also significant at the 0.01 level.

It can be seen that the inclusion of the temperature based indices provides small improvements on the stand growth model. The improvement increases when precipitation is taken into account. The best results are achieved when annual precipitation, precipitation effectiveness, Emberger's index or free bioclimatic intensity are included.

The coefficients for the non climatic variables are really similar in all models, showing a positive correlation between volume growth and number of stems per hectare and dominant height, and a negative correlation with SDI, which means that growth decreases when competition increases. It is interesting to notice that the coefficient for altitude is higher when no temperature based indices are used because of the relation between these variables.

It is also interesting to see that dominant height has a lower impact on growth when climatic variables are included into the model. This can be easily understood by thinking of dominant height as a site quality index as well as the climatic variables are.

According to this, a final model was fitted. It includes Emberger's and IBL indices and interactions with stand density index as a measure of stocking. When calculated as OLS regression with fixed effects only, the variance inflation did not show high correlations among the independent variables (not even between site variables and climatic ones). When the maximum likelihood method was used for comparison purposes, the AIC criterion was 3015.50, logarithm of the likelihood function was −1497.75 and pseudo R^2 was 0.6540, which clearly improves the basic model.

Table 7
Final best model (non linear mixed model) for stand volume increment IV in $m^3\ ha^{-1}\ year^{-1}$, estimated by the RMLE method. The independent variables units are described in Table 1.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	−5.736018	*0.212790*	*1609*	−26.9562	0.0000
$\log(N)$	*0.516268*	*0.021379*	*1609*	24.1489	0.0000
$\log(H_{dom})$	0.871199	0.049026	1609	17.7702	0.0000
Elevation^2	0.003785	0.000365	1609	10.3772	0.0000
Slope·cos(aspect)	0.004450	0.000764	1609	5.8277	0.0000
Emberger	0.003781	0.001364	1609	2.7712	0.0056
IBL	0.121244	0.017772	1609	6.8221	0.0000
IBL ∗ SDI	−0.000097	0.000030	1609	−3.2171	0.0013

The parameter estimates for the final non linear mixed model, using the RMLE method, are shown in Table 7. All of them are significant at 0.01 level. The mean value for the predicted volume increment is $0.774\ m^3\ ha^{-1}\ year^{-1}$ and its standard deviation is $0.51\ m^3\ ha^{-1}\ year^{-1}$). Residual plots for the main independent variables are shown in Fig. 5. Random effects are 0.0514 for the growth period between the second and the third SNFI and consequently −0.0514 for the growth period between the third and the fourth Inventories showing that the volume increment is slightly less in this last period.

3.2. Climate change scenarios

Fig. 3 shows the stand volume increment versus stems/ha for the different alternatives described in the methodology. Although

N ranges from 0 to 1200 stem/ha in the four different stand types considered, it is just to make comparable graphics. Real values of stem/ha depend on the other variables, thus for the first stand type, where a SDI value of 100 is considered, the range of N is between 50 and 500; for the second stand type, with SDI = 200, the range is between 100 and 700, for the third between 300 and 900 and for the fourth stand type, the value of N is between 500 and 1100 stem/ha.

In any case, Fig. 3 shows that stand volume increment is higher where site quality is better (higher values for SDI, H_{dom} and climate index).

A numerical analysis of the outcome obtained shows that the influence of climate change results in a smaller decrement in volume growth in relative terms for better conditions than for poorer ones. So, for the most likely scenario of climate change: sc2, it is expected that stand volume increment decreases about 7.5% for the poorest conditions and about 5.5% for the best conditions. Less conservative scenarios result in a decrease of stand volume growth between 11.5% and 9.5%, compared with the current climate.

4. Discussion

The inclusion of bioclimatic variables improves the growth model fit. Temperature-based indices are included in the model with a minus sign (Table 5), indicating that, in Mediterranean areas, high temperatures make potential evapotranspiration increase, with the consequent reduction of soil water reserves and the negative effect on growth (Moreno et al., 2005). This result contrasts with the situation in boreal and temperate forests, driven mainly by temperature, where a temperature increase leads to a significant and positive influence on growth (Bergh et al., 2003; Matala et al., 2005; Laubhann et al., 2009).

However, precipitation is the most important climatic factor when the stand volume increment of *P. halepensis* is studied. This is consistent with some authors that point to the declining precipitation in the Mediterranean region as a stress condition which will affect the growth and survival of this species, mainly in the most arid areas (Creus Novau and Saz Sánchez, 2004; Vicente-Serrano et al., 2010). Kramer et al. (2000), in the same direction, conclude that in the Mediterranean area seasonality in phenology is mainly due to seasonality in water availability which affects the amount of foliage, and consequently light interception and transpiration, resulting in a growth decrease.

A further evaluation of the last model shows that bioclimatic variables contribute to stand growth in a similar way to variables such as number of stems/ha and dominant height. So, Emberger's index increases with increasing precipitation and with decreasing temperature difference between the warmest month and the coldest month. Consequently, growth increases as expected with abundant rainfall and mild temperature regimes. This index is especially interesting in water-limited environments where, according to Vicente-Serrano et al. (2010), changes in precipitation may not be the main factor driving changes to forest, because temperature may also play a significant role as it interacts with precipitation to determine water availability. The same authors found that the future predictions of warming and declining precipitation result in an increase in stress conditions affecting *P. halepensis* forests in

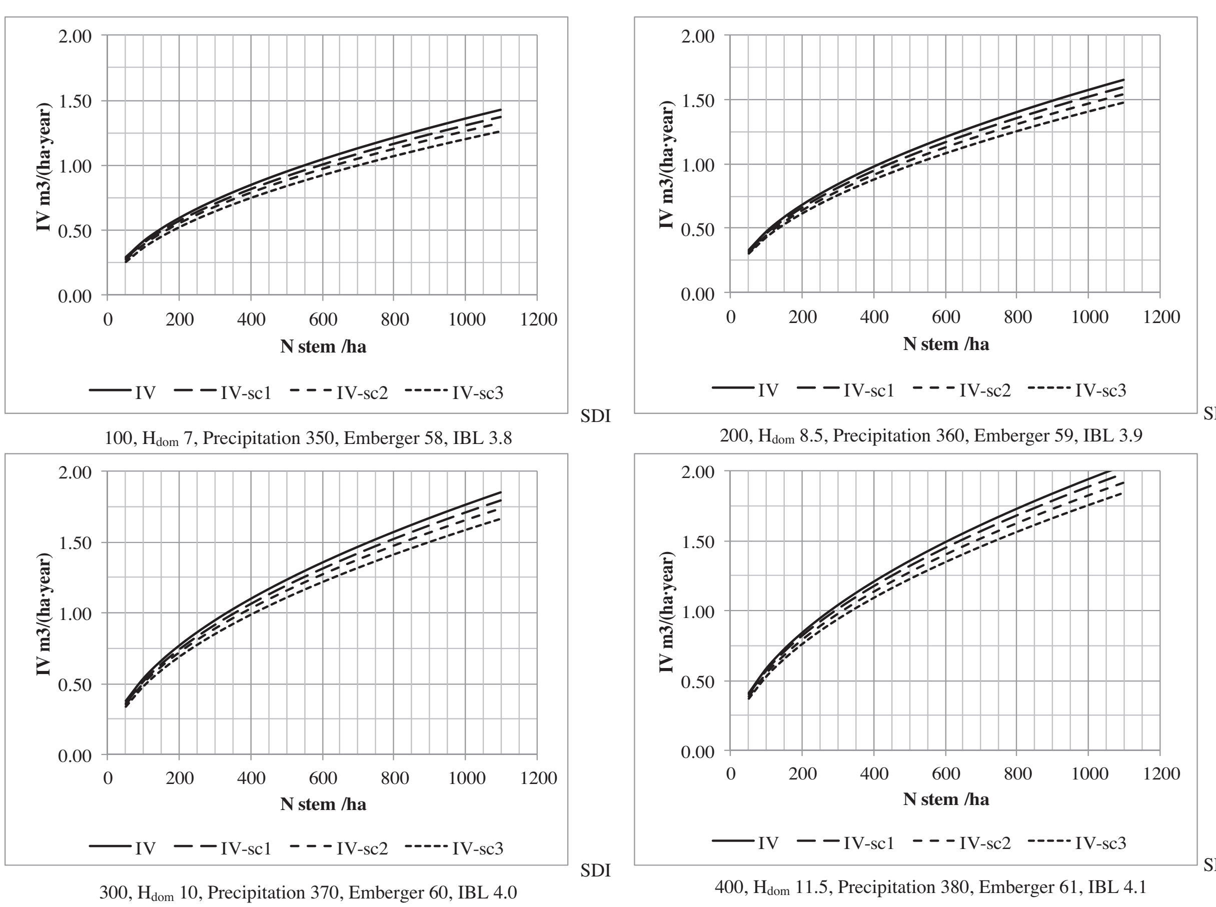

Fig. 3. Stand volume increment versus stem/ha. Scenario 1: Emberger's index decrease = 3, IBL decrease = 0.25. Scenario 2: Emberger's index decrease = 6, IBL decrease = 0.5. Scenario 3: Emberger's index decrease = 10, IBL decrease = 0.75.

the Mediterranean region, which is consistent with the result indicated by Emberger's index in the growth model.

Free bioclimatic intensity aims to quantify the ability of a climate to produce plant activity, and it takes into account the amount of water available in the soil for vegetation after the effect of evapotranspiration stress. This way, constant precipitation regimes and mild temperatures again contribute positively to growth. In a previous paper, Condés and Sterba (2008) already showed the influence of this index on both the basal area and the height increment of Aleppo pine individual trees in Murcia.

Bioclimatic effects exhibit an interaction with the stand density index, shown in the model as a product of the free bioclimatic intensity and that index. The effect of these interactions is readily apparent in Fig. 4. Six different categories of IBL and Emberger's index have been considered, showing that better climatic conditions always result in higher growth. Fig. 4.a) shows the variation of volume increment when a constant value of stem/ha is considered. The effect of competition can be seen in this figure: when SDI increases, and the value of stem/ha remains constant, the quadratic mean diameter increases, consequently competition is higher, and volume increment decreases. Moreover, it can be noticed that the higher the climatic site potential, the steeper the increment in stand volume increment when competition decreases.

Taken into account that there is a correlation between SDI and the number of stems/ha, the figure changes. Fig. 4b) shows how volume increment changes when SDI increment is accompanied by a corresponding N increment. It can be noticed that when density is high (high values of SDI and number of stems/ha) the effect of climate is more obvious.

Stands with higher SDIs are typically located in better site condition areas, where precipitation values are higher, affecting Emberger's and IBL indices in the same direction. In these areas, dominant height also reaches a higher value. These conditions are taken into account when proposing the different alternatives regarding stand characteristics shown in Fig. 3. This figure shows that the decrement in stand volume increment is slightly higher in absolute terms for stands in better conditions when a climate change scenario is applied, but in relative terms the decrement is higher in poorer than in better conditions (from 7.5% to 5.5% for the most likely climate change scenario).

It has to be considered that, for the analyzed scenarios, the proposed precipitation reductions from 2% to 10% are really conservative, taking into account that some authors predict decreases in rainfall up to 25% in the Mediterranean area, with temperature increments up to 3 °C (Giorgi and Lionello, 2008). Less conservative climate change scenarios would result in clear decrements in stand volume increment in absolute terms, and this decrement is more evident when density and competition are higher.

Few studies have analyzed the evolution of *P. halepensis* forests under climate projections, even less focused on the impacts of climate change processes on the *P. halepensis* forests located near their distribution limits (Vicente-Serrano et al., 2010).

In the Mediterran region of France, Gaucherel et al. (2008) use an ecophysiological model based on tree ring data; for this area the climate scenario consist of a precipitation significantly higher than the current values. In those conditions they conclude that for *P. halepensis* an increment of growth about 26% is expected during the 21st century basically as a response to CO_2 increment. The results agree with the outputs of a biogeochemistry model in Provence (Rathgeber et al., 2003).

In a further Southern area, the central Ebro Valley (Northeastern Spain), Vicente-Serrano et al. (2010) showed that forests located in the most water-limited areas are no favored by temperature increase and CO_2 fertilization. Where aridity is very pronounced, they conclude that the increased water stress predicted, resulting from a large decrease in precipitation (between 18% and 13%)

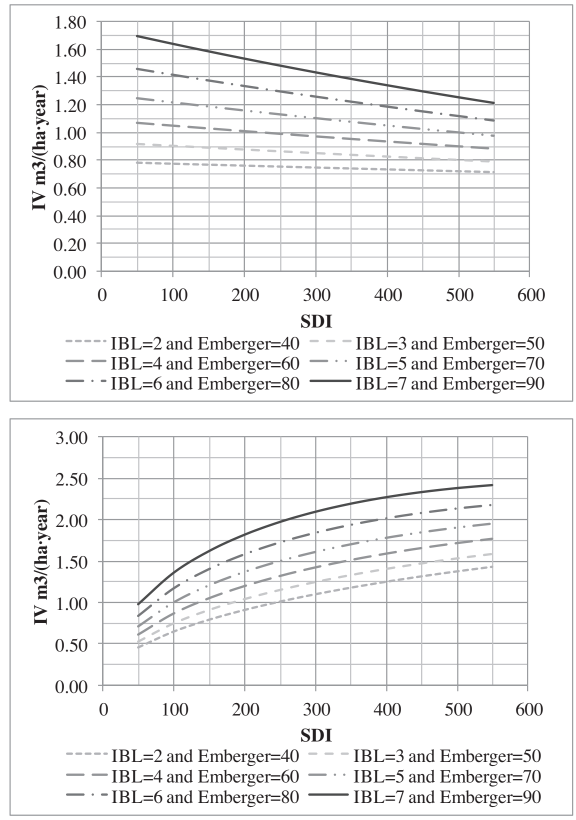

Fig. 4. Effect of interactions between climate conditions and stocking. H_{dom} = 10 m, Elevation = 7.75 hm, slope = 15% and aspect = 180°. (a) with a constant N = 300 stem/ha, (b) with N varying according to SDI value.

and increased evaporation rates, have a negative effect on forest growth.

Our model is focused in an area located near the distribution limits of *P. halepensis*. Although the CO_2 was left out of the model, the obtained results reinforce the argument that in forests located in the most water-limited areas climate change will negatively affect volume growth. In this sense, Sabaté et al. (2002) suggested that the positive effects of an increment in CO_2 concentration may not compensate the reduction of growth as a consequence of water constraints associated to precipitation decrease and temperature increase.

5. Conclusions

Spanish National Forest Inventory, together with data from the Spanish National Meteorological Agency, provides valuable information that allows the development of empirical stand growth models where climatic variables can be included. This new models become a fundamental management tool to estimate growth under new climatic conditions.

As the climatic factors driving stand growth are not identical for different regions, and considerable differences between regions can be expected in the effects of climate change, it is necessary to identify the climatic variables which are the most explanatory ones in each case.

In the Mediterranean area, where the limiting factor is mainly water availability, a positive relation between precipitation and growth has been found. In this area, the negative relation between temperature and growth is due to the influence of high temperature on potential evapotranspiration, with the consequent reduction of soil water reserves.

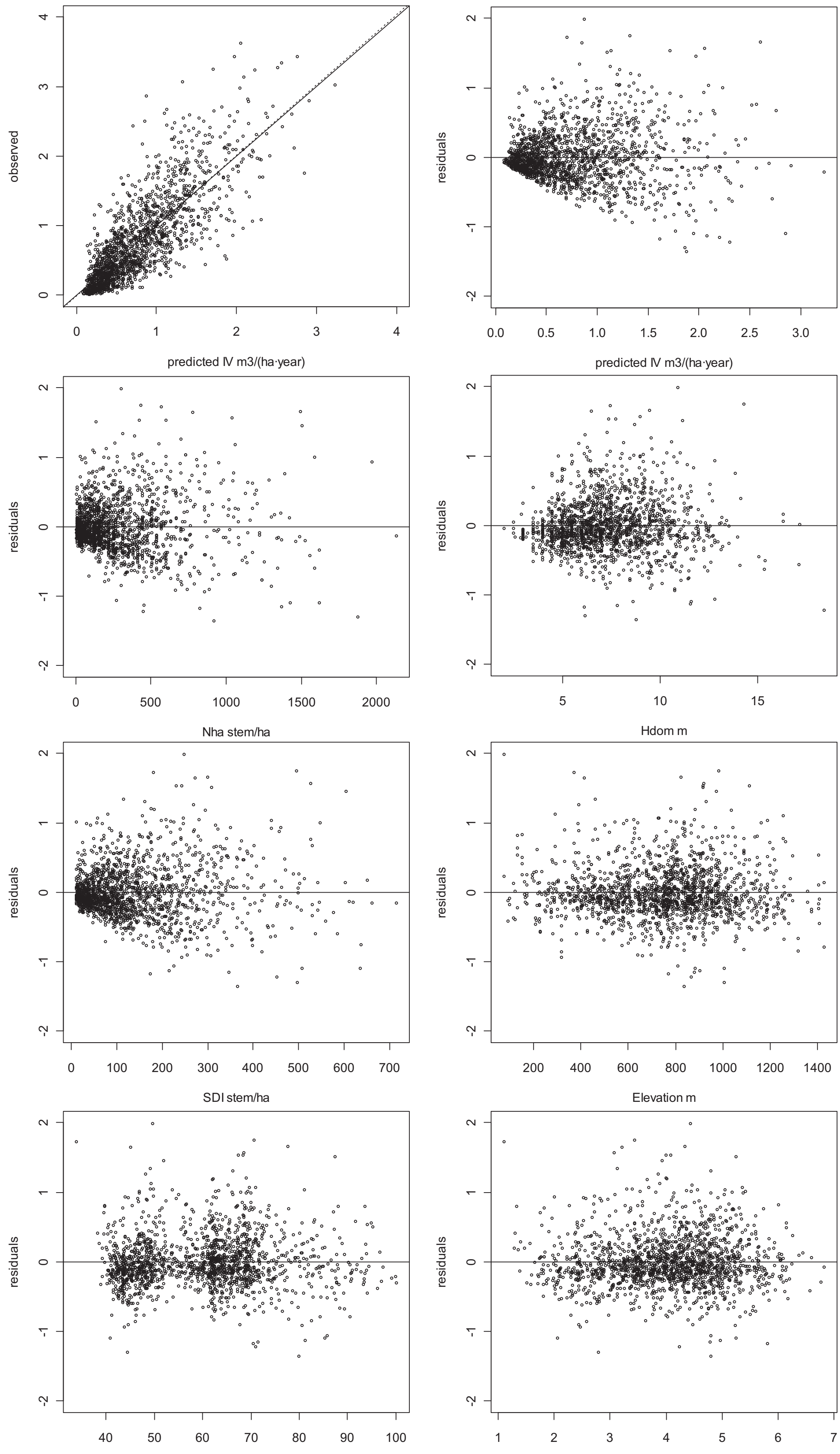

Fig. 5. Observed versus predicted values, residuals versus predicted, and residuals versus independent variables for the final non linear mixed model.

However, the most explanatory bioclimatic parameters are those that involve a combination of both variables, or those based on a water-balance approach. Particularly, for *P. halepensis* in the Mediterranean region of Murcia, Precipitation effectiveness, Emberger's index and free bioclimatic intensity are the three best bioclimatic indicators of stand volume growth.

The model for *P. halepensis* also shows an interesting interaction between competition and climate conditions. This model predicts a decrement of growth between 5.5% and 7.5% when a conservative 5% reduction of annual precipitation is considered. Higher decrements are expected in stands growing in poorer site conditions. The interaction between stand density index (SDI) and the bioclimatic index in the model shows that thinning, resulting in a reduction of competition, could help to reduce the negative influence of climate change, but the effect of thinning is more obvious when climate conditions are better.

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References

Assmann, E., 1961. Waldertragskunde. BLV.

Becking, J., 1954. Einige Gesichtspunkte für die Durchführung von vergleichenden Durchfostungsversuchen in gleichaltrigen Bestäden. In: IUFRO Congress, Rome, pp. 580–582.

Bergh, J., Freeman, M., Sigurdsson, B., Kellomäki, S., Laitinen, K., Niinistö, S., Peltola, H., Linder, S., 2003. Modelling the short-term effects of climate change on the productivity of selected tree species in Nordic countries. For. Ecol. Manage. 183, 327–340.

Briceno-Elizondo, E., Garcia-Gonzalo, J., Peltola, H., Matala, J., Kellomaki, S., 2006. Sensitivity of growth of Scots pine, Norway spruce and silver birch to climate change and forest management in boreal conditions. For. Ecol. Manage. 232, 152–167.

Condés, S., Sterba, H., 2008. Comparing an individual tree growth model for *Pinus halepensis* Mill. in the Spanish region of Murcia with yield tables gained from the same area. Eur. J. For. Res. 127, 253–261.

Creus Novau, J., Saz Sánchez, M.A., 2004. La sequía como principal factor limitante del desarrollo de Pinus halepensis Mill. en el sector central del valle del Ebro. In: Cantabria, U.d. (Ed.), El clima, entre el mar y la montaña: IV Congreso de la Asociación Española de Climatología, Santander, pp. 607–618.

de Vries, W., Vel, E., Reinds, G., Deelstra, H., Klap, J., Leeters, E., Hendriks, C., Kerkvoorden, M., Landmann, G., Herkendell, J., 2003. Intensive monitoring of forest ecosystems in Europe: 1. Objectives, set-up and evaluation strategy. For. Ecol. Manage. 174, 77–95.

DGCONA, 2002. Tercer Inventario Forestal Nacional 1997–2006: Región de Murcia. Ministerio de Medio Ambiente.

Emberger, L., 1932. Sur une formule climatique et ses applications en botanique. La Météorologie 92, 1–10.

Fontes, L., Bontemps, J.D., Bugmann, H., Van Oijen, M., Gracia, C., Kramer, K., Lindner, M., Rötzer, T., Skovsgaard, J.P., 2010. Models for supporting forest management in a changing environment. For. Syst. 19, 8–29.

Garcia-Gonzalo, J., Peltola, H., Briceño-Elizondo, E., Kellomäki, S., 2007. Effects of climate change and management on timber yield in boreal forests, with economic implications: a case study. Ecol. Model. 209, 220–234.

Gaucherel, C., Guiot, J., Misson, L., 2008. Changes of the potential distribution area of French Mediterranean forests under global warming. Biogeosciences 5, 1493–1504.

Gavilán, R.G., 2005. The use of climatic parameters and indices in vegetation distribution. A case study in the Spanish Sistema Central. Int. J. Biometeorol. 50, 111–120.

Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. Global Planet. Change 63, 90–104.

Gracia, C.A., Sabaté, S., Sánchez, A., 2002. El cambio climático y la reducción de la reserva de agua en el bosque mediterráneo. Ecosistemas 2.

Hart, H., 1928. Stamtal en dunning: Een oriënteerend onderzoek naar de beste plantwijdte en dunningswijze voor den djati. In. Veenman, Wageningen.

Hasenauer, H., Nemani, R.R., Schadauer, K., Running, S.W., 1999. Forest growth response to changing climate between 1961 and 1990 in Austria. For. Ecol. Manage. 122, 209–219.

Hébert, J., Bourland, N., Rondeux, J., 2005. Estimation de l'accroissement et de la production forestière à l'aide de placettes permanentes concentriques. Ann. For. Sci. 62, 229–236.

Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K.T., Strandman, H., 2008. Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. Phil. Trans. Roy. Soc. B: Biol. Sci. 363, 2339–2349.

Kramer, K., Leinonen, I., Loustau, D., 2000. The importance of phenology for the evaluation of impact of climate change on growth of boreal, temperate and Mediterranean forests ecosystems: an overview. Int. J. Biometeorol. 44, 67–75.

Lasch, P., Lindner, M., Erhard, M., Suckow, F., Wenzel, A., 2002. Regional impact assessment on forest structure and functions under climate change-the Brandenburg case study. For. Ecol. Manage. 162, 73–86.

Laubhann, D., Sterba, H., Reinds, G.J., De Vries, W., 2009. The impact of atmospheric deposition and climate on forest growth in European monitoring plots: an individual tree growth model. For. Ecol. Manage. 258, 1751–1761.

Linder, M., 2000. Developing adaptive forest management strategies to cope with climate change. Tree Physiol. 20, 299–307.

López-Serrano, F., Garcia-Morote, A., Andres-Abellan, M., Tendero, A., Del Cerro, A., 2005. Site and weather effects in allometries: a simple approach to climate change effect on pines. For. Ecol. Manage. 215, 251–270.

Martonne, E., 1926. Une Nouvelle Fonction Climatologique: L'Indice d'Aridite (A New Climatological Function: The Aridity Index). La Météorologie 2, 449–458.

Matala, J., Ojansuu, R., Peltola, H., Sievanen, R., Kellomaki, S., 2005. Introducing effects of temperature and CO_2 elevation on tree growth into a statistical growth and yield model. Ecol. Model. 181, 173–190.

Matala, J., Ojansuu, R., Peltola, H., Raitio, H., Kellomaki, S., 2006. Modelling the response of tree growth to temperature and CO2 elevation as related to the fertility and current temperature sum of a site. Ecol. Model. 199, 39–52.

Middleton, N.J., Thomas, D.S.G., 1992. World Atlas of Desertification: United Nations Environment Programme. Edward Arnold, London.

Montero de Burgos, J., González-Rebollar, J., 1974. Diagramas Bioclimáticos. ICONA, Madrid.

Moreno, J.M., Martínez, C., Mora, J., Picatoste, J., Fernández, F., Cruz, A., 2005. Principales conclusiones de la evaluación preliminar de los impactos en España por efecto del cambio climático, Madrid.

Rathgeber, C., Nicault, A., Kaplan, J.O., Guiot, J., 2003. Using a biogeochemistry model in simulating forests productivity responses to climatic change and CO2 increase: example of *Pinus halepensis* in Provence (south-east France). Ecol. Model. 166, 239–255.

Reineke, L., 1933. Perfecting a stand-density index for even-aged forests. J. Agric. Res. 46, 627–638.

Rivas-Martinez, S., 1983. Nuevo indice de termicidad para la region mediterranea. Avances sobre la investigacion en bioclimatologia, 377–380.

Sabaté, S., Gracia, C.A., Sánchez, A., 2002. Likely effects of climate change on growth of *Quercus ilex*, *Pinus halepensis*, *Pinus pinaster*, *Pinus sylvestris* and *Fagus sylvatica* forests in the Mediterranean region. For. Ecol. Manage. 162, 23–37.

Stage, A.R., 1973. Prognosis model for stand development. Intermountain Forest & Range Experiment Station, Forest Service, US Dept. of Agriculture.

Thornthwaite, C.W., 1931. The climates of North America: according to a new classification. Geog. Rev. 21, 633–655.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geog. Rev. 38, 55–94.

Vicente-Serrano, S.M., Lasanta, T., Gracia, C., 2010. Aridification determines changes in forest growth in *Pinus halepensis* forests under semiarid Mediterranean climate conditions. Agric. For. Meteorol. 150, 614–628.

Wallén, C.C., 1967. Aridity definitions and their applicability. Geog. Ann. Ser. A. Phys. Geog., 367–384.