# Regional changes of *Pinus pinaster* site index in Spain using a climate-based dominant height model

**Andrés Bravo-Oviedo, Clemente Gallardo-Andrés, Miren del Río, and Gregorio Montero**

**Abstract:** This study compares two site index estimations for Mediterranean maritime pine (*Pinus pinaster* Ait.) stands in the Iberian Peninsula. The first prediction was performed under the assumption of constant climate conditions, whereas the second one used foreseen climate according to an energy-use increment and high population growth (IPCC's A2 emission scenario). We used an existing climate-based dominant height model that incorporates temperature, seasonal precipitation in winter and autumn, and drought length as driver variables for dominant height growth. Climate attributes were retrieved from eight regional climate models nested in the same atmospheric–ocean global circulation model. Forest stand data from 188 experimental plots in four natural regions were used to compare regional climate change trends. Results indicated a climate-related diminishing trend of site index values, although some regional differences were evident. In the northern stands, the negative effects were not observed, and in some cases, forest productivity increased on low site index classes. Conversely, in the southernmost stands, there is a significant decrease in the site index across all productivity classes. Western and eastern stands also showed a decreasing trend but to a lesser extent. Our results confirm the vulnerability of stands to warmer and drier climate conditions in the southern Mediterranean region in relation to wood productivity.

**Résumé :** Cette étude compare deux méthodes d'estimation de l'indice de qualité de station pour des peuplements de pin maritime méditerranéen (*Pinus pinaster* Ait.) de la péninsule ibérique. La première méthode est basée sur l'hypothèse de conditions climatiques constantes alors que la deuxième méthode utilise des prévisions climatiques provenant d'un scénario d'accroissement de l'utilisation de l'énergie et d'une forte croissance de la population (scénario d'émission A2 du GIEC). Nous avons utilisé un modèle existant de hauteur dominante basé sur le climat qui tient compte de la température, des précipitations saisonnières en hiver et en automne et de la durée des périodes sèches comme variables déterminantes de la croissance en hauteur des arbres dominants. Les variables climatiques ont été tirées de huit modèles de climat régional imbriqués dans le même modèle de circulation générale, atmosphérique et océanique. Nous avons utilisé les données de peuplements forestiers de 188 parcelles expérimentales établies dans quatre régions naturelles pour comparer les tendances de changement des climats régionaux. Les résultats indiquent une tendance décroissante des valeurs d'indice de qualité de station en fonction du climat bien que certaines différences régionales soient évidentes. Dans les peuplements situés au nord, ces effets négatifs n'ont pas été observés et, dans quelques cas, la productivité forestière augmente dans les faibles classes d'indice de qualité de station. À l'inverse, dans les peuplements situés les plus au sud, il y a une diminution significative de l'indice de qualité de station dans toutes les classes de productivité. Dans les peuplements situés à l'ouest ou à l'est, il y a une tendance décroissante, mais à un degré moindre. Nos résultats confirment que les peuplements sont vulnérables aux conditions climatiques plus chaudes et plus sèches dans le sud de la région méditerranéenne en ce qui a trait à la productivité ligneuse.

[Traduit par la Rédaction]

## Introduction

The warming trend throughout Europe is well documented. One of the most recent syntheses reported an increase of 0.9 °C for the period 1901–2005 (Alcamo et al. 2007) and an even larger increment than the mean between 1979 and 2005. Although these trends are higher in northern and central Europe than in southern Europe (Klein Tank and Können 2003), the Mediterranean area is considered to be the most sensitive to climate change (Sala et al. 2000). Climate models predict an increase in mean temperature due to higher $CO_2$ and a concentration of other greenhouse gases as well as a decrease in annual precipitation, including their seasonal distribution with more frequency of severe droughts. These predictions have been confirmed in the Mediterranean area where a trend of increasing temperatures

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and higher variability in precipitation has been observed (Castro et al. 2005).

In parallel with these trends, a reduction of suitable area for forest species has been predicted in the Mediterranean region (Schröter et al. 2005; del Barrio et al. 2006; Harrison et al. 2006) and a decline in tree growth has also been reported (Sarris et al. 2007). However, other studies found positive trends in forest dynamics, such as diameter growth, indicating a site-specific response to climate change (Vila et al. 2008). In the same way, process-based models have predicted a positive impact of warmer scenarios in Mediterranean species assuming an adequate water supply (Sabaté et al. 2002).

Adaptive forest management strategies are needed to obtain goods and services from the forest in a sustainable manner. Some modelling results suggest that management practices influence forest dynamics under climate change (Lindner 1999, 2000). The inclusion of local growth trends in forest management could help both to develop adaptive strategies and to assess forest mitigation and adaptation capacity. Strategies for forest management adaptation require basic information about the impacts of climate change over the medium to long term (Spittlehouse and Stewart 2003).

Site index estimation, calculated as the dominant height attained at certain age, is by far the most frequently used method to estimate forest productivity by managers. The origin purpose of forest site index studies was to determine the potential wood production of a stand, but the importance of height growth patterns in forest dynamics (Oliver and Larson 1996) makes this indicator relevant for sustainable forest management (Smith et al. 1997). To define the objectives and the corresponding silviculture of forest stands, it is necessary to estimate their site index. Adaptation strategies should vary among site index classes so that increasing/decreasing site productivity can indicate the benefit of earlier/later, more/less intensive thinning and shorter/longer rotation (Kellomäki et al. 1997; Bravo et al. 2008).

Many efforts have been conducted to improve empirical site index estimation. Traditionally, site index models assign the same value for two stands with the same age and height, i.e., the value is constant irrespective of local conditions. Environmental attributes can be used to predict site index when suitable trees are absent (Wang 1995; Wang and Klinka 1996), but the constancy of site index remains. Other attempts try to include climate or soil variables during the model building phase (Woollons et al. 1997), and one of these models has been developed recently and parameterized for maritime pine (*Pinus pinaster* Ait.) in a region with a Mediterranean-type climate (Bravo-Oviedo et al. 2008). This model incorporates climate variables, such as mean annual temperature, winter and autumn precipitation, and drought length. The application of this model to a stand requires initial height, age, and local climate information. Any variation in local climate conditions leads to different site index estimation, even if we compare two stands of the same age and height.

The IPCC have built (IPCC 2000) a collection of economic and social scenarios that have been first translated into future greenhouse gas atmospheric emissions and then into concentrations of these gases in the atmosphere. The atmospheric–ocean global circulation models (AOGCMs) use these concentration scenarios to drive their simulations and to study the evolution of the climate system.

The AOGCMs are based on physical principles and represent the processes within the core components of the climate system and the interactions among them. They are currently used as the main analytical tool to study climate change. These models are also used to improve our understanding of climate and to provide projections of future climatic conditions (Giorgi and Mearns. 2002; Raper et al. 2002; Tebaldi and Knutti 2007). However, their spatial resolution (roughly 150–300 km at any longitude) is insufficient to be used in many regional or local assessment studies (IPCC 1994; Mearns et al. 2003). To overcome this limitation, several downscaling techniques have been proposed (Kidson and Thompson 1998; Mearns et al. 1999; Murphy 1999). Regional climate models (RCMs) are among those using these techniques. These models are similar to the AOGCMs in terms of complexity, as they solved atmosphere governance equations and incorporate physical parameterizations, which take into account atmospheric processes at a small spatial resolution. Despite their complexity, RCMs are built to be applied to regions facilitating a higher spatial resolution (10–50 km) suitable for many impact studies. Since late 1980s (Dickinson et al. 1989; Giorgi 1990), RCMs have been used, nested in global models, to analyze and project climate. However, only in the last decade have impact assessments used RCM scenarios in different fields such as water resource management (Stone et al. 2001), agriculture (Mearns et al. 1998; Mínguez et al. 2007), forestry (Wotton et al. 1998), or artic studies (Stendel et al. 2007).

Mediterranean maritime pine grows under highly variable ecological conditions and exhibits site-specific growth responses. Therefore, different climate change impacts can be expected in different geographic regions. The main objective of this study is to evaluate differences in site index estimation during 2071–2100 using two scenarios: a control one where climate remains unchanged between now and the end of the century and a climate generated according to an A2 emission scenario (IPCC 2000). The study includes a sensitivity analysis of model outputs to variations in climate inputs and uncertainty due to parameter estimation to corroborate the applicability of the statistical growth model for future climate scenarios. The comparisons will be made on a regional basis and according to discrete site index classes using the climatic-based dominant height growth model available and RCM outputs.

## Materials and methods

### Study area and stand data

The natural distribution of Mediterranean maritime pine in Spain is divided into seven geographic regions (Nicolas and Gandullo 1966) and occupies approximately 724 000 ha (DGCN 1998). This study deals with the following four regions. The Northern Plateau Stands (NPS) are characterized by a mean annual temperature of 11.3 °C and annual precipitation of 486.4 mm. The quality of these stands is considered to be low and stems are often poorly formed. The Central Mountain Range Stands (CMS) are located in the central part of the Iberian Peninsula with a wide area at altitudes above 1000 m, mean annual temperature of 12.5 °C, and annual precipitation of 635 mm. The Iberian Mountain Range Stands (IMS) grow in the eastern part of Spain where the mean annual temperature is 10.5 °C and annual precipitation reaches 546.7 mm. Finally, the Segura-Alcaraz Mountain Stands (SES) are located in the southeastern part of the Iberian Peninsula. The mean annual temperature for the region is 13.1 °C and annual precipitation is 651.7 mm.

We used a set of permanent sample plots belonging to the Experimental Plots Network established and maintained by the Forest Research Centre (INIA) (Montero et al. 2004) and to the Experimental Network on Sustainable Forest Management of the Department of Forest Resources (University of Valladolid) (Bravo et al. 2004). These plots cover the four studied regions and are distributed according to density, age, and site quality of the stands. A total of 188 plots were selected in the study area (Fig. 1). In every plot, dominant height was calculated according to the mean value of the 100 thickest stems per hectare (Assmann 1971). Total age was estimated through tree basal coring and stems analysis. Table 1 shows the descriptive statistics of height, age, and site index by region.

## Height growth model

Site index was calculated according to a dynamic dominant height growth model developed by Bravo-Oviedo et al. (2008). This model is a modification of that proposed by Cieszewski (2001) and allows the inclusion of climate attributes and parental material specific to each plot. The input data required are age and dominant height as initialization parameters, mean annual temperature (degrees Celsius), the sum of precipitation in winter and autumn (millimetres), and the number of months where the precipitation curve is under the temperature curve in the Walter–Gauss climatic diagram; this period is then used as drought length. If the plots are located on dolomite rock type, a categorical variable is also required. The height growth model was originally presented according to four structures related to the likely effects of climate and parental material on growth: additive or multiplicative. In this work, we have used the second additive structure because it showed a better performance in terms of accuracy and bias:

[1] $$H = H_0(t/t_0)^{\nu+\delta}(t_0^{\delta}R + \kappa)(t^{\delta}R + \kappa)^{-1}$$

$$R = Z_0 + \sqrt{Z_0^2 + \frac{2\kappa H_0}{t_0^{\nu+\delta}}}$$

$$Z_0 = \frac{H_0}{t_0^{\nu}} - \eta$$

where $\eta = a_0 \times \mathrm{PR} \times \sqrt{T}$, $\delta = b_0 + b_1 \times \mathrm{DOL}$, $\gamma = (c/\mathrm{DL} + 1)$, $\kappa = 2\alpha\gamma'$, $\gamma' = e^{\gamma}$, $\alpha = 0.5$, $H$ and $H_0$ are dominant height at age $t$ and $t_0$, respectively, PR is the sum of precipitation in winter and autumn (millimetres), $T$ is annual mean temperature (degrees Celsius), DL is drought length (months), DOL indicates the presence of dolomite lithology, and $a_0$, $b_0$, $b_1$, and $c$ are estimated parameters.

The dominant height growth model was fitted using climate data from a 30-year period (1961–1990) retrieved from the GENPET and COMPLET models (Fernández-Cancio and Manrique 2001; Manrique and Fernández-Cancio 2005) that interpolate data from the nearest meteorological stations to the target point, i.e., the plots in our database, according to geographic coordinates and elevation. Site index was defined as the dominant height at the age of 70 years. These kinds of curves are site specific and, consequently, two stands of the same age and height are allowed to have different average growth pattern, and thus site index, according to their local climate.

## Regional climate models

Climate projections were made using RCMs. The ability of RCMs to predict current and future climate may be enhanced by using a set of regional models nested in one common AOGCM. These models can be used separately or joined in an ensemble average. In this study, we have used eight RCMs developed by the following research centres, with the first acronym being the name of the model and the second the name of the project under which they were developed: the Danish Meteorological Institute (DMI, HIRHAM), the Swiss Federal Institute of Technology (ETH, CHRM), the GKSS Institute for Coastal Research (GKSS, CLM), the International Centre for Theoretical Physics (ICTP, RegCM), the Royal Netherlands Meteorological Institute (KNMI, RACMO), the Max-Planck Institute for Meteorology (MPI, REMO), the Swedish Meteorological and Hydrological Institute (SMHI, RCAO), and the University Complutense of Madrid (UCM, PROMES).

All of these RCMs have been nested in the version of the Hadley Centre's AOGCM known as HadAM3H (Hudson and Jones 2002). The horizontal resolution used was around 50 km and the simulations cover two different periods, current climate (1961–1990) and future climate (2071–2100) predicted under A2 emissions scenario. Both periods have been used in the present study. We have focused on the last 30 years of the 21st century because it allows obtaining a clearer signal due to climate change avoiding other sources of noise. RCM outputs have been interpolated to a common regular grid (0.5° × 0.5°) from the original grid of each model. Figure 1 shows the differences between control and the SRES-A2 scenario of temperature, precipitation in winter and autumn, and drought length of those plots finally selected for the analysis, as explained below.

## Data selection

Site index predictions, using eq. 1, require values belonging to a similar climate database to those used to fit the model. However, this is not the case for data retrieved from RCMs. GENPET data are specific for each land point, whereas RCM outputs are grid based. These lead to a common climate for those plots (land points) common to the same grid's cell. This could be a great disadvantage, as there are plots within a grid that show a different site index. This occurs, partially, owing to orientations or altitudes sharing the same cell. For instance, for two plots with the same age and height, one located in a dry south-facing slope and the other located in a wet north-facing slope, they should have a different site index according to GENPET climate, whereas the RCM data would show the same site index.

Furthermore, topography variation in the RCMs is smoother than actually observed, and ridges of mountains and bottoms of valleys could be lightly diverted confounding their likely effects on growth. Therefore, it is likely that

**Fig. 1.** Study area and predicted change of mean annual temperature (*T*), precipitation in winter and autumn (PR), and drought length (DL) according to the SRES-A2 scenario for the period 2071–2100. Circles are plot locations NPS, Northern Plateau Stands; CMS, Central Mountain Range Stands; IMS, Iberian Mountain Range Stands; SES: Southeastern Stands.

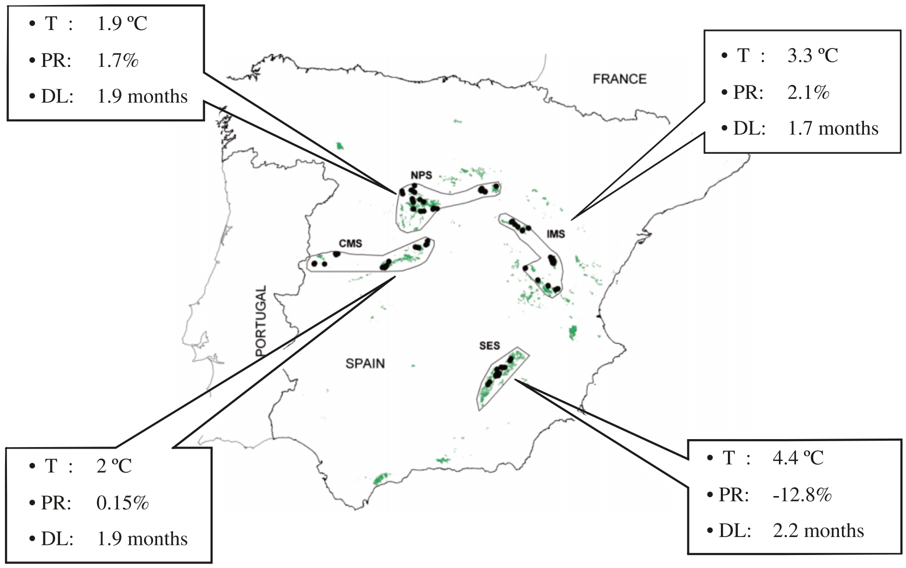



**Table 1.** Descriptive statistics of the field data.

| | | Height (m) | | | | Age (years) | | | | SI70 (m) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | No. of observations | Min. | Mean | Max. | SD | Min. | Mean | Max. | SD | Min. | Mean | Max. | SD |
| NPS | 55 | 9.2 | 15.1 | 21.5 | 2.8 | 30 | 69.6 | 110.0 | 24.3 | 7.8 | 15.6 | 21.0 | 2.7 |
| CMS | 39 | 8.3 | 17.8 | 28.3 | 4.4 | 25 | 67.9 | 140.0 | 27.0 | 10.8 | 19.5 | 25.4 | 4.2 |
| IMS | 71 | 6.2 | 12.5 | 20.1 | 2.9 | 30 | 88.5 | 170.0 | 32.0 | 4.4 | 11.3 | 20.6 | 3.7 |
| SES | 23 | 9.0 | 17.0 | 21.7 | 3.1 | 61 | 99.8 | 180.0 | 32.3 | 7.2 | 14.1 | 19.8 | 3.6 |

**Note:** NPS, Northern Plateau Stands; CMS, Central Mountain Range Stands; IMS, Iberian Mountain Range Stands; SES, Southeastern Stands. Site index (SI70) value calculated according to Bravo-Oviedo et al.'s (2008) model.

the site index estimation, corresponding to the RCM's climatic values, is more accurate using the climate from the adjacent grid's cell instead of that from the geographically corresponding one.

To overcome this problem, we tested if site index predictions using both kinds of climate data for the same control period (1961–1990) drew similar results. We also compared the suitability of the cell originally assigned to plots (target cell) with those data coming from the northern-, eastern-, southern-, and westernmost cells (adjacent cells). We considered a tolerance of ±2 m in site index estimation using RCM grid data in relation to GENPET point data. Beyond these limits, RCM output was not considered suitable for further analysis. Results will be presented as the percentage of correct observations for the eight RCMs and by region.

Once we have accepted the adequacy of using data from RCMs for estimating site index with eq. 1, we have only selected the correct plots and the more suitable cell to conduct the simulations to prevent the introduction of additional errors with the RCM grids.

## Sensitivity analysis

Sensitivity analysis was performed to study the impact of changes in climate variables on site index predictions and will be used to determine which variables might cause the greatest variation in model output using a climate-based model. We assumed a baseline scenario using control climate (1961–1990) and a common site index class of 15 m at 70 years. Sensitivity analysis was tested by comparing the model output with default climate values to model output with changing scenarios by varying one of the environmental drivers at a time. Changing values were ranged from the minimum to the maximum value of climate drivers predicted by the IPCC A2 emission scenario. These values depart from control climate by –2 to +6 °C in temperature and –50% and +100% in precipitation. Drought length is extended up to 6 months.

Parameter estimates of climate variables may contribute to site index uncertainty. We study this effect by changing their value 10% upwards and downwards. Sensitivity to parameter change was evaluated by plotting variable and parameter range of variation against the rate of change of site index estimation.

## Site index changes analysis

The initial age ($t_0$) selected to generate site index projections was 20 years, so we calculated the initial height ($H_0$) attained at this age for each plot from the dominant height and age plot measurements using the dominant height model (eq. 1) and suitable RCM climate during the control period.

These values simulate the dominant height pattern of young stands within the same growth trajectory, and thus the same site index, of actual stands. After that, the site index estimation with RCM climate generated by the SRES-A2 scenario was calculated using eq. 1.

The difference between control site index value and the SRES-A2 scenario site index value would indicate a shift in forest productivity as a consequence of climate change. The average value of such differences across RCMs will produce prediction intervals. The differences in predicted site index values were analyzed by regions and site index class. To illustrate the results, we used six site arbitrary site index classes established according to the range of site indices: I, >24 m; II, 20–24 m; III, 16–20 m; IV, 12–16 m; V, 8–16 m; VI, ≤8 m.

## Results

### Data selection

The percentage of plots, whose site index estimation is within the limits proposed in the previous section, was highly variable depending on the RCM and the geographic region (Table 2). In some cases, this implied a perfect fit under our acceptance criteria, like the GKSS, ICTP, and SMHI models in the SES region, while data from the GKSS model drew only 25.6% of the correctly assigned site index in the CMS region. The percentage of correct observations increased noticeably if data from the grid's cell with the most similar site index estimation were used. In the NPS and SES regions, the average number of correct classification increases by 10%, whereas in the IMS and CMS regions, increases of 17% and 31%, respectively, were observed. Finally, the best classification was found in the SES region and the greatest discrepancies in the CMS region.

Site index estimation using climate derived from RCM is within the range of actual site index (±2 m) in at least 60% of plots. The exception to this rule is the GKSS model in the CMS region. According to these results, we consider it appropriate to use the RCM climate values to estimate site index.

### Sensitivity analysis

The sensitivity analysis showed that model outputs are less sensitive to temperature changes (<3%) than to seasonal rainfall or drought length changes. The projected increases in precipitation lead to higher site index estimation in the NPS and CMS regions. The sensitivity curve showed an asymptotic behaviour and reached a maximum of 15% of site index increase. If precipitation is lower than current conditions, a decrease in site index estimation is expected for all regions, although the SES region is less affected. Drought length variation showed a common pattern for all regions. We set the minimum drought length to zero months and results showed an expected increase in site index estimation of over 30% in all regions. The SES region is more affected by negative changes in site index estimation when the drought period exceeds the current conditions. It reaches a critical point beyond 2–3 months of drought where site index decreases by around 15%. Site index in the NPS, IMS, and CMS regions was less impacted by drought changes (Fig. 2*a*).

Uncertainty associated with parameter $a_0$ is neglected, as it represents less than 3% in site index variation. The same applies to parameter *c*, although higher values of this parameter lead to higher site index in the SES region. The sensitivity model output to this parameter is moderate (≤6%, Fig. 2*b*).

As a consequence of this analysis, the climate-based model is considered to be robust in parameter estimation and sensitive to climate deviations from current climate conditions. Consequently, we compared the site index values estimated with current climate with those obtained with projected climate according to the A2 scenario.

### Site index analysis

The average difference between site index estimation using constant and changing climate showed a decreasing trend for all regions except for NPS (Table 3). However, there is some variability among results from different models, the total mean change being only statistically significant in the SES region. According to these results, forest productivity of the SES will be the most affected by the climate simulated for the period 2071–2100. In this region, all site qualities would decrease significantly (Table 3) from –0.4 m (2.7%) in the lower site index class to –2.9 m (20.3%) in the higher one.

NPS would experience some significant increment in their less productive stands (site qualities V and VI), whereas the most productive ones did not show any significant difference in the mean site index. The upper confidence limit for the most productive stands (site quality I), which are located in the Central Mountain Range, involves a site index beyond the highest observed today (25.4 m) (Table 1), but this value is still within the natural range of total dominant height for the species as we know it today (approximately 35 m; DGCN 1998).

Changes in average site index are indicative of an average increase or decrease in forest productivity. Consequently, nonsignificance indicates that the expected changes will be neglected on average, in spite of the different changes predicted with the eight RCMs. However, Table 3 shows that the lower and upper limits for some site index changes are high enough in some site index classes to be important for management purposes. Thus, a further inspection of what percentage of observations and in what direction it is affected by climate change is needed. The number of plots that were correctly assigned in the first step of this study is not the same for each RCM's data. Some plots may be classified correctly by some RCMs and incorrectly by others. Consequently, for each RCM, we calculated the percentage of observations that remained in the same quality class with current and changing climate and the percentage of those that changed upwards or downwards. Figure 3 depicts the average value of this percentage by region and site quality class.

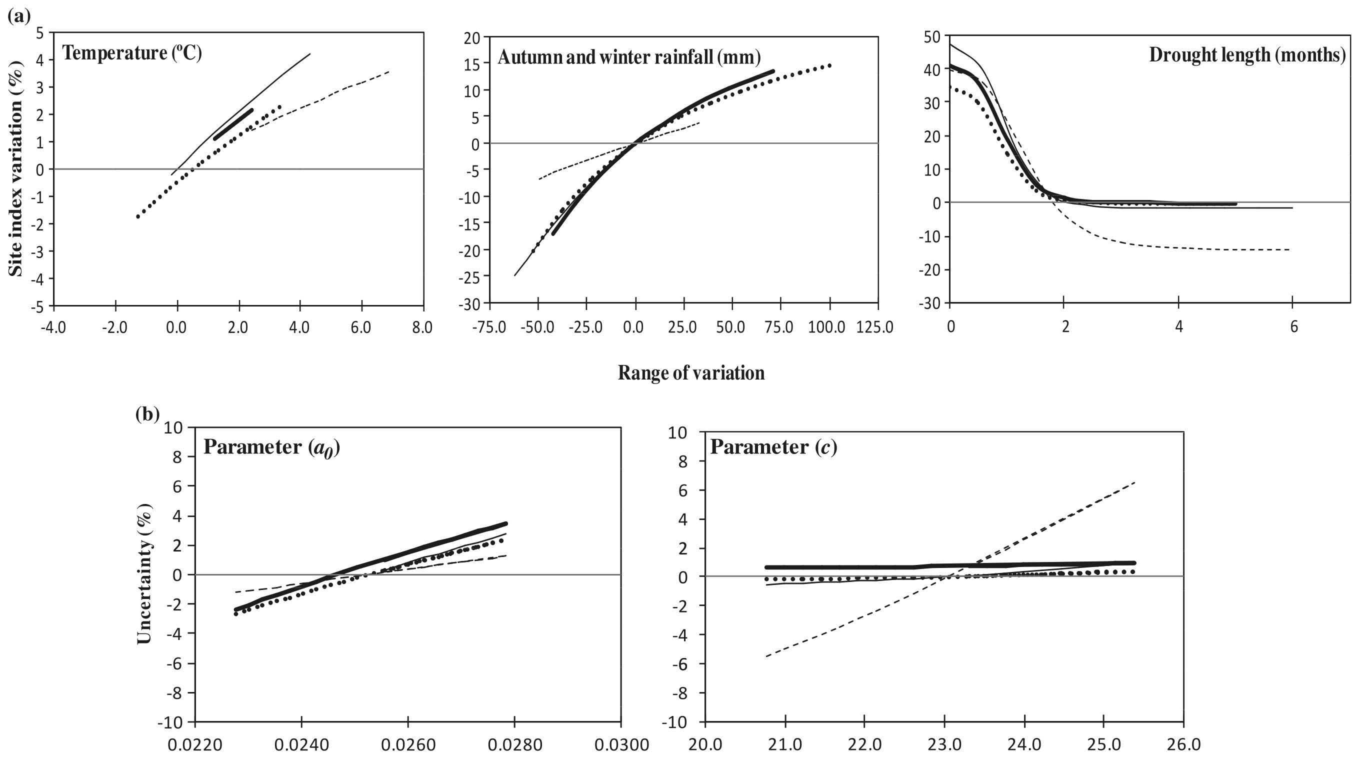
The most frequent change was a decrease in one site quality class in the higher classes, except in the NPS where more changes are toward one higher class. However, the confidence of the predictions was not equivalent across the site quality classes and regions. In the NPS region, 4% of stands of site quality II would increase to site quality I; however, this change was only shown by one RCM model (ICTP). The positive change from site quality III to site quality II was predicted by four models, whereas the in-

**Table 2.** Percentage of observations correctly classified according to region and grid cell.

| | | Regional climate model | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Region | Cell data | DMI | ETH | GKSS | ICTP | KNMI | MPI | SMHI | UCM |
| NPS | X | 63.6 | 78.2 | 41.8 | 76.4 | 78.2 | 70.9 | 94.5 | 54.5 |
| | Best cell | 65.5 | 80.0 | 60.0 | 85.5 | 90.9 | 78.2 | 100.0 | 70.9 |
| CMS | X | 35.9 | 56.4 | 25.6 | 53.8 | 53.8 | 30.8 | 53.8 | 25.6 |
| | Best cell | 66.7 | 100.0 | 35.9 | 84.6 | 74.4 | 64.1 | 100.0 | 61.5 |
| IMS | X | 64.8 | 94.4 | 56.3 | 66.2 | 71.8 | 64.8 | 87.3 | 56.3 |
| | Best cell | 84.5 | 100.0 | 71.8 | 91.5 | 98.6 | 81.7 | 98.6 | 73.2 |
| SES | X | 65.2 | 65.2 | 100.0 | 100.0 | 95.7 | 65.2 | 100.0 | 69.6 |
| | Best cell | 87.0 | 95.7 | 100.0 | 100.0 | 100.0 | 65.2 | 100.0 | 87.0 |

**Note:** NPS, Northern Plateau Stands; CMS, Central Mountain Range Stands; IMS, Iberian Mountain Range Stands; SES, Southeastern Stands. X, target cell; "Best" uses the climatic value for the adjacent or target cell.

**Fig. 2.** Sensitivity analysis of (*a*) model inputs and (*b*) model parameters by region. Thick solid line, Northern Plateau Stands; thick broken line, Central Mountain Range Stands; thin solid line, Iberian Mountain Range Stands; thin broken line, Southeastern Stands.




crease from site quality IV to site quality III was predicted by the seven RCMs (Table 4). On the contrary, the negative changes in this region were predicted by only one or two RCMs. In the CMS region, the most confident result was the decrease of 34% from site quality II to site quality III, which was predicted by seven RCMs. The small percent decreases in two qualities was only detected by UCM's model, whereas the rest of positive and negative changes were predicted by two or three models out of eight.

In eastern stands (IMS), there were 29% of observations from site quality IV that changed to quality V and they were predicted by seven models, whereas the decreasing number of stands of site quality V was detected by five models (Table 4). In this case, the 12% of observations that went two qualities downwards were predicted by two models (DMI and UCM). Positive changes were predicted by four or five models depending on site index class.

The most definite results were the decreasing number of stands of site quality III and site quality IV in the SES region. In both cases, seven models predicted the same impact. The changes of two qualities from quality III to quality V and that from quality V to quality VI are predicted by two models. None of the models showed any positive change in this region (Table 4).

## Discussion

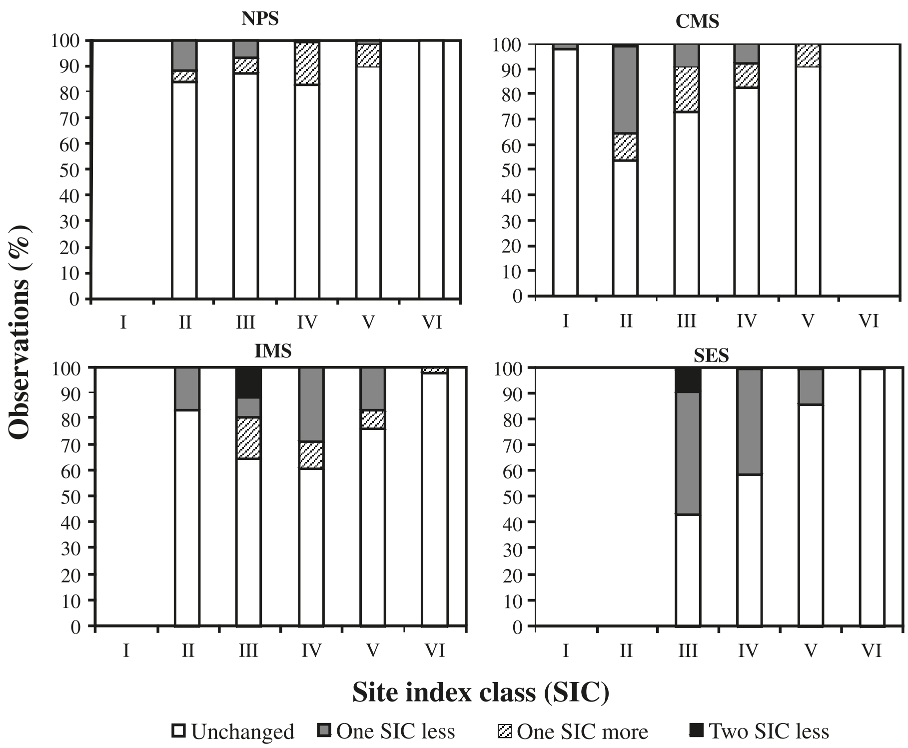
Site index is a key variable in forest growth modelling. It is traditionally estimated from statistical models that are based on the constancy of environmental drivers and associ-

**Table 3.** Mean difference value between site indexes using constant climate and the SRES-A2 scenario.

| Region | Lower limit | Mean | Upper limit | *p* | Site quality index | Lower limit | Mean | Upper limit | *p* |
|---|---|---|---|---|---|---|---|---|---|
| NPS | –0.13 | 0.33 | 0.78 | 0.133 | II | –1.41 | 0.15 | 1.71 | 0.825 |
| | | | | | III | –0.32 | 0.37 | 1.05 | 0.246 |
| | | | | | IV | –0.02 | 0.32 | 0.65 | 0.059 |
| | | | | | V | 0.01 | 0.15 | 0.29 | 0.035 |
| | | | | | VI | 0.01 | 0.07 | 0.14 | 0.024 |
| CMS | –1.44 | –0.38 | 0.68 | 0.428 | I | –0.76 | 0.84 | 2.44 | 0.233 |
| | | | | | II | –2.47 | –0.99 | 0.48 | 0.156 |
| | | | | | III | –0.94 | –0.05 | 0.84 | 0.902 |
| | | | | | IV | –1.11 | –0.14 | 0.83 | 0.744 |
| | | | | | V | –0.07 | 0.25 | 0.56 | 0.103 |
| IMS | –0.65 | –0.04 | 0.56 | 0.872 | II | –0.82 | 0.09 | 1.00 | 0.815 |
| | | | | | III | –1.67 | –0.31 | 1.06 | 0.613 |
| | | | | | IV | –1.09 | –0.19 | 0.72 | 0.641 |
| | | | | | V | –0.57 | –0.01 | 0.56 | 0.973 |
| | | | | | VI | –0.32 | –0.09 | 0.14 | 0.379 |
| SES | –2.95 | –1.90 | –0.85 | 0.004 | III | –4.26 | –2.86 | –1.46 | 0.002 |
| | | | | | IV | –2.67 | –1.60 | –0.53 | 0.010 |
| | | | | | V | –1.80 | –1.02 | –0.25 | 0.017 |
| | | | | | VI | –0.76 | –0.38 | 0.00 | 0.049 |

**Note:** NPS, Northern Plateau Stands; CMS, Central Mountain Range Stands; IMS, Iberian Mountain Range Stands; SES, Southeastern Stands. The mean is calculated according to the average value of eight models for each region and site quality index. Lower, upper, and *p* values are calculated for 95% of confidence.

**Fig. 3.** Frequency of site index classes that change or remain the same site quality by region under the SRES-A2 scenario.




ated plant physiological response. Consequently, they do not provide information on the mechanisms of change under environmental variability (Kimmins 2004). However, they are popular among forest managers, as data inputs are drawn from forest inventories and predictions are considered reliable (Mohren and Burkhart 1994). Although predictions in a changing environment could be questionable, the simplicity of these models is both a drawback and an advantage.

Model linking between statistical- and physiological-based approaches seems to be a promising area of research. The integration of both approaches has been done using hybrid models (Peng et al. 2002; Kimmins 2004) or transfer functions (Matala et al. 2005). Model hybridization can be done in two directions (Peng et al. 2002): by incorporating climate variables in empirical models to enhance its capacity to cope with changing climate (Nigh 2006; Monserud et al.

**Table 4.** Percentage of plots that remain the same quality or change by region, site quality, and regional climate model.

| Expected change | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|
| **Northern Plateau Stands** | | | | | | |
| DMI | | | | | | |
| Unchanged | 0.0 | 100.0 | 100.0 | 92.9 | 100.0 | 100.0 |
| One more | | 0.0 | 0.0 | 7.1 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| ETH | | | | | | |
| Unchanged | 0.0 | 100.0 | 93.3 | 83.3 | 85.7 | 100.0 |
| One more | | 0.0 | 6.7 | 16.7 | 14.3 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| GKSS | | | | | | |
| Unchanged | 0.0 | 0.0 | 45.5 | 84.6 | 85.7 | 100.0 |
| One more | | 0.0 | 0.0 | 7.7 | 0.0 | 0.0 |
| One less | 0.0 | 100.0 | 54.5 | 7.7 | 14.3 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| ICTP | | | | | | |
| Unchanged | 0.0 | 66.7 | 83.3 | 83.3 | 85.7 | 100.0 |
| One more | | 0.0 | 16.7 | 16.7 | 14.3 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| KNMI | | | | | | |
| Unchanged | 0.0 | 100.0 | 93.8 | 66.7 | 87.5 | 100.0 |
| One more | | 0.0 | 6.3 | 33.3 | 12.5 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| MPI | | | | | | |
| Unchanged | 0.0 | 100.0 | 100.0 | 82.4 | 87.5 | 100.0 |
| One more | | 0.0 | 0.0 | 17.6 | 12.5 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| SMHI | | | | | | |
| Unchanged | 0.0 | 100.0 | 78.3 | 66.7 | 83.3 | 100.0 |
| One more | | 0.0 | 21.7 | 33.3 | 16.7 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| UCM | | | | | | |
| Unchanged | 0.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Central Mountain Range Stands** | | | | | | |
| DMI | | | | | | |
| Unchanged | 100.0 | 90.9 | 100.0 | 75.0 | 100.0 | 0.0 |
| One more | | 0.0 | 0.0 | 25.0 | 0.0 | 0.0 |
| One less | 0.0 | 9.1 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| ETH | | | | | | |
| Unchanged | 85.7 | 61.5 | 100.0 | 87.5 | 100.0 | 0.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 14.3 | 38.5 | 0.0 | 12.5 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| GKSS | | | | | | |
| Unchanged | 0.0 | 14.3 | 66.7 | 50.0 | 0.0 | 0.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 85.7 | 33.3 | 50.0 | 0.0 | |

**Table 4** (*continued*).

| Expected change | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| ICTP | | | | | | |
| Unchanged | 100.0 | 66.7 | 33.3 | 66.7 | 66.7 | 0.0 |
| One more | | 0.0 | 66.7 | 33.3 | 33.3 | 0.0 |
| One less | 0.0 | 11.1 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| KNMI | | | | | | |
| Unchanged | 100.0 | 40.0 | 35.7 | 80.0 | 100.0 | 0.0 |
| One more | | 0.0 | 50.0 | 20.0 | 0.0 | 0.0 |
| One less | 0.0 | 20.0 | 14.3 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| MPI | | | | | | |
| Unchanged | 100.0 | 87.5 | 100.0 | 100.0 | 100.0 | 0.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 12.5 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| SMHI | | | | | | |
| Unchanged | 100.0 | 69.2 | 75.0 | 100.0 | 66.7 | 0.0 |
| One more | | 0.0 | 25.0 | 0.0 | 33.3 | 0.0 |
| One less | 0.0 | 7.7 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| UCM | | | | | | |
| Unchanged | 0.0 | 0.0 | 71.4 | 100.0 | 100.0 | 0.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 87.5 | 28.6 | 0.0 | 0.0 | |
| Two less | 0.0 | 12.5 | 0.0 | 0.0 | | |
| **Iberian Mountain Range Stands** | | | | | | |
| DMI | | | | | | |
| Unchanged | 0.0 | 0.0 | 33.3 | 50.0 | 72.2 | 100.0 |
| One more | | 0.0 | 33.3 | 20.0 | 13.9 | 0.0 |
| One less | 0.0 | 100.0 | 0.0 | 30.0 | 13.9 | |
| Two less | 0.0 | 0.0 | 33.3 | 0.0 | | |
| ETH | | | | | | |
| Unchanged | 0.0 | 100.0 | 87.5 | 84.6 | 92.1 | 90.0 |
| One more | | 0.0 | 12.5 | 15.4 | 7.9 | 10.0 |
| One less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| GKSS | | | | | | |
| Unchanged | 0.0 | 0.0 | 75.0 | 57.1 | 70.0 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 25.0 | 42.9 | 30.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| ICTP | | | | | | |
| Unchanged | 0.0 | 100.0 | 60.0 | 80.0 | 85.3 | 100.0 |
| One more | | 0.0 | 20.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 20.0 | 20.0 | 14.7 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| KNMI | | | | | | |
| Unchanged | 0.0 | 100.0 | 71.4 | 69.2 | 75.0 | 100.0 |
| One more | | 0.0 | 28.6 | 23.1 | 25.0 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 7.7 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| MPI | | | | | | |
| Unchanged | 0.0 | 100.0 | 80.0 | 57.1 | 73.3 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 20.0 | 42.9 | 26.7 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |

**Table 4** (*concluded*).

| Expected change | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|
| SMHI | | | | | | |
| Unchanged | 0.0 | 100.0 | 71.4 | 69.2 | 89.2 | 90.9 |
| One more | | 0.0 | 28.6 | 23.1 | 10.8 | 9.1 |
| One less | 0.0 | 0.0 | 0.0 | 7.7 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| UCM | | | | | | |
| Unchanged | 0.0 | 0.0 | 40.0 | 20.0 | 55.2 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 80.0 | 44.8 | |
| Two less | 0.0 | 0.0 | 60.0 | 0.0 | | |
| **Southeastern Stands** | | | | | | |
| DMI | | | | | | |
| Unchanged | 0.0 | 0.0 | 62.5 | 83.3 | 60.0 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 12.5 | 16.7 | 40.0 | |
| Two less | 0.0 | 0.0 | 25.0 | 0.0 | | |
| ETH | | | | | | |
| Unchanged | 0.0 | 0.0 | 0.0 | 9.1 | 100.0 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 100.0 | 90.9 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| GKSS | | | | | | |
| Unchanged | 0.0 | 0.0 | 28.6 | 36.4 | 100.0 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 71.4 | 63.6 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| ICTP | | | | | | |
| Unchanged | 0.0 | 0.0 | 57.1 | 81.8 | 100.0 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 42.9 | 18.2 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| KNMI | | | | | | |
| Unchanged | 0.0 | 0.0 | 57.1 | 90.0 | 100.0 | 0.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 42.9 | 10.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| MPI | | | | | | |
| Unchanged | 0.0 | 0.0 | 0.0 | 0.0 | 25.0 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 50.0 | 100.0 | 75.0 | |
| Two less | 0.0 | 100.0 | 50.0 | 0.0 | | |
| SMHI | | | | | | |
| Unchanged | 0.0 | 0.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |
| UCM | | | | | | |
| Unchanged | 0.0 | 0.0 | 37.5 | 66.7 | 100.0 | 100.0 |
| One more | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| One less | 0.0 | 0.0 | 62.5 | 33.3 | 0.0 | |
| Two less | 0.0 | 0.0 | 0.0 | 0.0 | | |

2008) or by relating management variables, such as site index, to physiological outputs (Battaglia et al. 1999).

Here, we used a statistical model in difference form for dominant height growth that incorporates climatic variables, as well as rock type origin, that smooth the growth pattern according to local environmental conditions. When the average climate is equal between plots of the same age and height, the response is the same, but if any variation occurs in the local climate, the growth trajectory changes. In spite of the advantage gained by incorporating forest inventory data and climate attributes in statistical models, some uncertainties remain, as we have assumed that the plant response to climate change is linear and it will be positive or negative depending on the functional structure of the model. Different modelling approaches have their advantages and disadvantages, but it should be noted that the results of most of the studies are consistent regardless of their approximation: a positive effect in cold sites, due to warming, provided that sufficient water supply is available. This fact indicates a high confidence of the general trends predicted by statistical forest growth models that include climate-based variables, like those used in this study and others (Nigh 2006; Monserud et al. 2008).

Other yearly difference approaches, such as that proposed by Cieszewski and Bella (1993), could have served as a basis for incorporating interannual climate variability predicting annual height growth increment from the current year's height and climate and age, for example, by replacing the $\alpha$ and $\beta$ coefficients in their model by functions of yearly climate variability. However, yearly measurements are not often taken in non-fast-growing species like Mediterranean maritime pine and some kind of interpolation is needed. This opens a new possibility that deserves further research, i.e., the incorporation of yearly climate information into annualization procedures such as those described in Weiskittel et al. (2007)

RCMs use a broader scale than plot-based measurements. This leads to some divergences between plot and RCM grid cell values. These divergences are mainly due to smoothing effects on topography that conduct to a similar climate pattern within an area where differences are actually detected at the plot level. We compared neighbouring cells to overcome this shortage and found a more realistic use of RCM grids in local impact studies (Table 2). Second, we have used a nonlinear climate-based dynamic growth model and RCM data to explore the variation of site index estimation in similar stands (same age and height) where climate conditions differ. Model outputs are robust when model coefficients are forced to vary within a range of ±10%. Consequently, any variation in site index estimation is assumed to be climate dependent. We can conclude that results show a decreasing trend in forest productivity of Mediterranean maritime pine stands for the period 2071–2100 under the SRES-A2 scenario in Spain but with some variability among regions and site quality classes.

The highest impact was predicted for southern stands (SES), whereas negligible impacts were found in the northern stands. The negative impact on southern stands in terms of diminishing productivity may be a sign of stand decline and unsuitability of part of the area for the species to exist. del Barrio et al. (2006) and Benito Garzón et al. (2008) predicted a decrease in Mediterranean maritime pine distribution area in Spain greater than the 50% in 2080 under the same scenario. In addition, Martín-Benito et al. (2010) found in *Pinus nigra* Arnold stands, within the SES region, a higher dependence of radial growth on precipitation than in northern regions, despite having the highest mean annual precipitation. They also found a more intense decrease trend during the end of the 20th century due to an increase in temperature and a decrease in precipitation, leading to a longer drought period. This tendency is expected to continue under changing climate. The rate of change in the precipitation regime is the highest in the SES region where a mean decrease of 12.8% is expected by the end of the century. Furthermore, the trends of precipitation in the rest of the regions are less marked or even nil in the northern area (Fig. 1). The consequences of a similar precipitation pattern were described by Sabaté et al. (2002) who predicted an increase in biomass production for Mediterranean maritime pine stands located in northeast Spain when the simulated precipitation is the same or even 1.3 times higher.

The general trend of site index estimation is towards a reduction in one quality class (Fig. 3), which should be considered consequential to forest management. The dominant height model allows detecting differences in growth pattern at a local scale. However, we did not do any analysis on the distribution shift of the species associated with climate change. This would probably have affected the results because some of the plots may be located in unsuitable areas under the A2 climate scenario. For example, Monserud et al. (2008) showed a shrinking area for lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) in Alberta and increasing site index values using the same climate scenario.

Impact studies of climate change on forests are based on simulations of both climate projections and tree responses to environmental changes. Although models can only approximate future impacts, they can nevertheless help us in predicting in advance the consequences of climate change and to compare observations with our hypothetical forecasts (Canham et al. 2003). Hence, hesitation is still high owing to, among others, uncertainties in plant growth response to climate, climate projection estimation, error propagation among models, and species' adaptation and plasticity. This means that the simulations should be accompanied by expertise observation of reality. In addition, the use of several RCMs offers the possibility of providing confidence intervals of estimations. This approach is rarely used in studies regarding climate change impacts and it can help to reduce the uncertainty of climate projections.

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