Dominant height growth modeling of Aleppo pine (Pinus halepensis Mill.) in Beni Imloul forest, northern Algeria

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Keywords:	Modeling, height growth, Pinus halepensis Mill., Beni Imloul

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Abstract

To predict the quality site-index for stands of the Aleppo pine forest of Beni Imloul (Algeria), six algebraic and generalized algebraic difference equations (ADA/GADA) derived from the three base functions of Hossfeld, Bertalanffy-Richards and Lundqvist-Korf were adjusted and compared using cross-sections collected from 51 cut trees based on the stem-analysis method. The Lundqvist-Korf model with the GADA formulation produced a high level of performance and was selected and applied for the site quality identification of 167 temporary sample plots. This parameter, ranging between 9.13 and 17.77 m with an average of 13.99 m, allowed identifying four quality classes with a 2 m step between each class. The efficiency of the selected model, as productivity estimation-key, was verified by confronting the observed and estimated volumes. This key was justified for 77% of the sampled plots, which maintained the same productivity ranking or slightly shift towards one close class, both in terms of volume and dominant height. Not justified for extreme densities, the developed growth model can cautiously be used as a forest management tool in stands with optimal densities.

Key-words: Modeling, height growth, *Pinus halepensis* Mill., Beni Imloul.

Introduction

In Algeria, Aleppo pine (*Pinus halepensis* Mill.) is the main forest species covering 40% of the forested area with 800,000 hectares (ha) (Daoui et al. 2007). The forest of Beni Imloul, which is one of the most important natural pine forests of the Aurès massif, occupies an area of 80,000 ha, representing 60% of the Aurès forest reserve. Due to the importance of the species for the area and its limited ecological requirements, the Aleppo pine is the most used species in reforestation in Algeria. The most emblematic program is the "green belt", which has been realized in the Algerian pre-Saharan area, where 100,000 ha were planted with Aleppo pine (Maestre et al. 2003, Bellot et al. 2004).

In addition to its ecological interest, this species constitutes the second forest species in the Algerian forest economy after the cork oak.

Several studies have been carried out on the Aleppo pine, dealing with its taxonomy (Nahal 1986, Quezel 1986), its productivity (Belghazi et al. 2000, Cyrille et al. 2002), and its growth and production (Sghaier et al. 2012, Montero et al. 2001, Rojo-Alboreca et al. 2017).

In Algeria, many studies devoted to different aspects can be mentioned: Madoui (2006) on the effect of fire on the composition of pine forests, Bentouati (2006) on the growth and productivity of this species in the forests of Ouled Yaâgoub and Beni-Oudjana, Smaihi (2009) on the influence of litter types in pine forests (pure and mixed with holm oak) on the behavior of seedlings. However, very few studies on growth and productivity have been carried out in the Beni Imloul forest (Frantz and Forester 1979, Goubi 2011, Kherchouche et al. 2011), despite its good fertility. To the best of our knowledge, this is the first study in this forest, using the *Generalized Algebraic Difference Approach* (GADA) proposed by Cieszewki and Bailey (2000), and largely applied in elaborating site index curves for Alepo pine and other species (e.g. Palahi et al. 2003, Sghaier et al. 2012, Lopez-Senespleda et al. 2014, Rojo-Alboreca et al. 2017).

Because of its close relationship with the total volume production, the dominant stand height at a reference age is an index of the site fertility, which can provide a good estimate of the stand productivity. Hence, the fertility classes of a given species on a given site are a very important element in the elaboration of production tables, which constitute a useful tool for almost all the forest management activities.

In order to deepen the aspect on the growth and productivity of Aleppo pine in the Beni Imoul forest, the current investigation was based on stem analysis on trees belonging to diversified environments of the massif, using the ADA and GADA approaches.

The main objective of this work is to establish an appropriate growth model for the Aleppo pine enabling a site index evaluation. Moreover, the useability of the developed model was verified and compared to other models developed for the same species in its natural area in Algeria or in other countries.

Study area

The study area is located in the Beni Imloul massif, which mainly consists of natural Aleppo pine stands with a total area of 80,000 ha. The massif is located between 6°18' and 6°53' east longitude and between 35°2' and 35°20' north latitude (Fig. 1). In general, the climate is semi-arid Mediterranean characterized by hot, dry summers and cold, wet winters, and marked by an important amplitude of temperature. The coldest month is January with an average minimum temperature of 3 °C, while the hottest month is August with an average maximum temperature of 33 °C. The mean annual precipitation ranges from 400 to 600 mm. The soil is typically calcimorphic at different stages of evolution. The most common type is the rendzines passing over marls to calcareous brown soils with a layer of humus undeveloped due to overgrazing, fires and erosion. The subsoil consists of the Turonian stage (Upper Cretaceous), much of which is limestone. The understory is composed by the green oak in the coolest stations while the cade juniper and Phoenician juniper characterize the driest and most degraded areas. The secondary understory plant species are *Globularia alypum*, *Phillyrea angustifolia*, *Ampelodesma mauritanica* and *Stipa tenacissima*.

[Here the Fig. 1]

Methods and data

The approach used in the current study is mainly based on a mixed method where the data derived from stem analysis and temporary plots for site index modeling and site quality determination respectively. Such approach has been used in many studies (Decourt 1964, 1966, 1972a, 1972b, Garbaye et al. 1970, Alder 1980, Ottoroni 1981, Le Goff 1982, Lemoine & Sartolou 1982, Abbas 1986, Couhert & Duplat 1993, Fonweban & Houllier 1995, Boisseau 1996, Sghaier & Palm 2002, Thibault et al.2002, Bentouati 2006, Kherchouche et al. 2011).

Data collected for site index modeling

The data used for the site index modeling are those used by Kherchouche et al. (2011) obtained from stem analysis of 51 representative dominant trees, distributed on stands of varying site qualities in the studied forest. Each selected tree was cut down at the height of 0.30 m, then cross-sections cuts were collected from each tree at defined heights. The number of cross-sections cuts per tree varies according to the tree height. For each selected tree cross-sections were cut at 0.30 m, 2.80 m, 5.30 m, 7.50 m, 9.50 m, then every 1 m beyond this cut. At the laboratory, the cross-sections cuts were fine-sanded and dated in order to determine the tree age at each of the considered heights.

To obtain the current age of the tree, an average number of 5 years was added to the number of rings accounted on the 0.30 m cut. This corresponds to the number of years needed for the tree to reach a height of 0.30 meters. The age at a given level is obtained by the difference between the current age of the tree and the number of rings accounted (Le Goff 1982, Duplat 1986) (Tab. 1).

[Here the Tab. 1]

Data collected for site quality determination

Data used for site quality identification come from 167 temporary sample plots of 0.1 ha each, located in the same forest. Plots were selected in order to cover the whole range of site quality and stand density detected. In each sample plot, total height and breast height diameter were measured at each tree. One core was taken at the 0.30 m level of the average basal area in order to determine the stand age by counting the number of tree rings. The heights of the ten trees with the largest diameter were averaged to determine the dominant height. In addition, other stand characteristics were calculated such as the density (N), the mean quadratic diameter (D_g), the basal area per hectare (BA), the mean height (Hg), the cubic volume per hectare (Tab. 2).

[Here the Tab. 2]

Model fitting

The methodology employed to model the dominant height growth was based on the algebraic and generalized algebraic differences approach (ADA/GADA) by using the dummy variable adjustment (Cieszewski et al. 2000a). More information on ADA/GADA methodology and dummy approach fitting technique can be found in Diéguez-Aranda et al. (2005), Gea-Izquierdo et al. (2008) and Sghaier et al. (2012, 2015).

The use of stem analysis data implies the autocorrelation among observations within the same tree (correlation between the residuals within the same tree), which invalidates the standard hypothesis testing (Gregoire et al. 1995). Therefore, to account for this possible autocorrelation, the error terms were modelled using a continuous-time autoregressive error structure (CAR(*x*)). This allows accounting for irregularly spaced, unbalanced data (Gregoire et al. 1995, Zimmerman & Núñez-Antón 2001), typical for many forestry data sets (West et al. 1984). The CAR(x) expands the error terms as follows (Zimmerman & Núñez-Antón 2001):

$$e_{ij} = \sum_{n=1}^{x} d_n \rho_n^{t_{ij}-t_{i(j-n)}} e_{i(j-n)} + \varepsilon_{ij} \qquad \text{(eq. 1)}$$

where e_{ij} is the jth ordinary residual on the ith tree (i.e., the difference between the observed and the estimated heights of tree i at age measurements j), $d_n = 1$ for $j > \text{n}$ and $= 0$ for $j \leq \text{n}$, ρ_n is the n-order autoregressive parameter to be estimated, and $t_{ij} - t_{i(j-n)}$ is the time distance (years) separating the jth from the jth–n observations.

To evaluate the presence of autocorrelation and the order of the CAR(*x*) to be used, graphs representing residuals versus lag-residuals from previous observations within each tree were examined visually. The dummy variables method and the CAR(*x*) error structure were implemented using the SAS/ETS® MODEL procedure (SAS Institute Inc. 2004), which allows for dynamic updating of the residuals.

Candidate functions

To select the adequate model for the dominant height growth, six algebraic and generalized algebraic difference equations (ADA/GADA) derived from the three base functions of Hossfeld (Hossfeld 1882), Bertalanffy-Richards (Bertalanffy 1949, 1957, Richards 1959) and Lundqvist-Korf (Lundqvist 1957) were adjusted and compared. From each base function, two dynamic models were developed by assuming one (ADA: M1, M3 and M5) or two (GADA: M2, M4 and M6) parameters as functions of local (site) productivity (M1-M6, see Tab. S1 in Appendix 1)).

Productivity is assumed to be dependent on an unobservable variable *X* which can neither be measured nor defined (Cieszewski et al. 2000a, Cieszewski 2002, 2004). The unobservable theoretical variable X, which represents the site productivity dimension is an unknown function of management regimes, soil conditions, and ecological and climatic factors, which cannot be reliably measured or even functionally defined (Cieszewski 2002). While ADA/GADA assures base-age invariance of the derived algebraic forms, the base-age invariance of the model parameter estimates was ensured by fitting them using the dummy variable approach (Cieszewski et al. 2000b, Cunia 1973).

Model comparison

All the fitted models were compared, taking into account the fitting performance, the predictive abilities and the normality of the errors distribution for each of them. The possible violation of the assumption of homoscedasticity of the errors distribution was examined by plotting the residuals versus predicted values.

1° The fitting performance of the selected models was evaluated by examining values of the root mean square error (*RMSE*) and adjusted coefficient of determination (R^2_{adj}):

Residual mean square error: $$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-p}} \quad \text{(eq. 2)}$$

Adjusted coefficient of determination: $$R^2_{adj} = 1 - \frac{(n-1)\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{(n-p)\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad \text{(eq. 3)}$$

where n is the number of observations, y_i , $\hat{y}_i$ and $\bar{y}_i$ are the measured, predicted and average values of the dependent variable, respectively, and p the number of free parameters estimated within the model.

2° Since an independent validation data set was not available, the predictive ability of the models was evaluated using the Leave-One-Out Jackknife method with *PRESS* (Prediction Sum of Squares) residuals or prediction errors (Sánchez-González et al. 2007, Sánchez-González et al. 2005). These residuals are equivalent to the residuals that are obtained by omitting each observation in turn from the data, fitting the model to the remaining observations, predicting the response for the omitted observation and comparing the prediction with the observed value: $y_i - \hat{y}_{i,-i} = e_{i,-i}$ (i = 1, 2, …, n) where y_i is the observed value, $\hat{y}_{i,-i}$ is the estimated value for observation i (where the latter is absent from the model fitting data set) and n is the number of observations. Each candidate function has n *PRESS* residuals associated with it and the *PRESS* is defined as:

$$PRESS = \sum_{i=1}^{n} (y_i - \hat{y}_{i,-i})^2 \quad \text{(eq. 4)}$$

The closer the *PRESS* statistic value is to the residual sum of squares, the better the predictive ability of the model in terms of precision. *PRESS* residuals were also used to compute statistics to evaluate the Prediction Mean of Absolute Deviations (*PREMAD*), bias ($Bias_p$) of prediction and Modeling efficiency (press R-square):

Prediction mean of absolute deviations:

$$PREMAD = \frac{1}{n}\sum_{i=1}^{n} \left| y_i - \hat{y}_{i,-i} \right| \quad \text{(eq. 5)}$$

Prediction mean residual:

$$Bias_p = \frac{1}{n}\sum_{i=1}^{n} (y_i - \hat{y}_{i,-i}) \quad \text{(eq. 6)}$$

Prediction RMSE:

$$RMSE_p = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_{i,-i})^2}{n-p}} \quad \text{(eq. 7)}$$

Modeling efficiency:

$$R^2_{press} = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_{i,-i})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \quad \text{(eq. 8)}$$

3° Normality of the errors distribution: The possible violation of the assumption of non-normality of the errors distribution was examined by the Ryan-Joiner test of normality (Ryan & Joiner 1976) and QQ-probability plots. The Ryan-Joiner test is a simpler alternative to the Shapiro-Wilk test (de Smith 2015). The statistical test is a correlation coefficient calculated as follows:

$$\rho_{obs} = \frac{\sum_{i=1}^{n} e_i z_i}{\sqrt{s^2 (n-1) \sum_{i=1}^{n} z_i^2}} \quad \text{(eq. 9)}$$

where the z_i values are the z-score values (i.e., normal scores or normal quantiles) of the corresponding e_i value and s^2 the sample variance. The normal scores (z_i) are calculated as follows (Altman, 1991):

$$z_i = \Phi^{-1}\left(\frac{i - 3/8}{n + 1/4}\right) \quad \text{(eq. 10)}$$

where $\Phi^{-1}(z)$ is the inverse values of the cumulative unit normal distribution function.

Values of ρ_{obs} closer to 1 indicate that the errors are normally distributed. The normality of residues should be rejected at $(1-\alpha)$ confidence level when $\hat{\rho}_{obs} < \rho_{\alpha}$. Critical values ρ_{α} are presented in a specific table (Looney & Gulledge 1985).

4° The biological realism of the models was evaluated by the prediction of the growth (height) at 250 years of age.

Selection of reference age for site quality evaluation

The practical use of the model to estimate the site quality from any given pair of height and age data requires the selection of a base age to which the site index will be referenced. Inversely, the site index and its associated base age may be used to estimate dominant height at any desired age. Therefore, the selection of a base age becomes an important issue when only one observation of a new individual is available (Diéguez-Aranda et al. 2005).

According to Goelz and Burk (1992), the reference age should be selected taking into account three considerations: (1) the reference age should be less than or equal to the younger rotation age for common silvicultural treatments; (2) the base age should be close to the rotation age and (3) the base age could be selected so that it is a reliable predictor of height at other ages. Diéguez-Aranda et al. (2005) consider that the reference age could be selected as young as possible, in order to help in earlier decision making of the silvicultural treatments to be applied to the stand. Different base ages and their corresponding observed heights were used to estimate heights at other ages for each tree. The estimated heights were compared with the observed heights from stem analysis. The relative error in prediction (RE%) was then calculated as follows:

$$RE\% = \frac{\sqrt{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 / (n-p)}}{\overline{y}} \times 100 \qquad \text{(eq. 11)}$$

where y_i, $\hat{y}_i$ and $\overline{y}$ are the measured, predicted and average values of the dependent variable, respectively; n is the total number of observations used to fit the model and p the number of model parameters.

It is important to note that the statistic described in this section is only meaningful if the site specific parameters are discarded because of the lack of repeated data within the same individual (Diéguez-Aranda et al. 2005). Otherwise, the site-specific parameters could be estimated and all the predictions would be identical whatever base age was selected.

Results and discussion

The characteristics of the stem analyses data are illustrated in Table 1, while the summary statistics of the 167 sampled plots are listed in Table 2.

To determine the order of the function CAR(x) in the growth models (stem analyses) to be used to make the autocorrelation correction, we first fitted all of the six studied models (Tab. S1 in Appendix 1) using nonlinear least squares without expanding the error terms to account for autocorrelation. It appeared that a trend in residuals as a function of height lag-residuals within the same tree was evident in all the models as expected, because of the longitudinal nature of the data used for model fitting. Figure S1 in Appendix 1 (first column) provides an example with model M6. After correction for autocorrelation using a second-order continuous-time autoregressive error structure CAR (2), the trends in residuals almost disappeared (Fig. S1 in Appendix 1, third column). So, a second-order continuous-time autoregressive error structure was used to fit all the tested models.

The statistics of the six models are given in Table 3.

The considered parameters were significant at the 0.0001 level. Models derived from GADA approach (M2, M4 and M6) present a slight superiority than those derived from ADA approach in terms of fitting ability and predictive ability. Moreover, the scan of Table 3 reveals that the estimated values of the average dominant height tree at 250 years old are biologically acceptable if we consider the mean values of age and height of all the cut trees used for stem analyses (Tab. 1).

As the six studied models presented almost similar performances (Tab. 3), bias and root mean square error (RMSE) in height estimation were calculated and plotted by age classes (Fig. S2 in Appendix 1).

The results show the superiority of model M6 to reduce values of bias and RMSE, especially for classes which exceed 50 years of age. Hence, this model, which the equation derived from the Lundqvist-Korf base function, involving two parameters as related to site productivity, was selected for the height growth prediction of *Pinus halepensis* in our study area. Its equation is as follows:

$$Y = \exp(X_0)\exp(-(57.2476 / X_0)t^{-0.5361}) \quad \text{(eq. 12)}$$

where Y is the predicted height (meters) at age t (years),

$$X_0 = \frac{1}{2}\left(\ln Y_0 \pm \sqrt{(-\ln Y_0)^2 + 4 \times 57.2476 t_0^{-0.5361}}\right) \quad \text{(eq. 13)}$$

and Y_0 and t_0 are the predictor variables height (Y_0) and age (t_0) at which Y_0 is observed. As the general use of the model involves making predictions using observed height and its associated measurement age in new individuals (Diéguez-Aranda et al. 2005), the method used to discard the autocorrelation coefficients (Cieszewski 2001) was adopted to discard the site-specific parameters presented in (12).

[Here the Tab. 3]

[Here the Fig. 4]

To appreciate the normality and homoscedasticity of the errors distribution obtained from the retained model (M6), Figure S3 in Appendix 1 shows QQ-probability plots, value of the Ryan-Joiner test of normality and projection of residuals versus predicted height. According to the graph representing the trend of residuals versus normal quantiles (Fig. S3a in Appendix 1), the obtained correlation value between the two variables (0.9632) and its comparison to the critical theoretical value (0.998), the distribution of residues seems deviate slightly from normal distribution. However, for similar great number of observations, usually, the tests of normality give significant results although the deviation to normality is not too significant. Model M6 which explains 99.8% of the total variance and presents good fitting statistics (Tab. 4) provides also a random pattern of residuals around zero with homogeneous variance and no detectable significant trends for predicted heights (Fig. S3b in Appendix 1).

To verify the base-age invariance of the selected model on site index estimations, a plot of the site index predictions against total age using M6 and the stem analysis data was performed (Fig. S4 in Appendix 1). Since the site index is a fixed stand attribute which should be stable over time, site index estimates at different ages should remain close for a given plot (horizontal trajectories). Plotted trajectories (Fig. S4 in Appendix 1) reveal the consistency of site index predictions over time except for the youngest ages (below 30 years).

Using different base ages to estimate heights at different ages for each tree, M6 was fitted in order to figure out the best reference age to determine the site index stands. In this study, the site specific parameters and the dummy variable approach were not used to fit the selected model.

Figure 2 presents the relative error in height prediction (RE%) according to age classes. The results suggest the selection of a reference age in the interval 100–140 years to define the site index (lowest relative errors). After 140 years the number of observations decreases significantly.

Since the reference age should be selected as young as possible (Diéguez-Aranda et al. 2005) and considering that a compromise needs to be found between the number of observations used in the estimation phase (too low after 140 years) and the relative error obtained, we conclude that a reference age of 100 years seems to be appropriate for *Pinus halepensis* of Beni Imloul forest stands.

[Here the Fig. 2]

The site index I_0 was determined as the dominant height recorded at 100 years old. According to the predicted values of this parameter for the 167 measured plots, ranging between 9.13 and 17.77 m with an average of 13.99 m (Tab. 4), four classes were determined around the mean value of 14 m, with an interval of 2 m between each class.

[Here the Tab. 4]

The curves derived from model M6 for the site index values of 11, 13, 15 and 17 m at the reference age of 100 years overlaid on the trajectories of the observed heights over time of the 51 cut dominant trees used for site index modeling and values of dominant height trees of the 167 measured plots are presented in Figure 3. The values of the awaited mean dominant heights at 250 years of age are estimated around 16, 19, 22 and 24 m, for site index values of 11, 13, 15 and 17 m, respectively. These estimates seem to be quite reasonable. However, for younger ages, erratic height growth may lead to inappropriate classification. Hence, the growth curves should be used for ages greater than 30 years (Fig. 3).

[Here the Fig. 3]

Table S2 in Appendix 1 gives the distribution of the 167 sampled plots in four classes of fertility and summary statistics of the measured variables.

To verify the efficiency of the developed growth model, to estimate the productivity (total production based on volume yield per hectare at a given reference age), the actual volumes of the sampled stands were projected on the growth curves bundle in volume instead of the dominant height (Fig. 4). For this purpose, a linear regression was adjusted between the stand volume and its dominant height. The table of volume formulas developed by Goubi et al. (2019) for the Aleppo pine forest of Ouled Yaâgoub (Aurès) was used to estimate the volume of the considered stands. The regression equation is as follows:

$$V = -20.3449 + 12.5396H_d$$

Where V is the stand total volume per hectare (m^3/ha) and H_d the stand dominant height (m).

This formula allowed, indirectly, refitting the growth curves in volume as function of age, replacing, for each age, the estimated dominant height in the equation.

Figure 9 shows the curves bundle in volume for the four fertility-classes on which were projected the actual stand volumes as well as the volumes estimated by this equation for the 167 plots.

[Here the Fig. 4]

In total, 128 plots (77%) keep the same dominant height class or slightly shift towards one close class. The classification is lagged by two classes for 36 plots, and by three classes for only three plots. A significant positive correlation was recorded between the volume residuals and the stand density (r = 0.50, n = 167, p = 0.000).

It is likely that the lower the stand density, the overestimated is the productivity and vice versa. The overestimated stands have a mean density of 209 trees per hectare, while the underestimated ones reach a mean density of 263 trees per hectare.

Similar trend has been reported by Kherchouche et al. (2011), who confronted the growth index with the spontaneous vegetation, noticing that the stands of the same fertility class were found in different vegetation groups and vice versa.

Many disturbance factors may be at the origin of this model weakness. The number of trees used in stem analysis could be insufficient to reflect all growth conditions. In addition, the used volume tables only estimate the log volume; the volume of the branches is not taken into consideration. This may result in underestimating the total volume. A loss in the production is also registered if the stand density is not sufficiently optimal. Moreover, the history of silvicultural practices, which is poorly understood in our study area, may affect this relation.

The dominant height growth curves for the Beni Imloul pine forest were compared with those reported for the same species in Algeria (Bentouati et al. 2005), in Tunisia (Sghaier & Garchi 2009), and in Spain (Rojo alboreca et al. 2017) (Fig. S5 in Appendix 1).

The curves obtained from the Algerian Aleppo pine forests almost overlap until the age of 100 years. Beyond that age, the growth curves of the Beni Imloul stands continue to increase and reach nearly 23 m at 200 years for the 17 m class, while those of Ouled Yagoub and Beni Oudjana show relative decrease, before they started to stabilize and reach 20.5 m at the same age for the same growth class (Fig. S5a in Appendix 1).

The trees from the Tunisian Aleppo pine stands (Fig. S5b in Appendix 1) show a very rapid growth during early ages, before registering a phase of decrease and stabilization, while the tree growth in our stands increases gradually until its 15 m class curve reaches the 17 m class of the Tunisian stands at the age of 200 years.

The growth curves of the Spanish stands show similar trend as those from Tunisia, but with less intense growth for young trees and with a stronger decrease phase. Our 15 m class curve intersects the 17 m class from Spain around the age of 175 years before exceeding it (Fig. S5c in Appendix 1).

The differences in trends observed between the curves we developed for our stands and those reported for Aleppo pine forests in Algeria and some other Mediterranean countries may be due to the developed models, which were different, as well as to the climatic conditions. Our curves are more or less similar to those developed for the stands of Ouled Yagoub and Beni Oudjana, even though the latter ones are located in the subhumid bioclimate with a cold winter (Bentouati et al. 2005). Our stands are located in an area characterized by a cold semi-arid to cold subhumid climate. These trees seem to have a greater growth after the age of 165 years, and this can be explained by the developed model.

The Tunisian Aleppo pine forest, which exhibits more accelerated growth at early ages and shows more similarities with that reported in Spain, extends from the upper-arid to the humid climates. However, the Spanish Aleppo pine forests grow under semi-arid and subhumid climates and are absent in the humid climate.

Conclusion

In order to elaborate a height-growth model for *Pinus halepensis* stands of Beni Imloul forest (Algeria), we compared six algebraic and generalized algebraic difference equations (ADA/GADA) derived from the three base functions of Hossfeld, Bertalanffy-Richards and Lundqvist-Korf.

The model derived from the Lundqvist-Korf base function, using GADA approach, showed a great performance and was selected for dominant height prediction. A reference age of 100 years seems to be appropriate to estimate the site index for *Pinus halepensis* of Beni Imloul forest stands and four quality classes were defined, around an average value of ~14 m, with a 2 m step between each class and site index values of 11, 13, 15 and 17 m. The selected height-growth model was used in estimating the stand productivity. The comparison between the observed and estimated volumes showed that the model can be considered as valid for 77 plots.

Our findings constitute a basic tool for decision support in forest management. Nonetheless, as the developed model was not justified for extreme densities, it can rather be cautiously used for stands with optimal densities. Moreover, because of the relatively low productivity of Alepo pine in the Beni Imloul forest, we suggest classes with a 2.5 to 3 m step at 100 years between each class. Finally, more sampling campaigns involving new plots for stem analysis, covering all the stand densities, are required in order to improve the developed model and define the density range for which this model can be applied.

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Tables

Table 1 - Characteristics of the stem analyses data coming from the 51 fallen trees used for modeling dominant height growth.

Variable	Average	Min	Max	Standard deviation
Tree age (years)	140.53	100	200	22.179
Height (m)	15.08	9.00	20.70	2.888
Number of cross-sectional cuts	9.73	4	15	2.89

Table 2 - Summary statistics for the 167 sampled plots.

Variable	Average	Min	Max	STD
Age (years)	128	68	196	20.922
N (stems/ha)	233	140	517	61.914
D_g (cm)	35.36	21.00	54.80	5.480
BA (m^2/ha)	22.65	7.26	39.21	6.442
H_g (m)	14.61	8.73	19.00	2.069

Table 3 - Parameter estimates and goodness-of-fit statistics.

Model	Par.	Est.	p-value	Fitting ability		Prediction ability				Pred. (250)
				RMSE	R^2_{adj}	$Bias_p$	$RMSE_p$	R^2_{press}	*PREMAD*	
M1	b_1	23.793	<0.0001	0.2680	0.9973	-0.0011	0.2759	0.9973	0.1972	19.01
	b_3	1.385	<0.0001							
	ρ_1	1.063	<0.0001							
	ρ_2	0.969	<0.0001							
M2	b_1	29.924	<0.0001	0.2500	0.9977	-0.0014	0.2564	0.9976	0.1730	17.95
	b_2	-77.024	<0.0001							
	b_3	1.561	<0.0001							
	ρ_1	1.063	<0.0001							
	ρ_2	0.969	<0.0001							
M3	b_1	20.103	<0.0001	0.2754	0.9972	-0.0021	0.2835	0.9971	0.2058	18.75
	b_3	1.323	<0.0001							
	ρ_1	1.063	<0.0001							
	ρ_2	0.968	<0.0001							
M4	b_1	0.019	<0.0001	0.2608	0.9975	-0.0027	0.2673	0.9974	0.1808	17.08
	b_2	-1.258	<0.0001							
	b_3	8.132	<0.0001							
	ρ_1	1.065	<0.0001							
	ρ_2	0.970	<0.0001							
M5	b_1	40.026	<0.0001	0.2608	0.9975	-0.0021	0.2679	0.9974	0.1897	19.71
	b_3	0.536	<0.0001							
	ρ_1	1.068	<0.0001							
	ρ_2	0.971	<0.0001							
M6	b_2	57.248	<0.0001	0.2578	0.9975	-0.0008	0.2634	0.9975	0.1782	18.91
	b_3	0.647	<0.0001							
	ρ_1	1.068	<0.0001							
	ρ_2	0.971	<0.0001							

Table 4 - Distribution of sampled plots in classes of fertility and descriptive statistics according to the site index I_0 (m).

Classes of Fertility	Limits of the Classes	Centre of the classes	Size	Average	Min	Max	Standard Deviation
1	$I_0 > 16$ m	17	13	16.47	16.01	17.77	0.505
2	$14 < I_0 \leq 16$ m	15	75	14.74	14.01	15.94	0.553
3	$12 < I_0 \leq 14$ m	13	65	13.26	12.00	13.98	0.559
4	$I_0 \leq 12$ m	11	14	11.08	9.13	11.96	1.061
Total	-	-	167	13.99	9.13	17.77	1.421

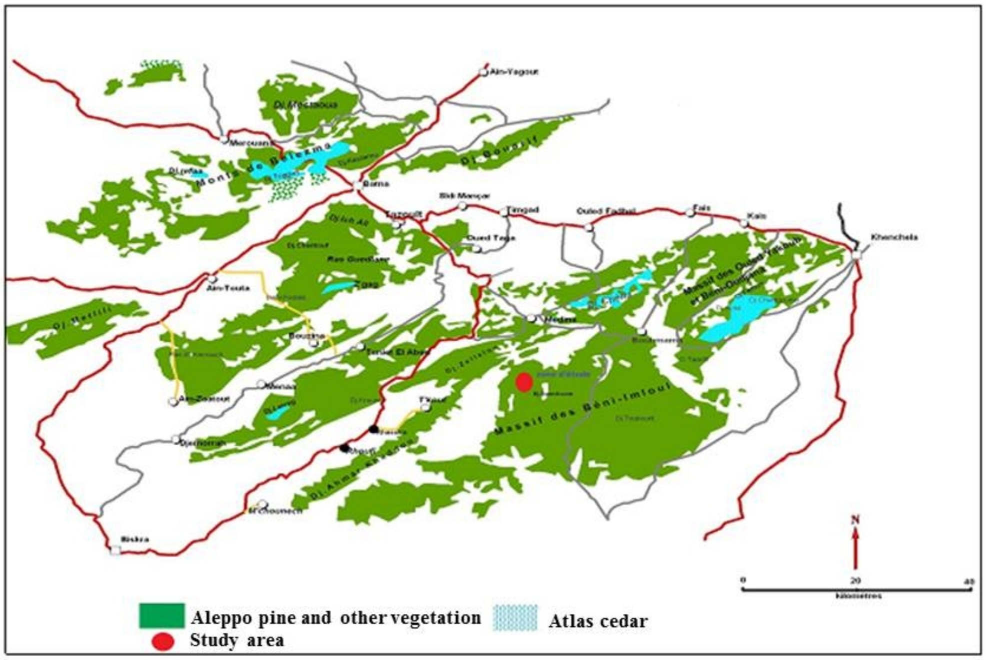
Figures captions

Figure 1 - Location of the study area.

Figure 2 - Relative error in height prediction (RE%) related to the choice of a reference age for Model (M6) adjusted with CAR(2) against age classes and corresponding number of observations (*n*).

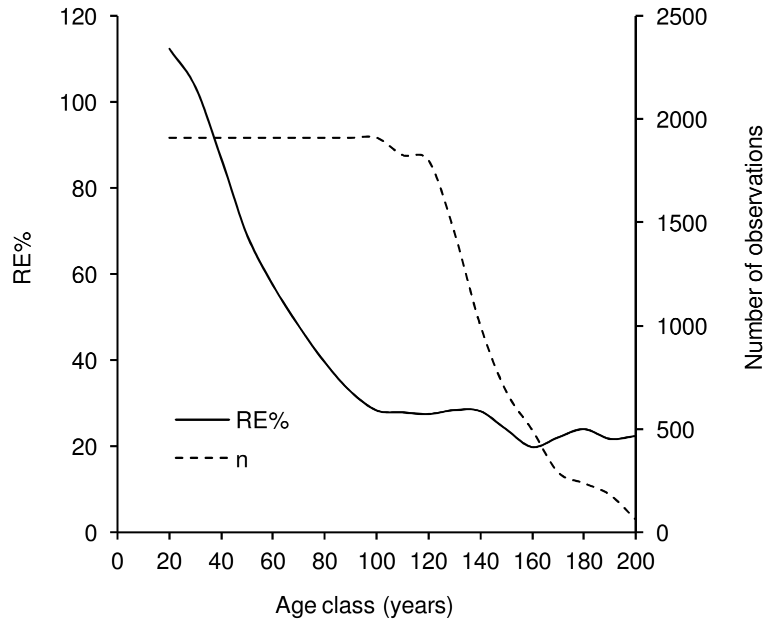
Figure 3 - Height growth curves obtained with model M6 for site index values of 11, 13, 15 and 17 m at the reference age of 100 years, overlaid on the trajectories of the observed heights of 51 sampled dominant cut trees over time and values of dominant height trees of the 167 measured plots. The four fertility classes are separated by the three red dashed lines.

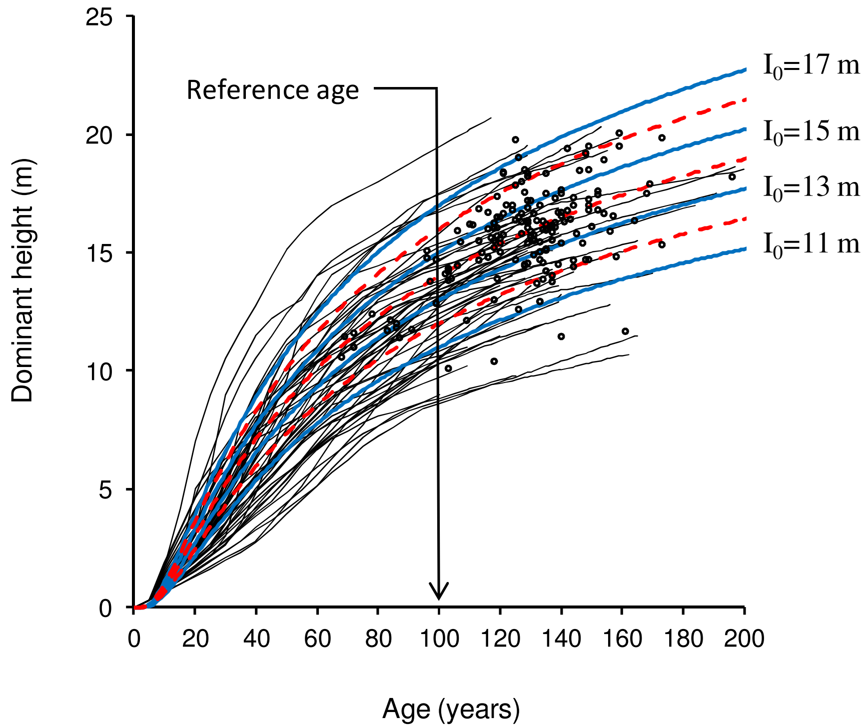
Figure 4 - Observed and estimated volumes of 167 plots, superimposed on the volume curves of four fertility-classes.



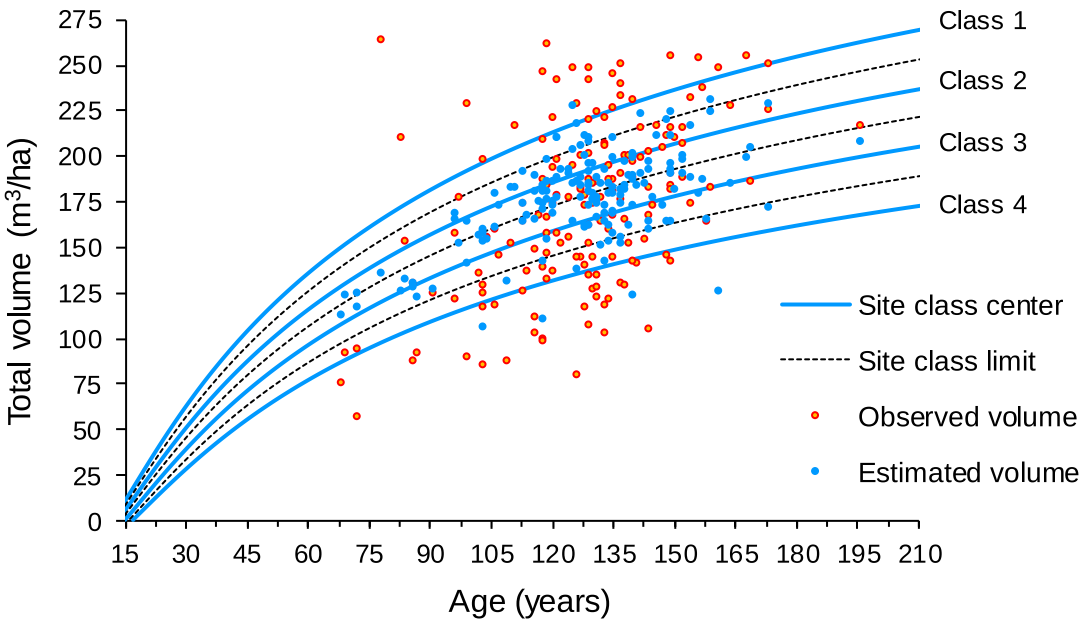
Location of the study area

224x150mm (96 x 96 DPI)


120
100
80
60
40
20
0
RE%
2500
2000
1500
1000
500
0
Number of observations
RE%
n
0
20
40
60
80
100
120
140
160
180
200
Age class (years)



25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
180
200
Reference age
I0=17 m
I0=15 m
I0=13 m
I0=11 m
Dominant height (m)
Age (years)


Total volume (m3/ha)
Age (years)
Class 1
Class 2
Class 3
Class 4
Site class center
Site class limit
Observed volume
Estimated volume