DOI: 10.5152/forestist.2021.20062
Forestist 2022: 72(1): 48-61

ISTANBUL UNIVERSITY CERRAHPAŞA

Original Article

Growth and Productivity Modeling of Seven *Eucalyptus* Species in Souiniet's Arboretum in the Northwestern of Tunisia

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ABSTRACT

This study consists of the development of tree growth models to deduce stands productivity and determine the highest productive species in the conditions of the concerned plantation. Seven *Eucalyptus*, introduced in the arboretum of Souiniet (north-west of Tunisia, wet Mediterranean bioclimate) in a Cork Oak natural forest, were studied. Stem analysis and non-linear growth modeling regression equations were used to predict wood productivities. Gompertz and Chapman–Richards growth function appeared as being great numerical models to estimate the *Eucalyptus* tree diameter and height evolutions, respectively. Moreover, an adapted Chapman–Richards model allowed predicting the volume of trees in an efficient manner. The values of mean annual volume productivity of the *Eucalyptus* spp.studied, allow us to classify them in order of increasing annual productivity, as follows: *E. sideroxylon*, *E. cinerea*, *E. maidenii*, *E. macrorhyncha*, *E. tereticornis*, *E. viminalis* and *E. bicostata*. The first three *Eucalyptus* spp. appeared as the best-adapted and most suitable *Eucalyptus* trees for new plantations in this area. These species had the highest mean annual increments, ranged from 5 to 10 $m^3.ha^{-1}.year^{-1}$ with 15 to 20 years of rotation. *E. bicostata* is the most promising, with annual average production exceeding 10 $m^3.ha^{-1}.year^{-1}$ after 25 years, and reaching 20 $m^3.ha^{-1}.year^{-1}$ at 40 years old. These modeling approaches provide additional knowledge on the productivity of the different *Eucalyptus* species, thus enabling forestry operators to simulate the development of forest stands in order to optimize timber production and harvesting.

Keywords: Annual mean increment, Eucalyptus, modeling, productivity, stem analysis, wet mediterranean bioclimate

Introduction

Eucalyptus spp. have been widely planted in several regions around the world, thanks to their high productivities, even in areas where drought and nutrient stress occur (Saadaoui et al., 2018). *Eucalyptus* spp. are extensively used in significant plantations in temperate regions, more commonly in subtropical and tropical regions all over the world. Their global estimation is over 20 million ha eucalypt plantations (excluding natural stands), of which 2.4 million ha are located in Africa (Hardwood, 2018). Morocco is the North African country with the largest *Eucalyptus* plantation area (215,000 ha), followed by Tunisia with about 55,000 ha (FRA, 2015; Hardwood, 2018). *Eucalyptus* spp. constitute the largest share of hardwoods species and represent 5% of the total forest cover in Tunisia, all species included. They are planted in forest production (40%) and forest protection (60%). *Eucalyptus* covers a surface of 28,500 ha in pure stands and 26,500 ha with mixed species (Zaibet, 2016). Their area of plantations provides an annual wood volume of 3 $m^3.ha^{-1}.year^{-1}$, which represents approximately 120,000 m^3, making 25% of the annual volume harvested in Tunisian forests (FAO, 2012).

Such a woody resource needs forest management and numerical simulation to enable foresters to evaluate the development of forest stands in order to optimize harvesting and timber production. Previous researches were carried out on various Tunisian wood species as *Pinus halepensis* and *Tectona grandis*. These surveys highlighted that modeling estimations of dendrometric parameters during forest management allowed to improve considerably the timber production and the biomass yield of farm forestry plantations (Curto et al., 2016; Fernández-Sólis et al., 2018; Goubi et al., 2019). In this sense, several authors have developed growth models for eucalypt plantations in temperate and tropical conditions (Delgado-Matas & Pukkala, 2014). These model equations have been extensively used in forest growth and yield studies to characterize height-age and diameter-age and growth rate-age relationships (Corral-Rivas et al., 2004; Pienaar & Turnbull, 1973; Pommerening & Muszta, 2015; Pyo, 2017). Among the most used models, we can cite the following ones: Smalian, Gompertz, Weber, and Chapman–Richards for the

Cite this article as:
Mhamdi, S., Tahar Elaieb, M., Souayah, N., Khouja, M., Larbi Khouja, M., Aloui, A., & Candelier, K. (2022). Growth and productivity modeling of seven eucalyptus species in souiniet's arboretum in the northwestern of tunisia. *Forestist*, 72(1), 48-61.

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Received:
December 18, 2020
Accepted:
March 22, 2021
Available Online Date:
August 27, 2021

height-age modeling, and Logistic, Gompertz, and Chapman–Richards for diameter-age modeling. Most of these equations have asymptotic functions, with two or three parameters that define a sigmoid curve characterizing the different growth stages as influenced by biological processes and behaviors (Peng et al., 2001). These last models can be considered more suitable for our present application than other functions describing empirical models (Sweda & Koide, 1981). A lot of equations used by scientific experts in tree log volume determination can be found in the literature, such as Schumacher and Hall, Spurr, Kopezky-Gehrhardt, Meyer, etc. (Melo et al., 2013; Miranda et al., 2014; Santos et al., 2012). All of these equations are dependent on the tree DBH. Owing to the importance of the *Eucalyptus* genus in Tunisia (Elaieb et al., 2019), and the gap in growth modeling at individual tree level, the objective of this work was to evaluate and compare various diameter, height, and volume models for individual *Eucalyptus maidenii, Eucalyptus bicostata, Eucalyptus viminalis, Eucalyptus cinerea, Eucalyptus tereticornis, Eucalyptus* macrorhyncha and *Eucalyptus sideroxylon* trees introduced since 1964 in the arboretum of Souiniet. All of these last species seem to have been well adapted to the extreme climatic conditions of this geographical area. Indeed, very little damages to the growth of these tree species have been observed in these arboretums. As a result, these *Eucalyptus* species can be considered very interesting in future reforestation programs based on favorable levels of wood production compared to other exotic or natural species. The target of this present project consists of the development of a growth model of trees to deduce stands productivity and determine the highest productive species in the conditions of the concerned plantation. The models developed through this study could enable foresters to simulate the development of forest stands in order to optimize harvesting and timber production while improving net income and economic profitability.

Methods

Study Area

The study was conducted in the northwest of Tunisia on mid-Khroumirie's mountains at Souiniet's arboretum (35.54° N, 8.48° E, 492 m alt.). The region is characterized by a low humid Mediterranean bioclimate with rainy winters and dry summers. The monthly maximum and minimum temperatures and total precipitation data were collected from Ain Draham meteorological station located approximately 10 km from the experimental site (from 1982 to 2012). The data are presented in the climatic diagram in Figure 2. The average annual rainfall was 1389 mm.year^{-1} (max: 227 mm in December; min: 2 mm in July). The mean annual temperature was 15.6°C, the hottest month is August (24.9°C), and the coldest one is January (6.7°C). The dry period usually extends from June to August. The number of snow days was estimated to be 7 days per year. The understory vegetation is dominated by *Erica scoparia* L. and *Halimium halimifolium* (L.) Willk. The landscape is dominated by hydromorphic soil and a clayey bedrock composed of sedimentary from the Mio-Pliocene substrates and Oligocene. The arboretum occupies part of the jbel Souiniet. The North Slope is made up of humus-rich soils of the leached brown to humus-rich mull to mull moder type. The South slope and the summit are made up of less rich soils. Hydromorphy is present in places where the clay is close to the surface. Generally, the following three soil types can be observed:

- Deep soil on the quaternary cover: It is a very deep soil up to 3 m thick, with good physical quality (texture and porosity). This soil offers the most favorable conditions for reforestation.
- Moderately deep soil with hydromorphic depth: It is a thinner soil, and the clayey floor appears at less than 1.5 m. This type of soil is suitable for the reforestation of a wide range of species. It can be found on slopes and in small, slightly eroded basins.
- Hydromorphic soil with clayey bedrock: This soil is found in the most eroded areas where clay occurs within l m. This type of soil is asphyxiating, and only species that are tolerant of hydromorphy are suitable.

Experimental Design and Data Collection

The study was conducted on the seven following *Eucalyptus* spp.: *E. bicostata* Maiden, Blakely & Simmonds; *E.* viminalis Labill.; *E. tereticornis* Sm.; *E. macrorhyncha* F. Muell. ex Benth.; *E. maideni* F. Muell.; *E. cinerea* F. Muell. ex Benth.; and *E. sideroxylon* A. Cunn. ex Woolls.

These seven varieties of *Eucalyptus* were planted in a common garden in 1969 in Souiniet Arboretum in association with *Pinus nigra* and *Pinus pinaster* species. The seeds used for the *Eucalyptus* reforestation and acclimation test program were harvested in 1968 by a Tunisian team in Australia, including about 40 ecotypes representative of the whole range of the species in Australia.

The growth and development of forest stands can be characterized by various quantitative values, including measures of tree height and mean diameter, determination of the number of trees per hectare, basal area per hectare, volume per hectare, and various other derived quantities.

A set of data was obtained from seven permanent plots, established for 40 years, in a continuous forest inventory of unthinned stands. These stands have not been managed, and no fire has been detected since they were planted. Each plot was from 1000 to 1600 m^2 with spacing between trees of 3×3 m^2, and the initial stand density was 1111 trees. ha^{-1}. Each of the *Eucalyptus* spp. studied in this work was planted in separate stands depending on the species considered. All the stands were, therefore, even-aged and monospecific.

Each plot has been characterized according to its area (m^2), tree mean diameter (in centimeter, measuring at breast height (DBH)), current density (tree per hectare), stand basal area (meter square per hectare), and the mean annual mortality rate percentage per year). These parameters, for each *Eucalyptus* wood species, are presented in Table 1. Trees with a diameter at DBH smaller than 7 cm were not measured, but they were counted and considered in the data set.

Figure 1 illustrates an overview of the different *Eucalyptus* tree diameter (at DBH) repartition within the plots. The determination of diameter distributions is essential to initialize individual tree models. In addition, tree diameter distribution allows for more efficient harvest planning, which accounts for most of the costs associated with wood production.

Figure 1 shows significant differences among the seven studied plots. It appears that *E. maidenii, E. cinerea, and E. tereticornis* plantations have trees with diameters centralized around 20–25 cm. While the distribution of the tree diameters from *E. bicostata*, *E. viminalis*, *E. sideroxylon,* and *E .macrorhyncha* plantations seem to be more spread from 5 to 80 cm.

In *E. maideni, E. cinerea, E. tereticornis,* and *E. sideroxylon* stand, 100% of the trees had a DBH below 50 cm, while in the *E. bicostata*, *E. viminalis,* and *E .macrorhyncha* plots, the DBH reached 80 , 70, and 75 cm, respectively.

Description of Measurements

The determination of the volume productivity of the seven species of *Eucalyptus* was based on the stem measurements, widely described and used by several authors to build wood productivity tables (Akossou et al.,

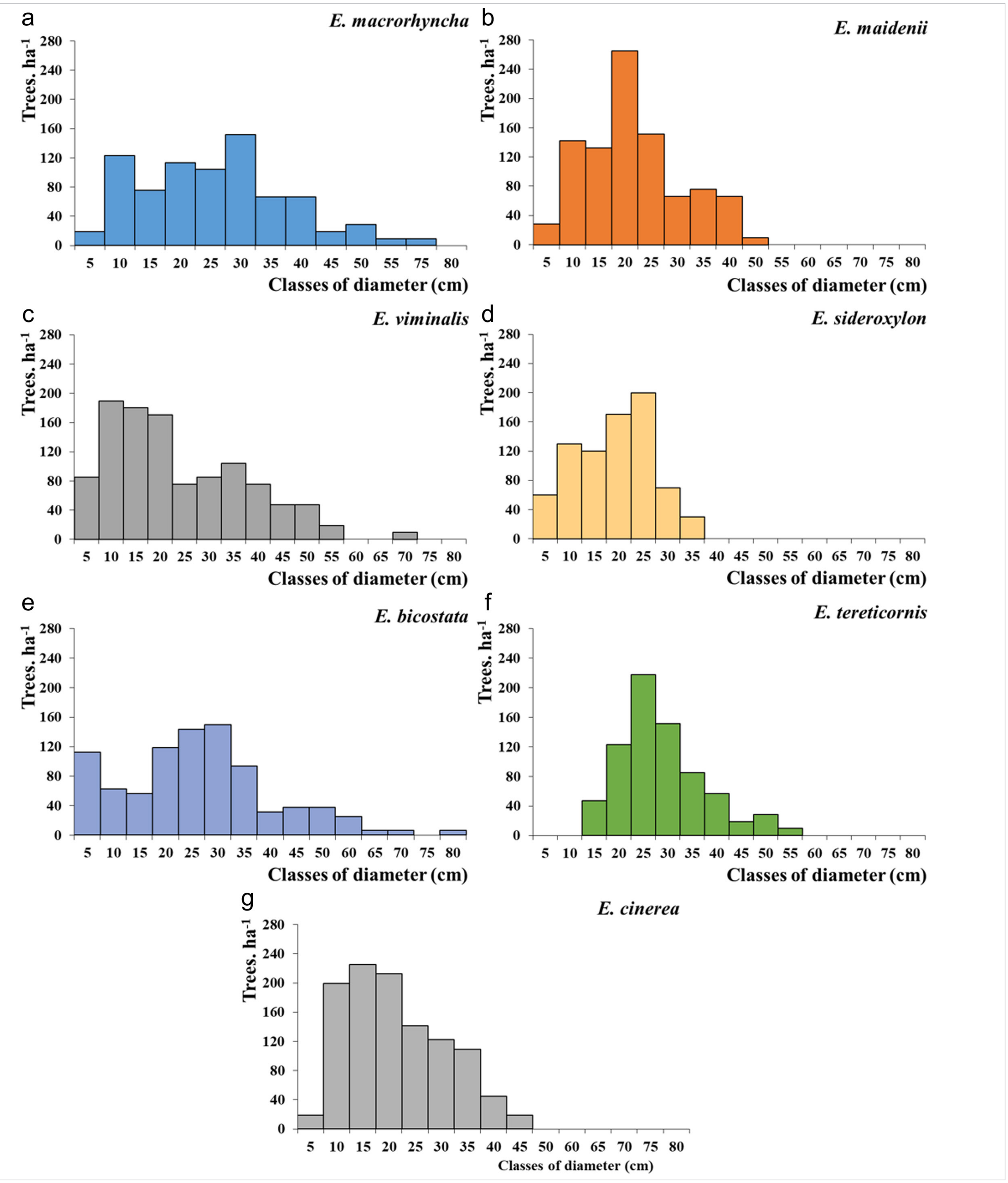


Figure 1.
Current Classes of Tree Diameter Repartitions of the Seven Eucalyptus *spp. plantations (a):* E. macrorhyncha*, (b):* E. maidenii*; (c):* E. viminalis*; (d):* E. sideroxylon*; (e):* E. bicostata*; (f):* E. tereticornis*, and (g):* E. cinerea

2013; Miguel et al., 2018). This method is based on the evolution of the dendrometric characteristics of the tree (diameter, height, volume) as a function of time. The integral measurement of the diameter of all the trees made it possible in a second step to choose three average trees in each species of *Eucalyptus* (trees with a diameter equal or very close to the average diameter calculated on all the trees per species). For each species, three basal area averages of trees were then cut down in order to study the history of their growth. The three felled trees were cut into bolts on which one disk (5 cm in thickness) was sampled at the following levels: 0.20, 0.50, and 1.30 m then at every meter until the level of large diameter wood of 7 cm then at each 50 cm until the end of the terminal bud of the main stem.

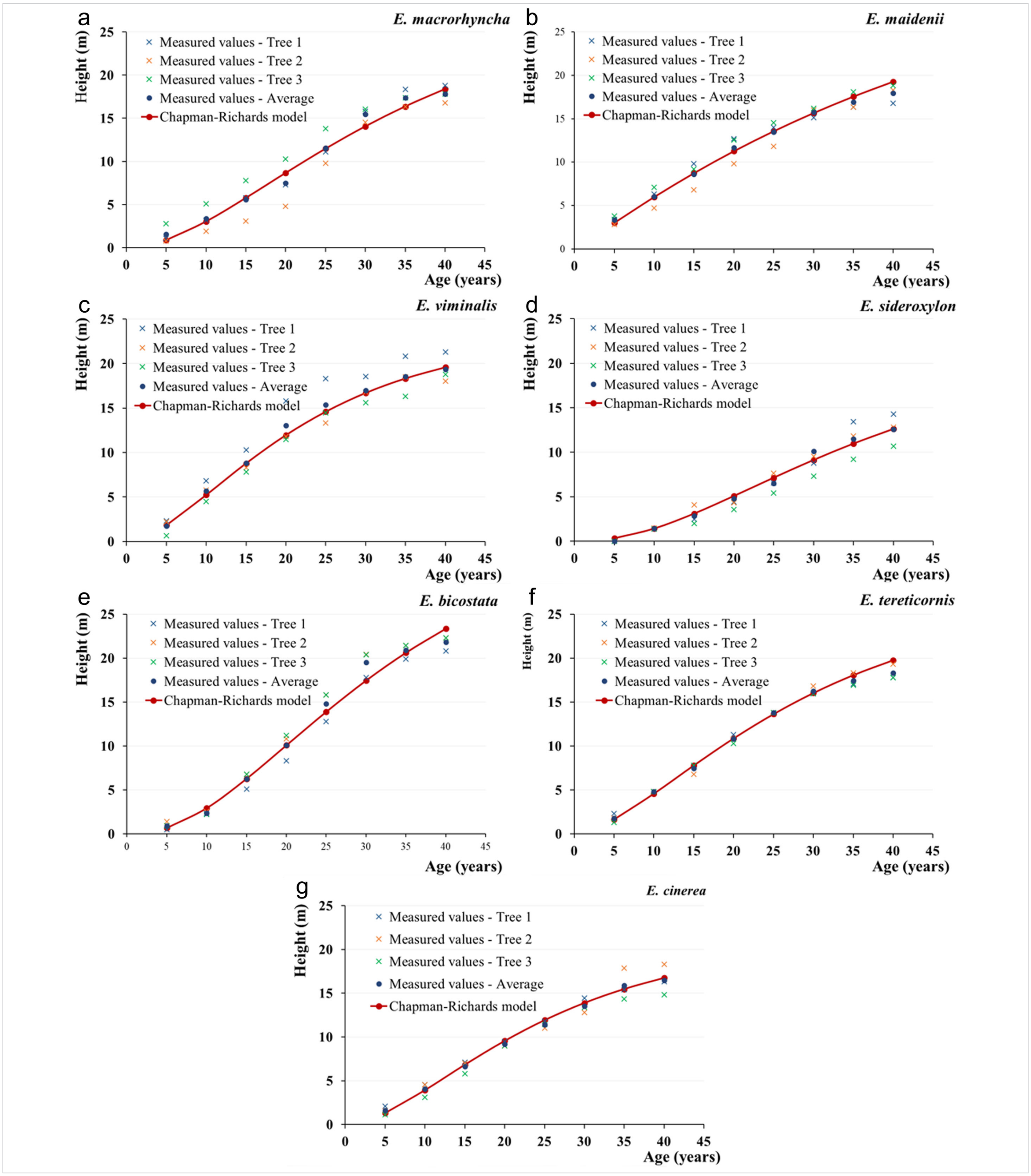


Figure 2.
Comparing Measured Values and Estimated Values From Chapman–Richards Equation to (a) E. macrorhyncha, *(b)* E. maidenii, *(c)* E. viminalis, *(d)* E. sideroxylon, *(e)* E. bicostata, *(f)* E. tereticornis, *and (g)* E. cinerea *Heights According to the Age of the Trees.*

The measurements of the diameters (centimeter) were covered and the counting numbers of rings were performed on each disk sample on two perpendicular diameters. From two diameters, the mean diameter was calculated and adopted for modeling diameter growth.

The analysis of each shot-down stem allowed us to determine, at intervals of 5 years and across different analyzed levels, the diameter under bark and the total length of the stem.

Annual rings in *Eucalyptus* spp. sometimes need to develop technical processes to be identified (Naidoo et al., 2010). For more accuracy,

Table 1.
Stand Characteristics of the Seven Eucalyptus *spp. During 40 Years Located in the Arboretum of Souiniet, Northwest of Tunisia*

Species	Area of the Plot (m^2)	Mean Diameter (cm)	Current Density (Tree/ha)	Stand Basal Area (m^2/ha)	Mean Annual Mortality Rate (%/year)
E. biscotata	1600	30.6	887	64.0	0.42
E. maidenii	1056	23.5	937	41.4	0.56
E. viminalis	1056	28.0	1089	64.4	0.04
E. cinerea	1554	23.4	1094	47.0	0.04
E. tereticornis	1056	29.9	738	52.2	1.17
E. sideroxylon	1000	20.5	780	24.3	1.01
E. macrorhyncha	1056	28.7	786	51.4	0.86

the growth rings have been analyzed by x-ray (SilviScan™) analysis techniques as used in the previous studies from Downes et al. (2002) and Naidoo et al. (2010). The cores were air-dried and scanned with a high-resolution Itrax® x-ray densitometer. A density software program was used to measure the annual rings and create a radial increment data file. The results of this identification are not included in this paper, but they were very useful to identify false rings and the limit of adjacent small-growth rings of the annual rings closest to the bark end.

Tree Height (H), Diameter (D), and Volume (V) Modeling

Developing height and diameter growth curves for each *Eucalyptus* tree species were done by selecting various non-linear models to compare the fitness of these models to data. We have selected different models among the most used in the literature. Four theoretical models (Smalian, Gompertz, Weber, and Chapman–Richards) were fitted to develop height growth equations, and three candidate equations (Logistic, Gompertz, and Chapman–Richards) were tested for the prediction of tree diameter growth.

The volume under the bark of the analyzed stems was determined by the Smalian's formula (Eq. 1):

$$V = \frac{A_1 + A_2}{2} \times L \quad (1)$$

where V is the volume of the log in m^3; A_1 is the area of the small end of the log in m^2; A_2 is the area of the large end of the log in m^2; L is the length of the log in m.

The Smalian's formula has been adopted as a rule on a cubic scale to calculate the traces on the basis of a parabolic log. To do that, the two inner diameters of the bark and the length were measured. By multiplying the average of the areas of the two log ends by the log's length, Smalian's formula allows us to estimate accurately the volume of a log.

Most of the equations usually used in tree log volume modeling dependent on the tree DBH. The aim of the present work is to evaluate tree volume growth according to the time (age of tree). For this reason, we chose to test a developing exponential equation that converts stem volume directly to the time-dependent term e^{cx} as the independent variable.

The height-age, diameter-age, and volume-age equations used to develop models for the seven Tunisian *Eucalyptus* spp. were presented in Table 2. For each model, the data set was composed by results from all the 21 *Eucalyptus* trees (7 species x 3 trees x 9 ages = 189 samples). From this data set, mathematical models of growth for each variable were developed using non-linear regression.

Models Validation and Statistical Analyses

The choice of the adequate model was carried out by the comparison of the coefficients of determination (R^2) and the root mean squared error (RMSE) representing the proportion of the variance in the dependent variable that is predictable from the independent variable(s) and the standard deviation of the residuals (prediction errors), respectively. BIAS ($\bar{E}$), the mean absolute difference (MAD), and the mean percent bias (MPB), representing the accuracy of the predictions, the statistical dispersion and the average of percentage errors, respectively, were also evaluated for each modeling equations developed in this study.

These statistical evaluations were computed as follows:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{n} \left(X_i - \check{X}_i \right)^2}{\sum_{i=1}^{n} \left(X_i - \bar{X}_i \right)^2} \right] \quad (2)$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \left(X_i - \check{X}_i \right)^2 / n} \quad (3)$$

Table 2.
Candidate Equations of Regression Used for the Modeling of the Growth in Height (H), Under Bark Diameter (D), and Volume (V), Depending on the Age of the Tree. Where H Is the Total Height of the Dominant Tree in m; D is the Diameter of the Tree in m; V Is the Volume of the Log in m^3; x Is the Tree Age in Year; and a, b, and c Are Model Parameters

Modeling	Name	Equation
Height-Age Equation	Smalian	H = x / (a + bx + cx^2)
	Gompertz	H = a.exp(–b.exp(–cx))
	Weber	D = a [1 –exp(-bx)]
	Chapman–Richards	H = a [1 –exp(-bx)]^c
Diameter-Age Equation	Logistic	D = a / [1 + c.exp(bx)]
	Gompertz	D = a.exp(–b.exp(–cx))
	Chapman–Richards	D = a [1 –exp(–bx)]^c
Volume-Age Equation	Exponential time-dependent equation (derived from Chapman–Richards)	V = a + b exp(cx)

$$\bar{E} = \frac{\sum_{i=1}^{n}\left(X_i - \check{X}_i\right)}{n} \quad (4)$$

$$MAD = \frac{\sum_{i=1}^{n}\left|X_i - \check{X}_i\right|}{n} \quad (5)$$

$$MPB = \frac{100}{n} \times \left(\frac{\check{X}_i - X_i}{X_i}\right) \quad (6)$$

where

X_i = observed values (Height (H), Diameter (D) or Volume (V)) for the tree i;

$\check{X}_i$ = predicted values (Height (H), Diameter (D) or Volume (V)) for the tree i;

$\bar{X}$ = observed mean values (Height (H), Diameter (D) or Volume (V)) for the tree I;

n = number of measures.

The under bark stem volume for each species per plot was calculated by 5-year intervals until 40 years whereas the total volume of the plot is equal to the average volume of tree basal area multiplied by the current full number of alive trees of the plot disregarding the volumes of all the dead trees.

The statistical analysis system non-linear (SAS NLIN) procedure (SAS, 2004) and the non-linear regression technique were used to fit the height-age, diameter-age, and volume-age data using all the tested functions for the seven Tunisian *Eucalyptus* spp.

The comparisons of the coefficients of determination (R^2), the root mean squared error (RMSE), BIAS (Ē), the mean absolute difference (MAD), and the mean percent bias (MPB) of the different non-linear regression equations allowed us to choose the best non-linear regression equations for each *Eucalyptus* spp. For each species, the model resulting in the greatest R^2 and the least RMSE, Ē, MAD, and MPB was selected as the best model.

Results and Discussion

Tree Height-Age Modeling

The parameters estimated and associated standard errors of all selected models for estimating the height of *Eucalyptus* trees are presented, by species, in Table 3. These results allowed us to compare the different tested models in order to select the best model equations to predict height for each *Eucalyptus* tree species.

According to Table 3, it appeared that the best one of the four models tested in the prediction of the height of the *Eucalyptus* tree was the Chapman–Richards equation. The validation of these prediction models was characterized by high R^2 values, and RMSE, Ē, MAD, and MPB values. The results indicated that none of the asymptotic 95% confidence intervals contained 0 for each parameter estimate; therefore, it was concluded that the equation parameters were significant. The developed model for tree height estimation was further evaluated using statistical analyses (Table 3). The R^2 minimal value of 0.943 was found for *E. macrorhyncha*. In other words, the developed models explained more than 94.3% of the total variation in the estimate of total height for all concerned Tunisian *Eucalyptus* spp. The RMSE maximal value was 1.393 m for the tree height model of *E. viminalis*. These low values of RMSE confirm that Chapman–Richards growth function in predicting the height of the seven *Eucalyptus* spp. showed a good performance. Peng et al. (2001) explained that a negative value of Ē indicates that the model over predicts total dominant height, while a positive value indicates under prediction. Our results showed that values of Ē were low and negative for *E. maidenii*, *E. tereticornis* and *E. cinerea*, indicated an over prediction of tree height. As the opposite, the Ē values of *E. macrorhyncha*, *E. viminalis, E. sideroxylon, and E. bicostata* indicated an underestimation. However, the low values of Ē of all *Eucalyptus* spp. indicated that the developed tree height growth models based on Chapman–Richards equation for these wood species are a really good predictor. Similar results were found by previous studies conducted in other wood species, in some *Eucalyptus* spp. (Lumbres et al., 2018; Shater et al., 2011). In addition, the low values of AMD (<1.151 m, observed for *E. macrorhyncha*) and MPB (<2.876 %, observed for *E. viminalis*) confirmed the efficiency of the Chapman–Richards model to predict the *Eucalyptus* tree height according to the age.

The predicted values from the Chapman–Richards model and measured values of height-age curves are presented in Figure 2, for each *Eucalyptus* spp. Height-age curve evolution of *Eucalyptus* differed significantly among different *Eucalyptus* spp. *E. bicostata* recorded significantly the higher height evolution curve (22.1 m, at 40 years), with a high growth rate between 20 and 40 years old. *E. bicostata* is closely followed by *E. viminalis* (19.6 m, at 40 years), *E. tereticornis* (19.5 m, at 40 years) and *E. maidenii* (of 17.7 m, at 40 years).

E. macrorhyncha and *E. cinerea* showed very similar behavior, represented by a medium growth rate and 40-year average height values of 17.4 m and 16.6 m, respectively.

The lowest height increment curve was recorded in *E. sideroxylon*, which is characterized by a very slow height growth rate (11.7 m, at 40 years).

According to the equation curves parameters (Table 3) and the results presented in Figure 3a, *Eucalyptus* spp. can be classified into three groups, as follows:

- Group 1 includes *E. bicostata, E. viminalis* and *E. tereticornis* and *E. maidenii*. This group has the most rapid growth rate in the area.
- The second group includes *E. cinerea* and *E. macrorhyncha* showed a medium growth rate.
- The third group includes only *E. sideroxylon* characterized by a very slow growth rate.

Tree Diameter-Age Modeling

The best tree growth diameter model was fitted by the Gompertz equation (Table 4). Even if it results that these models allow predicting the evolution of the seven *Eucalyptus* tree diameter according to the tree year's old, it appears clearly that the diameter predictions calculated by Gompertz equation are poorer than predictions of tree height using the Chapman–Richards model. The better results were obtained for *E. bicostata* and *E. macrorhyncha* with R^2 of 0.994 and 0.990, RMSE of 6.651 cm and 6.101 cm, and Ē of 0.260 cm and 1.092 cm, AMD of 5.516 cm and 5.257 cm, and MPB of 0.889 % and 0.271 %, respectively. While for the other *Eucalyptus* spp., these statistical criteria are worse. The least good diameter-age models are that of *E. maidenii* with the

Table 3.
Equations of Regression Used for the Modeling of the Growth in Height (H)

Species	Retained Mathematical Models	R^2	RMSE (m)	Ē (m)	AMD (m)	MPB (%)
	Model Smalian					
E. macrorhyncha	H= x / [2.491 − 0.029x + 0.0005x^2*]	0.928	1.642	−0.602	1.323	23.982
E. maidenii	H= x / [1.791 − 0.0189x + 0.0008x^2*]	0.966	0.924	0.180	0.743	−1.314
E. viminalis	H= x / [1.9391 − 0.0279x + 0.00075x^2*]	0.945	1.435	0.039	1.050	13.345
E. sideroxylon	H= x / [6.1391 + 0.0956x + 0.00055x^2*]	0.933	1.155	0.126	0.926	4.146
E. bicostata	H= x / [2.234 − 0.0359x + 0.00065x^2*]	0.945	1.845	−0.421	1.575	42.680
E. tereticornis	H= x / [2.1391 − 0.0379x + 0.00099x^2*]	0.988	0.641	−0.245	0.503	8.930
E. cinerea	H= x / [2.8391 − 0.0479x + 0.00099x^2*]	0.969	0.902	0.342	0.878	0.878
	Model Compertz					
E. macrorhyncha	H= 238.251*exp[−2.704 exp(−0.085x)]	0.936	1.551	0.547	1.249	0.643
E. maidenii	H= 208.251 *exp[−3.104 exp(−0.075x)]	0.968	0.903	−0.005	0.718	2.876
E. viminalis	H= 265.251 *exp[−2.554 exp(−0.074x)]	0.937	1.539	0.479	1.104	5.212
E. sideroxylon	H= 455.102 *exp[−5.954 exp(−0.006x)]	0.942	1.070	0.002	0.831	1.572
E. bicostata	H= 317.251 *exp[−3.784 exp(−0.082x)]	0.959	1.596	0.840	1.198	−0.407
E. tereticornis	H= 278.574*exp[−3.015 exp(−0.090x)]	0.985	0.697	−0.236	0.521	0.456
E. cinerea	H= 155.147 *exp[−3.884 exp(−0.085x)]	0.977	0.787	0.012	0.574	0.733
	Model Weber					
E. macrorhyncha	H= 299.445 [1−exp(−0.0015x)]	0.912	1.815	0.128	1.533	19.298
E. maidenii	H= 249.445 [1−exp(−0.0020x)]	0.914	1.478	0.809	1.250	−9.900
E. viminalis	H= 223.467 [1−exp(−0.0025x)]	0.910	1.839	0.298	1.355	10.746
E. sideroxylon	H= 215.241 [1−exp(−0.0014x)]	0.877	1.566	−0.636	1.422	27.578
E. bicostata	H= 255.245 [1−exp(−0.0021x)]	0.903	2.452	0.374	2.145	42.083
E. tereticornis	H= 184.452 [1−exp(−0.0028x)]	0.971	0.982	0.156	0.817	4.663
E. cinerea	H= 145.441 [1−exp(−0.0031x)]	0.968	0.926	0.127	0.700	5.705
	Model Chapman–Richards					
E. macrorhyncha	H= 28.645[1−exp(−0.041x)]^2.058	0.943	1.467	0.189	1.151	0.257
E. maidenii	H=35.137 [1−exp(−0.021x)]^1.062	0.960	1.011	−0.172	0.821	0.929
E. viminalis	H= 23.295 [1−exp(−0.061x)]^1.905	0.949	1.393	0.308	1.015	2.876
E. sideroxylon	H= 21.278 [1−exp(−0.011x)]^2.535	0.950	0.999	0.238	1.036	−0.242
E. bicostata	H= 35.648 [1−exp(−0.047x)]^2.550	0.973	1.288	0.171	1.017	−0.102
E. tereticornis	H= 27.145 [1−exp(−0.045x)]^1.755	0.985	0.710	−0.215	0.482	0.553
E. cinerea	H= 21.045 [1−exp(−0.055x)]^1.955	0.976	0.807	−0.101	0.610	−0.020

following statistical criteria*:* R^2 of 0.913, RMSE of 16.201 cm and Ē of −0.137 cm, AMD of 13.780 and MPB of 1.305 %. It has been shown that these types of models are not always the most suitable for older trees (Doi et al., 2010). Indeed, earlier dominant height models have been developed for young planting, whereas in our present work the stand age extended beyond 40 years.

The predicted values from the Gompertz model and measured values of diameter-age curves are presented in Figure 4, for each *Eucalyptus* spp. It appears that the Gompertz model developed for the volume tree diameter prediction is lower accurate than the Chapman–Richards model developed to predict the height of the tree. Most species had a rather constant increment in mean tree diameter (Figures 4 and 3b). However, it clearly appears that *Eucalyptus* diameter evolution relating to the tree year's old depends on the *Eucalyptus* genus. The diameter growing evolution curves of *E. bicostata and E. tereticornis* are similar and represent the largest diameters after 40 years which are respectively 275 mm and 256 mm (average values). The lowest diameter increment curve was recorded in *E. sideroxylon,* with a tree diameter of up to 103 mm, after 40 years (average values). Then, the analysis of diameter growth curves at breast height during the first 40 years allows us to cluster into three different groups of the species from the most successful to less successful as follows:

- Group 1 includes two or four better-adapted species *E. bicostata and E. tereticornis* presented by the mean diameter developed faster through years.
- Group 2 presented by *E. viminalis, E. maidenii,* and *E. macrorhyncha* presented by a medium diameter growing rate.
- Group 3 presented by *E. cinerea* and *E. sideroxylon* showed slow diameter growth. Therefore, less adapted to the conditions of the Khroumirie medium mountain.

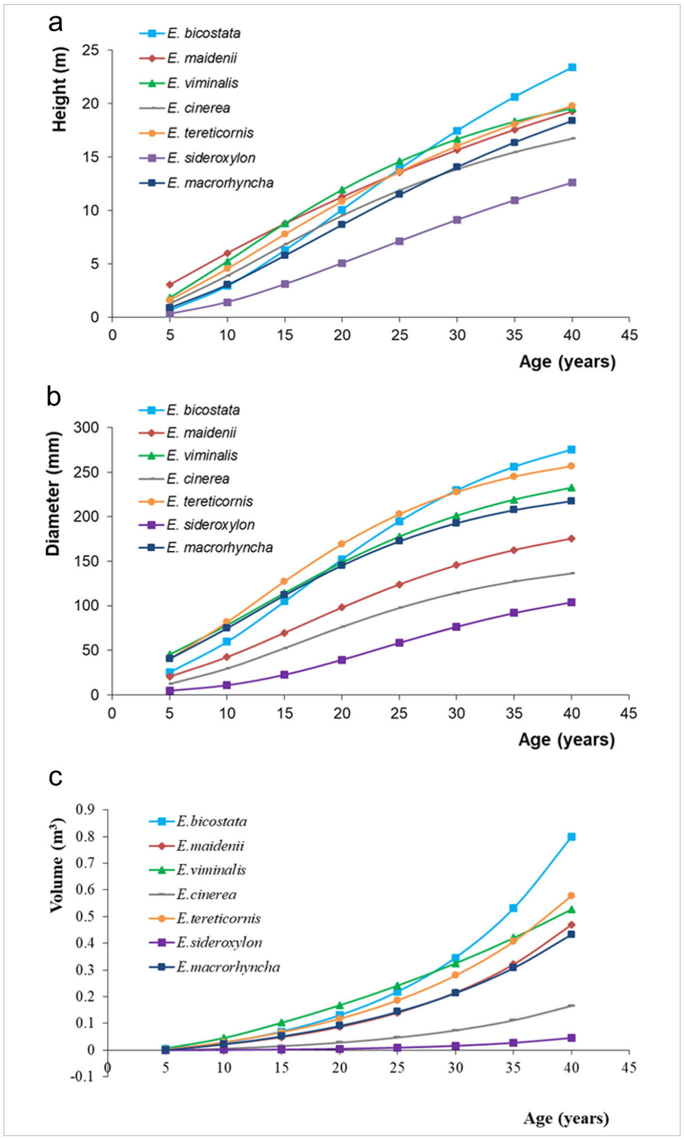


Figure 3.
(a) Height Growth, (b) Under Bark Diameter at Breast Height (DBH) Increment and (c) Volume Growth Curves of Different Eucalyptus *spp. Obtained According to the Age of the Tree.*

Growing in the same site, with respect to DBH, the studied *Eucalyptus* spp. showed similar DBH trends, as reported by various researchers for different *Eucalyptus* clones in Tanzania (Pima et al., 2016). According to Wamalwa et al. (2007), the differences in DBH within a site may be attributed to the genetic difference which suggests that the level of adaptation to site conditions is different. Wamalwa et al. (2007) showed that there was a highly significant difference in height, DBH, stem form, and branching habit of various *Eucalyptus* spp. and clones within and between sites in Kenya and more particularly depending on the altitude of the site. In addition, depending on the genus, *Eucalyptus* spp. adapt more or less well according to the climatic conditions and the nature of the biotope. This statement is comparable with the behavior of other wood species in Algeria (Ifticene-Habani & Messaoudene, 2016).

Tree Volume-Age Modeling

As shown in Table 5, the R^2 statistic indicates that there was a good fit of the volume-age based on an adapted Chapman–Richards model, in which 0.903 (*for E. viminalis*) of the variation in the volume of trees was explained by the independent variables. Each equation provided highly accurate estimates of volume, with RMSE values lower than 0.054 m^3 (obtained with *E. viminalis*), absolute values of $\bar{E}$ lower than 0.017 m^3 (obtained with *E. viminalis*), AMD values lower than 0.042 (obtained with *E. viminalis*), and MPB values lower than of 3.432% (obtained with *E. maidenii*). We also observed on the volume-age model, as for the diameter-age model, that the accuracy of predictions is not always accurate for the highest tree ages. The comparison of real total volumes of felled trees with those provided by the mathematical model shows that these forecasts are tainted with a relative error ranging from −7.9 to 1.5 % (Table 6). The mathematical models developed do not enable us to predict the volume of the tree accurately when these *Eucalyptus* trees are more than 30 years old, especially for *E. maidenii*, *E. sideroxylon,* and *E. cinerea*.

The predicted values from the adapted Chapman–Richards model and measured values of volume-age curves are presented in Figure 5, for each *Eucalyptus* spp.

The analysis of volume growth curves (Figure 3c) allows us to classify also the *Eucalyptus* spp. into three groups:

- Group 1 includes only *E. bicostata* as the most productive *Eucalyptus* species, with a volume of 0.800 m^3, after 40 years.
- Group 2 includes *E. tereticornis, E. viminalis*, *E .maidenii, and E. macrorhyncha* as medium productive *Eucalyptus* species, with a volume after 40 years of 0.579, 0.528, 0.470, and 0.434 m^3, respectively.
- Group 3 includes the two lower productive species which are the less adapted *Eucalyptus* spp. to the Khroumirie area conditions. *E. cinerea* and *E. sideroxylon* showed a very slow volumetric increment curve, reaching only 0.165 m^3 and 0.046 m^3 after 40 years, respectively.

The comparison of the growth rate in diameter, height, and volume of the seven Tunisian *Eucalyptus* spp. allowed us to select *E. bicostata, E. viminalis,* and *E .tereticornis* as well-adapted species to the site condition for reforestation, forest management, and silviculture treatment.

Productivity of Stands

Volumes on the foot of the stands were predicted directly from the mean values of the log volume multiplied by the number of stems that constitute the stand (Westfall & McRoberts, 2017). This method is tainted with an error, which is added to that caused by modeling. We estimated that this deviation was about −4.1% by comparing the actual total volume of 21 felled trees (7.713 m^3) to their total volume (7.392 m^3) assumed to be equal to 21 times the unit volume (0.352 m^3) of the tree medium basal area.

Figure 6 shows the standing volumes (Figure 6a) and the average annual production (Figure 6b), respectively, of the seven *Eucalyptus* spp. stands.

In terms of wood production during the first 40 years of the growth of trees, the results showed that the seven species of *Eucalyptus* were ranked from the most productive to the least as follows: *E. bicostata* > *E. viminalis*> *E. tereticornis* >*E. macrorhyncha* > *E .maidenii* > *E. cinerea* > *E. sideroxylon*.

The first three species are more adapted to the site conditions. Between 15 and 20 years, we did not find a difference between *E. bicostata* and *E. viminalis,* with annual average productivity between 5 and 10 m^3/ha/year. The other species have lower average productivity than 5 m^3/ha/year.

Table 4.
Equations of Regression Used for the Modeling of the Growth in Under Bark Diameter (D)

Species	Retained Mathematical Models	R^2	RMSE (mm)	Ē (mm)	MAD (mm)	MPB (%)
	Model Logistic					
E. macrorhyncha	D= 258.014 / [1+5.986*exp(−0.092x)]	0.970	10.621	3.269	7.950	2.145
E. maidenii	D= 227.267/ [1+9.086*exp(−0.088x)]	0.913	16.142	1.685	7.950	6.111
E. viminalis	D= 237.267 / [1+8.086*exp(−0.128x)]	0.951	14.662	2.743	11.984	1.402
E. sideroxylon	D= 117.267 / [1+11.858*exp(−0.102x)]	0.920	10.333	−3.383	8.487	18.828
E. bicostata	D= 295.587 / [1+12.086*exp(−0.127x)]	0.988	9.770	−3.352	8.329	9.604
E. tereticornis	D= 267.354 / [1+8.986*exp(−0.135x)]	0.973	12.451	0.278	10.523	4.477
E. cinerea	D= 157.584 / [1+9.145*exp(−0.102x)]	0.934	10.823	−0.291	9.098	9.344
	Model Compertz					
E. macrorhyncha	D= 238.251*exp[−2.704 exp(−0.085x)]	0.990	6.101	1.092	5.257	0.271
E. maidenii	D= 208.251 *exp[−3.104 exp(−0.075x)]	0.913	16.201	−0.137	13.780	1.305
E. viminalis	D= 265.251 *exp[−2.554 exp(−0.074x)]	0.958	13.614	0.314	10.945	3.480
E. sideroxylon	D= 455.102 *exp[−5.954 exp(−0.006x)]	0.963	7.039	0.198	5.093	−0.548
E. bicostata	D= 317.251 *exp[−3.784 exp(−0.082x)]	0.994	6.561	0.260	5.516	0.889
E. tereticornis	D= 278.574*exp[−3.015 exp(−0.090x)]	0.981	10.518	1.105	9.011	2.064
E. cinerea	D= 155.147 *exp[−3.884 exp(−0.085x)]	0.934	0.173	0.173	9.184	−1.383
	Model Chapman–Richards					
E. macrorhyncha	D= 245.445 [1−exp(−0.065x)]^1.655	0.987	6.968	3.909	5.830	−4.575
E. maidenii	D= 232.445 [1−exp(−0.051x)]^1.922	0.911	16.410	0.702	14.509	−3.560
E. viminalis	D= 261.467 [1−exp(−0.061x)]^1.512	0.961	13.100	0.566	10.237	0.781
E. sideroxylon	D= 255.241 [1−exp(−0.031x)]^2.420	0.959	7.412	−0.473	5.428	−0.084
E. bicostata	D= 305.245 [1−exp(−0.078x)]^2.712	0.991	8.574	−0.172	7.257	−3.215
E. tereticornis	D= 304.452 [1−exp(−0.0578x)]^1.567	0.986	9.042	2.044	7.515	−0.119
E. cinerea	D= 185.441 [1−exp(−0.042x)]^1.512	0.938	10.485	−1.405	9.218	5.047

Only the annual average productivity of *E. bicostata* exceeds 10 m^3/ha/year after 25 years to reach annual average productivity of 20 m^3/ha/year at the age of 40 years.

For short rotations of less than 25 years, *E. bicostata* and *E .viminalis* are recommended for the study area. *E. tereticornis* can be added with rotations of more than 25 years.

There were clear differences between the species regarding growth, productivity, and other characteristics. On the first 40 years of their life and in Khroumirie's conditions, that enabled us to give preference to the usage of *E. bicostata*. *E. viminalis* keep track of *E. teretecornis*. This productivity remains lower than the productivity average of 20 m^3/ha/year recorded in the world on *Eucalyptus* plantations (Brown et al., 1997).

On the other hand, growth differences have been found in other *Eucalyptus* species, tested under South African growing conditions (Gardner, 2001), highlighting the importance of site-species matching, as well as site provenance matching.

The cold winter and dry summer characterizing the mountain of Khroumirie decrease the growth rate of these sensitive species to these two factors. Only cold sheltered stations on southern slopes, stations in damp valleys may agree to allow these species and probably increase productivity. In addition, *Eucalyptus* spp. plantation yields in the drier tropics are often about 5–10 m^3/ha/year on 10–20 year rotations, whereas in moister regions, volumes up to 30 m^3/ha/year may be achieved (Evans, 1992). For example, the mean values of annual increases in wood volume produced by *Eucalyptus camaldulensis* plantations, with rotations ranging from 7 to 15 years, are very different depending on the countries and on the forestry methods implemented in the stand (Lamprecht, 1990): 20–25 m^3/ha/year in Argentina, 30 m^3/ha/year in Israel (irrigated plantation), 17–20 m^3/ha/year in Turkey (heartwood growth), 25–30 m^3/ha/year in Turkey (1st coppice generation), 3–11 m^3/ha/year in Morocco, 2–10 m^3/ha/year in Portugal, and 6–7 m^3/ha/year in Italy. According to this statement, the growth of trees seems to be affected by different factors such as species genotype, environmental conditions, and forestry management. On average rotations comprised between 15 and 20 years, the mean diameter under the bark of the *Eucalyptus* trees could be ranged from 10 to 15 cm and may only produce industrial woods, suitable for pulping or firewood.

Researches on *Eucalyptus* forest management planning methods have been expanded. Productivity of *Eucalyptus* plantations varies greatly, depending mainly on the genus, on the geographical location (Saïdi et al., 2011), and the soil composition (Barbier & Gbadoe, 2001). For example, mean annual increments of *Eucalyptus globulus* in Ethiopia of about 18 m^3/ha/year can be achieved in the best sites, whereas in medium and poor sites, the maximum mean annual increment is 13 and 5 m^3/ha/year, respectively (Guzmán et al., 2012). Concerning the wood species, Mughini (2000) highlighted that, in the

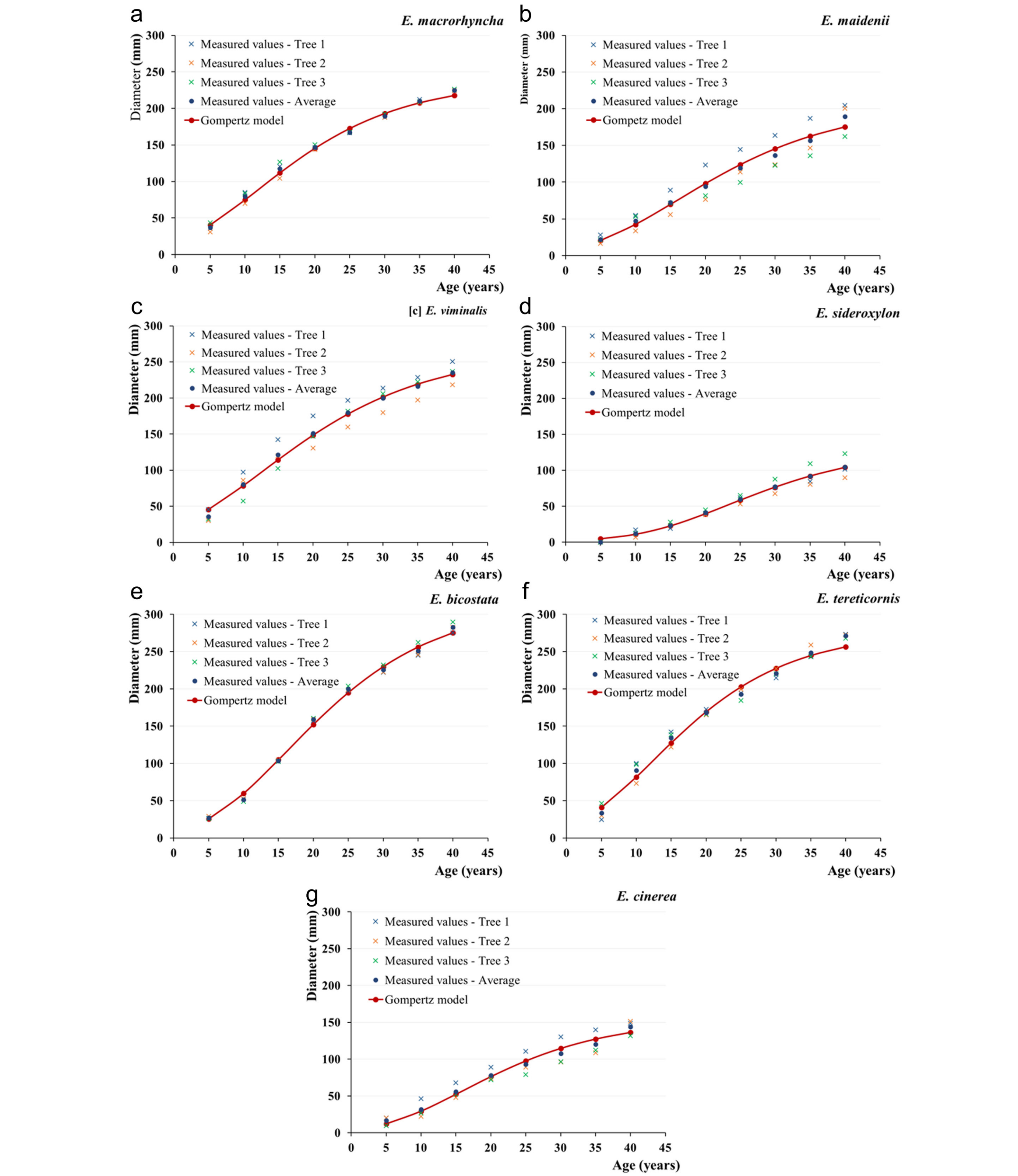


Figure 4.
Comparing Measured Values and Estimated Values From Chapman–Richards Equation to (a) E. macrorhyncha*, (b)* E. maidenii*, (c)* E. viminalis*, (d)* E. sideroxylon*, (e)* E. bicostata*, (f)* E. tereticornis*, and (g)* E. cinerea *Diameters According to the Age of the Trees.*

same plantation area, the productivity of *E. globulus* ranges from 10 to 35 m^3/ha/year, while those of *E. occidentalis* are comprised between 3 and 8 m^3/ha/year. Dimensional growth in terms of diameter and height is part of an individual tree growth model, but it is subjected to strong and complex interactions (Martins et al., 2014). Several authors have developed typical equations for tree growth models according to the different plantations conditions, such as temperate climatic conditions in Portugal (Soares & Tomé, 2002) and in northwestern Spain

Table 5.
Equations of Regression Used for the Modeling of the Growth in Under Bark Volume (V) of the Tree Average Basal Area

Species	Retained Mathematical Models	R^2	RMSE (m^3)	$\bar{E}$ (m^3)	MAD (m^3)	MPB (%)
	Model Chapman–Richards					
E. macrorhyncha	H= −0.065 + 0.049 exp(0.058x)	0.942	0.034	−0.009	0.023	0.267
E. maidenii	H= −0.046 + 0.034 exp(0.068x)	0.926	0.037	−0.010	0.024	−3.432
E. viminalis	H= −0.388 + 0.337 exp(0.025x)	0.903	0.054	−0.017	0.042	−0.122
E. sideroxylon	H= −0.002 + 0.001 exp(0.097x)	0.928	0.005	0.002	0.003	−0.592
E. bicostata	H= −0.068 + 0.045 exp(0.074x)	0.983	0.036	0.005	0.029	−0.683
E. tereticornis	H= −0.075 + 0.057 exp(0.061x)	0.946	0.046	0.002	0.030	−0.774
E. cinerea	H= −0.016 + 0.011 exp(0.07x)	0.927	0.016	−0.001	0.011	-0.329

Table 6.
Comparison of Real Under Bark Volumes of Average Felled Trees (V1) to their Volumes Estimated by Mathematical Models (V2) at the Age of 40 Years Old

Species	V1 (m^3) Real Means of Three Trees Felled	V2 (m^3) Estimated by the Mathematical Models	Precision (%) (V2–V1)/V1)100
E. macrorhyncha	0.445	0.434	−2.5%
E. maidenii	0.440	0.465	5.7%
E. viminalis	0.520	0.528	1.5%
E. sideroxylon	0.051	0.048	−5.9%
E. bicostata	0.835	0.800	−4.2%
E. tereticornis	0.605	0.579	−4.3%
E. cinerea	0.190	0.175	−7.9%

(Garcia & Ruiz, 2003), but also in the tropical area (Brazil) (Pinto et al., 2005). These types of tree growth models are not focused only on *Eucalyptus* models but they are also developed for many other tropical and subtropical wood species, all over the world (Fernández-Sólis et al., 2018; Fétéké et al., 2015), and they become a great tool in the management of agroforestry systems (Proces et al., 2017).

Conclusion and Recommendations

Eucalyptus plantations in the world have revolutionized forestry in many tropical or Mediterranean countries. These *Eucalyptus* stands allow producing a huge amount of biomass, withstand rotations averaging 10 years. These stand rotations can even be reduced to 3 years for the fastest-growing *Eucalyptus* spp. Compared with this observation from the literature, the seven species of *Eucalyptus* introduced into the Souiniet arboretum (humid Mediterranean bioclimate with a temperate variant) seem to have rather low growth rates, limiting their levels of wood production.

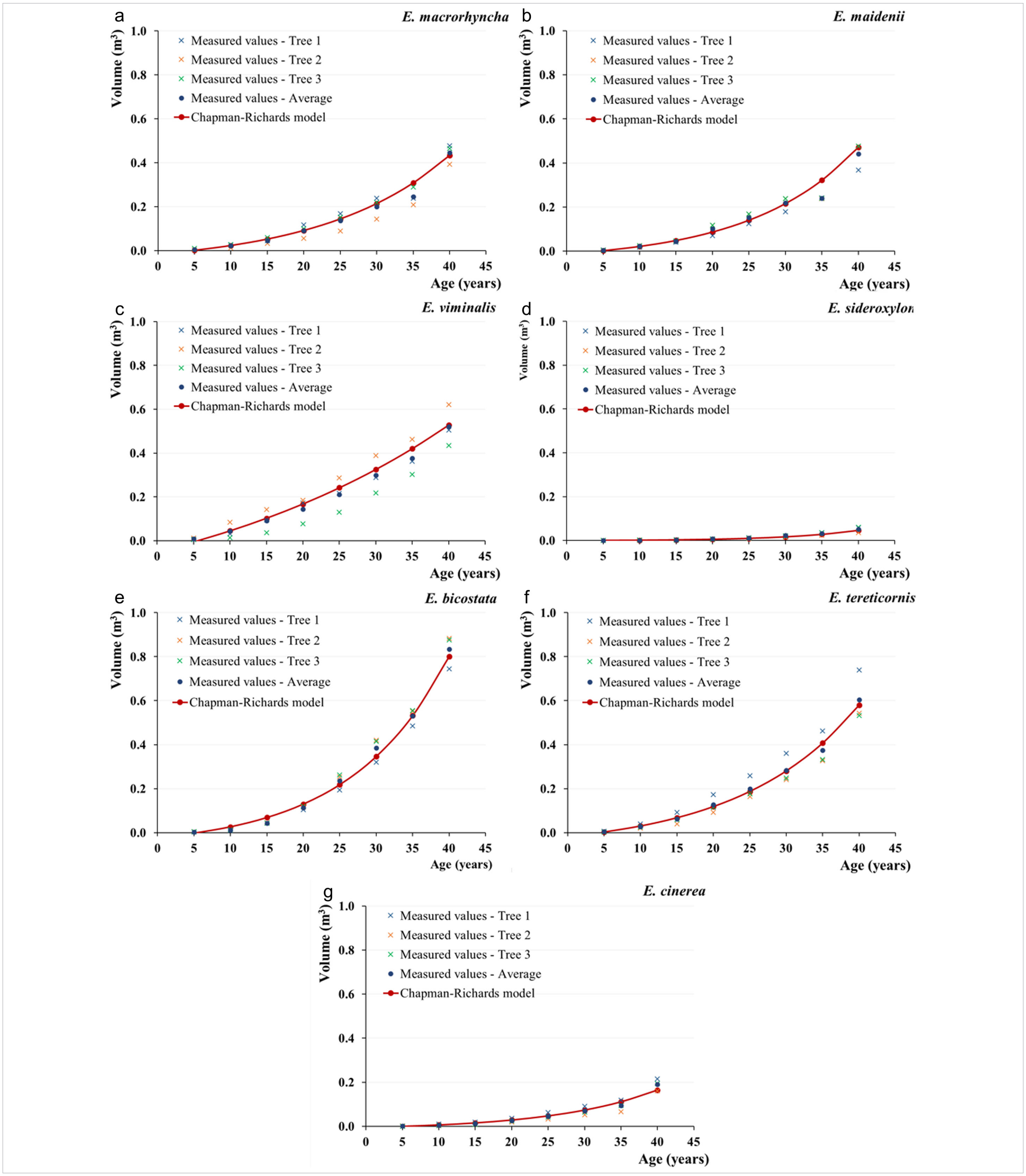
From the trials reported above, it is clear that selected provenances of *E. bicostata, E. tereticornis,* and *E. viminalis* have good potential for plantation. These species have the highest annual average productivity in the region but did not exceed 20 years 10 m^3/ha/year.

The rapid growth of discards in the first cut would slightly increase these performances. The choice of stations under and less dry microclimatic conditions could ensure the ecological requirements of these species and improve their productivity. More intensive silvicultural could also improve the productive efficiency of the performing species.

The *Eucalyptus* plantations in Tunisia occupy an area of 28,535 ha and cover 3.4% of the total area of the forest field of the state, mainly in humid and sub-humid bioclimate. The productivity of these plantations could be improved using *E. bicostata; E. tereticornis, and E. viminalis* and raise it by at least 285,350 m^3/year equivalents to 2/3 of the overall annual Tunisian forest production. With an intensification of the silviculture of *Eucalyptus* through soil preparation, adequate fertilization, and a better selection of species, it is possible to reach the overall average annual production of *Eucalyptus* plantations estimated at 20 m^3/ha/year.

For such development of *Eucalyptus* plantations, the economical (genetic improvement, wood materials for construction), social (change of practices toward fast-growing plantations, land-use planning), and environmental (carbon storage, soil erosion and sterilization, biodiversity) aspects will be the essential components to be taken into consideration.

Our current study suffers from some limitations, such as the small number of samples of plots on only one site. It would be very important to establish more experiments in order to access the influence of the silvicultural treatments on *Eucalyptus* plantation productivity as well as their interaction with the environment. Likewise, the experiments should be extended to timber and wood characteristics. Our perspective is to expand sampling to other areas and to increase the number of populations sampled across the entire geographic range of this species to provide a large- and medium-scale view of its behavior. In addition, since *Eucalyptus* spp. in the study zone are currently concentrated in a homogenous area where there is no great variability in climatic and soil data, the future incorporation into the model of information about plantations in neighboring areas, including the respective environmental data (dry and wet periods, soils composition, diseases, temperature variations, comparison with other wood species, etc.), would be of great value in increasing data variability and facilitating readjustments of the model.



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However, these preliminary results obtained by these modeling approaches provide additional knowledge on the productivity of the different *Eucalyptus* spp. installed in Tunisia, thus enabling forestry operators to simulate the development of forest stands in order to optimize timber production and harvesting. In addition, these comparative model results show us that various effective models can be developed. The equation used in the tree growth modeling can be different according to the *Eucalyptus* spp. In this sense, more

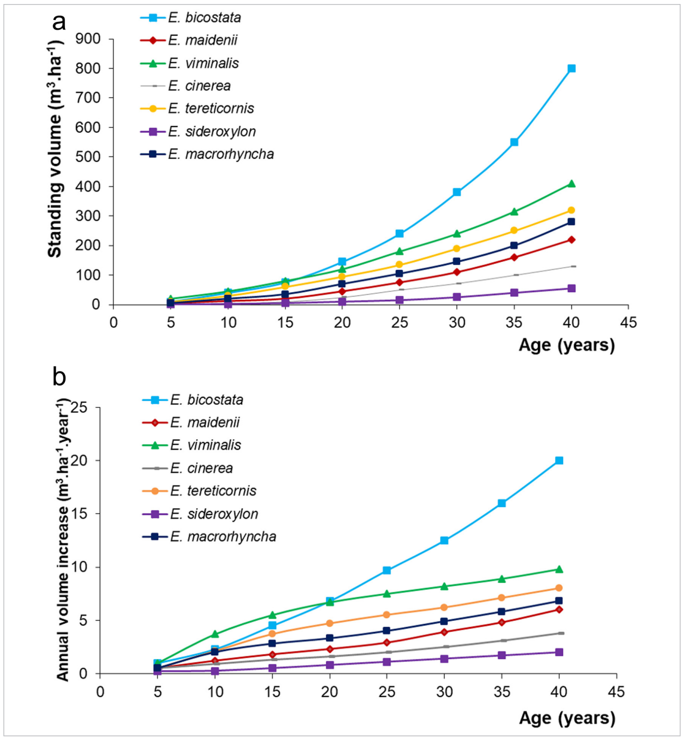

Figure 6.
Standing Volume (a) and Annual Average Volume Increment of Eucalyptus *Stands (b), at Souiniet Arboretum.*

comprehensive studies will be carried out in the near future, which may involve more organizations and harvesters interested in such an approach to select the best model for each *Eucalyptus* spp.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – S.M., M.T.E., M.L.K.; Design – M.T.E., K.C.; Supervision – M.T.E., M.L.K., K.C.; Resources – M.L.K.; Materials – M.T.E., N.S., M.K., A.A., K.C.; Data Collection and/or Processing – S.M., N.S., M.K., A.A., K.C.; Analysis and/or Interpretation – S.M., M.T.E., N.S., M.K., M.L.K., A.A., K.C.; Literature Search – K.C.; Writing Manuscript – S.M., M.T.E., M.L.K., K.C.; Critical Review – M.T.E., M.L.K., K.C.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors declared that this study has received no financial support.

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