

Production and silviculture of cork oak forests in Ain Snoussi, Tunisia*

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* This paper was partially funded by the Spanish-Tunisian cooperation project 'Conception of models for sustainable sylvo-pastoral management in the mountainous Mediterranean areas: Application to cork oak forest in Spain (Cadiz) and Tunisia (Ain Snoussi)', code: 6P/02, and by the Tunisian Secretary for Scientific Research and Technology (SERST). We especially wish to thank A. Khaldi for technical assistance in field work, and C. Nielsen for her constructive comments on the manuscript.

ABSTRACT

Cork and wood yield measurements are necessary in order to establish sustainable cork oak forest management models. First of all, this paper aims to develop growth models for cork oak forests at Ain Snoussi in the north of Tunisia. Two models based on stem data analysis by using difference equations were employed to predict height and diameter growth of dominant cork oak trees. Fifty-eight trees, randomly selected from ninety-one plots, were used for stem analysis. Cork growth was adjusted by using different functions, with actual cork age as an independent parameter.

The second aim of this paper was to present a silvicultural model of different treatments during an entire cork oak rotation, first established artificially by planting and later regenerated naturally and permanently from seeds. The growth models estimated the cork yields of both types of simulated stands. A steady cork oak stand would normally be reached after two rotations of natural regeneration.

Key words: growth models, silviculture model, cork oak, Tunisia.

1. INTRODUCTION

Tunisian cork oak forests are primarily located in the northwest region characterized by 700-1500 mm of annual precipitation and by an altitude of 0-1.200 m. These forests grow in acidic soil on sandstone substrate. They have high ecological, economic and social values and play an essential role in wildlife preservation. The forests are all natural and occupy a special Mediterranean ecosystem rich in other evergreen sclerophyllous plants and shrubs (maquis or scrubland). Cork (bark) and firewood are the most valuable byproducts of these forests. Cork production depends on both periodic tripping of the cork layer covering the stem and on the trees' aptitude to regenerate new cork cambium after each cork removal (Costa, Pereira and Oliveira, 2001).

The region is inhabited by a large poor population using the land for grazing and its other resources. Overgrazing and other forest abuses like clear cutting for cultivation, as well as forest fires, tree decline, stand aging and lack of natural regeneration, have in part led to a regression of cork oak forests. Currently, cork oak forests occupy 73.000 ha, of which only 45.500 ha are productive and the rest declined (DGF, 1995a), even though their natural habitat spreads over 150.000 ha (DGF, 1995b). A large reforestation-by-planting program has recently been started by the Tunisian government to help restore these forests.

The Tunisian cork oak forests were harvested for the first time in 1884 (DGF, 1995b). Some rules for cork stripping have since been made. Cork (bark) is first stripped when the tree has reached a circumference of 70 cm at breast height (virgin cork) and every 12 years subsequently (reproduction cork). The selection system was chosen to manage and maintain the uneven-aged cork oak stands. However, these stands have never really been managed. They are only periodically stripped for cork extraction (DGF, 1995b). The other silvicultural treatments, such as vegetative regeneration by sprouting, thinning and pruning operations are not applied despite the fact that the stands are often dense and getting older. Furthermore, in some forests the management plans need to be updated. The situation of the Tunisian cork oak stands appears then to be worrisome (DGF, 1995b). Particular attention is needed to manage these stands, by defining and applying an appropriate and flexible silvicultural system, a planned program extending throughout the life of a stand (Smith et al., 1997) which would help to maintain sustained yield and other goods and services.

The development of flexible growth and yield models for cork oak trees helps plan a silvicultural system for sustainable forest management by studying and predicting the effects of different silvicultural treatments (e.g., release operations, thinning) on the stand yield (cork and firewood). Unfortunately, these management orientation models are as yet unavailable in Tunisia, but have begun to be developed in other countries (Tomé, Coelho and Pereira, 1999, for Portugal; Montero et al., 2002, for Spain). The available growth models in Tunisia are in fact limited to site-specific cork yield tables. Little research has concentrated on the effects of factors such as debarking intensity and tree diameter on cork thickness (Sghaïer and Garchi, 2005). Furthermore, permanent sample plots are not yet established which would allow more accurate stand growth modeling.

The first aim of this study was to fit stand growth models for a cork oak forest. First, individual tree growth models for diameter under bark and cork thickness at breast height and models of height growth were fitted for dominant cork oak trees, by using data from natural cork oak stands. After that, stand growth models were developed for natural stands by including, among other factors, estimated natural mortality at

each stage. The second aim was to use these models in order to develop a silvicultural model for sustainable management that includes different silvicultural treatments carried out during the whole rotation of a planted cork oak stand (1st rotation) followed by other naturally established rotations (NS: natural stands). Due to lack of some data, particularly for young stand stages, some assumptions were used to achieve this objective. The selected region to carry out this research was Ain Snoussi, an important cork-producing area in northwest Tunisia.

2. MATERIAL AND METHODS

2.1. STUDIED AREA

Cork oak growth models were developed for the Ain Snoussi area (Altitude: 150-650 m) located in Ain Draham subdivision in northwestern Tunisia. The surface area is about 3.230 ha. The annual rainfall averaged 1.006 mm and the mean annual temperature was 17,5 °C, while the mean minimum temperature of the coldest month and the mean maximum temperature of the hottest month were 7,2 °C and 31,4 °C, respectively. According to Emberger's biogeographic climate classification (Emberger, 1955), the site belongs to a humid Mediterranean climate with a hot winter. The soil has a clayey texture with a Numidian sandstone substrate.

Forests dominated by cork oak trees of various ages occupy the majority of the area (81%). Maquis (3%), grasslands (2%), croplands (8%), and unproductive lands (6%) occupy the remainder. The local inhabitants consist of 325 households. They take advantage of grazing and harvesting of wood, acorns and other fruits from the forest and maquis. They also benefit from agriculture in small private farms scattered around the forest.

2.2. INDIVIDUAL TREE GROWTH MODEL

2.2.1. Height and diameter under cork at breast height

Data from stem analysis were used to fit the height (H) and diameter under cork at breast height (DBH) growth models. Fifty-eight dominant trees randomly selected from 91 approximately even-aged plots located in different site conditions were analyzed. Table 1 gives some characteristics of the selected trees. These were cut at the base at a height of 0,3 m, and disks were then cut at this height, at a height of 0,5 m, at breast height (1,3 m), and at every 0,5 m-long interval along the main stem. Rings were counted on each disk in order to find out the age at each height level. Tree age was estimated from the number of rings of the base disk, and the age at each height level was the difference between tree age and the number of rings at that level. On top of that, ring widths for disks cut at breast height were measured along the mean radius direction using a linear positioning digitizer tablet (LINTAB) and the data were saved and processed by TSAP software (Sánchez, Tomé and Montero, 2006). Since cork oak trees are generally characterized by slow height growth, the possible error for age estimation was supposed to be negligible and Carmean's correction (Carmean, 1972) to the height was not made.

Reciprocal difference equation models were used to fit dominant height (H) and DBH under bark growth. The general form of the difference model is:

$$Y_i = f(T_i, Y_j, T_j, \beta) + e_i \quad (1)$$

where Y_i is a predicted height i (or DBH i) by using height j (or DBH j): Y_j ; T_i is age i , T_j is age j , β is the vector of parameters and e_i is the error term that is supposed to be independent and identically distributed. In the difference equation model (1), either

one of the height-age pairs (or DBH-age pairs), Y_i-T_i , and Y_j-T_j , can be replaced by the site index pair SI-80 for height (or DBH) and site index predictions, after the model has been fitted. Moreover, the two height-pairs (or DBH-age pairs) can be switched without influencing height (or DBH) and site index predictions. Therefore, the difference equation models have the advantage of estimating: (1) site index (SI) for a base age (80 years for the case of cork oak forests), giving height (or DBH) at any age; and (2) height (or DBH) for a desired age from SI at the base age.

The McDill-Amateis difference equation (McDill and Amateis, 1992; Amateis, 1994) and several forms of Chapman-Richards (Richards, 1959) and Lundqvist-Korf functions were tested for each dependent variable (Table 2). The McDill-Amateis difference equation is based on dimensional analysis and does not have an integral form (Amateis and McDill, 1989). These candidate functions have been widely utilized in modeling tree growth (Amora et al., 1998).

All possible growth intervals in both directions in data structure were used. This data structure generally provides the most stable and reliable results (Huang, 1999). To reduce problems caused by high correlation between inter-tree observations and also to improve SAS software performance, the DBH increment model used a fixed 5-year interval to define projection steps (Sánchez, Tomé and Montero, 2006).

Model selection was accomplished using both statistical (e.g., model mean squared error, MSE, coefficient of determination: R-square) and biological criteria (e.g., biological meaning of parameters, particularly those indicating the asymptotic or maximum values) (Amaro et al., 1999, and 1998; Huang, 1999).

2.2.2. Virgin cork growth model at breast height

Virgin cork thickness (first cork harvest) was fitted using a power model with age as an independent parameter. The cork age was determined by counting the number of distinct layers of virgin cork, which were often hard to identify. The measurements were carried out on a different sample of 60 dominant cork oak trees from the same forest.

2.2.3. Reproduction cork growth model at breast height

The evolution of reproduction cork thickness (second and subsequent extractions) along successive cork extractions was not studied because of a lack of data, and it is considered to remain relatively constant.

The accumulated reproduction cork thickness was fitted in function of its age using a second degree polynomial function. Data were collected from 101 dominant cork trees located in 11 different plots.

Nonlinear least-squares (NLS) fits of the growth models were performed using the PROC MODEL procedure on SAS/ETS software (SAS, Institute Inc., 1988).

2.3. GROWTH AND CORK AND FIREWOOD YIELDS FOR PLANTED AND NATURAL STANDS

Planted and natural stands are referred to as established artificially by planting and naturally from seeds, respectively.

2.3.1. Simulation of stand growth and silvicultural treatments

The individual tree height growth model was used to estimate the minimum time to reach a height of 1,3 m for natural stands (2nd and subsequent rotations), which is the starting age for DBH under bark calculation, and also the minimum time needed to fence the plantation or the natural regeneration. According to Montero and Cañellas (1999), the regeneration must be fenced until the young trees are 2,0 m tall.

The height growth of planted stands (during the 1st rotation) was supposed to be 60% faster during the first year than of natural stands (2nd and subsequent rotations), and this growth difference percentage was supposed to decrease linearly until there was no difference in growth between the two stands when they were 70 years old.

Moreover, it is assumed that virgin cork started to be accumulated when the diameter under bark reached a value of ~ 6,5 cm, so at this stage the over bark diameter at breast height for natural stands was estimated by adding the virgin cork thickness to the under bark diameter; the over bark diameter predicted the minimum time required to attain the minimum diameter at breast height to be debarked (~22,28 cm; or circumference of 70 cm). As for height growth prediction, the diameter under bark at breast height of planted stands was supposed to be 60% greater at the beginning than of the natural stands.

After the first cork stripping, diameter over bark was calculated by adding the reproduction cork thickness to the diameter under bark. The subsequent cork extractions are to be done every 12 years.

After that, growth was developed for both stand types (planted and natural) by including initial density, natural mortality estimation and density reduction caused by silvicultural treatments such as cleaning and thinning operations.

Cork oak plantations located in the studied zone are still young and there is a lack of information concerning natural mortality. Referring to Montero et al. (2002), the initial annual mortality for planted trees having diameter at breast height less than 10 cm was supposed to equal 1,50 % for an initial density of 833 trees/ha, and 0,20 % annually afterwards. For convenience sake, the annual mortality of the natural stands (NS) and fully stocked, having an initial density of 1.500 seedlings, starts to be counted when the trees reached a diameter of 10 cm at breast height.

After the seeding cutting, the annual mortality of the seed trees would have a value of 0,40 %.

Thinning is an important treatment to consider for simulating silvicultural treatments in cork oak stands. The criteria used to decide the opportunity for the next thinning is to maintain the basal area less than 25 m²ha⁻¹ for optimal cork yield (Montero et al. 2002). For convenience, thinning and cork oak extraction operations are done the same year.

Detailed silvicultural treatments for planted and natural stands will be presented in the results section.

2.3.2. Cork and firewood yields

The stand growth models were used to predict cork and firewood yields. Cork yield is estimated using the previously-established yield table expressing cork biomass in function of the diameter over bark as the only independent variable (Table 3; Forest management plan, 1983). This table separates only virgin and reproduction corks. The coefficient of debarking was assumed to vary between 2 and 2,5.

In order to estimate cork yield at the beginning, it was postulated that at the first cork extraction (giving virgin cork), only 50% of the remaining trees after thinning would be harvested. The remaining 40% and 10% of the surviving trees were to be harvested during the second and the third cork extractions, respectively.

Firewood yield coming from natural tree mortality or silvicultural cutting operations was estimated in stacked cubic meters using the following relationship with the diameter over bark (DBH in cm) as the only independent variable:

$$\text{Cubic Volume} = 0.000265 \times D.B.H.^{2.22864}$$

This relationship was refitted using the firewood yield table of the Forest management plan of the studied forest (Forest management plan, 1983).

3. RESULTS

3.1. INDIVIDUAL TREE GROWTH MODELS

Table 4 showed the results of the fitted candidate functions for both dominant height and diameter under bark at breast height growth.

3.1.1. Height growth model

The difference equation form of Chapman-Richards, leaving k as a free parameter, as well as the two Lundqvist-Korf difference equations having respectively n and k as free parameters, have failed to converge. The Chapman-Richards difference equation having n as a free parameter was not selected because it overestimated early height growth.

The Lundqvist-Korf difference equation, having A as a free parameter, was selected to simulate height growth (H in m):

$$H_i = H_j \times e^{k \times \left(\frac{1}{A_j^n} - \frac{1}{A_i^n} \right)} \quad (k = -2,82948, n = -0,16812) \quad (2)$$

$$(R^2 = 0,7193, \text{MSE} = 0,6178)$$

H_i and H_j are the heights reached at the actual ages T_i and T_j , respectively. The parameter k and n were significantly different from zero at a level of 0,05.

A residual plot from the fit was drawn (Figure 1).

3.1.2. Diameter under cork at breast height model

The following Chapman-Richards equation form that leaves k as a free parameter (R_k) was chosen for the diameter under cork at breast height (DBH in cm):

$$DBH_u = A \times \left(1 - \left(1 - \left(\frac{DBH_v}{A} \right)^{(1-m)} \right)^{\frac{A_u}{A_v}} \right)^{\frac{1}{(1-m)}} \quad (A = 57,48058, n = -0,14479) \quad (3)$$

$$(R^2 = 0,9275, \text{MSE} = 9,0309)$$

DBH_u and DBH_v are respectively the diameter at breast height in cm for ages T_u and T_v (counted after reaching a breast height of 1,3 m above ground). In order to calculate these ages, it was necessary to add the age at which the trees reached the base height of 1,3 m minus one year.

The difference form of Lundqvist-Korf function that leaves n as a free parameter did not converge. The difference equation form of Chapman-Richards, leaving n as a free parameter, overestimated DBH in early stages. The McDill-Amateis (MA) equation form gave a closer estimation of DBH as the selected one, but the early DBH growth was slightly higher.

A residual plot from the fit is shown in Figure 1.

Site index curves based on base age 80 are shown in Figure 2.

3.1.3. Virgin cork growth model at breast height

Virgin cork thickness (mm) was fitted using the model

$$V_cork_i = b_0 \times T_i^{b_1} \quad (b_0=0,016896, b_1=1,805043) \quad (4)$$

$$(R^2=0,9167, MSE=7,4911)$$

V_cork_i is the virgin cork thickness, in mm, measured at breast height and built up after A_i years. The fitted model is shown in Figure 3.

Reproduction cork growth model at breast height:

The accumulated reproduction cork thickness (mm) was fitted by:

$$R_cork_i = a_2 T_i^2 + a_1 T_i + a_0 \quad (a_2=-0,04102, a_1=2,713569, a_0=0) \quad (5)$$

$$(R^2=0,8885, MSE=4,2019)$$

R_cork_i is the accumulated reproduction cork thickness, in mm, measured at breast height, for T_i years after the cork extraction.

The fitted model is shown in Figure 4.

This model does not take into account the evolution of cork calliper over the following cork extractions.

3.2. STAND GROWTH MODELS AND PRESCRIBED SILVICULTURAL TREATMENTS

In this study, stand height, DBH growth, and yields were only predicted for a site considered of relatively good quality (DBH_v of 30 cm and H_j of 8 m for base age T_j of 80 years) in the studied area.

3.2.1. Stand growth and yield

According to the height growth model (2), cork oak trees from natural stands (NS) would need 9 years to be 1,3 m tall. According to the assumption that trees from planted stands (PS) grow in height and in diameter 60% faster in the first year than the former, they would take only 4 years to reach the base height (Figure 5). Cork oak trees from planted and natural stands started to accumulate cork when they were 5 and 7 years old, respectively.

Table 5 summarizes the predicted ages corresponding to several silvicultural treatments in planted stands during the first rotation, and in natural stands, for the second and the subsequent rotations.

3.2.2. Prescribed silvicultural treatments for planted stands (during the 1st rotation)

Site preparation and plantation:

Prior to planting, a mechanical site preparation is carried out in order to reduce undesirable vegetation, namely maquis, and loosen compacted soils. First of all, the maquis is brush-cleared in 4 m wide strips, leaving undisturbed intercalary vegetation bands of about 2 m wide. This treatment is followed by ripping (80 cm deep), used to rupture subsurface hardpans, and scarification.

This mechanical site preparation is generally carried out during the summer months and the planting then delayed until December to allow the disturbed soil to settle and avoid the risk of root death caused by air pockets.

The planting is done manually (notch planting) by digging a hole of 50 cm large and 50 cm deep and placing a 1 year-old containerized seedling in the middle at correct depth.

The soil is then pressed gently around the seedling.

The spacing between trees is 3 m x 4 m giving a density of plantation of 833 trees per hectare.

The seedlings are watered immediately after planting and afterwards during the first three to four years to avoid summer drought. Three to five manual scalpings are applied in April or May during the first three to five years of the new plantation to help control competing vegetation.

Seedling mortality is about 20%. Subsequent planting (refilling or beating up), applied to scattered losses of planted seedlings, comes during the first two years following the planting.

Damage by domestic animal grazing is controlled by herding or fencing till the trees are 10 years old (2m tall).

Cleaning and thinning:

Cleaning is used to separate the best trees from undesirable ones that overtop them. The first cleaning is carried out when the trees are 15 years old. The number of trees released was 500 trees /ha (Table 6).

For optimal cork yield, more growing space is allocated to healthy trees by eliminating (thinning) some of their neighbors. The first thinning is applied during the first cork extraction, leaving only 300 trees. As mentioned before, thinning was used to maintain the basal area less than 25 m²ha⁻¹ for optimal cork growth (Montero et al. 2002).

Formative pruning:

The first formative pruning is applied to the trees when they are 15 years old, just after the cleaning operation. The lower branches are removed, leaving healthy branches in the upper two-thirds of the main stem. This helps improve the form of the crown, lengthen the branch-free bole, facilitate the cork extraction operation and improve cork quality. Funds permitting, two other formative prunings are carried out ten years later and after the first thinning (reserved only for the trees not debarked yet).

Salvage cutting:

Salvage cuttings are limited only to dead trees. Fallen trees are systematically removed by local inhabitants and used as firewood.

3.2.3. Prescribed silvicultural treatments for natural stands (2nd and subsequent rotations)

Regeneration:

After nine cork harvests, the seed-tree method is used to naturally regenerate the old plantation, established during the first rotation. Fifty vigorous seed trees (large live crown ratios) uniformly distributed over the whole area of the stand are reserved primarily for seeds (Seeding cutting). During the same year, site preparation by brush clearing and scalping, as a means of controlling competing vegetation of the maquis and preparing the seedbed, is done over 50% of the stand regenerated area.

The number of established trees constituting a satisfactory stocked stand is estimated at 1.500 trees/ha of 10 cm DBH (Table 7).

The final cutting is carried out when the new regeneration is established.

Other silvicultural treatments:

Two formative prunings, followed by manual brush clearing around the cork oak trees, are done when the new established stands are 24 and 52 years old, respectively.

The first cleaning and thinning are done during the same year. As for stands established by planting, the following thinnings are based on the rule that the amount of standing tree after each thinning has a basal area less than $25 \text{ m}^2\text{ha}^{-1}$ (to get optimal cork yield) until the next thinning (Montero et al., 2002).

The first cork extraction and the final cutting would fall on the same first thinning year.

The stands established naturally would be regenerated in the same manner and repeatedly during the following rotations when they are 148 years old, after 9 cork extractions.

The seeding and final cuttings are done when the stands are 148 and 184 years old.

The result of the simulation of individual tree DBH under and over bark, taking into account the silvicultural treatments, is illustrated in Figure 6.

3.3. CORK YIELD

In planted stands (during the 1st rotation), the maximum of reproduction cork yield would be reached when the trees are 85 years old (Table 8). Total virgin cork yield for the whole rotation is estimated at 86.506 Kg/ha of dry weight. The reproduction cork yield is estimated to be 20.613 Kg/ha for stands of site index 30 cm.

In natural stands (2nd and subsequent rotations), the maximum reproduction cork yield would be attained when the trees are 112 years old (Table 9). Total virgin and reproduction cork yields are estimated at 8.674 Kg/ha and 21.658 Kg/ha of dry weight, respectively.

3.4. FIREWOOD YIELD

Firewood yield is estimated by calculating the cumulative yield between two silvicultural treatments. Sellable trees are in the 10 cm DBH or more category.

Total firewood yields from planted (during the 1st rotation) and natural stands (2nd and subsequent rotations) are 275,95 and 378,82 cubic meters/ha, respectively.

3.5. DISCUSSION

Individual tree growth models for height and diameter at breast height were fitted for dominant cork oak trees of the studied region. The difference equation method was used for this purpose. These models were used to construct site index curves, a fundamental task in forest research yield. They considerably enhance our knowledge of cork oak growth in Tunisia and need to include other regions and cover the main productive cork oak forests.

Cork oak growth models were adjusted for the first time in this country. They were not fitted a long time ago because of (1) the problems met in distinguishing increment cores and determining tree age at the base and the ages of the sampled disks along the stem, (2) the difficulty defining the main stem to sample since the tree has a forked crown, (3) the difficulty getting permission to cut some cork oak trees which are of precious value and hard to regenerate, and (4) the lack of permanent sample plots for cork oak growth measurements. Part of the difficulties encountered for ring identification in cork oak wood may be due to the presence of callused areas resulting from cork extraction (Sánchez, Tomé and Montero, 2006). The installation of permanent sample plots for the main productive regions may partly solve some of these problems and may lead to more reliable growth and yield models as well as better study of tree mortality and the effects of silvicultural treatments such as thinning and stripping.

A Lundqvist-Korf difference equation model was selected for height growth of dominant cork oak trees in the studied zone. In another similar study, the McDill-Amateis described the best individual tree height growth (Sánchez, Tomé and Montero, 2006). The best model to select compromises between both statistical and biological constraints.

The selected model was not accurate enough and also had the inconvenience of over-estimating height, especially at earlier and older stages, perhaps because of the lack of accuracy of age estimations - by ring counting - reached at different tree height levels. In fact, our model had estimated the height of 140-year-old cork oak trees growing in stands of the best (quality I: 14 m at the base age of 80 years) and worst (quality V: 6 m) site qualities, at 25,1 m and 10,7 m, respectively, whereas the model developed by Sánchez, Tomé and Montero (2006) in Spain, estimated these values to 17,1 m and 9,9 m.

The quality of the fitted model could be partly improved by using the generalized least squares method (GLS) in order to solve the encountered problem of heteroscedasticity (heterogeneous variances) and dependence on stem analysis data, which comes from taking repeated measurements on the same trees at different heights (Huang, 1999). New data are also needed to improve the quality of the fit.

The individual tree height growth model was used to estimate the required number of years for a tree to be 1,3 m and 2,0 m tall, respectively. It could be also used - with some reservations since it is sometimes difficult to define and measure individual tree height due to the round shape of the cork oak trees - to define site index for cork oak stands which is the dominant height attained at the base age of 80 years (Sánchez, Tomé and Montero, 2006). This reference height reveals site quality better than diameter growth which depends on site density, and it is relatively easy to measure on a standing tree.

The Chapman-Richards equation form leaving k as a free parameter gave a relatively good estimate of diameter growth, even though this growth was still slightly overestimated in early growth stage. On the other hand, for older stages, for example when trees are 140 years old, which is apparently the upper age limit for production of quality cork in Spain (Montero and Cañellas, 1999), the diameter values obtained using our model were similar to those obtained in the models developed by Tomé (1999) and by Sánchez, Tomé and Montero (2006) for open woodlands of medium to low quality. For example, for site quality V (DBH of 25 cm when trees are 80 years old), the DBH under bark using our model was estimated at 35,4 cm, close to those found using Tomé (35,5 cm) or Sánchez, Tomé and Montero model (30 cm). However, for good site quality (quality I), our model gave a lower value (53 cm), in comparison to those given by Tomé (85,7 cm) or Sánchez, Tomé and Montero (70 cm) models. This result could be explained by the fact that our model was fitted by using data coming from lower site qualities (IV and less) and it would give a better diameter growth prediction for trees that belong to stands of the same range of site quality.

As mentioned for the individual tree height growth model, the quality of the diameter model could be enhanced by using the generalized least squares method (GLS) in order to take into account the repetitive nature of stem analysis data (Huang, 1999). Since growth diameter depends on stand density, the fitted model could also be improved by including in its parameters both the height to diameter ratio, which reflects stand density, and site quality, measured in terms of dominant height value reached at base age of 80 years (Sánchez, Tomé and Montero, 2006), which does not depend to a certain extent on stand density and reveals site potential.

Both individual tree height and diameter at breast height growth were not validated due to the small amount of available data. All these data were used for model development. Quantitative validation could be made as soon as separate data is available.

The accumulated cork thickness at breast height was fitted separately for virgin and reproduction cork by using, respectively, power and polynomial models. However, cork calliper evolves over the following cork extractions (Tomé, Coelho and Pereira, 1999), and the cork growth model needed to be improved by getting new data and taking into account this cork calliper evolution. The relationship between site productivity or quality and cork quality (e.g., calliper, porosity, defects) should be included.

This preliminary version of management orientation growth models was useful to simulate silvicultural treatments and to predict growth at stand level for sustainable management. These models should be tested by using available growth data or by monitoring the growth of cork oak stands regenerated artificially or naturally. Unfortunately, oak plantations located in the studied zone are young and the validation process will take a long time. Moreover, trials must be installed in order to test and model the effects of different silvicultural treatments and intensities (e.g., thinning) on cork growth and yield. Cork quality (porosity and defects) should be also studied.

Acorn yield is an economically important product used by local inhabitants to feed domestic animals during a specific period. Acorn biomass was not estimated and it would be interesting to include this yield with the other forest benefits. It could also be interesting to predict other forest goods (e.g., medicinal plants) and services (e.g., recreation).

The current developed growth models could in addition be improved by:

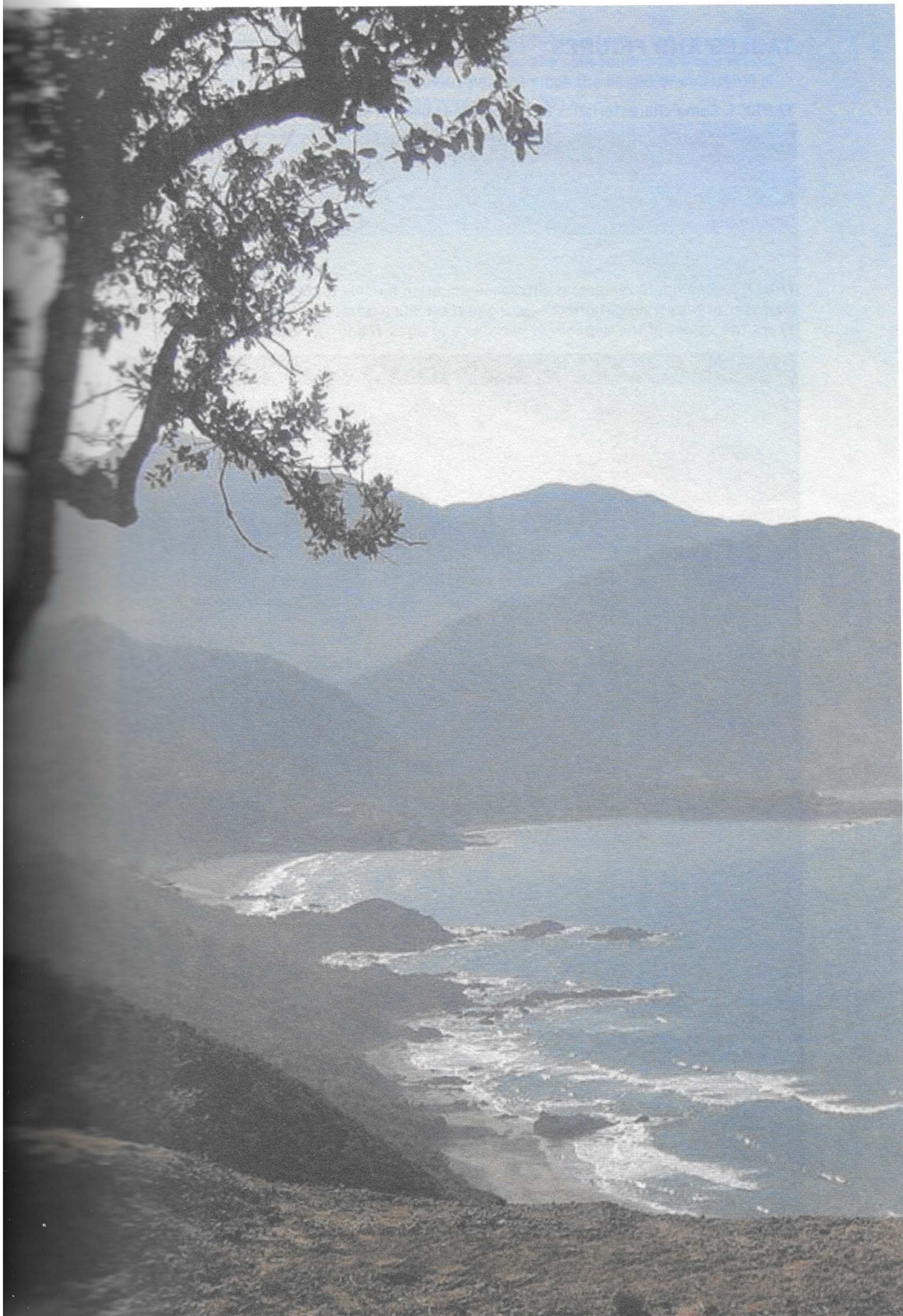
- Fitting a cork yield model by including other tree characteristics such as the height of debarking (coefficient of debarking multiplied by circumference over bark measured at breast height) (e.g., Fonseca and Parresol (2001)), separating the three cork categories (virgin, second and reproduction).
- Fitting a firewood model which includes cubic volume of the branches in addition to the main stem volume.
- Estimating natural tree mortality and fitting a model to predict it by monitoring the growth in stands of different ages.

After all these improvements, the current models could be used by foresters as a decision-making tool for sustainable cork oak forest management.

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TABLES AND FIGURES

TABLE 1. Some characteristics of the 58 trees used in stem analysis

Variable	Mean	Standard deviation	Minimum	Maximum
Age (years)	99,55	29,75	38,0	174,0
Cicumference at 1,3 m (cm)	98,40	39,44	37,0	193,0
Crown diameter (m)	6,62	2,76	2,0	13,5

TABLE 2. Candidate reciprocal difference equation models tested to fit height and diameter at breast height growth. (A, k and n are the parameters to be estimated. Y_i and Y_j are the values of the dependent variable y at ages T_i and T_j , respectively)

	Integral Function	Difference equation
Richards	$Y_i = A \times (1 - e^{-kT_i})^{\frac{1}{1-n}}$	$Rn: Y_i = A \times \frac{1 - \frac{\ln(1 - e^{-kT_i})}{\ln(1 - e^{-kT_j})}}{1 - \frac{\ln(1 - e^{-kT_i})}{\ln(1 - e^{-kT_j})}} \times Y_j$ $Rk: Y_i = A \times \left(1 - \left(1 - \left(\frac{Y_j}{A} \right)^{(1-n)} \right)^{\frac{T_i}{T_j}} \right)^{\frac{1}{(1-n)}}$ $RA: Y_i = Y_j \times \left(\frac{1 - e^{-kT_i}}{1 - e^{-kT_j}} \right)^{\frac{1}{1-n}}$
Lundqvist-Korf	$Y_i = A \times e^{-\frac{k}{T_i^n}}$	$Ln: Y_i = \frac{A}{\ln(T_i) \sqrt{\left(\frac{1}{k} \right)^{\ln\left(\frac{T_i}{T_j}\right)} \times \ln\left(\frac{A}{Y_j}\right)^{\ln(T_i)}}}$ $Lk: Y_i = A \times \left(\frac{Y_j}{A} \right)^{\left(\frac{T_j}{T_i} \right)^n}$ $LA: Y_i = Y_j \times e^{k \times \left(\frac{1}{T_j^n} - \frac{1}{T_i^n} \right)}$
McDill-Amateis		$MA: Y_i = \frac{A}{1 - \left(1 - \frac{A}{Y_j} \right) \times \left(\frac{T_j}{T_i} \right)^n}$

TABLE 3. Cork yield (dry weight in kg) in function of DBH over bark. (Two classes of cork are separated: virgin and reproduction corks. For the subsequent cork extraction, virgin represents the cork above the previous harvest since the height of debarking is increased as the tree grows (Forest Management Plan, 1983))

DBH over bark (cm)	1st cork extraction	Subsequent cork extraction		
	Virgin cork	Reproduction	Virgin	Total
20	5,7*	7,1	1,1	8,2
25	9,0	9,0	1,5	10,5
30	12,0	11,2	2,3	13,5
35	15,5	14,0	2,8	16,8
40	19,5	17,1	3,5	20,6
45		21,0	4,0	25,0
50		24,6	5,4	30,0
55		27,0	8,8	35,8
60		28,7	9,9	38,6
65		30,0	10,0	40,0
70		31,1	9,8	40,9
75		32,0	9,6	41,6
80		32,8	9,4	42,2

*Calculated values

TABLE 4. Estimated parameters of the fitted candidate functions for height and diameter growth models. (Rn, Rk and RA: Richards difference equations; Ln, Lk and LA are Lundqvist-Korf difference equations; and MA: McDill-Amateis difference equation. MSE: square error. SE: standard error)

Function	MSE	R-Square	Function parameters		
			A (±SE)	k (±SE)	n (±SE)
Height growth:					
1) Rn	0,5850	0,7342	11,600 ± 1,636	0,0074 ± 0,0018	
2) Rk	---	---	---		---
3) RA	0,6354	0,7113		-0,0210 ± 0,0022	-0,678 ± 0,032
4) Ln	---	---	---	---	
5) Lk	---	---	---		---
6) LA	0,6178	0,7193		-2,8295 ± 0,3599	-0,168 ± 0,015
7) MA	---	---	---		---
DBH growth:					
1) Rn	6,8422	0,9451	142,873±3,107	0,0015 ± 0,0001	
2) Rk	9,0309	0,9275	57,481±0,387		-0,145 ± 0,002
3) RA	12,0001	0,9036		0,0024±0,0001	-0,282 ± 0,003
4) Ln	---	---	---	---	
5) Lk	9,5853	0,9230	17,061,39 ± 1.837,10		0,102 ± 0,001
6) LA	12,1482	0,9025		39,073 ± 2,820	0,020 ± 0,002
7) MA	9,1026	0,9269	94,388 ± 1,029		0,899 ± 0,002

TABLE 5. Ages of silvicultural treatments performed during the first rotation on planted stands (PS) and during the second one on natural stands (NS) of SI = 30 cm (DBH) reached at the base age of 80 years in Ain Snoussi

Silvicultural treatments	1st rotation:	2nd rotation:
	Planted stand	Natural stand
Period of herding or fencing	10	17
First clearing	15	24
First formative pruning	15	24
First thinning	37	52
Virgen cork extraction	37	52
Maximum cork yield *	85	112
Seeding cutting	133	148
Final cutting	169	184

* Virgin and reproduction corks.

TABLE 6. Intermediate cuttings performed during the 1st rotation on planted cork oak stands (PS) of SI = 30 cm (DBH) reached at base age of 80 years: formative pruning, cleaning and thinning. (These stands will be regenerated naturally during the 2nd rotation by using the seed-tree method (seed and final cuttings))

Age	Circumference over bark (m)	Basal area (m ² /ha)	Number of trees per hectare				
			Before thinning	Thinned	Productive	1st harvest	2nd harvest
15	0,34	6,16	671	171			
37	0,71	19,04	478	178	300	300	
49	0,91	19,38	292		292	117	148
61	0,99	22,08	285	80	205	24	145
73	1,04	17,27	200		200		
85	1,12	19,72	196	36	160		
97	1,21	18,06	156		156		
109	1,28	19,81	152	52	100		
121	1,35	13,98	97		97		
133	1,41	14,93	95	45*	50		
145	1,46	8,13	48		48		
157	1,51	8,14	45		45		
169	1,55	8,24	43	43**	0		

*Seed cutting

**Final cutting

TABLE 7. Regeneration cuttings (brush clearing, seed cutting and final cutting), and intermediate cuttings (formative pruning, cleaning and thinning) done on natural stands (NS) of SI = 30 cm (DBH) established during the 2nd rotation. (The method of reproduction used during the 3rd rotation is the same: Seed-tree method: one seed cutting followed by a final cutting)

Age	Circumference over bark (m)	Basal area (m ² /ha)	Number of trees per hectare				
			Before thinning	Thinned	Productive	1st harvest	2nd harvest
24	0,29	10,18	1.500	900			
36	0,47	10,46	584				
52	0,70	19,04	566	266	300	300	
64	0,91	19,36	292		265	117	148
76	1,02	23,45	285	82	285	24	115
88	1,11	19,41	198		198		
100	1,19	21,87	193	43	193		
112	1,27	18,81	147		147		
124	1,34	20,29	143	43	143		
136	1,40	15,20	98		98		
148	1,45	15,91	95	45*	95		
160	1,50	8,59	48		48		
172	1,54	8,73	46		46		
184	1,58	8,59	43	43**	43		

*Seed cutting

**Final cutting

TABLE 8. Evolution of cork biomass (air dried weight in Kg/ha) and of firewood yield (stacked cubic meters /ha) during the 1st rotation of a planted cork oak stand of site index 30 cm (DBH at base age of 80 years)

Age	DBH under bark (cm)	Height (m)	Cork yield (Kg/ha)			Firewood yield (cubic meters/ha)
			Total	Reproduction	Virgin	
15	10,67	1,88				
37	20,95	3,90	11,60	2.254,85		2.254,85
49	23,74	5,01	52,14	3.325,13		1.732,65
61	26,08	6,15	2,53	2.359,42	1.592,48	970,80
73	27,83	7,31	49,02	3.112,50	1.388,63	522,50
85	30,46	8,50	2,57	3.385,90	2.590,00	565,95
97	33,07	9,72	30,75	3.028,35	2.819,95	511,88
109	35,41	10,97	3,06	3.220,37	2.516,48	542,13
121	37,51	12,25	55,95	2.254,28	2.678,24	368,60
133	39,40	13,56	2,86	2.375,00	1.885,68	380,00
145	41,11	14,89	59,14	1.275,00	1.995,00	213,00
157	42,66	16,26	3,61	1.265,63	1.062,00	219,38
169	44,05	17,66	2,72	1.263,13	1.046,25	224,68

FIGURE 2. Diameter under bark growth (DBH in cm) model for dominant cork oak trees in function of site index (DBH reached at base age: 80 years) in the Ain Snoussi region. Diameter growth curves of the sampled trees are represented by dotted lines

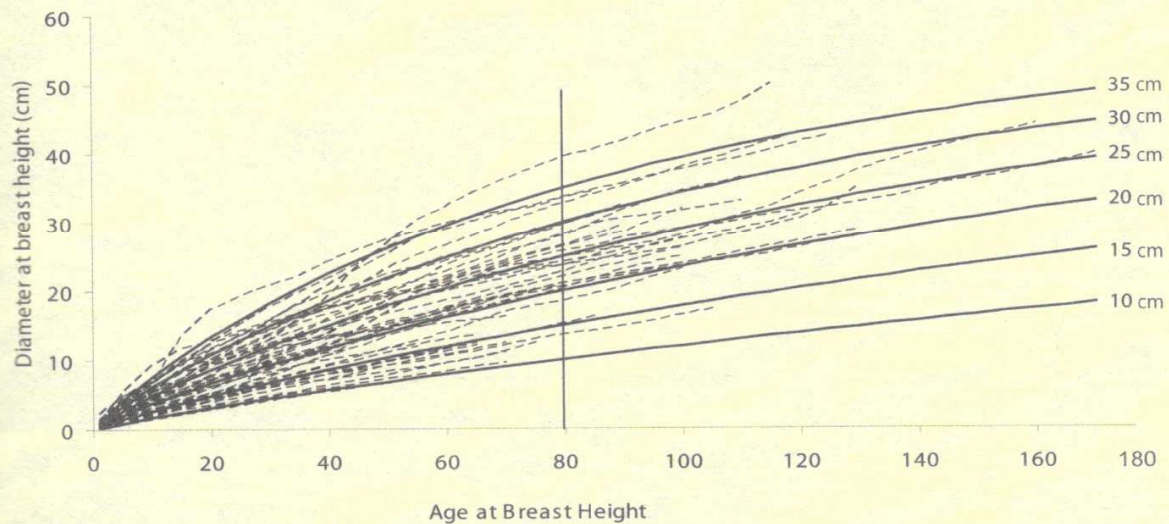


FIGURE 3. Actual (2) and predicted (3) values of virgin cork thickness (mm) as a function of age (Model 3)

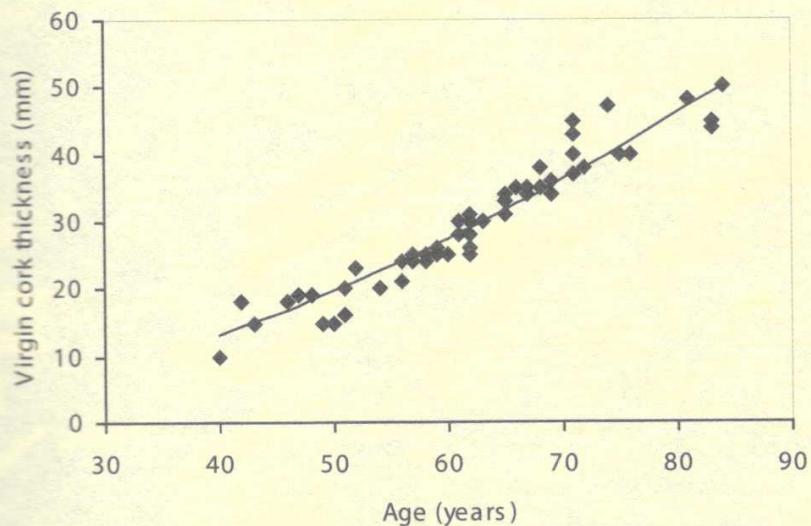


FIGURE 4. Actual (—) and fitted (---) curves of the accumulated reproduction cork thickness (mm) over age (Model 4)

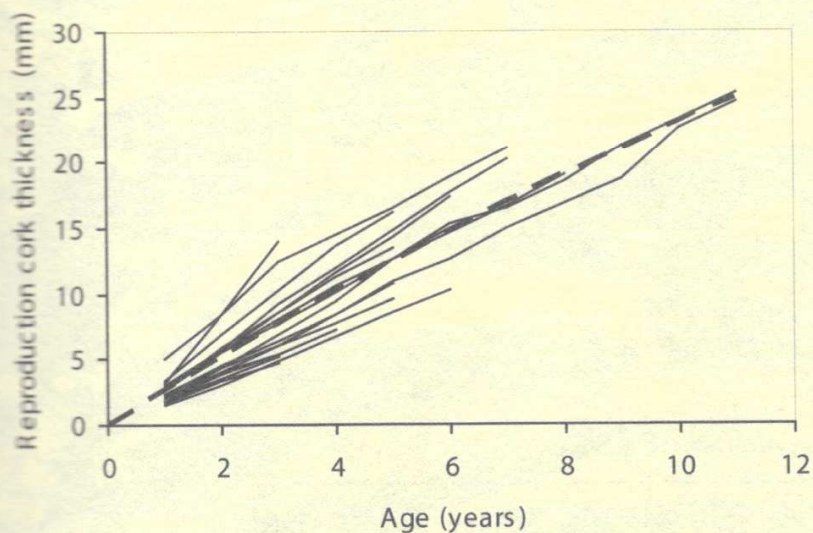


TABLE 9. Evolution of cork biomass (air dried weight in Kg/ha) and of firewood yield (stacked cubic meters /ha) during the 2nd rotation on natural stands (NS) of site index 30 cm (DBH at base age of 80 years)

Age	DBH under bark (cm)	Height (m)	Cork yield (Kg/ha)			Firewood yield (cubic meters/ha)
			Virgin	Reproduction	Total	
24	9,08	3,05				34,42
36	14,21	4,28				
52	19,99	5,96	2.227,38			76,61
64	19,99	7,24	1.731,27	1.592,48	2.227,38	2,59
76	23,72	8,55	1.011,45	1.449,00	3.323,75	53,85
88	27,04	9,90	504,90	2.810,36	2.460,45	2,37
100	30,00	11,28	616,39	3.038,54	3.315,26	41,26
112	32,65	12,70	519,40	2.551,92	3.654,94	3,40
124	35,03	14,14	538,63	2.742,74	3.071,32	51,42
136	37,17	15,62	388,73	2.032,52	3.281,37	2,06
148	39,10	17,14	413,25	2.080,50	2.421,25	64,52
160	40,84	18,69	229,80	1.105,20	2.493,75	2,47
172	42,41	20,27	236,33	1.100,55	1.335,00	4,15
184	43,83	21,88	256,57	1.064,25	1.336,88	74,12

FIGURE 1. Residual plot from models (2) and (3) selected to model height and diameter at breast height under bark (DBH)

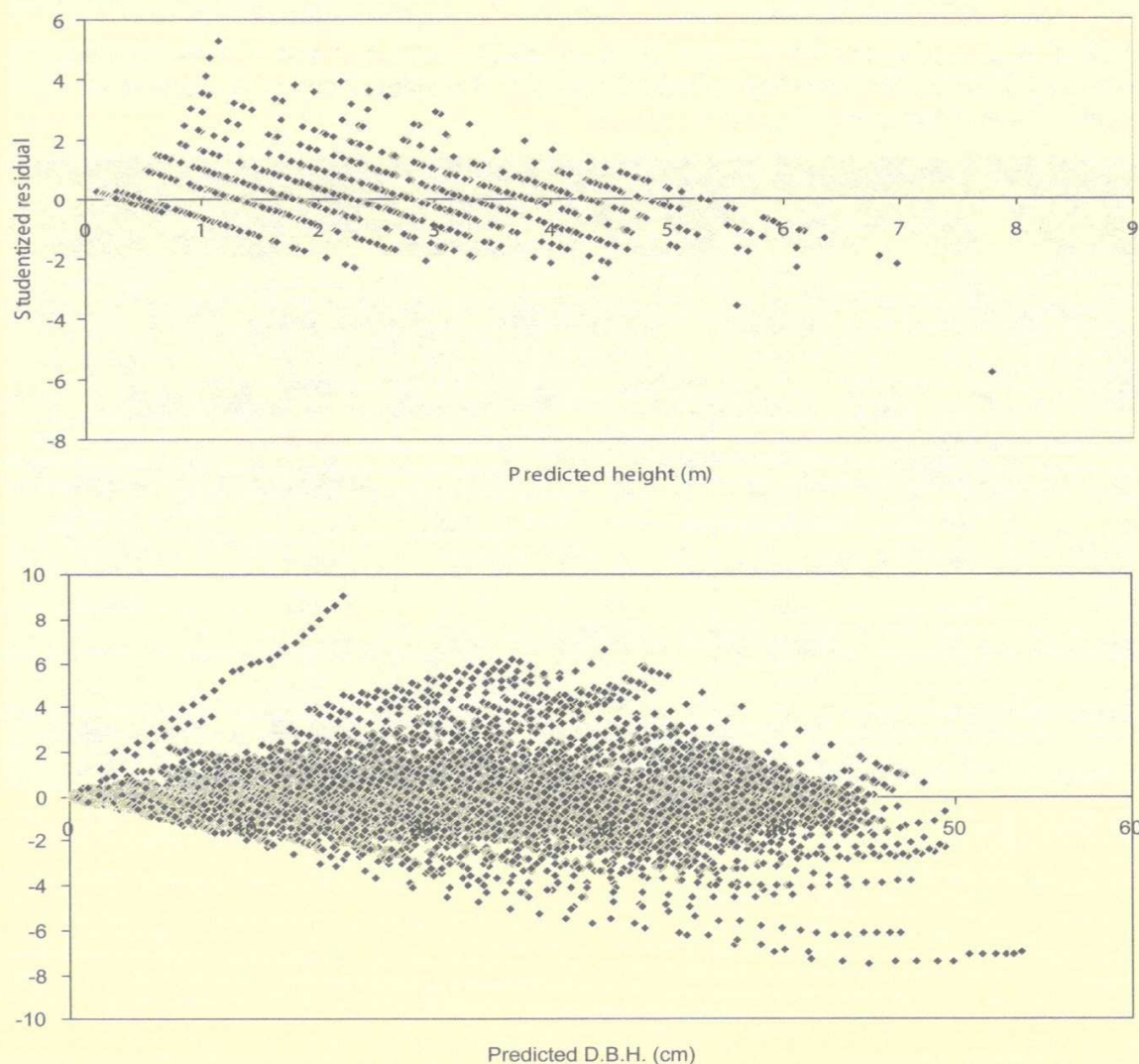


FIGURE 5. Plot of predicted tree height as a function of age for planted (--) and natural (-) stands having a site quality of 8 m for age base of 80 years (Model 1)

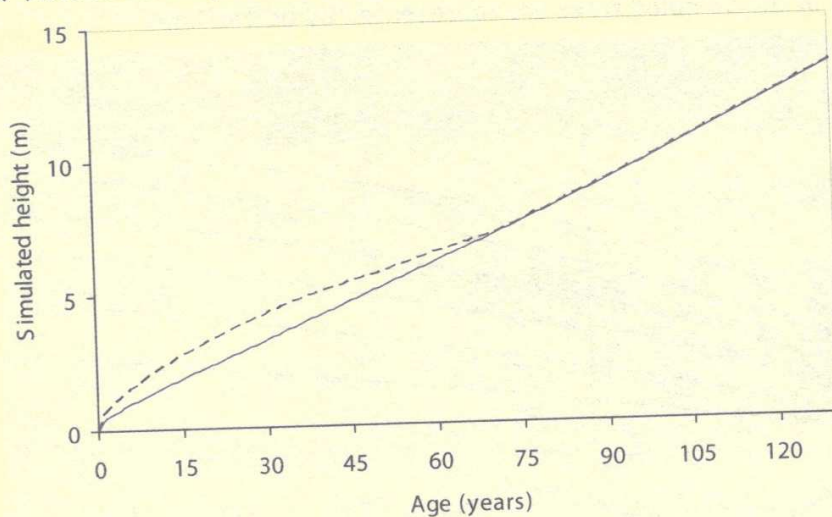
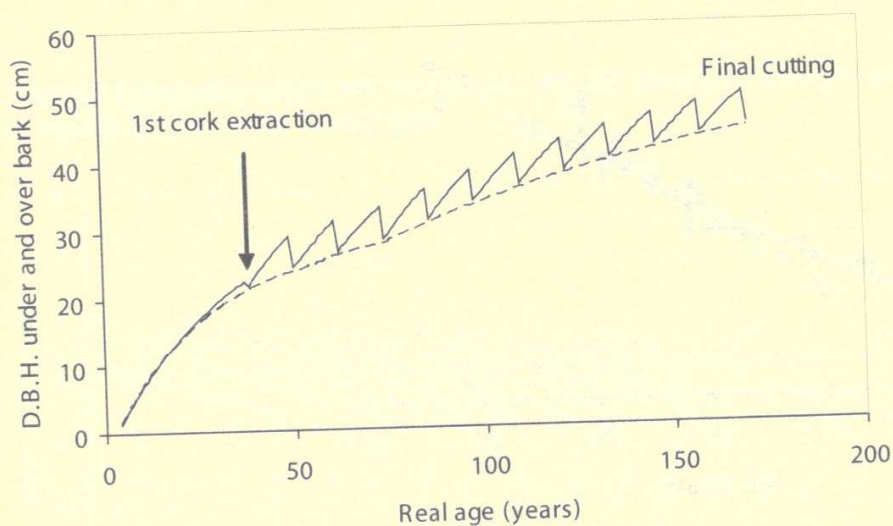


FIGURE 6. Plots of predicted tree D.B.H. under (--) and over (-) bark as a function of real age for planted and natural stands of site quality of 30 cm at base age 80

Planted stand



Natural stand

