Geo-Eco-Trop., 2019, 43, 1 : 145-160

Effect of the substrates used for forest seedlings production on the survival and growth of trees in a reforestation site in North-West of Tunisia

Effet des substrats utilisés pour la production de jeunes plants forestiers sur la survie et la croissance des arbres en site de reboisement dans le Nord-Ouest de la Tunisie

SGHAIER[1] T., CLAUSTRIAUX[2] J.J., AMMARI[1] Y. & OTHMANI[1] H.

Abstract : The purpose is to compare in reforestation site, through a statistical evaluation of dendrometric data collected from field trial, the behavior of *Pinus pinea* trees coming from plants produced in various substrates at the forest nursery level. The experiment was established in the framework of the modernization program of Tunisian forest nurseries which aims to substitute the forest or diverse textured agricultural soil-based substrates by compost produced from locally available forest biomass to improve the quality of forest plants produced for reforestation programs and to reduce the forest soils degradation. For this experiment installed in 1997, five compost substrates, mixed with different support and aeration materials, and a control substrate made of peat were used to produce *Pinus pinea* plants. Three measurements were taken at 6, 9 and 15 years after plantation concerning the height and diameters. Sixteen years after plantation, 72 trees were cut for stem analyses. These data were used to establish two growth models by substrate by using algebraic and generalized algebraic difference approaches (ADA/GADA). For the statistical evaluation, we proceeded in two steps:
- Analyses of data resulting from measurements taken directly on all trees.
- Analyses of simulated data models, for which heights and diameters measured after 15 years of age were used as exogenous variables to generate data for various ages from 1 to 100 years and to compare the substrates.

Keywords: Substrate, Seedlings, Generalized Algebraic Difference Approach, Pinus pinea, Tunisia.

Résumé : L’objet de ce travail et d’étudier le comportement en site de reboisement des arbres de pin pignon (*Pinus pinea*) issus de plants produits en pépinière dans différents substrats d’élevage. L’essai a été installé dans le cadre d’un programme de modernisation des pépinières forestières visant la substitution du substrat traditionnel d’élevage de plants en pépinière (terreau forestier) par le compostage de la biomasse forestière produite localement en vue d’améliorer la qualité des plants et réduire la dégradation des sols. Pour cet essai installé en 1997, cinq substrats à base de composte mélangé avec différents matériaux d’aération et un substrat témoin composé de terreau forestier ont été utilisés pour la production de plants de pin pignon. Trois mesures ont été effectuées à 6, 9 et 15 ans après la plantation et ont concerné la hauteur et les diamètres des arbres. Après 16 ans de croissance en site de reboisement, 72 arbres ont été coupés et ont fait l’objet des analyses de tiges. Les données collectées à partir des arbres coupés ont été utilisées pour élaborer deux modèles de croissance par substrat en utilisant la technique d’équations en différences et celle d’équations en différences généralisées (ADA/GADA). Pour l’évaluation statistique de cet essai, nous avons procédé en deux étapes :
- Analyse des données mesurées directement sur tous les arbres de l’essai.
- Analyse des données simulées à l’aide des modèles élaborés en considérant la hauteur et le diamètre des arbres mesurés après 15 ans de croissance en site de reboisement comme variables exogènes (indépendantes) pour générer des données et comparer les substrats aux différents âges allant de 1 à 100 ans.

Mots clés : Substrat, plant, équations en différences généralisées, pin pignon, Tunisie.

INTRODUCTION

The great quantities of organic material collected each year under the forest trees and used as substrate (peat) for seedlings production in the traditional forest nurseries constitute a real ecological and economic problem in Tunisia. Indeed, in addition to the impoverishment of the forest soils by the extraction of the organic matter, this practice supports the erosion and the degradation of forest resources.

[1]Institut National de Recherches en Génie Rural, Eaux et Forêts (INRGREF),
BP 10, 2080 Ariana- Tunisia.
E-mail : sghaier.tahar@iresa.agrinet.tn
[2]Gembloux Agro-Bio Tech/Université de Liège / Statistique appliquée,
Avenue de la Faculté d’Agronomie,8 - 5030 Gembloux (Belgium).
Corresponding author: Sghaier Tahar (sghaier.tahar@iresa.agrinet.tn)

Conscious of this problem, the Tunisian forest administration initiate during the Nineties of the last century a program of modernization of the forest nurseries in order to improve the quality of forest plants produced for reforestation programs by the substitution of the forest or diverse textured agricultural soil-based substrates by compost produced from forest biomass. In the framework of this program, a field trial containing plants of *Pinus pinea* produced in five compost-based growing media (S1, S2, S3, S4 and S5) mixed with different support and aeration materials locally available and a control substrate (ST) made of peat was installed by INRGREF in 1997. Figure 1 shows two lines of trees coming from two different substrates after 16 years of growth in the experimental site, and figure 2 presents a non thinned artificial stand of *Pinus pinea* in North-West of Tunisia.

Fig.1: Experimental design after 16 years of growth (two lines of trees coming from two different substrates).

Fig. 2: Non thinned artificial stand of *Pinus pinea* in North-West of Tunisia.

The main objective of this experiment was to evaluate in the field at short, medium and long-term, the survival rate and growth of the forest plantations coming from seedlings of *Pinus pinea* produced in particular substrates. We propose in this study to evaluate statistically the data collected from this long-term trial after 15 years of growth on the field in the objective to select the best substrates for the seedlings production at the nursery level for the future reforestation programs in Tunisia.

MATERIAL AND METHODS

Study area, experimental material, experimental design and data collected

The experimental site is located at Djebel Messid (Nefza) in the north-west of Tunisia on Oligocene sandstones and clay. The climate is humid, with an annual average precipitation of 993 mm with 96% of rain falls between September and May. The average minimum temperatures for the coldest month (February) and maximum for the hottest month (August) are 7.9 and 34.2 °C, respectively (BOUSSAIDI, 2005). Five compost-based growing media (S1, S2, S3, S4 and S5), mixed with different support and aeration materials, and a control substrate (ST) made of peat habitually used in Tunisian forest nurseries were used to produce *Pinus pinea* plants used for this experiment (table 1). The experimental trial was installed in October 1997 according to a randomized complete blocks design with four replicates. Each treatment (substrate) was represented in each block by one line with 45 trees. Seedlings at six months of age were planted according to 2x3 m spacing (approximately 1667 trees/ha).

Three measurements were taken at 6, 9 and 15 years after plantation. They have concerned the total height and diameter of trunk at 0.30 and 1.30 m. During 2013 (16 years after plantation), three trees per treatment and replicate (block) were selected systematically for stem analyses. The selected trees were cut down to 0.10 m and total heights were measured. Each tree was then cut at 0.5 m intervals, until the diameter 7 cm. The number of rings was counted at each cross sectioned point and then converted to stump age. To measure the annual diameter increment, the discs obtained at the cross section 0.10 m for the 72 cut trees were used. Annual radial growth was measured from the discs with the LINTAB table and TSAP software.

As cross-section lengths for the cut trees do not coincide generally with periodic height growth, we adjusted the height/age data from stem analysis to account for this bias using Carmean's method (CARMEAN**,** 1972), and the modification proposed by NEWBERRY (1991) for the topmost section of the tree, based on earlier studies (DYER & BAILEY**,** 1987; FABBIO *et al.***,** 1994). These corrections remove the bias when we assume that the height of the section is the maximum height attained at a given age.

Table 1: Composition of the studied substrates.

Substrate	Composition in percent (%)						
	Compost	Bark of pine	Cork	Burnt clay	Sand gross	Peat	Vermiculite
S1	50	-	20	15	15	-	-
S2	-	-		-	-	75	25
S3	50	30	10	-	10	-	-
S4	50	30	-	10	10	-	-
S5	45	45	-	-	10	-	-
ST	-	-		-	-	100	-

Model fitting

The methodology employed to model the height and diameter growth is based on the algebraic and generalized algebraic differences approach (ADA/GADA), using the dummy technique to make the adjustment (CIESZEWSKI *et al*., 2000). 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) or 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 and Núñez-Antón, 2001), typical for many forestry data sets (WEST *et al*., 1984). The CAR(x) expands the error terms in the following way (ZIMMERMAN & NÚÑEZ-ANTÓN, 2001):

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

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 $j > n$ and it is zero for $j \le n$, 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 by use of the SAS/ETS® MODEL procedure (SAS Institute Inc., 2004b), which allows for dynamic updating of the residuals.

Candidate functions

To select the adequate model for each growth variable (total height and diameter), 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 (Table 2).

The height and diameter growth modelling was carried out in two steps: (i) selection of the adequate model for each studied variable (height; basal diameter under bark) by using all the 72 cut trees in the trial, and (ii) for each treatment, the parameters of the selected models in step (i) were estimated by using the 12 cut trees by treatment (3 cut trees/treatment/replicate). In this case, we obtained one model by treatment and variable. These last fitted models were used for data simulations for all trees in the trial by using the corresponding model for each treatment and variable.

Table 2: Base models and ADA/GADA formulations considered for height and diameter growth modeling.

Base equation	Parameter related to site	Solution for X with initial values (t_0 Y_0)	Dynamic equation	Model
Hossfeld $Y = \frac{a_1}{1+a_2 t^{-a_3}}$	$a_2 = X$	$X_0 = t_0^{b_3}\left(\frac{b_1}{Y_0} - 1\right)$	$Y = \frac{b_1}{1-\left(1-\frac{b_1}{Y_0}\right)\left(\frac{t_0}{t}\right)^{b_3}}$	M1
	$\begin{cases} a_1 = b_1 + X \\ a_2 = b_2 X \end{cases}$	$X_0 = \frac{Y_0 - b_1}{1 - b_2 Y_0 t_0^{-b3}}$	$Y = \frac{b_1 + X_0}{1 + b_2 X_0 t^{-b_3}}$	M2
Bertalanffy-Richards $Y = a_1(1-\exp(-a_2 t))^{a_3}$	$a_2 = X$	$X_0 = -\ln\left(1-\left(\frac{Y_0}{b_1}\right)^{1/b_3}\right)\Big/ t_0$	$Y = b_1\left\{1-\left[1-\left(\frac{Y_0}{b_1}\right)^{1/b_3}\right]^{t/t_0}\right\}^{b_3}$	M3
	$\begin{cases} a_1 = \exp(X) \\ a_3 = b_2 + b_3 / X \end{cases}$	$X_0 = \frac{1}{2}\left(\ln Y_0 - b_2 F_0 \pm \sqrt{(b_2 F_0 - \ln Y_0)^2 - 4 b_3 F_0}\right)$ with $F_0 = \ln\left(1-\exp\left(-b_1 t_0\right)\right)$	$Y = Y_0\left(\frac{1-\exp(-b_1 t)}{1-\exp(-b_1 t_0)}\right)^{(b_2 + b_3 / X_0)}$	M4
Lundqvist-Korf $Y = a_1 \exp(-a_2 t^{-a_3})$	$a_2 = X$	$X_0 = -\ln\left(\frac{Y_0}{b_1}\right) t_0^{b_3}$	$Y = b_1\left(\frac{Y_0}{b_1}\right)^{\left(\frac{t_0}{t}\right)^{b_3}}$	M5
	$\begin{cases} a_1 = \exp(X) \\ a_2 = b_2 / X \end{cases}$	$X_0 = \frac{1}{2}\left(\ln Y_0 \pm \sqrt{(-\ln Y_0)^2 + 4 b_2 t_0^{-b_3}}\right)$	$Y = \exp(X_0)\exp(-(b_2 / X_0) t^{-b_3})$	M6

Model comparison

The models selected from the ones derived from each one of the base growth functions were compared by taking into account the fitting performance, the predictive abilities and the realism biologic for each of them. The possible violations of the assumption of homoscedasticity and the non-normality of the errors distribution were examined by plotting the residuals versus predicted values and QQ-probability plots respectively.

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}) :

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

Adjusted coefficient of determination: $R_{adj}^2 = 1 - \frac{(n-1)\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{(n-p)\sum_{i=1}^{n}(y_i - \overline{y})^2}$ (3)

where *n* is the number of observations, y_i, $\hat{y}_i$ and $\overline{y}_i$ are the measured, predicted and average values of the dependent variable and *p* is 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:

$$PRESS = \sum_{i=1}^{n}(y_i - \hat{y}_{i,-i})^2 \quad (6)$$

The closer the *PRESS* statistic value is from 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 modelling efficiency (press R-square):

Prediction mean of absolute deviations: $PREMAD = \frac{1}{n}\sum_{i=1}^{n}\left|y_i - \hat{y}_{i,-i}\right|$ (7)

Prediction mean residual: $Bias_p = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_{i,-i})$ (8)

Prediction RMSE: $RMSE_p = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_{i,-i})^2}{n-p}}$ (9)

Modelling efficiency: $R_{press}^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_{i,-i})^2}{\sum_{i=1}^{n}(y_i - \overline{y})^2}$ (10)

3° The realism biologic of the models was evaluated by the prediction of the growth (height and diameter) at 100 years of age.

Other developed and used sub models

As the diameter growth was modelled by using basal diameter under bark (BDUB), some relationships were established in order to estimate basal diameter (BD) and diameter at breast height (DBH). These relationships will be used (for data simulation) to predict the height and diameter growth of the other not cut trees (not used for modelling) in the trial:

$$BDUB = f(BD) \quad (11)$$

$$BD = f(BDUB) \quad (12)$$

$$DBH = f(BD) \quad (13)$$

In order to compare treatments by using the volume of trees, equation of volume (wood) developed by SGHAIER *et al.* (2013) in the framework of another study on *Pinus pinea* stands of the north-west region in Tunisia was used (equation 14 and figure 3). This equation is as follow:

$$V = 6.448 \times 10^{-3} \times CBH^{1,874} \times H^{0,998} \;, \quad R^2 = 0.957, \quad RMSE = 67.94 \quad (14)$$

with V: wood volume (dm^3), CBH: circumference at breast height (cm) and H: total height (m). This equation of volume must be used for trees with total height between 6 and 22 m and circumference at breast height between 35 and 135 cm.

Data simulation

To simulate the height and diameters growth of all trees in the trial, the selected models by treatment and variable were used. Age (t), total height (H) and basal diameter (BD) measured in 2012 were used as initial and exogenous values for the data simulation procedure. Figure 4 shows the data-processing simulation diagram from 1 till 100 years of age for the tree ijk (i: treatment, j: block and k: replicate).

Statistical analyses

To compare the six studied treatments, univariate and multivariate statistical analyses were used. Variables concerned by these analyses are total height (H), diameter at breast height (DBH) and tree volume (V). Treatments were compared at short-term by using the measured data at 6, 9 and 15 years of age; and at medium and long-terms by using the simulated data at 30 and 50 years of age. The univariate analyses were accomplished by using the two way analyses of variance (ANOVA) by the use of SAS/STAT® Mixed procedure (SAS Institute Inc., 2004a). Equality of variances was verified by using the Bartlett test (DAGNELIE, 2011). Multivariate analyses were concerned the survival rate (SR) measured at 15 years of age and the Lsmean of variables H, DBH and V measured after 15 years of growth and predicted at 50 years of age by the use of SAS/STAT® Princomp and Cluster procedures, respectively.

For the global analyses by taking in account the various measurements and simulated data for the same variable, regarding the repeated measurements on the same trees (longitudinal data), it is not possible to test the interactions treatment-year (treatment-age) by using the analysis of variance which requires the independence of the successive observations. In this way, treatments can be ranked for each measurement (year) and variable according to annual averages and the *Kendal's coefficient of concordance* (DANIEL, 1978) can be calculated. This statistic, which is designed W, is a nonparametric test realized on the ranks whose the null hypothesis supposes the dependence between ranks of treatments and the years of measurements. The objective was to test if the ranks occupied by treatments depend on the age of the trees or, on the contrary if the treatments occupy more or less the same ranks during the various years of measurements.

For *k* treatments and *m* years of measurements, the *Kendal's coefficient of concordance* is as follow:

$$W = \frac{12\sum_{j=1}^{k} R_j^2 - 3m^2k(k+1)^2}{m^2k(k^2-1)} \quad (15)$$

where R_j represents the sum of ranks assigned to the j^th^ treatment during the *m* years of measurements.
For small values of *m* and *k*, specific tables (DANIEL, 1978) can be used to decide whether to reject the null hypothesis. For values of *m* and *k* not covered by the cited tables, the variable χ^2 can be calculated as follow:

$$\chi^2_{obs} = m(k-1)W \quad (16)$$

and compared to a theoretical value of chi-square with (*k* – 1) degrees of freedom.

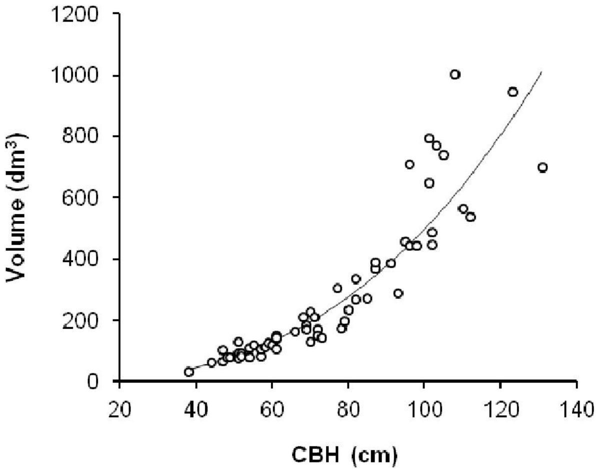

Fig. 3: Equation of volume at tree level for *Pinus pinea* plantations in north-west of Tunisia (SGHAIER *et al.*, 2013).

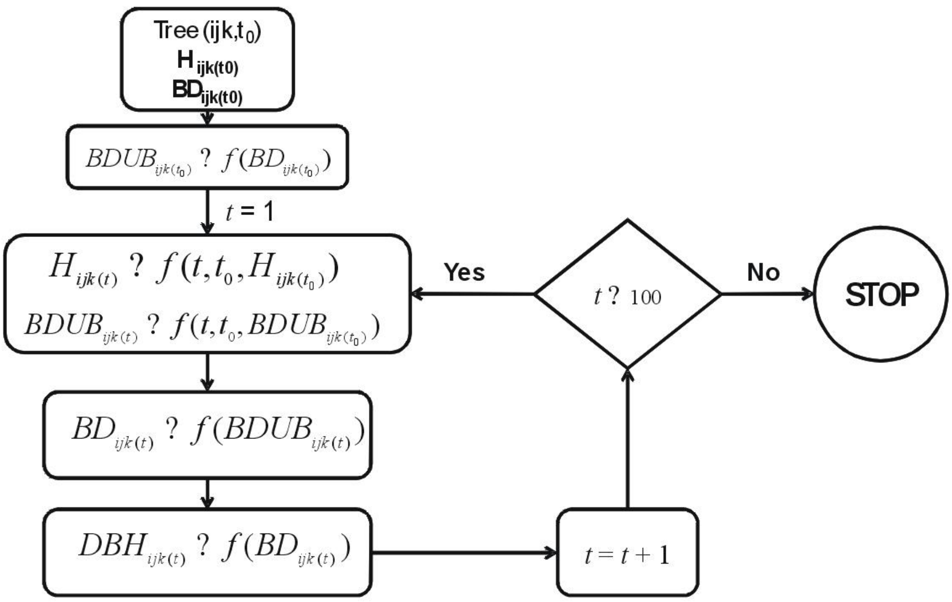

Fig. 4: Data-processing simulation diagram.

RESULTS AND DISCUSSION

Order of the function CAR(x)

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 for each variable (H, BDUB) all the six studied models (table 2) using nonlinear least squares without expanding the error terms to account for autocorrelation. It appeared that a trend in residuals as a function of both height and diameter lag-residuals within the same tree was evident in all models as expected because of the longitudinal nature of the data used for model fitting. Figure 5 (first column) provides an example for diameter (DBUB) with model M5. After correction for autocorrelation using a second-order continuous-time autoregressive error structure CAR(2), the trends in residuals disappeared (Fig. 5 third column). So, a second-order continuous-time autoregressive error structure was used to fit all the tested models for the two studied variables (H and BDUB).

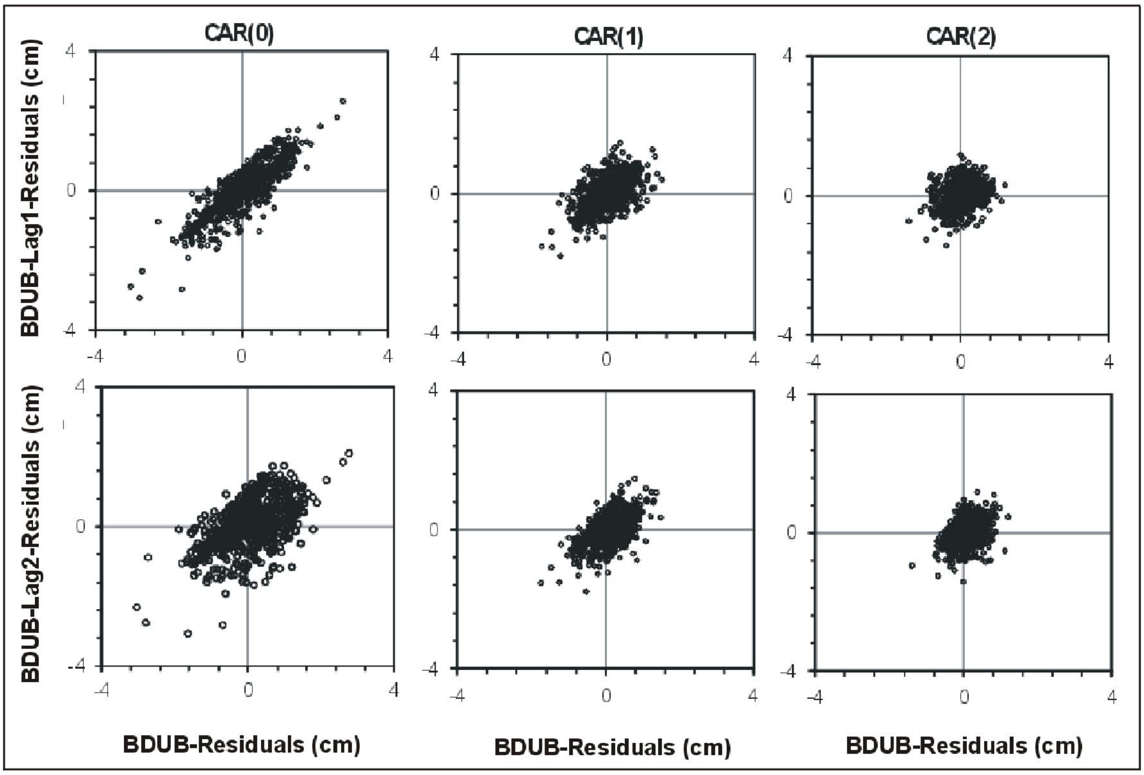

Fig.5: BDUB-Lag1-Residuals and BDUB-Lag2-Residuals versus BDUB-Residuals for model M5 fitted without considering the autocorrelation parameters (first column), and using continuous-time autoregressive error structures of first and second order (second and third columns, respectively).

Mean curves for all the cut trees in the trial

Among the six evaluated models for height and basal diameter under bark growth prediction (Table 2), Model M5 (ADA formulation) and M6 (GADA formulation), both derived from the Lundqvist-Korf base function by considering one and two parameters as related to site productivity, were selected. The parameter estimates for each of the two selected models and their corresponding goodness-of-fit statistics are shown in Table 3.

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

Model	Par.	Est.	p-value	Fitting ability		Prediction ability				Pred. (100)
				RMSE	R^2_{adj}	$Bias_p$	$RMSE_p$	R^2_{press}	*PREMAD*	
BDUB (cm) M5	b_1	73.6727	<0.0001	0.3756	0.9941	0.0068	0.3994	0.9934	0.3039	32.19
	b_3	0.3805	<0.0001							
	ρ_1	1.2529	<0.0001							
	ρ_2	0.8364	<0.0001							
H (m) M6	b_2	28.7463	<0.0001	0.1377	0.9948	0.0008	0.1605	0.9929	0.1153	16.00
	b_3	0.2100	<0.0001							
	ρ_1	1.1033	<0.0001							
	ρ_2	0.8199	<0.0001							

The two selected model are as follow:

- Basal diameter under bark growth (M5): ADA formulation of the Lundqvist-korf base equation that considers one site-specific parameter.

$$Y = 73.6727\left(\frac{Y_0}{73.6727}\right)^{\left(\frac{t_0}{t}\right)^{0.3805}} \tag{17}$$

where Y is the predicted BDUB (cm) at age t (years), and Y_0 and t_0 represent the predictor variables BDUB (Y_0) and age (t_0) at which Y_0 is observed.

Figure 6 presents the QQ-probability plots of residuals (a) and residuals versus predicted values (b) for BDUB obtained with M5. This figure shows that the normality and homoscedasticity of residues can be considered as respected.

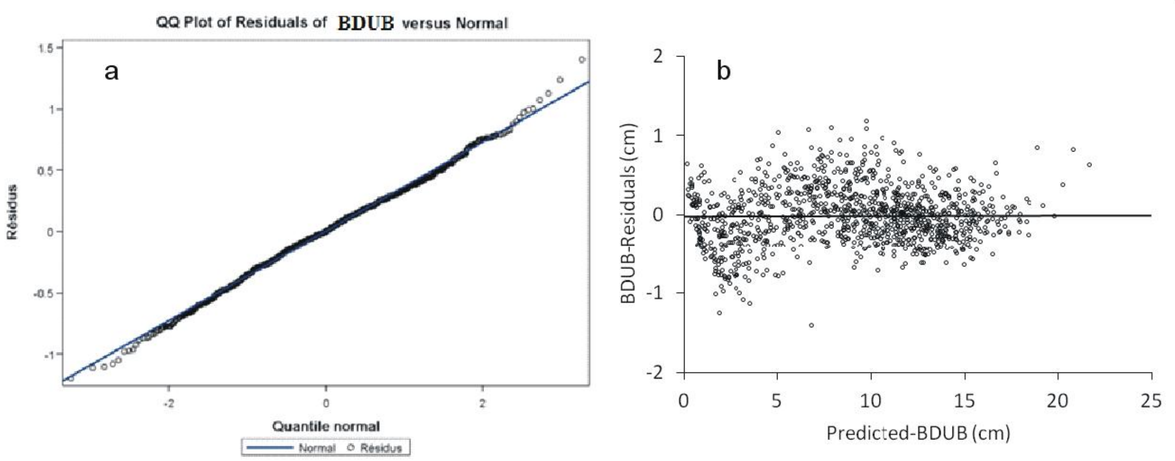

Fig. 6: QQ-probability plots of DBUB residuals (a) and residuals versus predicted BDUB (b) for model M5 (the ADA formulation of the Lundqvist-korf base equation that considers one site-specific parameter) fitted with a second-order continuous-time autoregressive error structure (CAR(2)).

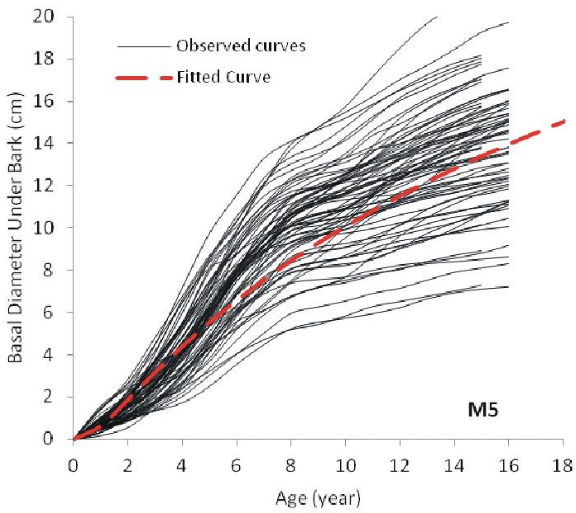

Fig. 7: Mean curve of the BDUB growth overlaying the trajectories of the observed BDUB over time for model M5.

Figure 7 shows the mean curve of the BDUB growth overlaying the trajectories of the observed BDUB over time for model M5. Age (16 years) and BDUB mean (13.97 cm) of the 72 cut trees were used as initial values to draw the mean curve. The BDUB for the mean tree in the trial was estimated to 32.19 cm at 100 years of age (Table 3).

- Total height growth (M6): GADA formulation of the Lundqvist-korf base equation that considers two site-specific parameters.

$$Y = \mathrm{e}^{X_0}\, e^{\left(\frac{-28.7463}{X_0} t^{-0.2100}\right)} \tag{18}$$

$$X_0 = \frac{1}{2}\left(\ln Y_0 \pm \sqrt{(-\ln Y_0)^2 + 4 \times 28.7463 t_0^{-0.2100}}\right) \tag{19}$$

where Y is the predicted Height (m) at age t (years), and Y_0 and t_0 represent the predictor variables H (Y_0) and age (t_0) at which Y_0 is observed.

Mean curves by treatment

Models M5 and M6 were rebuild by using data resulting from stem analyses collected from each 12 cut trees by treatment. Tables 4 and 5 show the estimated parameters and the adjusted and press r-square for each model (M5 for BDUB and M6 for total height) for each treatment.

Table 4 – BDUB growth by treatment: Parameters of model M5.

Treatment	***Model parameters***		R^2_{adj}	R^2_{press}
	b_1	b_3		
S1	56.0259	0.4174	0.9935	0.9930
S2	78.8121	0.3560	0.9945	0.9935
S3	47.4136	0.4317	0.9921	0.9915
S4	76.3643	0.3805	0.9950	0.9946
S5	50.7326	0.4702	0.9941	0.9936
ST	74.4735	0.4292	0.9949	0.9944

Table 5 – Total height growth by treatment: Parameters of model M6.

Treatment	***Model parameters***		R^2_{adj}	R^2_{press}
	b_2	b_3		
S1	30.8359	0.2005	0.9912	0.9878
S2	45.9790	0.1477	0.9955	0.9944
S3	33.9931	0.1860	0.9947	0.9930
S4	32.5491	0.1928	0.9947	0.9931
S5	21.0430	0.2580	0.9949	0.9934
ST	22.9442	0.2603	0.9949	0.9931

Constructed sub-models

- ***Relations between basal diameter under bark (BDUB) and basal diameter (BD): (n = 72 cut trees)***

Two relationships were developed:

$$BDUB = 0.889 - 1.748 \times BD \quad \text{with } R^2 = 0.9829, \quad RMSE = 0.381 \qquad (20)$$

and

$$BD = 2.240 + 1.108 \times BDUB \quad \text{with } R^2 = 0.9829, \quad RMSE = 0.426 \qquad (21)$$

- ***Relation between DBH and BD:*** **(n = 1834 measurements of 2006 - 2012)**

$$DBH = 75.8035 \times (1 - e^{(-0.0216 \times BD)})^{1.6268} \quad \text{with } R^2 = 0.802, \quad RMSE = 1.743 \qquad (22)$$

Data simulation

Total height (H) and diameter at breast height (DBH) were estimated at 30, 50 and 100 years of age for each tree in the trial by using the data-processing simulation diagram (Figure 4) and the various developed corresponding models (equations 17, 18, 19, 20, 21 and 22). Total height and basal diameter (BD) measured in 2012 were used as initial and exogenous values for data simulation.

Treatments comparison

- Mortality:

Figure 8 presents the mortality rate observed for each treatment after 15 years of growth on the field. Treatments S1 and S3 are the most affected by the mortality at the field level (> 10%). The least treatments touched by mortality are S2 and S4 (< 7%). Control substrate (ST) occupies an intermediate position (around 8%).

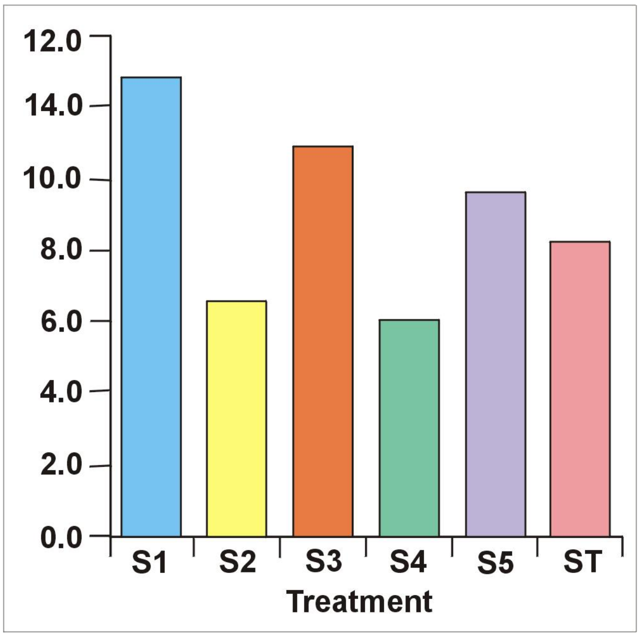

Fig. 8: Mortality in percent after 15 years (2012) of growth on the field.

***- Interactions treatment-age*:**

To test the existence of possible interactions between treatment and age, treatments were ranked at 6, 9, 15, 30, 50 and 100 years of age and the *Kendal's coefficient of concordance* was calculated and the independence Chi-square test was done for each studied growth variable. Table 6 which gives the results of these statistics shows that the change of the rank of treatments versus age is significant only for total height (H) of trees (null hypothesis accepted: dependence between ranks of treatments and age).

Table 6 – Test of the treatment rank-year interaction.

Variable	Number of years	W	χ^2_{obs}
Total height (**H**)	6	0.2095	6.29
Basal diameter (**BD**)	6	0.4603	13.81^{*}
Diameter at breast height (**DBH**)	5	0.7440	22.32^{***}

*: significant at level $\alpha = 0.05$

***: significant at level $\alpha = 0.001$

- Height growth:

Figure 9 presents for the height of trees, the obtained average by treatment and the results of treatments comparison at 6, 15, 30 and 50 years of age. The most important remark concerns the control substrate (ST) who occupied the last position till 6 years of age and who becomes since 30 years of age classified in the first group with the other treatments except treatment S5 who becomes in the last and significant position at 50 years of age.

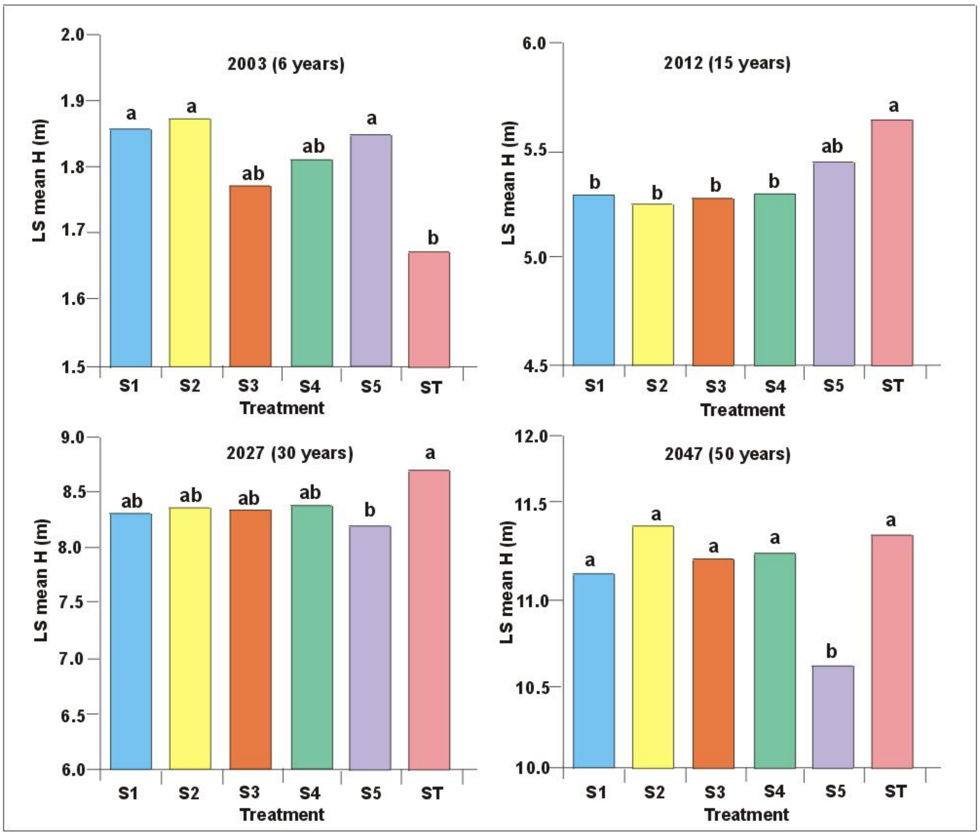

Figure 9: Total height - mean values and substrates comparison (bars with same letter are equal).

- *Diameter growth* (DBH):

Contrary to the total height, the control treatment (ST) occupied the first and significant position since the first measurements done in 2006 (9 years of age) when all the trees in the trial exceeded 1.30 m of height (Figure 10). The other five tested substrates give statistically the same values until 15 years of age. From 30 years of age, the six experimented substrates are classified in three distinct groups: first group (ST), second group (S1, S2, S4 and S5) and third group (S3).

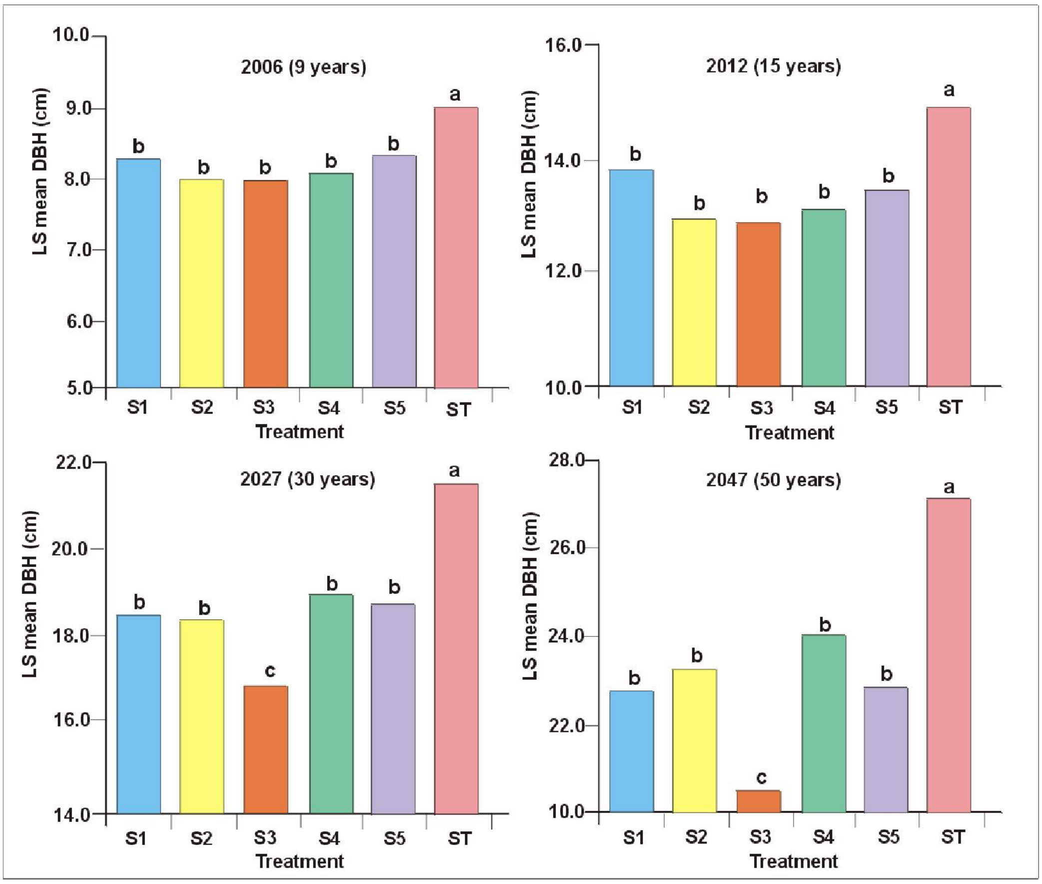

Figure 10: DBH - mean values and substrates comparison.

- *Volume growth*

Volume (wood) of trees was calculated by using the measured data at 15 years of age and the simulated data at 30 and 50 years of age.

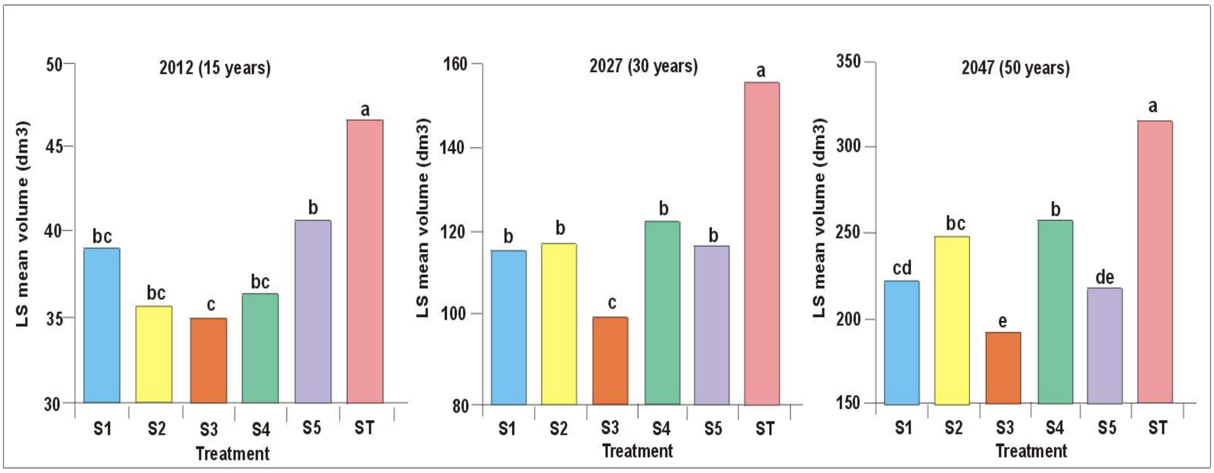

Figure 11: Volume - mean values and substrates comparison

The variable volume (V) is a combination of total height (H) and diameter at breast height (DBH) of trees (equation 14). Given the importance of the economic value of wood and its direct relationship to the fixed quantity of CO_2 by the trees, the treatments comparison by using volume is also important. In addition, figure 11 who presents the mean volume obtained by each treatment and the comparison of these means, shows that the variable volume discriminate better the studied substrates than the height (H) or diameter at breast height (DBH) separately.

According to Figure 11, the control substrate (ST) occupied the first and significant position for the three ages of comparison. The two treatments which saw their volume increasing with age more than the other treatments are S2 and S4. Indeed, these two treatments which are classified in the last group at 15 years of age, occupied the second position at 50 years of age.

- *Multivariate analyses:* (PCA and Cluster analyses)

To take in the account all the measured and/or calculated variables for treatments comparison, principal component analyses (PCA) was done by using the survival rate (SR) measured after 15 years of age and the Lsmean values of variables H, DBH and V measured and simulated at 15 and 50 years of age respectively. Figures 12 and 13 give the obtained results at 15 and 50 years of age respectively. To identify the groups of treatments with similar behavior, Cluster analyses were done on the same data matrix used for PCA analyses.

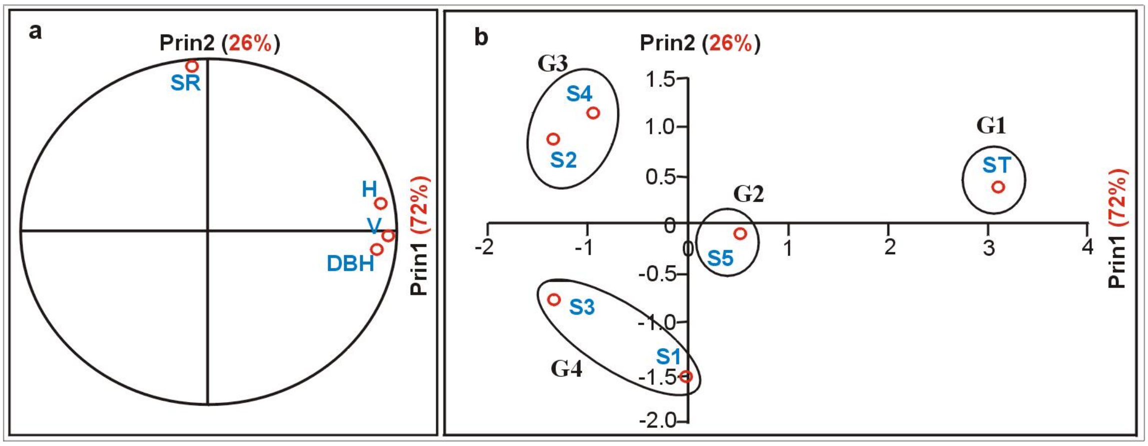

Figure 12: PCA at 15 years of age - Circle of correlation (a) and factorial plan (b).

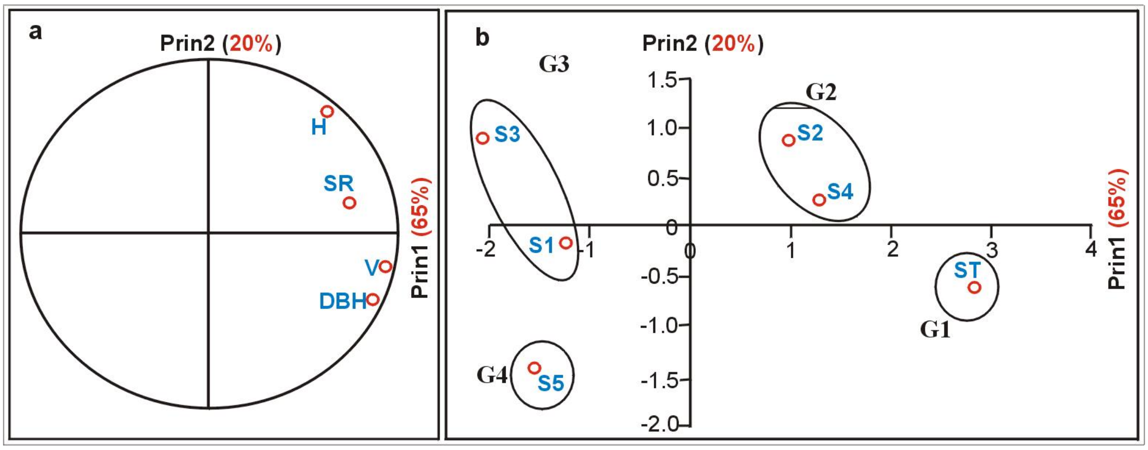

Figure 13: PCA at 50 years of age (Circle of correlation (a) and factorial plan (b)).

At 15 years of age, figure 12 (a) shows the high correlation between the first axe (Prin1) which explains 72% of the total variability with the three growth variables (H, DBH and V). This axe can be considered as a growth axe. The second axe (Prin2) which explains 26% of the total variability is more correlated with the survival rate (SR). Figure 12 (b) shows four groups of treatments or substrates:

G1: ST - Best growth with an intermediate survival rate.
G2: S5 - Growth (H, DBH, V) and survival rate less than ST.
G3: S2 and S4 - Best survival rate and bad growth.
G4: S1 and S3 -Bad growth and bad survival rate.

At 50 years of age, figure 13 (a) shows the high correlation between the first axe which explains 65% of the total variability with SR, DBH and V. The second axe which explains 20% of the total variability is more correlated with H. Figure 13 (b) shows also four groups of treatments or substrates:

G1: ST - Best DBH and volume with an intermediate survival rate and H slightly less than group G2.
G2: S2 and S4 - DBH and volume less than ST and survival rate and H slightly better than ST.
G3: S1 and S3 - Bad DBH, volume and survival rate and same H than G2.
G4: S5 - Low values of DBH, H, V and SR by comparison to substrates of groups G1 and G2.

CONCLUSION

The obtained results within the framework of this long-term field trial show that the trees coming from seedlings produced in the control substrate (ST) with approximately 8% of mortality observed after 15 years of growth on the field occupy an intermediate position and are classified after those obtained from substrates S2 and S4 with approximately 6% of mortality. The same trees produced in the control substrate see their growth slowing during the first years after plantation (till 6 years of age) then their growth accelerates to take the first position around 15 years of age and the same position with the substrates S1, S2, S3 and S4 around 50 years of age. Concerning the diameter growth, Substrate ST has a slight superiority at 9 years of age (first DBH measurement) than the other substrates and this superiority increase with age. By taking in the account the four measured, calculated and simulated variables (RS, H, DBH and Volume) at different ages (multivariate analyses), the following substrates can be retained:

- Short-term or short rotation (for biomass production for example): Substrates ST (100% peat) and S5 (45% Compost + 45% Bark of pine + 10% Sand gross).
- Long-term or long-rotation (for wood production): Substrates ST, S2 (75% Peat + 25% Vermiculite) and S4 (50% Compost + 30% Bark of pine + 10% Burnt clay + 10% Sand gross).

However, according to the composition of the 3 new selected substrates (S2, S4 and S5), substrate S2 which contain 75% of peat and 25% of vermiculite is to be omitted because vermiculite is totally imported. The two other retained substrates S4 and S5 which contain approximately 50% of compost mixed with other local materials can be used in parallel with the control substrate ST(100% peat) or to substitute it totally. The use of those two new substrates S4 and S5 can reduce significantly the forest soils degradation and ensure the sustainability of the forest resources.

REFERENCES

BERTALANFFY L.V., 1949. Problems of organic growth. *Nature* 163: 156−158.

BERTALANFFY L.V., 1957. Quantitative laws in metabolism and growth, *Q.Rev. Biol*. 32: 217−231.

BOUSSAIDI N., 2005. Parcours en forêt et risque de dégradation des potentialités pastorales dans la IVème série forestière de Mekna (Tabarka). Mastère de l'INAT en LCD. Université Tunis-Carthage. Mémoire online.

CARMEAN W.H. 1972. Site index curves for upland oaks in the Central States. *For. Sci.* 18: 109–120.

CIESZEWSKI C.J. & BAILEY R.L., 2000. Generalized algebraic difference approach: theory based derivation of dynamic site equations with polymorphism and variable asymptotes. *For. Sci*. 46: 116–126.

DAGNELIE P., 2011. *Statistique théorique et appliquée. Tome 2. Inférence statistique à une et à deux dimensions.* Bruxelles, De Boeck, 736 p.

DANIEL W.W., 1978. *Applied Nonparametric statistics*. Georgia State University, 503 p.

DIÉGUEZ-ARANDA U., BURKHART H.E. & RODRÍGUEZ-SOALLEIRO R., 2005. Modeling dominant height growth of radiata pine (Pinus radiata D. Don) plantations in north-western Spain. *For. Ecol. Manage*. 215, (1-3): 271-284.

DYER M.E. & BAILEY R.L., 1987. A test of six methods for estimating true heights from stem analysis data. *For. Sci*. 33: 3–13.

FABBIO G., FRATTEGIANI M. & MANETTI M.C., 1994. Height estimation in stem analysis using second differences. *For. Sci*. 40: 329–340.

GEA-IZQUIERDO G., CANELLAS I. & MONTERO G., 2008. Site index in agroforestry system: age-dependent and age-independent dynamic diameter growth models for Quercus ilex in Iberian open oak woodlands. *Can. J. For. Res.* 38, (1): 101-113.

GREGOIRE T.G., SCHABENBERGER O. & BARRETT J.P., 1995. Linear modelling of irregularly spaced, unbalanced, longitudinal data from permanent-plot measurements. *Can. J. For. Res*. 25: 137–156.

HOSSFELD, J.W. 1882. Mathematik für Forstmänner,Ökonomen und Cameralisten. *Gotha*, 4. Bd., S. 310.

LUNDQVIST B., 1957. On the height growth in cultivated stands of pine and spruce in northern Sweden. *Medd. Fran Statens Skogforskningsinstitut*. 47 (2).

NEWBERRY J.D., 1991. A note on carmean's estimate of height from stem analysis data. *Forest Science* 37 (1): 368-369.

SÁNCHEZ-GONZÁLEZ M, CA ELLAS I & MONTERO GONZÁLEZ G (2007). Generalized height-diameter and crown diameter prediction models for cork oak forests in Spain. Investigación agraria. *Sistemas y recursos forestales* 16: 76-88
SÁNCHEZ-GONZÁLEZ M, TOMÉ M & MONTERO G (2005). Modelling height and diameter growth of dominant cork oak trees in Spain. *Ann Forest Sci* 62: 633-643
RICHARDS F.J., 1959. A flexible growth function for empirical use. J. Exp. Bot. 10: 290–300.
SAS Institute Inc, 2004a. SAS/STAT 9.1 Users's Guide. SAS Institute Inc, Cary, NC
SAS Institute Inc, 2004b. SAS/ETS 9.1 User's Guide. SAS InstituteInc, Cary, NC
SGHAIER T., PALAHI M.,GARCHI S., BONET J.A., AMMARI Y. & PIQUE M., 2012. Modeling Dominant Height Growth in Planted Pinus pinea Stands in Northwest of Tunisia. *International Journal of Forestry Research.* Article ID 902381, 12 pages doi:10.1155/2012/902381
SGHAIER T., GARCHI S. & AMMARI Y., 2013. Tables de cubage pour les plantations du pin pignon (*Pinus pinea*) du Nord-Ouest de la Tunisie. *Annales de la Recherche Forestière au Maroc*, 42 : 154-170.
SGHAIER T., SANCHEZ-GONZALEZ M., GARCHI S., AMMARI Y., CANELLAS I. & CALAMA R., 2015. Developing a stand based growth and yield model for thuya (*Tetraclinis articulata* (Vahl) Mast) in Tunisia. *Forest - Biogeosciences and Forestr*y 9 (1): 79-88. - doi: 10.3832/ifor1389-008
WEST P.W., RATKOWSKY D.A. & DAVIS A.W., 1984. Problems of hypothesis testing of regressions with multiple measurements from individual sampling units. *Forest Ecology and Management* 7: 207–224.
ZIMMERMAN D.L. & NÚÑEZ-ANTÓN V., 2001. Parametric modelling of growth curve data: An overview (with discussion). *Test* 10: 1–73.