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Original article

Forecasting wood resources on the basis of national forest inventory data. Application to *Pinus pinaster* Ait. in southwestern France

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Abstract – The objective of this paper is to propose a method for simulating and predicting the evolution of wood resources in the 'Landes de Gascogne' region. Lemoine's growth and yield model has been successfully utilized to predict future timber resources from existing data collected in two successive surveys (1977 and 1988) conducted by the National Forest Inventory (NFI). Lemoine's model was calibrated by analysing the error in estimation of stand features between the NFI plots and experimental plots originally used to built Lemoine's model. The proposed corrected term is based on the best linear unbiased predictor of the error. The calibrated model exhibited a better accuracy than the original model version. We suggest that coupling the calibrated Lemoine's model with NFI data is a useful method for predicting timber resources at a regional level.

wood resource / national forest inventory / growth model / model calibration / maritime pine

Résumé – Prédiction des ressources futures en bois à partir des données d'inventaire forestier national. Application au massif de pin maritime (*Pinus pinaster*) des Landes de Gascogne. L'objectif de cet article est de proposer une méthode de prédiction de l'évolution de la ressource dans les Landes de Gascogne. Le modèle de production de Lemoine a été employé avec succès pour évaluer la disponibilité en bois de la région, en utilisant les données des deux cycles de l'Inventaire Forestier National (IFN ; 1978 et 1988). Le modèle a été calibré, en considérant l'erreur d'estimation des caractéristiques dendrométriques des peuplements, entre les placettes de l'IFN et les parcelles expérimentales employées pour construire le modèle. Le terme de correction est basé sur le meilleur prédicteur linéaire non biaisé de l'erreur. La validation du modèle calibré a été menée sur des placettes non utilisées dans la procédure de calibration: la précision dans les prévisions a été sensiblement améliorée. Nous suggérons que le couplage des données recueillies par l'IFN et du modèle calibré constitue un bon outil pour prédire la disponibilité régionale en bois.

ressource forestière / inventaire forestier national / modèle de croissance / calibrage du modèle / pin maritime

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1. INTRODUCTION

The data produced by the French National Forest Inventory (NFI) are used to estimate stand wood resources, their increment and their past change at the regional and national level [15]. However, these data alone do not provide predictions on the future availability of wood resources. Indeed, forest survey data yield only qualitative and quantitative information on stands at a particular date [38, 44].

On the other hand, growth and yield models have notably progressed in recent decades [2, 9, 10, 13]. These models are used to simulate tree and stand growth from an initial state (estimated from a stand inventory), and as a function of site quality and alternative silvicultural schedules [23]. Since it is important for public and private interests to know the volume of timber that could be harvested annually from an extensive forested area [32, 43], some of these models have been applied to regional inventory data in order to forecast the future evolution of wood resources and of the 'available cut' [33, 34]. Different approaches have been proposed in the literature for modeling the growth of wood resources at a regional level [17, 33, 45, 46].

The current study concerns 'Landes de Gascogne' region, which harbors a one-million-hectares maritime pine (*Pinus pinaster*) forest, i.e. the largest monospecific forest in southwestern Europe. Between the second (1978) and third (1988) inventory cycles, NFI reported an increase of the total standing volume from 110 million m^3 to 125 million m^3 [14, 16]. This fact is very important in the definition of forest policies in this region, where the intensification of silviculture applied to *Pinus pinaster* aims at accelerating forest growth and yield [19].

In this context, the aim of this paper is to propose a method for projecting forest growth at a regional level for pure even-aged stands: this method is based on the coupling of NFI data and of a stand growth model. The general method used in this study may be described as follows: (1) to obtain data from the national forest inventory service; (2) to build a new, or to adapt an existing growth model for the forest under study; (3) to design global silvicultural regimes at a regional level; (4) to write a simulator on the basis of the calibrated growth model, with NFI data and silvicultural schedules as inputs, and the future wood resources and available cut as outputs; (5) to run the simulator according to alternative silvicultural regimes.

This article addresses three specific problems that are posed by this method: (*i*) the adaptation and calibration of the model, which is necessary because NFI data have particular features which make them different from those issued from the experimental plots used to build the stand growth model; (*ii*) the formulation of global, or average, silvicultural regimes at a regional level; (*iii*) the procedures for aggregating NFI data (before or after predicting forest growth; level of aggregation: plot or age-, stand density-, or site-based strata.)

2. MATERIALS AND METHODS

2.1. Landes de Gascogne forest

The 'Landes de Gascogne' region covers 3 districts in France: 'Landes', 'Gironde' and 'Lot-et-Garonne' (*figure 1*). The region is characterized by an oceanic climate, with two humidity and temperature gradients: humidity decreases from west to east, i.e. from the Atlantic coast inland, while temperature decreases from south to north [20]. In this study, we only considered the pure even-aged stands of maritime pine situated in the 'Plateau Landais' ecological subregion, in the 'Landes' and 'Gironde' districts. In this subregion, NFI considers 3 site types on the basis of site quality and soil drainage: humid (H), mesophyl (M), and dry (D) sites [1].

2.2. Lemoine's stand growth model

Lemoine's model was designed for maritime pine in the 'Landes de Gascogne' region in order to simulate the growth and yield of a stand or compartment submitted to variable silvicultural regimes. The age and intensity of thinnings are not fixed, but can vary according to these regimes. The inputs of the model are the initial characteristics of the stand as well as some features of the site (*figure 2*). This model was developed using three stand attributes: the height and basal area of the average dominant tree (respectively h_0 and g_0), and the basal area of the average tree in the stand ($g = G/N$). The model was built from stem analysis data, from semi-permanent and temporary sample plots which had experienced different silvicultural treatments, and from thinning and fertilization experiments [11, 20, 23, 24]. The model was validated using temporary plots [25].

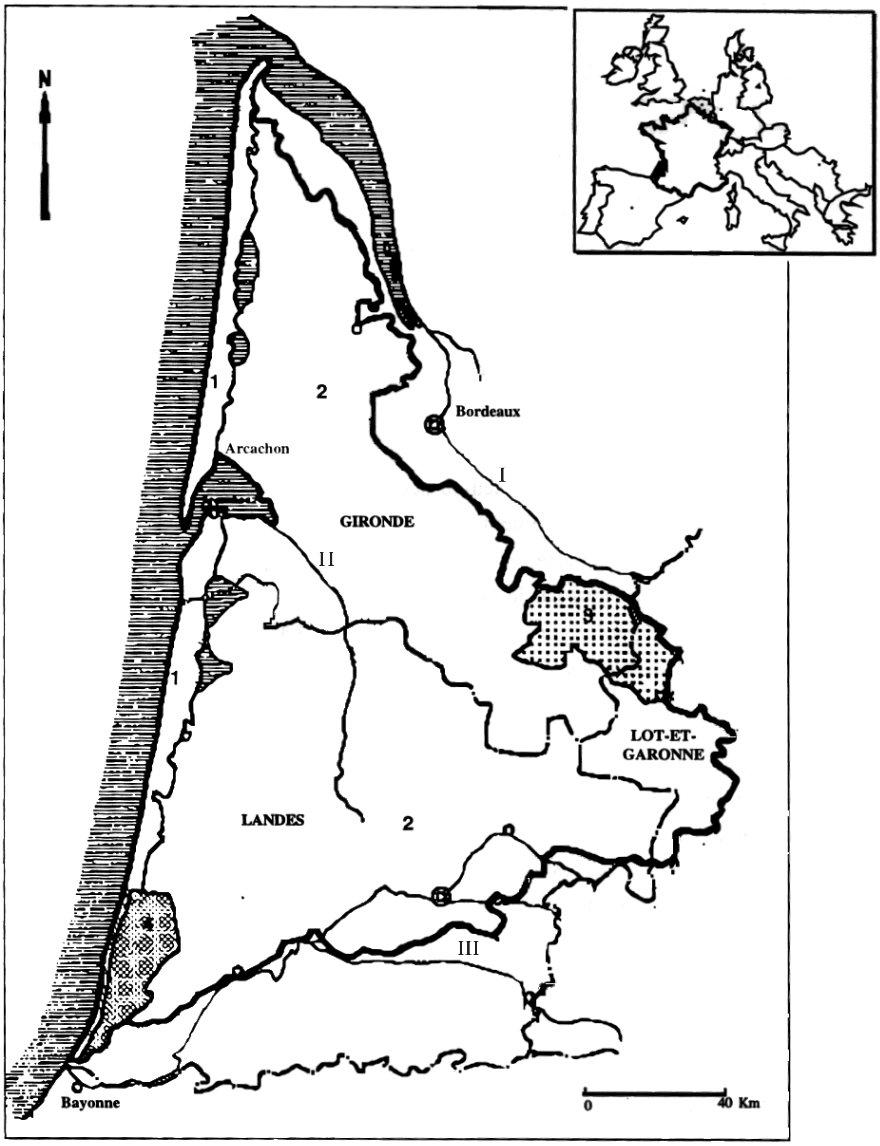

Figure 1. The study area, "Plateau Landais" in the Gironde and the Landes districts.

Using stem analysis data and principal component analysis method, the dominant height growth was modeled as [21]:

$$h_0 = \beta_0(A) + \beta_1(A) \times Y_1 + \beta_2(A) \times Y_2 \qquad (1.1)$$

where A is stand age, $\beta_0(A)$ is the guide curve, represented by Chapman-Richard's model, while $\beta_1(A)$ and $\beta_2(A)$ are two curves that account respectively for the global level and for the shape of the height growth curve:

$$\begin{cases} \beta_0(A) = 29.93 \times \left[1 - \exp(-0.036 \times A)\right]^{1.5} & (1.2) \\ \beta_1(A) = r_1 \times x/2.98 & (1.3) \\ \beta_2(A) = r_2 \times x/0.959 & (1.4) \end{cases}$$

if $\beta_0(A) \leq 11$ then $r_1 = \sqrt{1 + 0.1404 - 1.95/(\beta_0(A) + 1)}$
if $\beta_0(A) > 14$ then $r_1 = \sqrt{1 + 0.0886 - 0.00763 \times \beta_0(A)}$
if $11 < \beta_2(A) < 14$ then $r_1 = \sqrt{1 + 0.0419 - 0.0018 \times \beta_0(A)}$

$$r_2 = -1.32 + \sqrt{1.671^2 - (\beta_0(A)/20 - 1.64)^2}$$
$$x = \beta_0(A) \times (0.155 - 0.00283 \times \beta_0(A))$$

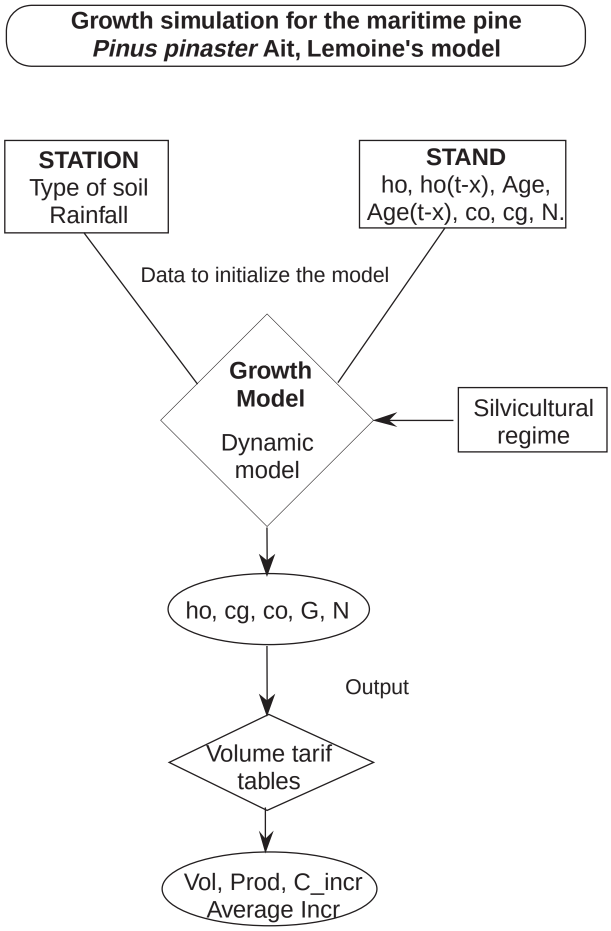

Figure 2. Schematic view of a simulation performed with Lemoine's model. Stand features and site quality are needed to initialize the model; the data were taken from NFI database. The model allows simulating the effect of different silvicultural scenarios on stand growth. The outputs are the new stand features and increments. The characteristics of cut trees are also estimated.

Y_1 and Y_2 are stand parameters that account for stand vigor (Y_1 is correlated with $h_0(40)$, the dominant height at the reference age of 40 years) and for the initial growth. For example, phosphorus fertilization at the time of stand establishment improves both $h_0(40)$ and the initial growth.

The basal area increment of the average dominant tree (ig_0) is predicted from the height increment (ih_0), the dominant height at 40 years ($h_0(40)$), and dominant girth (c_0):

$$ig_0 = \frac{comp \times \left[2 \times C_0 \times ih_0 \times kicm + (kicm \times ih_0)^2 \right]}{4\pi} \quad (2)$$

where tree-to-tree competition is expressed as a function of stand density (N) and basal area of the average dominant tree (g_0):

$$comp = 1 - \exp\left[(-115.854/g_0 + 215) \times (10000/N) \right] \quad (2.1)$$

and *kicm* is a function of the dominant height $h_0(40)$:

$$\begin{aligned} &\text{if } h_0 < 3, \text{ then } kicm = 8 \\ &\text{if } 3 \le h_0 < 6, \text{ then } kicm = 10.49 - 0.83 \times h_0 \\ &\text{if } h_0 \ge 6, \text{ then } kicm = 4.97 + 0.0892 \times h_0 \end{aligned} \quad (2.2)$$

The basal area increment of the average tree in the stand (ig) is predicted from the basal area of the average tree, the dominant basal area and its increment:

$$ig = b_0 + b_1 \times g + b_2 \times g^2 - 1.08 \quad (3)$$

where:

$$\begin{cases} b_0 = ig_0 - b_1 \times g - b_2 \times g^2 \\ b_1 = \dfrac{ig_0 - ig_{0,50} - 2 \times ig_{0,75} \times g_0^2}{0.5 \times g_0} \\ b_2 = \dfrac{ig_0 + ig_{0,50} - (2 \times ig_{0,75})}{0.125 \times g^2} \end{cases} \quad (3.1)$$

where $ig_{0,50}$ is

$$ig_{0,50} = (-2.35 - 1.68\, comp) + 0.894\, ig_0 + (-0.0339 + 0.047\, comp - 0.018\, comp^2\, ig_0^2)$$

and $ig_{0,75}$ is

$$ig_{0,75} = (-3.3 - 1.56\, comp) + 0.973\, ig_0 + (-0.0268 + 0.0464\, comp - 0.022\, comp^2\, ig_0^2)$$

Average tree volume (v) and average tree height (h_g) are estimated using statistical relationships. In Lemoine's model, the nature of the thinning (i.e. the relative size of the harvested trees as compared to the average tree) depends on thinning intensity, but customarily the smaller trees are selected rather than the larger (because it has been observed that slow-growing trees never recover a place in the canopy). The thinning with selection of taller trees is only practiced after the smaller trees have been removed, and when the silviculturist wants to establish an adequate distance among trees [20]. *Figure 2* shows a flow chart with the data needed to feed the model and with the outputs of the model.

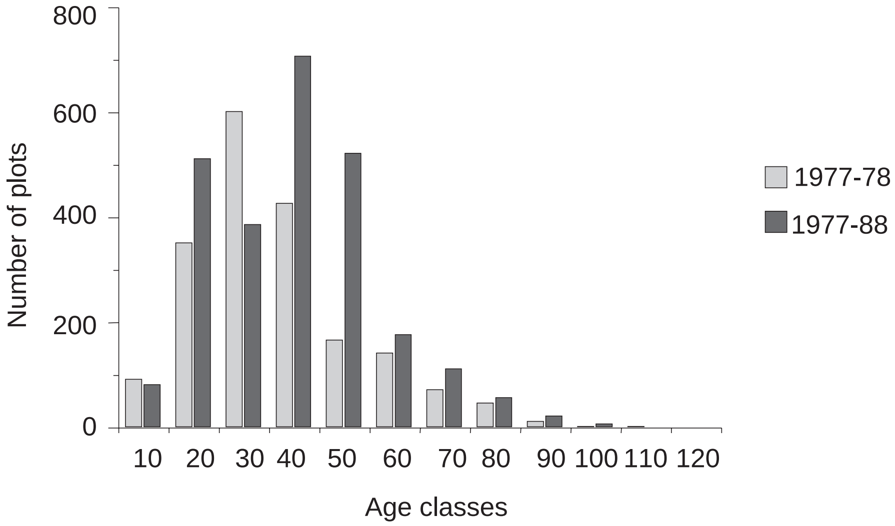

Figure 3. Distribution of the sample plots in the studied area by age class and by inventory survey, in pure stands of maritime pine in the "Plateau Landais" region.

2.3. Data used in the study

2.3.1. National Forest Inventory data

In order to forecast the future timber resources in the region, NFI data were used to initialize Lemoine's stand growth model. The study area has been inventoried 4 times by NFI. Since the method in the first survey was not similar to that in the last three surveys (1977–1978, 1987–1988, 1998–1999), we discarded the data from the first survey. Furthermore, the data from the fourth survey were not available when we started the study, so that we only used the data from the second and third surveys. The estimated forest area and the number of NFI sample plots in the subregion under study are shown in *table I* and *figure 3*.

The general method and procedures utilized by NFI to evaluate forest resources are as follows: (*i*) stratification of stands using aerial photographs; (*ii*) random selection of field control points of 25 m radius, with a number of plots proportional to the surface of each stratum. On these control points, some stand characteristics are noted: species composition, stand density (N), crown closure; (*iii*) random selection of field survey units: these units are composed of three concentric circles with a radius of 6, 9, and 15 m (*figure 4*). Trees are included in each circle, trees are sampled according to their circumference. These sample trees are then measured in detail [7, 15]. Local stand estimates are then derived from these measurements.

Table I. Forest area (pine stands only) and number of NFI sample plots in the region under study.

Cycle	Forest area (ha)	Number of plots
1977–1978	580 550	1 947
1987–1988	570 637	2 612

Among the variables estimated by NFI, those needed to initialize and calibrate the growth model were selected: the age (A), the dominant height (h_0) and its annual increment over the 5 years preceding the survey (ih_0), the dominant girth at breast height (c_0) and its annual increment over the 5 years preceding the survey (ic_0), the stand density (N). Other variables were also used to calibrate the model: the basal area of the average tree (g) and its annual increment over the 5 years preceding the survey (ig), the number of trees cut during the 5 years preceding the survey (N_{ecl}), the number of dead trees during the 5 years preceding the survey (N_{mort}), the basal area exploited during the 5 years preceding the survey (G_{ecl}), the basal area of the trees that died during the 5 years preceding the survey (G_{mort}), and the total stand volume (V).

2.3.2. Temporary and permanent NFI plots

The usual procedure of NFI is only based on temporary plots. We used these plots to calibrate and validate the two equations of the growth model that predict ig_0 and ig. In addition, in 1987–1988, NFI also remeasured

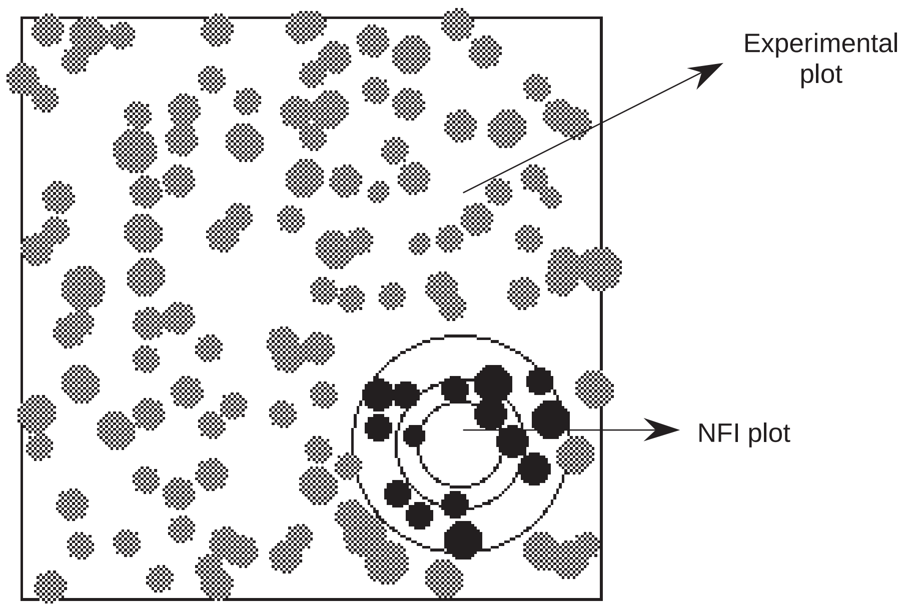

Figure 4. Example of one large experimental plot used to build Lemoine's model (squared shape). They had a surface ranging from 1000 to 5000 m^2. In contrast, national Forest Inventory plots have a surface ranging from 100 to 700 m^2. In these three circles, the trees are measured by the NFI depending on their girth; small trees: 24.5–52.5 cm, medium trees: 54.5–94.4 cm, big trees: > 94.4 cm.

446 plots that had already been measured in 1977–1978. These plots are termed here as 'permanent'; they cover the main three soil types in the region. These permanent plots were used to calibrate and validate the height growth model.

2.3.3. Experimental plots

A set of 259 experimental plots was used to build Lemoine's original growth model [22, 23]. Of these, 27 were used by Salas et al. [39] in order to compare the stand estimates derived either from large plots or from small concentric NFI plots (*figure 4*). The aim was to assess the precision and accuracy of the point estimates derived from NFI plots and to know whether there was a risk in considering such local estimates as the initial state of stands when using Lemoine's growth model.

Furthermore, NFI measures only the trees which have a girth at breast height larger than 24.5 cm. Because our objective was to predict all the timber produced in the region and in subsequent years, it was necessary to estimate the total density and basal area of the stands. For this reason in an earlier study, 37 new large temporary plots were employed to estimate accurately these stand characteristics [40].

2.4. Calibration of Lemoine's growth model

Some problems had to be solved before beginning the process of prediction and simulation. Lemoine's model was built on the basis of experimental plots observed from the 1960s to the 1980s and which were not chosen in order to be strictly representative of the 'Landes de Gascogne' forest. Moreover, the area of these plots ranged from 1,000 to 5,000 m^2. In contrast, NFI plots are supposed to be globally representative of the forest but their ranges from *ca.* 100 to *ca.* 700 m^2. Salas et al. [40] have shown: (*i*) that the design and plot size used by NFI resulted in a high coefficient of variation (CV) of the estimates of stand features such as density (N) and basal area (G); (*ii*) that average and dominant circumference (c_g and c_0) had a lower coefficient of variation, but that c_0 was biased with an average underestimation of *ca.* –2 cm. Since these stand characteristics, together with h_0 and A, are needed to initialize the growth model, the projections obtained by simulation using NFI data as inputs could be significantly less accurate and precise than the predictions obtained from larger sample plots, such as those used to build the model.

Therefore, in order to avoid biased predictions, the model had to be calibrated on the basis of NFI data. The calibration could be carried out by two means: (*i*) either by fitting the original model using NFI data in order to re-estimate its parameters; (*ii*) or by correcting the output supplied by the model. The second option was chosen, because of the complexity of the model. Let us consider two variables, X and Y, where X is the variable of interest while Y can be obtained by a model (i.e. as a prediction) or by direct observation: the aim of calibration is to predict the values of X, from the values of Y. In sciences such as physics, methods and techniques of calibration have been developed and widely applied [4, 18, 37]. Chaunzhong provides an application in forestry sciences [6]: in this case, the volume of the stand was estimated by two different methods, that had a different accuracy and a different cost; the aim was thus to calibrate the cheap and low-accuracy estimates, Y, using the expensive and high-accuracy estimates, X, using a sample where both variables had been measured.

In our study, the situation was similar, with a relationship between the stand values predicted by the growth model (predictor $\hat{x}_i$) and the stand values observed by NFI (x_i), where i =1,...,n denotes sample plots. Our aim was thus to predict x_i from $\hat{x}_i$, i.e. to calibrate the increment predicted by the model on the basis of NFI increment observations. This calibration procedure was used for h_0, ig_0 and ig. The way to correct the bias of predictions was thus:

$$x_i = \delta_0 + \delta_1 \times \hat{x}_i + e_i \tag{4}$$

where δ_0 and δ_1 are the parameters to be estimated, and e_i is an independent random variable. The magnitude of the bias, $E[x_i - \hat{x}_i]$ is determined by the parameters of the model, particularly by the parameter δ_0.

The general approach to calibrate the model was: (*i*) validation of the original Lemoine's model, with the aim to search for bias and to analyze prediction errors; (*ii*) correction of systematic deviations in predictions; (*iii*) validation of the calibrated model.

The validation of the non-calibrated and calibrated models was performed by studying the bias, i.e. the average deviation between the values predicted by the model and the values observed by NFI. The bias of variable Y was estimated as:

$$B_Y = \frac{1}{n}\sum_{i=1}^{n}(\hat{Y}_i - \tilde{Y}_i) \tag{5}$$

where $\tilde{Y}_i$ is the value observed by NFI and $\hat{Y}_i$ is the value predicted by Lemoine's model.

2.4.1. Calibration of the dominant height growth model

Projection of individual plots

Validation of the non-calibrated model

Before calibrating the height growth model, it was necessary to assess whether this model was biased. The validation of the original model was carried out using 130 NFI permanent sample plots. The parameters Y_1 and Y_2 of equation (1.1) were estimated from the measurements of h_0, ih_0 and age from the 1977–78 survey. Therefore, we had: t_2 = 1978 and t_2–5 = 1973. Predictions were then made for t_2+5 (1983) and t_2+10 (1988). Using a paired *t*-test, these predictions were compared with data obtained by the 1988 survey on the same plots.

Calibration of the model

From a set of permanent sample plots, in which were included stands of all ages, one hundred plots were randomly chosen to calibrate the height growth model. The parameters Y_1 and Y_2 of equation (1) were estimated using the records of h_0, ih_0 and age from the 1977–1978 survey. Ten-year predictions were then calibrated using the data obtained by the 1988 survey and a simple linear regression (see Eq. (4) in the above described procedure).

Validation of the calibrated model

This step was carried out with 30 independent permanent plots. The precision and accuracy of the calibrated model were assessed using a paired *t*-test in which the discrepancies between observed and predicted values were examined.

Projection of aggregated plots

In order to simulate the growth at the regional level, an option was to reduce variability in the estimation of stand characteristics by aggregating the plots before applying the growth model. It was necessary to know which was the best strategy for plot aggregation. For that purpose, 76 permanent plots from the 2nd survey were selected to form 19 aggregates. The aggregates were formed on the basis of age class and of similar fertility index, estimated from the h_0 versus A relationship in 1978.

The prediction of height growth with these aggregates was performed according to two methods: (*i*) plot-by-plot simulation of height growth, followed by the aggregation of the predicted values; (*ii*) computation of average plot characteristics for each aggregate, followed by the prediction of height growth at the aggregate level. On the basis of data from 1977–1978, parameters Y_1 and Y_2 of equation (1.1) were estimated from the measurements of h_0, ih_0, and A. Height growth predictions were performed over 5- and 10-year time steps (up to 1983 and 1988 respectively). The discrepancies between observed and predicted values were analyzed with a *t*-test.

2.4.2. Calibration of the dominant and average basal area growth models

Validation of the non-calibrated models

These models were validated on the basis of temporary plots and by site type. Two data sets were utilized for this purpose: (*i*) the data from the 1977–1978 survey (1332 plots); (*ii*) the data from the 1988 survey (1955 plots). All the plots considered for the calibration and validation of the model were grouped by site type and none of them had any record of thinning or dead trees, at least in the previous 5 years.

The variables involved in the models were corrected for bias and stand density. Salas et al. [40] indeed showed that it is necessary to correct N, G and c_0 estimated from NFI plots because of their small size and of the minimum tree census threshold ($gbh \geq 24.5$ cm). Total N and G were thus estimated using the following equation:

$$X = \frac{X_r}{(1 - \exp[-\beta_{1,x}(c_0 - 24.5)^{\beta_{2,x}}])} \qquad (6)$$

where: X is the total value of N or G (including the trees that fell below the NFI census threshold); X_r is the same variable computed from only the measurable trees (over NFI census threshold); $\beta_{1,x}$ and $\beta_{2,x}$ are parameters which depend on the variable under study (N or G); c_0 was corrected by systematically adding 2 cm.

The discrepancies between observed and predicted values were analyzed with a paired *t*-test.

Calibration of the models

The calibration was performed using 80% of the available temporary plots for each survey, these plots being randomly selected randomly within each type of land. The calibration method was a simple linear regression. Because of the non-linearity of the models and of their complexity, it seemed that this method avoided amplification of prediction bias.

Validation of the calibrated models

The validation of calibrated models was performed using the 20% the temporary plots that had not been used in the calibration process, i.e. 20% of the plots. In order to evaluate the calibrated models, the discrepancies between the values predicted by the model and the values observed by NFI were examined with a paired *t*-test.

2.5. Forecasting the available regional wood resources

2.5.1. Criteria for plot aggregation

The aggregation of plots had the advantage of diminishing the variability of the variables needed to initialize the model. The criteria considered for this aggregation were:

Site type: NFI and Lemoine's model agree in the differences in yield among the 3 types of land. Since the differences in site index are important to correctly forecast the growth, this classification was kept to obtain a post-stratification of the maritime pine forest.

Canopy cover: this stand feature of the stands gives informs about the degree of crown closure. Cover is estimated by NFI over a surface of ca. 0.2 ha. *Table II* shows that cover classes defined by NFI depend on stand density and age.

Dominant height: this stand characteristic is not influenced by factors other than site quality [35]. Since Maugé [27] had suggested that, in stands taller than 3 m, growth did not depend on age, but only on site quality and h_0, we merged the plots into 1-meter height classes.

2.5.2. Silvicultural scenarios

A wide range of silvicultural regimes is practiced in the 'Landes de Gascogne', according to needs and goals

Table II. NFI cover classification: total cover and cover of trees above census threshold.

Cover Type	Total cover (%)	Cover of censable trees* (%)
1	10–24	< 10
2	25–50	< 10
3	> 50	< 10
5	10–19	> 10
6	20–24	> 10
7	25–49	> 10
8	50–75	> 10
9	> 75	> 10

* Trees with gbh > 24.5 cm

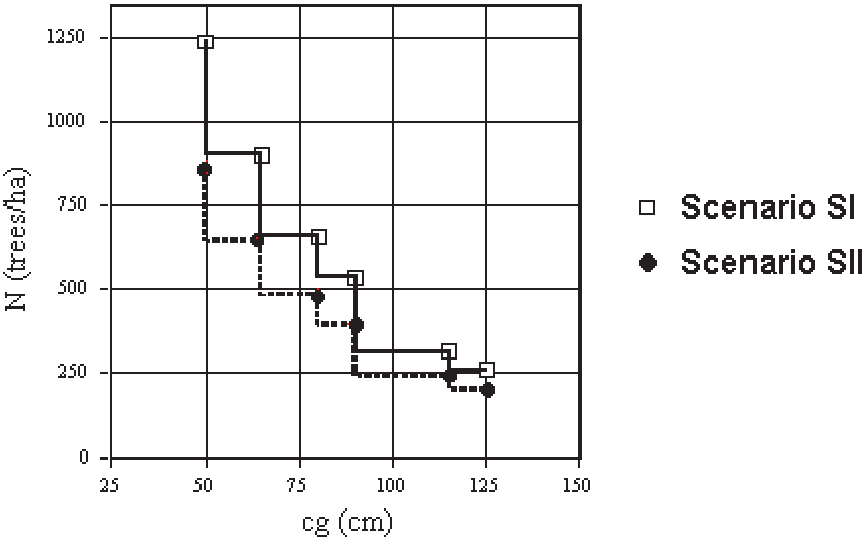

Figure 5. Silvicultural scenarios proposed in this study to estimate the annual available wood cut in Landes de Gascogne region. Scenario SI represents the current silviculture practiced in the region. Scenario SII represents an alternative silviculture regime, with thinnings more intense than in the SI.

of the owners. Under these scenarios the number of thinnings and the final cuts are determined as a function c_g or c_0 [5, 25, 29]. Since Maugé [28] had indicated that thinnings and final harvests in the region tended to be delayed, no marked caution scenarios were contemplated in this study.

Preliminary simulations achieved with a very ‘dynamic’ silvicultural regime (i.e. a regime with intensive thinnings and an early final harvest) showed that such a regime was not consistent with the current structure of the maritime pine stands and with the observed global level of harvests [30, 31]. Therefore, the total volume of timber cut in final harvests and intermediate thinnings was guided by the partial statistics of the regional wood production, and two scenarios were retained (*figure 5*): the traditional silviculture, noted ‘SI’; and a scenario taken from the experimental and semi-permanent plots, where the thinnings had been more intense than in the traditional silviculture, noted ‘SII’ [30, 31].

Thinning regimes

The following equations describe the limits between which stand density should be maintained, given the average circumference of the stand (c_g). For SI, stand density varies between $N = 3524.866 \times 10^{(-0.0091 \cdot cg)}$ (maximal) and $N = 2310.534 \times 10^{(-0.0091 \cdot cg)}$ (minimal). For SII, stand density varies between $N = 2584.208 \times 10^{(-0.0078 \cdot cg)}$ (maximal) and $N = 1884.377 \times 10^{(-0.0078 \cdot cg)}$ (minimal). Thinning should thus be carried out as a function of c_g.

Final harvest

The choice of stands to be clearcut (i.e. for final harvest) was based on both A and c_g. Among the stands whose average circumference was greater than 120 cm, we first selected the oldest, with $A > 60$ years, then the mature stands, with A between 50 and 60 years, and finally the other stands that had an average girth of 130 cm at the end of the growth period.

The above defined criteria are deterministic. Under such criteria, a high quantity of wood could be removed by thinnings or final cuts in the first years of a simulation. However, it was not realistic to assume that the wood industry installed in the region could absorb all this available timber estimated in the short term. Therefore, for the thinnings one alternative was to select the stands which had a higher competition index [22], assuming that these stands had not undergone thinnings recently. For the final cut of mature stands, a competition index was also calculated: when its value was lower than 0.90, for SI, or 0.88, for SII, the final cut was achieved.

A simulator program was written in Pascal language to forecast the growth and wood production. The validation of the entire method (calibrated Lemoine’s model for h_0, ig_0 and ig, plus silvicultural regimes), was performed for the period from 1977–1978 to 1987–1988. Then the annual availability of yield was simulated for the period from 1987–1988 to 1998, on the basis of the third survey (1987–1988).

3. RESULTS

3.1. Prediction of dominant height increment (ih_0)

3.1.1. Projection of individual plots

Validation of the non-calibrated model

5-year predictions were not biased. The average of discrepancies between predicted and observed values in that period was only 0.01 m. In contrast, 10-year predictions were significantly biased: the underestimation was 0.31 m. The error of estimation was 0.03 m yr^{-1} (*table III*).

Calibrated model

The calibration of the model was performed to forecast the growth over a 10-year period, searching to eliminate the bias and to reduce the variance. The results of the fitted model are shown in *table IV* (Eq. (4)). In this equation, the observed h_0 was estimated using the predictions derived from the non-calibrated Lemoine's model. In average, the predictions made by the calibrated model were more reliable than those based on the non-calibrated model (*table V*). The bias disappeared and the precision remained similar. The difference between predicted and observed height were not significant and errors did not exhibit any trend (*figure 6*).

3.1.2. Projection of aggregated plots

Results of the two methods of aggregation are shown in *table VI*. The variable $\overline{\hat{E}}_5$ (respectively $\overline{\hat{E}}_{10}$) indicates the average discrepancy between the values observed by NFI and the values predicted by the calibrated model over 5 years (respectively 10 years), when predictions are performed plot by plot. The variable $\hat{\overline{E}}_5$ (respectively $\hat{\overline{E}}_{10}$) indicates the average discrepancy between the values observed by NFI and the values predicted by the calibrated model over 5 years (respectively 10 years), when predictions are performed after data aggregation.

The t-test was significant, when 10-year predictions were performed plot by plot, while it was not significant for 5-year predictions. The t-test was never significant, when predictions were performed after data aggregation; however the bias also existed in that case, but it was not significant because degrees of freedom were less than for

Table III. Accuracy and precision of estimates derived from the non calibrated growth model: bias (B_y) and variance of predictions for dominant height increment (ih_0), dominant girth increment (ig_0) and average girth increment (ig).

Year	Model (y variable)	Site type	n	B_y	Variance
1983	ih_0 (m yr^{-1})	H, M, D	130	–0.010	1.45
1988	ih_0 (m yr^{-1})	H, M, D	130	–0.308*	1.66
1978	ig_0 (cm yr^{-1})	H	616	1.209*	112.58
1978	ig_0 (cm yr^{-1})	M	518	3.049**	156.01
1978	ig_0 (cm yr^{-1})	D	198	1.573	128.40
1988	ig_0 (cm yr^{-1})	H	838	5.165**	190.14
1988	ig_0 (cm yr^{-1})	M	849	6.969**	249.40
1988	ig_0 (cm yr^{-1})	D	268	8.525**	167.19
1978	ig (cm yr^{-1})	H	409	1.299**	20.27
1978	ig (cm yr^{-1})	M	359	0.409	26.73
1978	ig (cm yr^{-1})	D	128	0.721	25.48
1988	ig (cm yr^{-1})	H	542	0.869**	19.42
1988	ig (cm yr^{-1})	M	552	0.015	21.14
1988	ig (cm yr^{-1})	D	173	0.835**	10.26

* Bias is significant at $p = 0.05$., ** Bias is significant at $p = 0.01$
H: humid land, M: mesophyl land, D: dry land.

Table IV. Calibration of the growth model for: dominant height increment (ih_0), dominant girth increment (ig_0), and average girth increment (ig). The calibration equation is $x_i = \delta_0 + \delta_1 \times \hat{x}_i + e_i$, where x_i is an observation, $\hat{x}_i$ is a prediction, δ_0 and δ_1 are the parameters to be estimated, and e_i is a random error.

Cycle	Model	Site type	df	MSE	$\delta_0 \pm \sigma(\delta_0)$	$\delta_1 \pm \sigma(\delta_1)$	R^2
3	ih_0 (m yr^{-1})	H, M, D	98	2.87	1.43 ± 0.77	0.94 ± 0.04	0.87
2	ig_0 (cm yr^{-1})	H	408	88.4	3.19 ± 1.19	0.70 ± 0.03	0.47
2	ig_0 (cm yr^{-1})	M	357	106.4	6.93 ± 1.52	0.54 ± 0.04	0.32
2	ig_0 (cm yr^{-1})	D	127	87.7	3.42 ± 1.82	0.65 ± 0.06	0.45
3	ig_0 (cm yr^{-1})	H	540	169.4	15.43 ± 1.93	0.55 ± 0.04	0.26
3	ig_0 (cm yr^{-1})	M	553	189.2	19.62 ± 2.07	0.49 ± 0.03	0.22
3	ig_0 (cm yr^{-1})	D	171	91.9	10.43 ± 2.15	0.54 ± 0.04	0.42
2	ig (cm yr^{-1})	H	407	18.40	1.28 ± 0.43	0.89 ± 0.02	0.87
2	ig (cm yr^{-1})	M	357	24.23	2.78 ± 0.58	0.86 ± 0.02	0.81
2	ig (cm yr^{-1})	D	126	21.02	2.73 ± 0.77	0.79 ± 0.04	0.75
3	ig (cm yr^{-1})	H	540	18.37	1.22 ± 0.41	0.92 ± 0.01	0.89
3	ig (cm yr^{-1})	M	550	20.22	2.11 ± 0.45	0.93 ± 0.01	0.88
3	ig (cm yr^{-1})	D	171	10.07	0.14 ± 0.53	0.96 ± 0.02	0.92

H: humid land, M: mesophyl land, D: dry land.

Table V. Accuracy and precision of estimates derived from the calibrated growth model: bias (B_y) and variance of predictions for dominant height increment (ih_0), dominant girth increment (ig_0) and average girth increment (ig).

Year	Model	Land type	n	B_y	Variance
1988	ih_0 (m yr^{-1})	H, M, D	30	0.088	0.65
1978	ig_0 (cm yr^{-1})	H	103	–2.1303	86.91
1978	ig_0 (cm yr^{-1})	M	85	–0.0696	88.12
1978	ig_0 (cm yr^{-1})	D	36	1.8770	56.49
1988	ig_0 (cm yr^{-1})	H	139	–0.8660	113.31
1988	ig_0 (cm yr^{-1})	M	135	1.0477	119.51
1988	ig_0 (cm yr^{-1})	D	40	–0.4447	160.75
1978	ig (cm yr^{-1})	H	103	0.3643	21.99
1978	ig (cm yr^{-1})	M	85	0.8255	23.57
1978	ig (cm yr^{-1})	D	36	0.1996	14.57
1988	ig (cm yr^{-1})	H	139	0.4592	63.83
1988	ig (cm yr^{-1})	M	134	0.7959	22.02
1988	ig (cm yr^{-1})	D	40	–1.5243*	16.03

*Bias is significant at $p = 0.05$
H: humid land, M: mesophyl land, D: dry land.

Table VI. Accuracy of the aggregation methods for predicting height growth with the calibrated model. $\overline{\hat{E}}_5$ (respectively $\overline{\hat{E}}_{10}$): average discrepancy between NFI values and 5-years (resp. 10-years) predictions, when prediction precedes plot aggregation. $\hat{\overline{E}}_5$ (resp. $\hat{\overline{E}}_{10}$): average discrepancy between NFI values and 5-years (resp. 10-years) predictions, when prediction follows plot aggregation.

Method	Bias (m)	Variance (m^2)
$\hat{\overline{E}}_5$	–0.102	0.586
$\overline{\hat{E}}_5$	–0.011	0.549
$\hat{\overline{E}}_{10}$	0.247	0.770
$\overline{\hat{E}}_{10}$	0.347	0.560

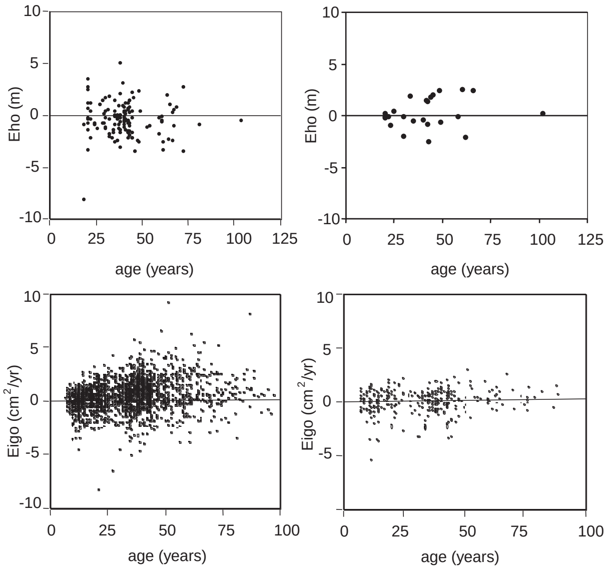

Figure 6. Residuals of the model before and after calibration. Top: dominant height, the dispersion of points was lower after the calibration of the model (right plot); the prediction was carried out over a ten-year period. Bottom: basal area increment of the average tree in the stand (ig_0). Left plot, a trend was observed on the uncalibrated model. The uncalibrated model underestimates igo in young stands whereas it overestimates this increment in mature and old stands. After the calibration the model did not show a tendency in residuals (right).

the plot-by-plot projection. Both projection-aggregation methods gave similar predictions over 5 and 10 years; nevertheless, it seems that the 2nd method (i.e. aggregation followed by projection) slightly reduces the bias and variance of the predictions. This method was utilized for forecasting the evolution of forest resources.

3.2. Prediction of dominant basal area increment (ig_o)

3.2.1. Validation of the non-calibrated model

The increment of the basal area of the average tree was always significantly overestimated. The average bias was + 1.94 cm^2 yr^{-1} (respectively + 6.89 cm^2 yr^{-1}) for the 2nd (resp. 3rd) survey (*table III*); the predictions of the model were thus more biased for the 3rd survey than for the 2nd survey. The errors of estimation were correlated with stand variables, including age: for example, the overestimation was evident in mature stands (*figure 6*).

3.2.2. Calibrated model

The results of the calibration equation (Eq. 4) are given in *table IV*. In this equation, the observed value of ig_0 was estimated using the predictions derived from the original Lemoine's model. The calibrated model was then validated (*table V*): the estimations of ig_0 were not significantly biased anymore; the average overestimation was reduced to 1.36 cm^2 yr^{-1} (respectively 0.77 cm^2 yr^{-1}) for the 2nd (resp. 3rd) survey. In some cases, the variance of estimation of the calibrated model was less than half of the variance of estimation of the non-calibrated model.

3.3. Prediction of average basal area increment (*ig*)

3.3.1. Validation of non-calibrated model

The increment of the basal area of the average tree was also overestimated. This bias was significant for humid sites at the 2nd survey, and for humid and dry sites for the 3rd survey. The average overestimation was 0.81 cm^2 yr^{-1} (respectively 0.57 cm^2 yr^{-1}) for the 2nd (resp. 3rd) survey (*table III*).

3.3.2. Calibrated model

This model was calibrated using equation 4 (results are given in *table IV*). In this equation, the observed value of *ig* was estimated using the predictions derived from the original Lemoine's model. The calibrated model was then validated (*table V*): the predictions of *ig* were not biased any more, but for the dry sites at the 3rd survey (the overestimation was 1.52 cm^2 yr^{-1}). The variance of estimation was not really improved by the calibration procedure: it globally decreased for the 2nd survey, while it increased for the 3rd survey.

3.4. Forecasting available wood resources in the 'Landes de Gascogne'

3.4.1. Retrospective evolution of the forest between 1978 and 1988

We used this period for jointly testing the adequacy of the method of calibration and the validity of the silvicultural regimes. For that purpose we compared the results of simulations with data recorded by the NFI.

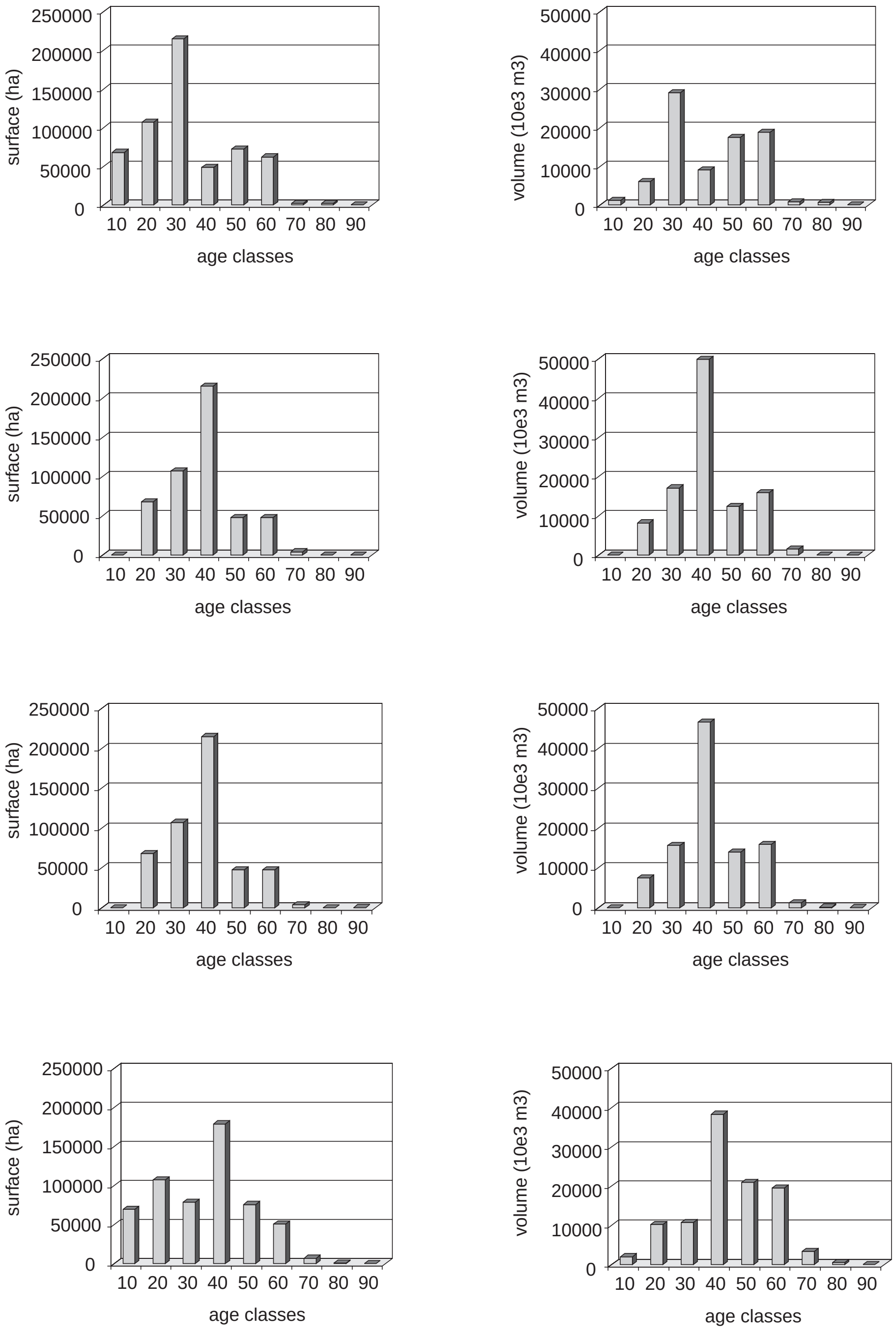

Figure 7. Changes in the age structure of the forest resources from 1978 to 1988. Top: NFI data in 1978. Middle: SI and SII scenario predictions in 1988. Bottom: NFI data in 1988.

Mean annual increment and mean volume

Between 1978 and 1988, the global behavior of the two scenarios SI and SII was fairly similar. Nevertheless, SI simulated a lower harvest and a higher mean annual volume increment (*figures 8* and *9*). At the end of the cycle, the mean annual increment was estimated at 9.4 $Mm^3\ yr^{-1}$ (respectively 9.1 $Mm^3\ yr^{-1}$) for SI (resp. SII), as compared to 7.5 $Mm^3\ yr^{-1}$ reported by the NFI in 1984–1988.

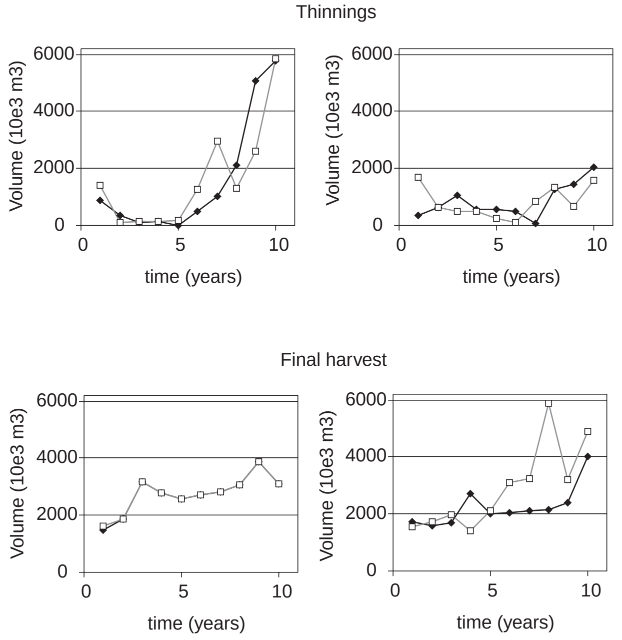

Figure 8. Top: Evolution of simulated thinnings during the period 1978–1988 (left) and 1988–1998 (right). Bottom: Evolution of simulated final harvest during the period 1978-88 (left) and 1988–1998 (right). —◆— SI = scenario I, —□— SII = scenario II.

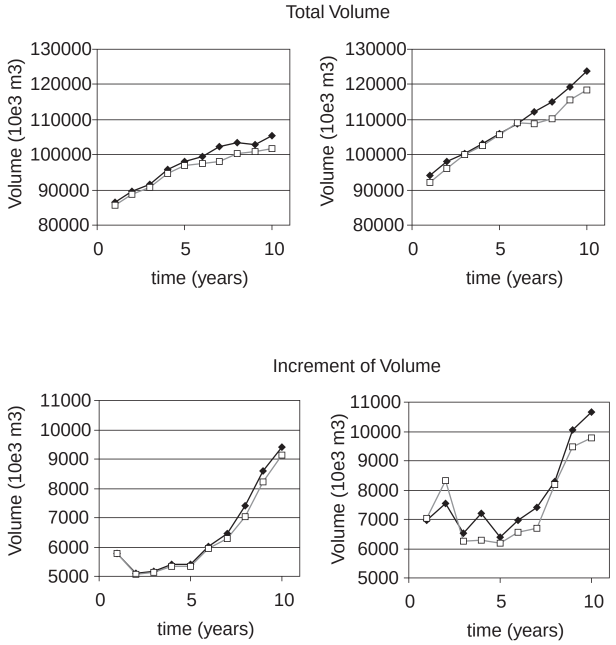

Figure 9. Top: Evolution of the simulated total volume in the studied area during the period 1978–1988 (left) and 1988–1998 (right). Bottom: Evolution of the volume increment in the studied area during the period 1978–1988 (left) and 1988–1998 (right). Despite the increment in wood taken in cuts, the wood seems to accumulate in the region. —◆— SI = scenario I, —□— SII = scenario II.

Because of the intensity of the final cuts (both observed and simulated), the total volume of stands older than 40 years was reduced. In contrast, there was an accumulation of wood in the age classes younger than 40 years. It seems that the thinnings were not regular and not intense in these age classes (*figures 7* and *8*).

For this period, the predictions made by Maugé [28] overestimated by 16% the total volume (116–124 Mm^3), and he predicted a mean annual increment between 9.2 and 9.4 Mm^3 yr^{-1} in the region. In general, his predictions of volume increment were higher than ours and than the observed increments. Partial statistics of the regional timber production [30, 31] estimated an annual average of thinnings of 1.7 Mm^3 yr^{-1} and an annual average of final cuts of 2.1 Mm^3 yr^{-1}. Our predictions were 1.4 Mm^3 yr^{-1} for the thinnings and 3.0 Mm^3 yr^{-1} for the final cuts.

According to NFI, the total volume of the stands in the region was 102 Mm^3 in 1988, while SI and SII scenarios respectively predicted 104 Mm^3 and 102 Mm^3 (*figure 9*). The total predicted volume was not far from the actual values observed by the NFI, and it must be considered that almost all the wood present in the 'Plateau Landais' was included, even the trees with a girth lower than NFI census threshold.

Final harvest

During the first six years, the average annual simulated harvests was 2.5 million m^2 yr^{-1} (Mm^3 yr^{-1}), while for the rest of this period it raised up to 3.9 Mm^3 yr^{-1}. There was a slight difference between the two proposed scenarios, with the main differences observed at the beginning and at the end of the period. Partial statistics collected by the Ministry of Agriculture indicated that the annual average harvest exploited during the first six years was actually 2.6 Mm^3 yr^{-1} and that it then increased up to 3.1 Mm^3 yr^{-1} [30]. The harvests recorded by the Ministry of Agriculture were very regular with a smoothly tendency to increasing trend at the end of the period. In contrast, as shown in *figure 8*, our predictions of the final harvests were very irregular: as already mentioned, this is due to the deterministic nature of the criteria. Furthermore, a tendency to intensify the volume harvested in final cuts was also observed.

The simulated clearcut area followed a similar pattern. It increased with time, from 5,000 ha yr^{-1} to 13,000 ha yr^{-1} at the end of the period. As a result, the proposed scenarios almost eliminated all the older stands. On the contrary, in 1988, NFI still recorded more than 2% of the timber in old stands.

Thinnings

The deterministic criteria chosen for the silvicultural scenarios yielded irregular cuts in the first five years. Consequently, the average simulated thinned volume in the first six years was very low, with 0.35 Mm^3 yr^{-1} for SI, and 0.61 Mm^3 yr^{-1} for SII. At the end of the cycle, the simulated thinned volume of cuts raised up to 3.0 Mm^3 yr^{-1} for SI, and 3.2 Mm^3 yr^{-1} for SII. Partial statistics of the Ministry of Agriculture [30] indicated that the average volume of thinnings increased from 1.6 Mm^3 yr^{-1} to 1.8 Mm^3 yr^{-1} over this period. In overall there was a good agreement between observed thinnings and thinnings simulated with SII, but the simulated trend was much too sharp.

We analyzed the actual distribution of forest by age classes in the 'Plateau Landais' in 1978 and 1988 (*figure 7*). We also featured the predictions obtained from SI and SII scenarios in 1988. The simulated thinnings were more intense than the observed ones in the older stands: surfaces and volumes were reduced markedly in the age classes older than 50 years. In contrast, in the 30- and 40-year age classes, simulated volume and surface were slightly higher than those reported by NFI.

3.4.2. Forecast of forest evolution between 1988 and 1998

Mean annual increment

The simulated mean annual increment was higher during this cycle than during the previous one. This may be partially explained by the fact that NFI had observed an increase in standing volume in each age class between 1978 and 1988. This indicates that the age structure of the forest and the present silvicultural treatments were not balanced: the simulated cuts were less than the increment and wood accumulated.

According to the two scenarios proposed in the current study, the average annual increment was estimated as being higher than 10.5 Mm^3 yr^{-1} in the region (*figure 9*), a figure which is higher than the predictions that Maugé had made (9.2 Mm^3 yr^{-1}). During the period from 1988 to 1998, the two scenarios were similar until the 6th year. The higher final cut simulated by SII after 1994, resulted in a lower total standing volume and annual increment at the end of the period. For the region included in this study, the final total volume was 118 Mm^3 for SII and 124 Mm^3 for SI (*figure 9*). Despite the increasing intensity of final cuts and thinnings, the simulations indicated that wood resources continued to increase in the 'Landes de Gascogne' during 1988–1998.

Final harvest

The simulated volume harvested in the final cuts exhibited an increasing trend with time; the cuts raised up to 4 to 5 Mm^3 yr^{-1} at the end of the period. For SII, the simulated cuts were higher in the 4 last years than for SI. In both cases, the area and average volume of stands over 50 years increased from 1978 to 1998: the area increased by 45% for SI and 37% for SII (*figure 8*), while the standing volume increased by 90% for SI and 80% for SII. There was thus an accumulation of older stands that could be clearcut in the future.

Maugé [28] had suggested a scenario to attain the delay of the final harvest, rather than follow with the traditional practices for the final cut. Nevertheless, the total volume estimated by him was still higher than that predicted with the two scenarios proposed here. The Ministry of Agriculture [30] estimated for 1998, an annual volume of final harvest of around 5 Mm^3 yr^{-1} for all the stands present in the region, while our simulations yielded 6 Mm^3 yr^{-1} for SI and 7 Mm^3 yr^{-1} for SII.

Thinnings

The intensity of thinnings increased by at least 50% during this period. Nevertheless, the wood continued to accumulate during this period. SI scenario was more regular than SII and finally slightly more wood was thinned in SI. The accumulation of wood observed during 1978–1988 in the age classes under 50 years, was the main reason for which the thinnings increased during 1988–1998 (*figure 8*).

4. DISCUSSION AND CONCLUSIONS

Lemoine's model (Eq. (1–3)) performed better predictions after it had been calibrated with a simple linear regression model, which fitted the predicted and observed values (Eq. (4)). This simple method had demonstrated its usefulness in other sciences such as physics, and more recently in mathematics and agriculture [4, 8, 18, 36, 37].

Original Lemoine's model underestimated the height growth. Note that this bias was only statistically significant for 10-year predictions: the larger is the lap of the forecast, the more important is the error of estimation. Three explanations are possible for this discrepancy: (*i*) sampling errors: the original height growth model had been built on the basis of the stem analysis of dominant trees. In contrast, the dominant height was estimated by NFI on small sample plots, which might result in a similar underestimation problem [35] yet described for c_0 [40]. However, this bias, if any, is likely to be small; (*ii*) measurement errors: NFI measures height increments on standing trees by counting whorls and shoots and measuring (from the ground) the length of the shoots: this method is not very precise for tall trees, and an overestimation is possible. Nevertheless, in this region maritime pine can bear 2 shoots per year (polycyclism); in such cases, the main risk is to under-estimate periodic height increments. Anyway, this error only applies to direct height increment measurements, not to height increments obtained as the difference between 2 successive measurements; (*iii*) climatic variability: Lemoine's model describes the average height growth over tree life, whereas 5-year and 10-year height increments may be altered by climatic events such as droughts. The only way to cope with this problem would be to replace this empirical model by an environment-sensitive height growth model and to develop regional environmental indices for maritime pine [46].

Although the causes of the discrepancies in height growth projections cannot be traced exactly, it seems that there is a global increase in the apparent fertility in the stands. This trend has been detected in NFI data of all stands for *Pinus pinaster*, in the 'Landes de Gascogne' [41]. NFI has also observed such an apparent change in site fertility in other regions and species in France, e.g. for *Picea alba*. The literature concerning the growth and forest yield has reported several causes, including stand structure, abiotic factors such as climatic fluctuations [3], and human management [26], such as the silvicultural treatments and genetic selection of trees. At this stage, the increase in height growth of *Pinus pinaster* cannot be attributed only to environmental factors or to long-term changes in management regimes [42].

Since Salas et al. [40] had demonstrated that NFI sampling scheme resulted in biased estimates of c_0 (underestimation due to plot size), N and G (for young stands only because of census threshold), that these biases could be corrected, the variables N, G and c_0 were corrected before testing the original model of the basal area increment of dominant trees (Eq. (2–2.2)). However, its 5- and 10-year predictions were significantly biased: the model overestimated the observed ig_0. The same simple linear regression method was used for calibrating the model: it resulted in better predictions for this variable.

For the basal area increment of the average tree (ig), the biases were much smaller. Again, the previsions were improved with the same calibration method.

Yaussy [46] indicates that empirical models are accurate only when they are used in the range of data for which they were developed. Because the sampling scheme of NFI is fairly different from the experimental designs used to derive the model (i.e., plot size, but also silvicultural regimes and stand generation), we had to calibrate the models. In addition, the competition or density indices and functions are only valid for the conditions in which the model was created. Estimates of ig_0 from the original Lemoine's model were thus highly variable because of the large diversity of management methods used in the 'Landes de Gascogne', and also because of the variability of site quality across the region. This is easily observed in *figure* 6, where the overestimation is systematically observed in stands over 50 years; the stands of that age that remain uncut are in general, those with the lower fertility. In contrast, the young stands were underestimated, in agreement with reasons proposed by Salas et al. [40].

The two silvicultural scenarios that were tested were close to the current average silviculture practiced in the region. For instance, in the period 1978–1988, the simulated harvest by clearcuts and thinnings was comparable to the values recorded by the Ministry of Agriculture [30]. However, the simulated cuts were more irregular than the actual ones. This is due to the deterministic nature both of the model and the scenarios.

The total volume estimated with our simulation procedure was similar to that recorded by the NFI. The discrepancy that was observed was due to the thinning scenario (i.e. to the delay of real thinnings) and maybe because we did not consider regeneration or because we reconstituted the fraction of stands neglected by the NFI (below census threshold). Our simulations could therefore be considered as realistic, also because the silvicultural practices did not strong change in the last years.

Between 1978 and 1988, wood accumulated in the region: this was observed by NFI and simulated by our model and scenarios. Between 1988 and 1998, the harvests increased, and it seems that during the period 1998–2008 available wood in the region should be maintained at a high level. The mean annual increment was higher than the harvest: this is due to the current trend to retain a higher level of biomass, and to the apparent increase of fertility caused by intensive silviculture.

Within the same age class and site class, we observed that the stand characteristics observed by NFI were highly variable. This is due to both the variability of the silvicultural regimes practiced in the ‘Landes de Gasgogne’ and the technical variability associated with NFI sampling design (i.e. small plots). The method of plot aggregation was therefore useful. Aggregated plots represent the average conditions of a class of stands and can be considered as homogenous strata, as those used in sampling theory.

Our method of simulation based on the calibration of the Lemoine´s model was a reasonable approach to evaluate the mid-term impact of the proposed management scenarios in the ‘Landes de Gascogne’. As signaled by Wei et al. [45], it is sometimes difficult to validate the previsions generated by simulation methods. In our case we had the possibility to globally test our simulation process, i.e. the calibrated model, the scenarios and the method of aggregation, between 1978 and 1988. According to the results, this global method is operational. However it would be interesting to test other methods of aggregation and other ways of designing silvicultural regimes, including stochastic criteria.

NFI’s main objective is to evaluate, at a particular moment, the existing wood resources and their (past) changes (increment, harvests, natural mortality, etc.). Nevertheless, in order to estimate the future evolution of wood resources, it is necessary to apply growth models to these data. Such models should be adapted to NFI data gathered. The test of our simulation process could be carried out because we had several data types: successive forest inventories including increment data on temporary plots as well as permanent plots; harvest data. Goulding [12] indicates that, depending on the species, the permanent plots should be kept for at least 15 or 20 years. For this study, such plots were indeed very useful for validating and calibrating the growth model.

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