Integrative modelling approach to assess the sustainability of the Eucalyptus plantations in Congo

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ABSTRACT

Since 1978, 42000 ha of clonal Eucalyptus plantations have been established in the littoral savannas of Congo, mainly for pulpwood production. These plantations were established on sandy soils, characterised by low reserves of available nutrients and a low water retention capacity. An intensive silviculture is carried out, resulting in the removal of high amounts of biomass and nutrients every 7 years. Therefore, a decision-making tool is needed (i) to assess stand productions under different silvicultural options, (ii) to evaluate the risks of nutrient deficiencies and non sustainable production, and (iii) to estimate the economic return of different harvesting strategies. For many years, field trials have been established focusing on clonal selection, silvicultural practices, stand growth and quantification of the biogeochemical cycles of nutrients. This high amount of data was used (or will be used) to elaborate a chain of models named "EUCALYPT-Dendro" that includes three main modules ;

- the growth module : a single tree distance-independent model was elaborated. The dominant height growth model is similar to the equation developed by Dhôte (1996). However, two main differences can be reported : (i) the model was segmented in order to take into account a change in height growth rate that occurs during stand rotation, (ii) tree spacing affected the dominant height growth and was introduced as regressor in the equation. The stand basal area increment is function of the dominant height increment. Individual tree basal area is function of a potential (given by the stand basal area increment) and a reductor (given by the size of the tree). The height of the trees is obtained from a height – girth relationship. Tree mortality is not yet taken into account (but in our case, tree mortality is limited owing to the short rotation length) ;

- the tree properties module : a generic stem taper equation was constructed. It explicitly takes into account the global taper of the bole (when the trunk is assumed to be a cone), the but swell and the decrease in diameter within the crown. The equation allows accurate estimations of diameters and volumes along the bole. The wood density model was based upon a non-parametrical modelling approach but is not yet introduced within the chain of models. Allometric relationships were also fitted for evaluating the biomass of roots, branches, stem, bark and leaves throughout the whole rotation ;

- the biogeochemical module : a model was built to assess the distribution of nutrient concentrations (N, P, K) in individual rings within the bole and their changes with the ring ageing. Furthermore, different allometric relationships estimated the nutrient contents within the branches, roots, leaves and bark. Input-output budgets of nutrients at the plot level were simulated during the whole planted crop rotation from (i) measurements of nutrient fluxes in a clonal stand between ages 6 and 9 years, (ii) a chronosequence approach to quantify the main fluxes of the biological cycle throughout stand rotation, and (iii) hypotheses concerning nutrient losses by deep drainage during the juvenile stand growth.

Work is in progress. All these models are embedded within Capsis (for the growth modelling part) and will be introduced within Win-Epifn (for the wood properties part and logging). Key points concerning the building of the models are presented. Input-output budgets of nutrients during the planted crop rotation are simulated to assess the influence of various silvicultural practices (spacing, rotation length, harvesting options) on the amount of available nutrients in the soil. Economical aspects are not evaluated.

INTRODUCTION

Since 1978, 42,000 ha of clonal eucalyptus plantations have been established in the littoral savannas of Congo, mainly for pulpwood production. Two companies are involved. ECO-sa is the industrial partner in charge of the

plantations. UR2PI is the R&D partner in charge of (i) the production of the new clones by reciprocal recurrent scheme selection (Vigneron, 1991) and (ii) the definition of optimal silvicultural practices.

The plantations are based on two natural hybrids and, increasingly, on the artificial hybrid *E. urophylla* S.T. Blake x *E. grandis* W. Hill ex Maiden. Over 170 different clones have been planted but a few part of them (12) are covering nearly 60% of the planted area. The plantations were established on sandy soils, characterised by low reserves of available nutrients and a low water retention capacity. A complete description of the edaphic and climatic conditions can be found in Laclau et al. (2000). The silviculture practices have changed over time : in the early eighties, the stocking density was about 400 stems/ha whereas it ranges now between 800 and 1100 stems/ha. Half of the forest area is managed in high forest regime and the rest in coppice regime. No thinning and pruning are carried out during the stand rotation (7 years). This intensive silviculture results in the removal of high amounts of biomass and nutrients every 7 years (Laclau, 1997, 2001). Therefore, a decision-making tool was needed (i) to assess stand productions under different silvicultural options, (ii) to evaluate the risks of nutrient deficiencies and non sustainable production, and (iii) to estimate the economic return of different harvesting strategies.

For about 20 years, field trials have been established focusing on clonal selection, silvicultural practices, stand growth and quantification of the biogeochemical cycles of nutrients. More recently, various permanent plots were settled up in the industrial stands by ECO-sa. This high amount of data was used (or will be used) to elaborate a chain of models named " EUCALYPT-Dendro ".

The following constraints were laid out :

(i)   GENERICITY : the chain of models has to be adapted to the different clones which are known to present very different growth patterns (Bouvet, 1991 ; Saya and Vigneron, 1999 ; Vigneron *et al.*, 2000),

(ii)   OF EASY ACCESS : the parameters of each sub-model should be meaningful in order to facilitate clone comparisons,

(iii)   OF EASY CALIBRATION : for the new clones obtained from the reciprocal recurrent scheme selection, the calibration of each sub-model has to be done using the genetic trials and few silviculture trials,

(iv)   OF EASY USE : the set of equations for a given clone should be easy to introduce within CAPSIS (de Coligny *et al.*, 2002).

The project started in July 2000. The main sub-models are now available and are integrated within the simulation software. In this paper, the whole chain of model is presented. We also focus on different sub-models that present singularities and / or illustrate our approach. Some examples of simulation will be presented.

THE CHAIN OF MODELS – EUCALYPT-DENDRO

EUCALYPT-Dendro (Fig. 1) includes three main modules : (i) the growth module evaluates the tree and the stand growth (dbh and height increment, mortality), (ii) the wood properties module includes the stem taper equation (tree volume and annual ring sheath increments), biomass and wood density models, etc. (iii) the biogeochemical module focuses on the mineral content within the trees and the relationships with atmosphere and soil mineral inputs and outputs.

EUCALYPT-Dendro
Integrative Modelling Approach

Figure 1 : Presentation of EUCALYPT-Dendro – An integrative modelling approach to assess the sustainability of Eucalyptus plantations in Congo. Dotted lines indicate that the relationship/model is not yet completed.

The growth module

We developed a tree distance independent model for four main reasons : (i) plantations are mono-specific and even-aged, (ii) the material is homogenous (clones), (iii) within-tree information are needed for meeting end-user requirements : different length of logs, wood quality varying along the tree etc., (iv) such models are known to be efficient for large simulation sets that is of major importance if the chain has to be run on the 42,000 ha. There are five main components within this module (Fig. 2). The input is a stand inventory at date (t) and the output is a new stand inventory at date (t+1).

EUCALYPT-Dendro
The growth module

Figure 2 : Description of the growth module. Dotted lines indicate that the relationship/model is not yet completed.

The dominant height growth model is similar to the one developed by Dhôte (1996). However, two main differences were noted in our case : (i) the model was segmented in order to take into account a change in height growth rate that occurs during stand rotation, (ii) tree spacing affected the dominant height growth and was introduced as regressor in the equation (Fig. 3). The final equation had 7 parameters (Eq. 1) and was calibrated from a tree-spacing x clone trial. The model was tested using an independent sample from the industrial plantations. At least two inventories (performed at different ages) were available for each industrial stand. Site-dependent parameters (k_0 and hmax) were estimated by simulated annealing from the first inventory. Dominant heights of the later inventories were simulated using the model and compared to the actual values. There was no bias and the standard deviation of errors was about 2m, corresponding to about 10% of the dominant height. A complete description of the model can be found in Saint-André *et al.* (2002b).

Figure 3a : Change in growth rate during rotation (2500 st/ha).

Figure 3b : Dominant height growth at various the stand tree spacing.

$$if \ h_o \le c \ then \quad \partial h_o = r_1(k - h_o) \qquad with \ \ r_1 = r_{10} + r_{11}T_S$$

$$else \quad \partial h_o = r_1(k - c) - r_2(h_o - c) \qquad k = k_0(1 + e^{-k_1 T_S})^{k_2}$$

$clone - dependent \ parameters : r_{10} \ r_{11} \ k_1 \ k_2 \ I_0$

$site - dependent \ parameters : k_0 \ h_{max}$ $\qquad c = k - (I_0 / r_1)$

$T_S = tree - spacing \quad and \quad h_o = dominant \ height$ $\qquad r_2 = -r_1(k - c)/(c - h_{max})$

(Eq. 1)

The stand basal area increment is function of the dominant height increment (Eq. 2). Tree spacing does not affect this relationship.

$$\partial G = \alpha + \beta . \delta h_o$$
$$\alpha, \beta = f(clone)$$

(Eq 2)

The tree basal area increment followed the model proposed by Dhôte (1996). It was found to be well adapted to describe the tree basal area growth for the eucalyptus. The model (Eq. 3) is a function of a potential (dΓ) and two factors : the first one expresses the global social oppression (α) and the second one represents the social status of the tree (the biggest is the tree, the more it grows). One major interest of this model is that it takes explicitly into account the change of scale between the tree and the stand : the sum of the tree basal area increment equals to the stand basal area increment. Parameters of the model were obtained from an iterative procedure described in Dhôte (1996). Figure 4 shows for the calibration set, the d_{bh} distribution simulated at 74 months using as input the stand inventory at 5 months.

$$\text{if } c_i < \sigma \quad \text{then} \quad \partial g = 0$$
$$\text{else} \quad \partial g = \partial \Gamma . \alpha(\Sigma_\sigma).(c_i - \beta(\Sigma_\sigma).\bar{c}_{\Sigma\sigma})$$

$$\text{with } \Sigma_\sigma = \sum_{i; c_i \geq \sigma}^{n_\sigma} c_i ; \quad \bar{c}_{\Sigma\sigma} = \frac{\Sigma_\sigma}{n_\sigma} ; \quad \alpha(\Sigma_\sigma) = \lambda.e^{-\mu.\Sigma_\sigma} ; \quad \text{and} \quad \beta(\Sigma_\sigma) = 1 - \frac{\left(1 - e^{-\lambda.\Sigma_\sigma}\right)}{\alpha(\Sigma_\sigma).\Sigma_\sigma}$$

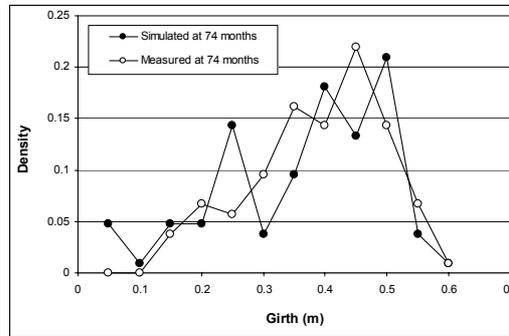$$\lambda, \mu = f(clone)$$

(Eq 3)

Figure 4 : Simulated girth-distribution at 74 months versus measured girth-distribution for clone L2-123.

The height of the trees are obtained from a height-girth relationship (Eq. 4 ; Dhôte and de Hercé, 1994 ; Deleuze *et al.,* 1996). The tree spacing affected the relationship. One parameter was found to be nearly the dominant height and permits to fasten the chain of model (the average height of the 100 biggest trees nearly equals to the dominant height estimated from Eq.1).

$$h_i = 1.3 + \frac{\mu_1 + \mu_2.c_i - \sqrt{(\mu_1 + \mu_2.c_i)^2 - 4.\mu_1.\mu_2.\mu_3.c_i}}{2.\mu_3}$$

$$\text{with } \mu_1 = p_1.h_o ; \quad \mu_2 = p_{20} + p_{21}.Ts^{p_{22}}.\ln(h_o)^{p_{23}}$$

$$p_1, p_{20}, p_{21}, p_{22}, p_{23}, \mu_3 = f(clone)$$

(Eq. 4)

The tree mortality is not yet taken into account. However, in our case, the tree death is limited owing to the short rotation length. For a given stand, most of mortality occurs at the very beginning of the stand growth when cuttings present root system not enough developed or when they are not planted cautiously. Thereafter, the tree spacing is almost stable and starts to decrease again far later after the planned stand harvesting (about 7-8 years).

The wood properties module

Figure 5 : Description of the tree properties module

The plantations have been established mainly for pulpwood production. Stem taper equations were developed to assess the volume and the annual ring sheath increment. A set of biomass equations were also developed to evaluate both the above-ground and the below-ground biomass. Other wood characteristics could be introduced such as the fiber length and lignin content (relevant for pulpwood production), or the carbon content (relevant for charcoal production).

Stem taper equation. A new stem taper model was elaborated for the eucalyptus. The tree form changes a lot between clones but also from the first year (neolidic) to the 7th year (mature tree). Our objective was then to develop an equation that would satisfy the following constraints : (i) being rather simple and have a good predictive quality, (ii) having meaningful parameters, (iii) having low correlated parameters, (iv) being generic enough to be transposable to other eucalyptus clones or species.
The equation finally had five main parameters (Eq. 5) that are specific to each zone along the bole (Fig. 6) : the global taper of the trunk (a and b), the range of the butt swell (both in height and in diameter, c and d), the diameter decrease within the crown (e). The Root Mean Square of Errors (RMSE) was below 1cm for the diameter estimates, and there was also a good agreement between the measured tree volume and the simulated one (Fig. 6)

$$d(h_r) = a.D_{130}(1 - b.h_r).(1 + c.e^{-d.h_r}) - a.D_{130}(1 - b).h_r^e$$ (Eq. 5)

$$\text{with} \quad a = (a_0 + e^{-a_1 t}).(a_2 + a_3.\frac{h_i}{d_i}); \quad b = (b_0 + e^{-b_1 t}); \quad d = d_0 t$$

$$a_0, a_1, a_2, a_3, b_0, b_1, d_0 = f(clone)$$

Figure 6 : The stem taper equation : example of simulated trees for clone 1-41 (left),
simulated volume versus measured one (right).

Biomass equations. These equations where developed for evaluating the carbon balance along an age series in the plantations (see Nouvellon *et al*., 2001 ; Saint-André *et al.,* 2002c for details). Different above- and below-ground compartments where considered (Fig. 5). Allometric relationships were fitted between the dry matter (Dm) of each compartment and the tree characteristics (age, height, d_{bh}). All equations were of the form :

$$\boldsymbol{Dm} = a + \boldsymbol{b}.(d_i^2.\boldsymbol{h})^c$$ (Eq. 6)

where parameters a, b and c varied (or not) with stand age depending on the considered compartment.

Because of heteroscedasticity that often occurs with such data, a particular attention was paid to the construction of these models (Gregoire and Dyer, 1989 ; Parresol, 1999). Furnival's index was used to find the optimum weight for the regressions (Furnival, 1961 ; Williams and Gregoire, 1993 ; Bi and Hamilton, 1998 ; Bi, 1999) and d'Agostino test of normality were systematically applied to verify the distribution of residuals (d'Agostino *et al.,* 1990).
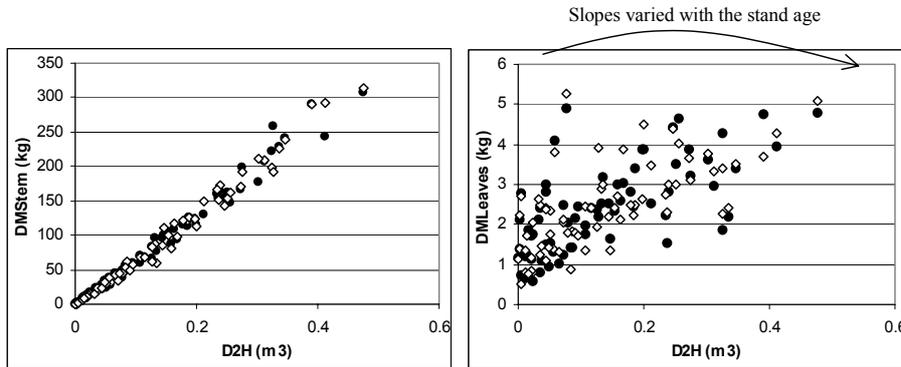
Figure 7 : Biomass allometric relationships, example for the stem (left) and the leaves (right). Black dots are measurements, white ones are simulations (variance increases with d^2h).
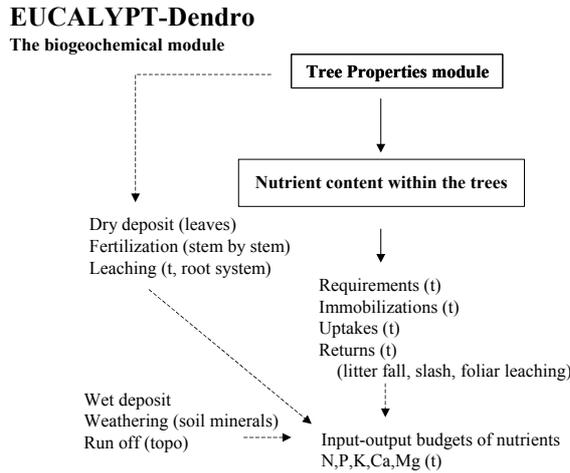
The biogeochemical module

Figure 8 : Description of the biogeochemical module.

The intensive silviculture carried out in Congo results in the removal of high amounts of biomass and nutrients every 7 years (Laclau, 1997, 2001). Therefore, we introduced the biogeochemical module in the global chain of model to evaluate the risks of nutrient deficiencies and non sustainable production (Fig. 8).

A model was built to assess the distribution of nutrient concentrations (N, P, K) in individual rings within the bole and their changes with the ring ageing (Eq. 7). A complete description of the equations and definitions was given by Saint-André *et al.* (2002a). The model was evaluated using an independent sample. Results were satisfactory : whatever the nutrient, the average of residuals was close to zero and the standard deviation was similar to the RMSE found for the calibration sample (Fig. 9).

$$C_{t_{in},h,t} = I_c \exp^{-kt} + F_c \frac{t}{t_{fin}} \quad \text{where } C_{t_{in},h,t} \text{ is the concentration of the ring at a given height (h) and a given time(t)} \qquad \text{(Eq. 7)}$$

Figure 9 : Results of model evaluation for nitrogen (left), potassium (middle), and phosphorus (right). The average of residuals are plotted at different ages for the dominant tree (black dot), the co-dominant one (white dot) and the suppressed one (grey square). Bars represent one standard deviation. Values are expressed in % of dry matter.

Different allometric relationships estimated the nutrient contents within the branches, roots, leaves and bark. These equation were elaborated by Laclau (1997) and were just introduced in the chain of model.

Finally, input-output budgets of nutrients at the plot level were simulated during the whole planted crop rotation from (i) measurements of nutrient fluxes in a clonal stand between ages 6 and 9 years, (ii) a chronosequence approach to quantify the main fluxes of the biological cycle throughout stand rotation, and (ii) hypotheses concerning nutrient losses by deep drainage during the juvenile stand growth.

EXAMPLES OF SIMULATIONS

Presently, the growth module was calibrated for two clones PF1 1-41 and HS2 L2-123 which represent respectively 16% and 6% of the planted area in Congo (first and second rank). The two other modules (wood properties, biogeochemical cycles) are only available for clone PF1 1-41. We will present four examples of simulation : (i) effect of tree spacing on tree and stand growth for clone L2-123, (ii) effect of thinning on the tree and stand growth for clone 1-41, (iii) evaluation of biomass production for clone 1-41 and comparison with an existing field trial, (iv) simulation of input-output budgets of nutrients for clone 1-41.

Effect of tree spacing on tree and stand growth

Figure 10 : Effect of tree spacing on the tree and stand growth for clone L2-123 – Screen shots of Capsis.

Figure 10 illustrates the effect of tree spacing (a = 625 stems/ha and b = 2500 stems/ha) on the tree and stand growth for clone L2-123 in a medium fertility site (starting age of simulation = 6 months, end of simulation = 96 months). As expected there is a clear difference on the average tree diameter at the end of rotation : d_g is about 10cm for the 2500 stems/ha- stand but reaches 20cm for the 625 stems/ha- stand). Concerning the dominant height, the model reacts as expected : in the early growth there is a positive effect of tree spacing (less weed competition, the same amount of fertilisation is applied tree by tree whatever the tree spacing), whereas there is a negative effect at the end of the rotation : the difference is here about 2m. The maximum production of stand basal area is reached at 41 months for the 625 stems/ha- stand but only at 13 months for the 2500 stem/ha- stand.

Effect of thinning for clone 1-41

This simulation was based upon an industrial inventory (stand H9807, age 22 months, actual tree spacing 553 stems/ha). Two different types of thinning were simulated by removing at each intervention ¼ of the trees : the first scenario where all the smallest trees are removed, and the second one where the average basal area of the removed trees equals to the one of the standing trees after thinning. Results are given in Figures 11 and 12.

For the first thinning regime, the decrease in stand basal area occurred only at the second intervention. This means that at age 42 months (date of the first thinning), there is about ¼ of standing trees that are growing very slowly. When these trees are removed, stand basal area is not strongly affected. For the second thinning regime, there is, at each intervention, a loss in stand basal area which is not offset by stand growth.

Whatever the thinning regime, the dominant height is affected and as a consequence of the model formulation the maximum dominant height is reached faster at low stand density.
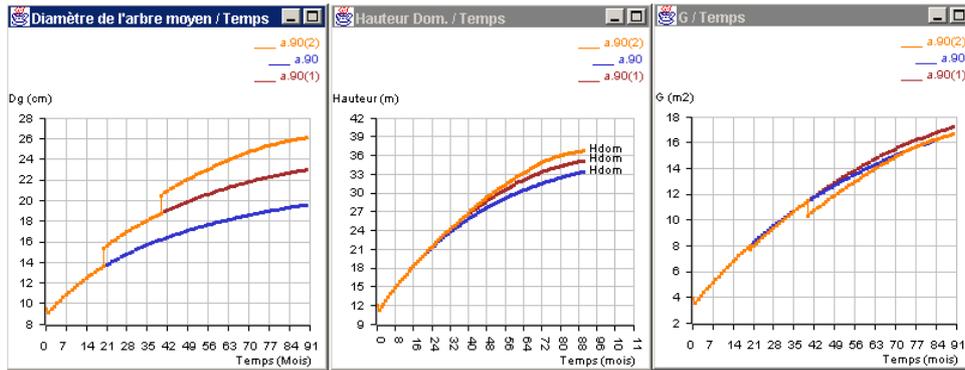

Figure 11 : Thinnings where the smallest trees are removed.
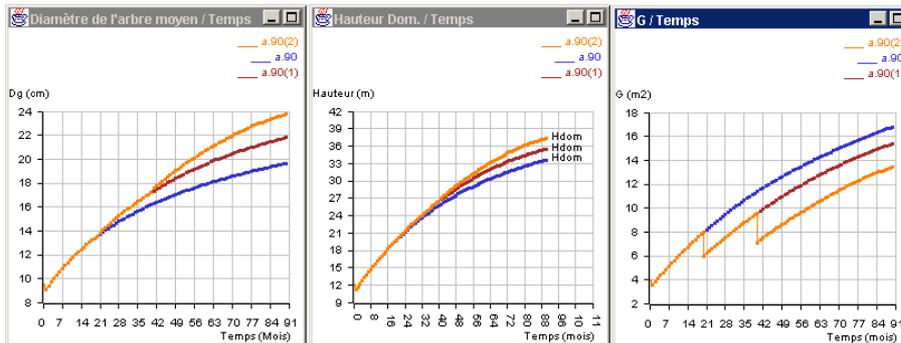

Figure 12 : Thinnings where the average basal area of removed trees equals to the average basal area of standing trees after thinning.
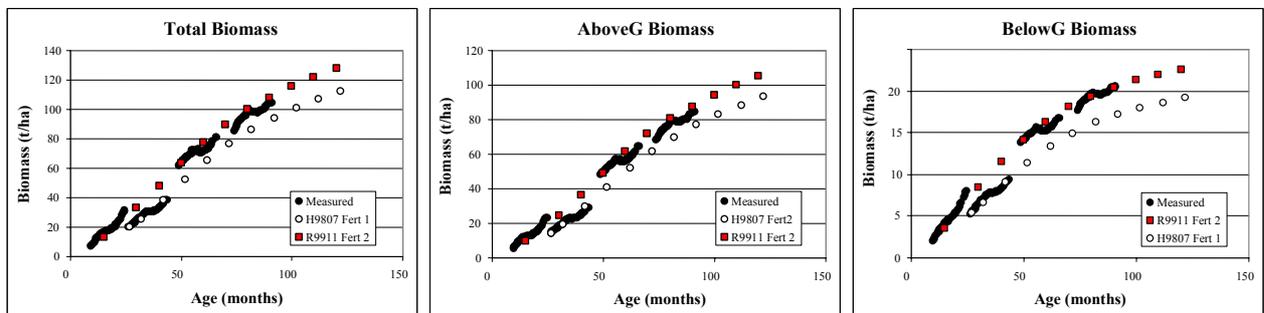
Biomass estimation for clone 1-41

Figure 13 : Simulation of biomass production using as inputs the inventory of two different stands, R9911 grey squares, H9807 white dots, compared to the measured biomass recorded along an age series. One group of black points corresponds to 1,5 growth year for one stand.

Simulations were compared to the biomass measurements along an age series (see Nouvellon *et al*., 2001 ; Saint-André *et al.,* 2002c for details). The second plot of the age series (plot H9807) was clearly below the others when considering the biomass production. However, thank to lower fertility parameters (k_0 and Hlim see Eq. 1),

simulations of biomass fitted well to the measured values whatever the considered compartment (below-ground, above-ground and total biomass).

Nitrogen input-output budget for clone 1-41

The removal of nutrients were estimated when considering the scenarios presented in Figure 11 (two thinnings, versus no thinning). At each thinning, trees were felled and left within the stand because they were too small to be harvested. Table 1 gives the total amount of nitrogen within the stand at different ages for the two management regimes. Felling trees led to a nitrogen return of about 27 kg/ha. This amount could offset 1/5 of the nitrogen deficit of the input-output budget assessed by Laclau (2001) for the whole planted crop rotation. However, a close look to the final step (harvesting of the trees that dbh is above 11cm) showed that 190 kg/ha is exported from the stand whatever the considered regime. The difference of standing nitrogen between the two regimes at the final age (33.6 kg/ha) is only due to a higher foliar biomass within the 550 stems/ha-stand. The nitrogen balance between the two regimes is then equivalent when the total amount is only considered ($27.2+386.4 \approx 420$), but differs when considering the nature of litter (more wood in the two-thinning regime).

		Two thinnings (1/4 of stem removed at each time)		No thinning		
Age (months)	S/ha	N Returns (soil)	Standing N	S/ha	N Returns (soil)	Standing N
42	550	4.8	168.2	550	-	173
62	415	22.4	203.4	550	-	220.6
112	310	-	386.4	550	-	420

= **27.2 kg/ha**
Can offset 1/5 of the negative Input/Output (Laclau 2001)

190 kg/ha   **191 kg/ha**
Within the harvested stems ($\Phi > 11$ cm)

Table 1 : Simulation of the nitrogen content within the stands for two management regimes (two thinnings versus no thinning). Nitrogen content are given in kg/ha.

CONCLUSION

Many works are still necessary to get a complete tool that estimates both production, carbon and nutrient budgets. However, we can start to simulate different options for silvicultural practices and implications on carbon storage and/or sustainability.

There is still improvement to be done concerning the estimations of the stands fertility parameters (k_0, hlim).Variations of these parameters led to very different growth patterns and the simulated annealing procedure needs to be improved.

Each model and the complete chain should be validated/evaluated using the industrial data, including estimation of the confidence interval for the estimations. Some models are already done and have to be embedded within Capsis, such as the litter decay. Some models are missing and have to be fitted such as the self thinning equation (mortality) or the feed back of the nitrogen input/ouput budget on stand growth.

Finally, in order to get a decision making tool and not only a research simulator, it is necessary to

1- create links with other softwares
   o Win-EPIFN for wood properties and logging,
   o Mapinfo for planning management,
2- transfer methods, tools and knowledge to the end-user
   o defining protocols for settling up the permanent plots used for the model's calibration,
   o training courses on Capsis,
   o defining an easy procedure to add and/or update models within Capsis,
   o training courses on the modelling techniques.

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