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# Relationships between Tree Diameter, Height, and Stocking in Even-Aged Eucalypt Stands in Pointe-Noire (Republic of Congo)

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**Abstract:** The study highlights the complex dynamics governing the growth of forest stands, particularly in eucalyptus plantations in Congo. Factors such as soil fertility, planting density, clone genetics, and resource competition significantly influence forest productivity. Thinning practices, when well implemented, help to rebalance competition among trees and maximize diameter growth. However, forest growth models, like Vanclay's model, must be adapted to local conditions to provide more accurate and relevant predictions. Despite the progress made, questions remain about the best way to optimize forest stand management. The use of more sophisticated models that can account for the diversity of ecological conditions and management practices represents a major challenge for researchers and forest managers.

**Key words:** Growth model, planting density, fertilization, thinning.

## 1. Introduction

The growth of forest stands is a key factor in the sustainable management of forest resources. Estimating growth in terms of volume and biomass is essential for assessing forest productivity. This assessment requires a deep understanding of the variations associated with stand age, density, thinning practices, and fertilization regimes [1-5]. Despite numerous studies on the allometric relationships between dendrometric traits such as height, diameter, and volume, the link between tree size and stand density remains complex and debated. The effect of density on diameter and height growth is often confounded by other environmental factors, further complicating the identification of an optimal density for maximizing volume [6].

The theoretical foundations of dendrometry can be traced back to earlier work, such as De Perthuis [7], which established key principles of modern dendrometry by linking site fertility to natural mortality and correlating height with diameter [8-10], as cited by Skovsgaard and Vanclay [11], further advanced the field by demonstrating that the relationship between volume and density is influenced by silvicultural practices [12]. Research into these relationships has resulted in the development of equations that, despite their simplicity, have been the subject of ongoing debate regarding their validity and practical application [13, 14].

Forest growth models have proliferated, aiming to decompose growth processes into fundamental components such as the site fertility index and inter-tree competition. However, many of these models lack generalizability, which limits their capacity to accurately

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predict stand growth across diverse conditions [15]. Furthermore, validating these models against genetic, environmental, and competitive factors is crucial for enhancing the understanding of forest dynamics. Indeed, studies by Vanclay [14, 16, 17] underscore the necessity of adapting growth models to incorporate factors such as fertilization, competition, and mortality, while considering the specific characteristics of each species and their ecological contexts.

This study aims to investigate the growth dynamics in eucalypt plantations in Congo, which offer an ideal setting for examining the effects of fertility, genetics, and competition on stand development. The distinctive characteristics of these plantations, including their draining, nutrient-poor soils, combined with tailored management practices, render this subject a relevant model for understanding the complex interactions that govern forest growth.

## 2. Materials and Methods

### *2.1 Description of the Experimental Site*

The study was conducted at plot L7909, located near Pointe-Noire, with GPS (Global Positioning System) coordinates of 4°40′46″ S and 11°55′29″ E. Pointe-Noire has a tropical wet and dry climate, characterized by two distinct seasons: a long dry season from May to September and a rainy season from October to April. The average annual rainfall is around 1,200 mm, with temperatures ranging between 24 ℃ and 28 ℃ throughout the year. The soils in this region are predominantly sandy, characterized by low water retention capacity and minimal mineral content. The experiment was implemented in two fertility zones:

(1) Conventional Zone: This zone was fertilized with 200 g of 27% ammonium nitrate per plant at the time of replanting.

(2) Non-Limiting Zone: This zone was enriched with nitrogen, phosphorus, and potassium. Prior to planting, 1 tonne of limestone per hectare was applied to achieve a minimum of 200 to 300 kg of calcium, 150 to 200 kg of potassium, and 20 to 30 kg of magnesium. Additionally, boron was added at a rate of 5 kg per hectare during the sixth month, followed by NPK fertilization (13-13-21) at 500 kg per hectare every six months for a duration of three years.

### *2.2 Plant Material*

Three Eucalyptus clones were selected for this study:

- Clone 1-41: A widely planted natural hybrid used as a control for the experiments. This clone is believed to be the result of a cross between *Eucalyptus alba* (mother) and a poorly identified hybrid (father).
- Clones 18-50 and 18-157: These clones, which have been cultivated since 2000, are the product of hybridization between *Eucalyptus urophylla* and *Eucalyptus grandis*. They are noted for their high productivity, achieving 40 $m^3$/ha/year in clonal trials.

### *2.3 Planting Density*

Two sub-tests were conducted in each fertility zone. The first sub-test involved two densities (833 and 10,000 stems per hectare) and two clones (1-41 and 18-147). Each clone was distributed across 12 plots, configured as 3 × 4 trees for the density of 833 stems/ha and 9 × 9 trees for the density of 10,000 stems/ha. The second sub-test included three clones (1-41, 18-50, and 18-147), starting at a density of 10,000 stems per hectare, followed by two thinning interventions to achieve final densities of 5,000, 2,500, 1,200, and 600 stems per hectare. Each fertility zone was organized into two blocks, each comprising four plots measuring 36 m × 36 m per clone, with one useful plot measuring 21 m × 25 m, totaling 525 trees.

### *2.4 Model Selection*

The following relationship proposed by Vanclay [14, 16] was tested:

$$\boldsymbol{D}bh = \beta(Ho - 1.3)/\ln N \qquad (1)$$

where $D$ is the diameter at breast height (1.3 m above ground), $H$ is the average height of the tallest trees in a stand, and $N$ is the number of trees per hectare. This model estimates a single parameter and provides a distribution of residuals consistent with conventional statistical assumptions.

*2.5 Data Collection and Analysis*

The trees were measured for height (using a pole for heights below 10 m and Vertex III for heights above 10 m) and circumference at 1.30 m (using a dendrometric tape) at regular intervals based on the growth rate of the stands over a period of up to 30 months. Mortality and actual density were also recorded. The dominant height was determined from the tallest trees in the stand. All statistical analyses and model adjustments were conducted using SAS software [18]. Analyses of variance were performed using the PROC MEANS procedure, linear regressions with PROC GLM, and non-linear regressions with PROC NLIN. Mean comparisons were made using Scheffe's criterion for balanced groups [19], and graphs were generated using R Core Team [20].

## 3. Results

*3.1 Growth of Stands*

Growth in diameter (Fig. 1) and dominant height (Fig. 2) is greater in non-limiting fertility zones for all clones. However, dominant height varies among clones, regardless of planting density. The Urograndis clones are generally taller (Fig. 2) than the 1-41 clone, while the opposite is true for diameter growth (Fig. 1) when measured at 30 months.

*3.2 Relationship between Growth Variables and Stand Density*

The relationship $D = \beta(H_0 - 1.3)/\ln(N)$ [14, 16, 17] illustrated in the age (Fig. 3), fertilization (Fig. 4), and clone (Fig. 5) study plots within the industrial Eucalyptus plantation massif at Pointe-Noire demonstrates an allometric relationship characterized by two distinct phases: an initial phase of rapid growth, followed by a notable decline near the abscissa of 0.5 at 14 months of age, when all the stands appear to converge (Fig. 3), and a subsequent phase of growth. The Vanclay model [14, 16, 17] is segmented (Eq. (2)) into two parts and has been fitted to the dataset.

$$\boldsymbol{Dbh} = \begin{cases} \beta 1 . HolnN, si \;\; HolnN < 0.5 \\ \beta 1 \;.0.5 + \;\beta 2 \;.[HolnN \;\; - 0.5], si \;\; HolnN \geq 0.5 \end{cases} \quad (2)$$

In this model, *Dbh* is the dependent variable, *H*ln*N* is the independent variable, and $\beta_1$ and $\beta_2$ are the model coefficients that determine the effect of *H*ln*N* on *Dbh* in the two defined segments.

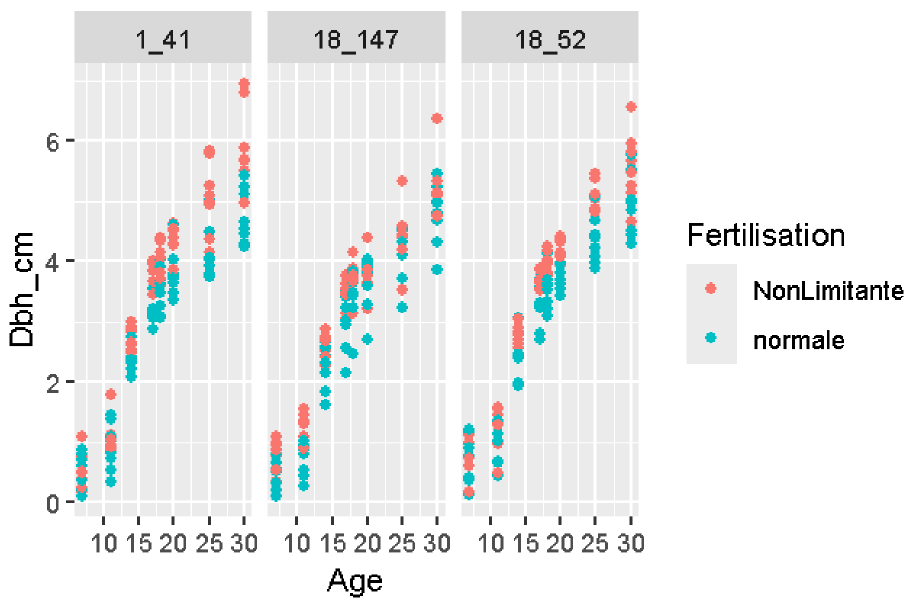


**Fig. 1 Diameter growth.**

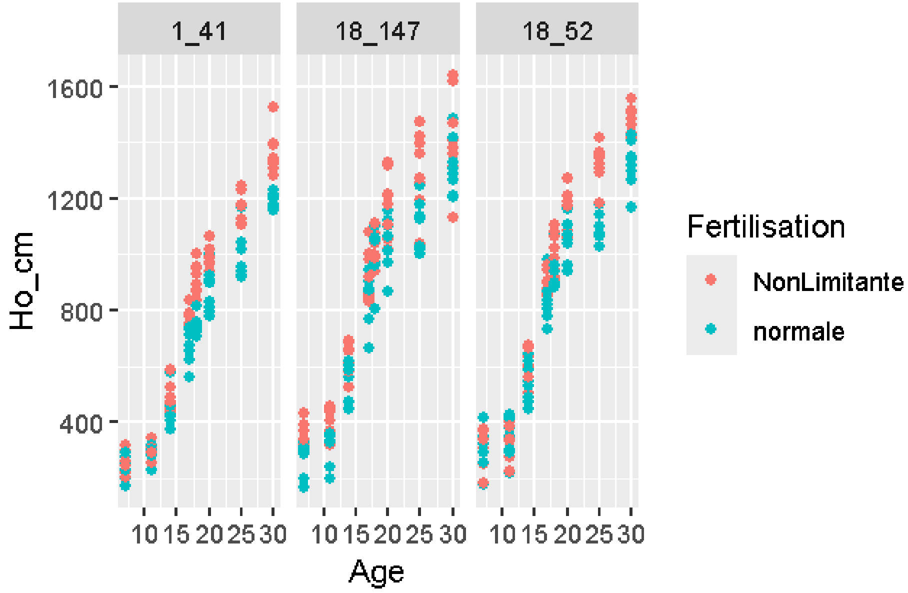


**Fig. 2 Dominant height growth.**

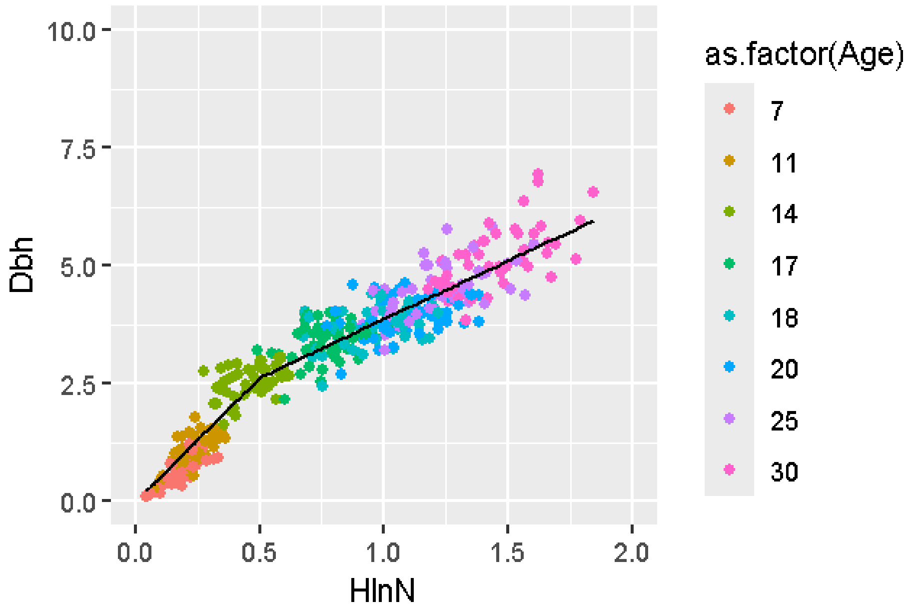


**Fig. 3 Age effect on the relationship between diameter and ($H_0$ - 1.3)/ln($N$).**

The $\beta_1$ parameter in the segmented model is significantly different among clones ($p < 0.0009$), with a decreasing gradient of 1-41 > 18-52 > 18-147; it varies from 4.51 for clone 18-147 to 6.38 for clone 1-41. The $\beta_2$ parameter is not significant among clones but differs between fertilization zones for each clone ($p < 0.5$). The inflection point of the curve did not differ among clones, but it did vary between fertility zones ($p > 0.05$) (Table 1).

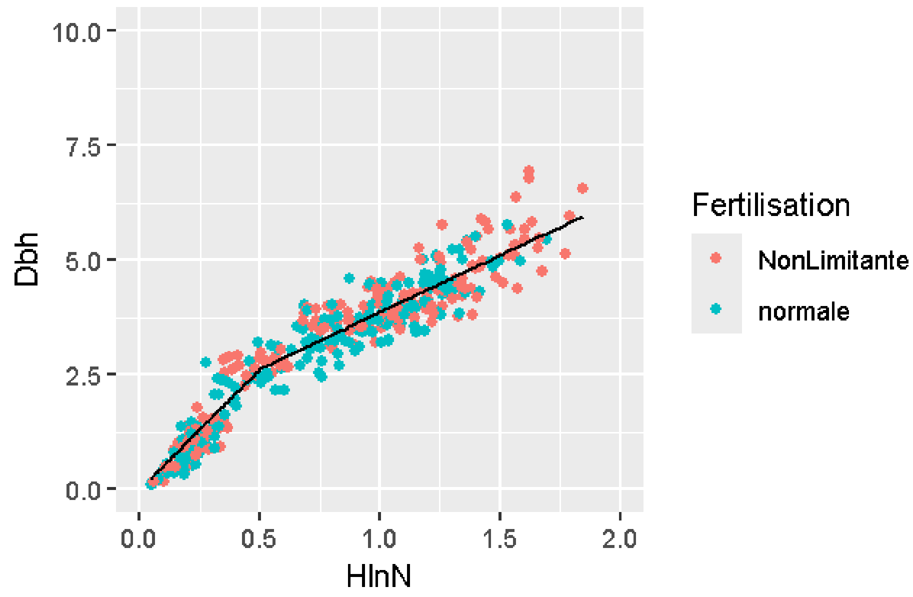


**Fig. 4** **Fertilization effect on the relationship between diameter and ($H_0$ - 1.3)/ln($N$).**

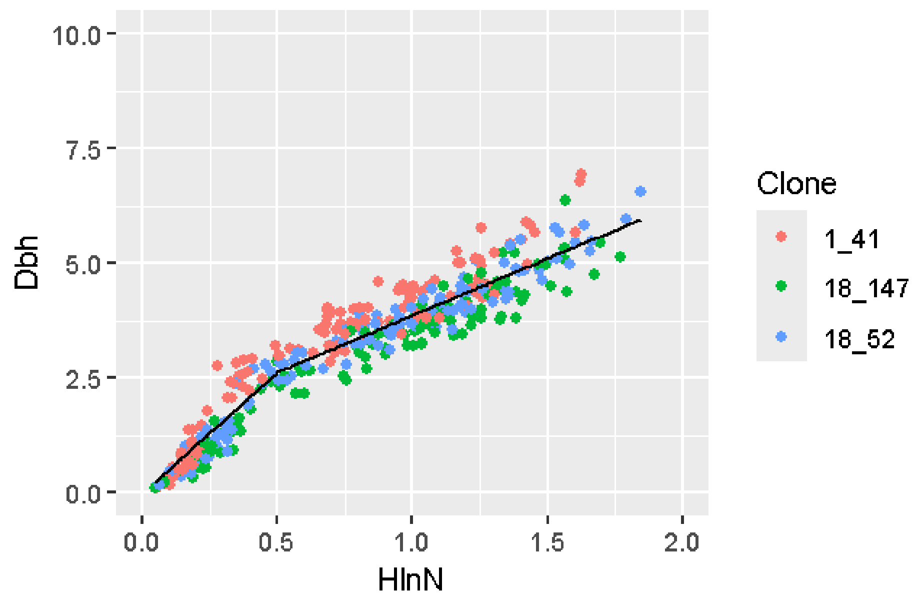


**Fig. 5** **Clone effect on the relationship between diameter and ($H_0$ -1.3)/ln($N$).**

**Table 1** **Adjusted model parameters**

| | Estimate | Std. Error | $t$ value | Pr[>\|$t$\|] |
|---|---|---|---|---|
| $\beta_1$ | 5.25764 | 0.08861 | 59.34 | < 2e-16*** |
| $\beta_2$ | 2.48041 | 0.07413 | 33.46 | < 2e-16*** |

Significance codes:

0 '***' indicates highly significant (p < 0.001)

0.001 '**' indicates very significant (p < 0.01)

0.01 '*' indicates significant (p < 0.05)

0.05 '.' indicates marginally significant (p < 0.1)

0.1 ' ' indicates not significant (p ≥ 0.1)

Residual standard error: 0.4318 on 382 degrees of freedom.

## 4. Discussion

Analysis of the growth dynamics of eucalyptus stands in the Congo revealed several important results concerning the effects of fertility, genetics, and plantation density. The results show that growth in height and diameter is significantly higher in areas of non-limiting fertility, confirming the importance of nutrient supply for tree development. This aligns with the observations of Vanclay [14] regarding the need for adequate fertilization to maximize forest productivity. The differences observed between clones also illustrate the genetic variability in tree responses to density and fertility. The Eucalyptus urophylla × Eucalyptus grandis clones exhibited faster growth, suggesting that they are better adapted to the specific planting conditions of the study site. This variability highlights the importance of genetic selection in establishing productive plantations [3].

The effect of plantation density on diameter and height growth is also notable. The allometric relationship observed, as described by Vanclay [14], highlights a phase of rapid growth followed by saturation, where competition between trees can reduce individual growth. This observation reinforces the idea that density management is crucial for optimizing forest productivity. The results indicate that excessively high planting densities can be detrimental to tree growth, consistent with previous work by Zeide [6, 15], which discusses the effects of competition on forest growth. In terms of forest management, these results suggest that thinning practices could be beneficial for improving stand growth. By reducing density, the remaining trees could benefit from more light, water, and nutrients, thus promoting more vigorous growth [1, 2].

Finally, the results of this study highlight the importance of adapting forest growth and development models to local specificities. Vanclay's [14] models proved to be applicable, but it is essential to continue refining these models by considering environmental, genetic, and management factors in order to improve the predictability of forest growth in various contexts.

## 5. Conclusion

This study on the growth dynamics of eucalyptus plantations in the Congo reveals valuable insights regarding the interactions between soil fertility, plantation density, and clone genetics, with a particular focus on Vanclay's model. While Vanclay's model is widely used, it has limitations when it comes to describing the complex relationships between tree growth and environmental factors. Our observations indicate that the allometric relationship described by Vanclay, characterized by two distinct phases—an initial phase of rapid growth followed by a slowdown—is particularly relevant in the context of dense plantations. The inflection point observed around 0.5 in the relationship between diameter and density ($D = \beta(H_0-1.3)/\ln(N)$) suggests that competition for resources plays a crucial role in determining tree growth, further supporting the idea that thinning practices can be beneficial for improving stand productivity.

In conclusion, although Vanclay's model provides a useful foundation for predicting forest stand growth, its effectiveness depends on the proper integration of interactions between fertility, density, and clone genetic characteristics. The results of this research emphasize the importance of a tailored approach to forest management, ensuring sustainable and optimal productivity of forest resources.

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