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Effect of Soil Fertility and Planting Density on the Partitioning of the Above-Ground Biomass of Eucalyptus in a Plantation (Pointe-Noire, Republic of Congo)

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Abstract

Afforestation and reforestation are useful approaches to improve carbon sequestration. With the advent of forest plantations, growing environment conditions have become increasingly restrictive for light, soil nutrients, and interactions between trees to acquire available resources. Tree biomass data are essential for understanding the forest carbon cycle and plant adaptations to the environment. The distribution of tree biomass depends on the sum of multiple stand conditions. The data are from a dedicated experiment with two very contrasting areas of fertility, and two planting densities, including a high density at planting in order to achieve thinning. The plant material consists of the high-performance clones of *Eucalyptus urophylla* × *E. grandis* and the reference clone *E. PF1*. We hypothesize that the distribution of biomass changes as the intensity of competition changes and that this is accelerated by the fertility of the sites in time. The results indicate that fertilization, planting density and clones have an impact on biomass partitioning.

Keywords

Biomass, Carbon, Plantation, Eucalyptus, Competition Effect, Soil Fertility

1. Introduction

The average surface temperature of the planet is steadily increasing [1] and [2] due to human activities which have led to rising atmospheric concentrations of greenhouse gases (GHGs), notably carbon. Forests not only supply essential forest products to meet human needs, but also play a critical role in carbon sequestration through photosynthesis [3] and [1]. Afforestation and reforestation are effective strategies for enhancing carbon sequestration to mitigate the effects of climate change and improve other ecosystem services. For the past 4 decades, the total area of planted forests in the world has increased by more than 105 million hectares and planted forests are the main source of fuelwood, fiber and other raw materials, thereby helping to reduce the immense pressure on natural forests caused by wood demand [4].

Planting trees in tropical countries is becoming an increasingly important forestry activity as many tropical countries that depend on wood supply from natural forests are recognizing the need to establish plantations to augment supplies from dwindling and unsustainable natural forests. Though most species used for tropical plantations are fast-growing, their growth rate can be improved substantially through appropriate silviculture [5]. With the rise of plantation forestry, environmental conditions for tree growth are becoming increasingly constrained in terms of light, soil nutrients and interactions between trees for accessing resources. It is recognized that tree biomass allocation is influenced by environmental factors [6]. However, there is limited understanding of plant biomass allocation strategies and the interactions between tree species within forest stands. This information is important to reveal plant biomass allocation strategies in the context of plant competition [7]. For instance, young trees allocate more biomass to the stem for height growth and to branches and leaves for expanding the canopy to be more competitive in accessing light resources over neighboring trees [8]-[10]. As it stands mature, biomass accumulation in stems and branches tends to increase due to a higher proportion of heartwood formation at the expense of foliage [11].

Data on tree biomass is essential for understanding the forest carbon cycle and plant adaptations to the environment [12]-[16]. It is also crucial for studying the impacts of silvicultural practices on forest productivity [17] [18] and the provision of ecosystem services such as bioenergy and biomass products [19]. Changes in the biomass distribution of plant organs are an important mechanism for maintaining productivity [16] [20] [21].

Tree biomass distribution is determined by the overall stand conditions [22]. An essential aspect of forest ecology is biomass allocation, which examines how plants allocate their resources to the different plant organs (stems, leaves and roots). Biomass distribution directly affects plantation productivity, and productivity is closely linked to competition in forests [7]. The allocation pattern of plant biomass is a critical issue in ecology [23] [24] with significant practical implications for global change and timber production. Changes in site conditions can have profound effects on forest biomass allocation [25] [26].

The effects of age and site on biomass allocation have been widely studied [16] [27]-[29]: stand age influences biomass distribution; branches and leaves are more sensitive to the environment and are the tree components most affected by stand age [30]. Stand age influences size, shape, biomass distribution and subsequently allometric relationships [31]-[33] have postulated that biomass allocation is mainly determined by plant size. In addition, highly heritable wood density [34]-[36] can also increase with stand maturity [37]. Wood density is the parameter linking tree volume to biomass [38].

Competition among individuals influences growth, form and structure, and mortality [39] [40]. Some studies have shown that competition can significantly enhance the productive potential of forest stands [41]. Studies highlight the relationship between biomass distribution and plant competition. An individual-based model was proposed by [42], which explored the plant mass-density relationship by representing the plasticity of biomass allocation and the different modes of competition in the above-ground and below-ground compartments. When the effect of competition was eliminated, the above-ground biomass of Douglas-fir (*Pseudotsuga menziessi*) increased significantly [43]. These examples show that competition is closely linked to biomass distribution.

Site conditions, such as climate and soil fertility [27] [44]-[47] and stand structure in terms of stand density or species composition influence interactions (competition vs. facilitation) between trees or tree species in complex forests [48]. [49] found that *Pinus taeda* allocated more resources to modify canopy structure. Nitrogen availability promotes plant growth and increases carbon storage [50]. Total carbon sequestration is significantly higher on high quality sites [51].

The shape and crown structure vary with stand age, so that allometric relationships between tree biomass components and dimensional variables differ greatly [22] [52]. Substantial differences are observed between dominant and dominated trees [12] [53].

The eucalyptus plantations covering approximately 40,000 ha adjacent to the city of Pointe-Noire in the Republic of Congo (with more than 1,500,000 inhabitants) are established in an exceptionally poor site characterized by very draining sandy soil with poor chemical properties. *E. Urophylla* × *E. grandis* (*E. Urograndis*) are more productive (reaching up to 40/m^3/ha/year in the experimental plot), we hypothesize that the distribution of biomass in tree compartments undergoes changes when the intensity of competition changes (with thinning scenarios) and that this is accelerated by fertility over time. Theories of biomass allocation indicate that plants preferentially allocate carbon to organs that demand more of the available resource [54] [55]. Despite the fact that substantial gains in productivity (*i.e.*, stem wood volume or dry mass) associated with genetic improvement have been observed [14] [56], the physiological and morphological basis for high productivity remains relatively unclear [57]. This study aims to describe the impact of fertilization and planting density on the allocation of biomass in the tree in eucalyptus plantations in the Pointe-Noire region.

2. Materials and Method

2.1. Materials

2.1.1. Location and Description of the Study Area

The Eucalyptus plantations in the Pointe Noire region of the Republic of Congo are located on the coast at 40˚ south latitude and 120˚ east longitude. The average elevation of the area is 100 m asl, with a relatively flat relief. Only flat, gently sloping areas (<12%) were planted. The experimental design is located in the Luvuiti station near the village of Mengo.

The climate is humid tropical, with an average annual rainfall of 1470 mm over the period from 2002 to 2014 (Source: ASECNA, Pointe-Noire airport). The average temperature is 25˚C, with small seasonal variations (<5˚C) and little interannual variation. Relative air humidity averages 85%, with slight annual variations. The soils of the Kouilou department where eucalyptus plantations grow are continental sedimentary sandy formations dating from the Plio-Pleistocene. These sand deposits were transported from the Mayombe mountain range located around 80 km from the coast [58]. They belong to the Ferralic Arenosols group [59] and have a grain size dominated by coarse sand fractions (around 91%), to which 6% clay and 3% silt are added [60]. The vegetation is dominated by savannah as you approach the coast. There are also gallery forests on the barrier beaches, in certain depressions and in swampy or flooded areas. On the whole, the coastal savannah is made up of small Poaceae (50 to 150 cm high) which do not completely cover the ground [61].

2.1.2. Plant Material

A clone of the natural hybrid *Eucalyptus PF1* (clone 1-41) and two clones of the hybrid *Eucalyptus urophylla* × *Eucalyptus grandis* (18-147, 18-52) resulting from the same full-sib family were selected for this study. Clone 1-41 is the most widely planted and currently constitutes a control for all field experiments in Pointe-Noire (Republic of the Congo). It may have originated from a crossing between *Eucalyptus alba* (female tree) with a poorly identified hybrid (male tree), which includes probably *E. grandis*, *E. robusta*, *E. urophylla* and *E. botryoïdes*. The clones of *E. urophylla* × *E. grandis* came from artificial hybridization and genetic selections. Since 2000, they represented the majority of plantations because of their high productivity (40 m^3/ha/year in clonal test and 20 m^3/ha/year in plantations [16]) compared to *Eucalyptus PF1* (clone 1-41) which has a maximum productivity of only 18 m^3/ha/year.

2.2. Methods

2.2.1. Experimental Design

Two contrasting fertilization regimes were used to compare stands in a situation of normal fertilization (corresponding to that achieved in the industrial plantations at Pointe-Noire, *i.e.*, 500 kg/ha of ammonium nitrate at 27% applied around each plant at plantation) to a situation of non-limiting fertilization by the complete application of macro- and micro-elements, *i.e.* 1 ton/ha of limestone before planting (to obtain a minimum of 200 to 300 kg of Ca; 150 to 200 kg of K and 20 to 30 kg of Mg, and 5 kg per hectare of boron at planting). Then, every six months, 500 kg/ha of combined NPK fertilizer (13-13-21) was added. The two zones (non-limiting and normal fertilization) are delimited by a trench 50 cm wide and 50 cm deep to avoid root competition between neighboring stands in the two fertility zones. In each fertility zone, two blocks of 12 plots each were delimited. That is 4 plots per block and per clone. Two contrasting densities were chosen at planting, one at 10,000 stems/ha (*i.e.*, 1 m × 1 m spacing) to explore a range of possible growing conditions with thinning (2500 stems/ha 1.5 years after planting), and the other at 833 stems/ha.

2.2.2. Data Collection

Biomass measurements were carried out on a sample of trees that was highly representative of the stand (Figure 1) in each fertility zone and for each clone The biomass survey was carried out on three dates: 1.7, 2.5 and 3.5 years, each time following an inventory of trees in circumference at 1.30 m and in height, leading to the selection of 12 trees representative of the stand to be felled on each date. The trees were measured in height with the pole below 10m or the vertex III above 10 m; and in circumference at 1.30 m with the tape. Precise measurements of the biomass of individual trees were obtained by destructive sampling. The tree was felled, the branches extending from the trunk were removed and the stem was cut every meter or every two meters (respectively for trees under 10 m and over 10 m) down to a 2-cm-diameter-over-bark log at the end. The different compartments of the tree: wood, bark, living branches, dead branches and leaves were separated (Photo 1) and weighed; aliquots of 100 grams were taken from each compartment and then dried to estimate their moisture content (at 65˚C). This protocol follows international standards [62]. A total of 488 trees were

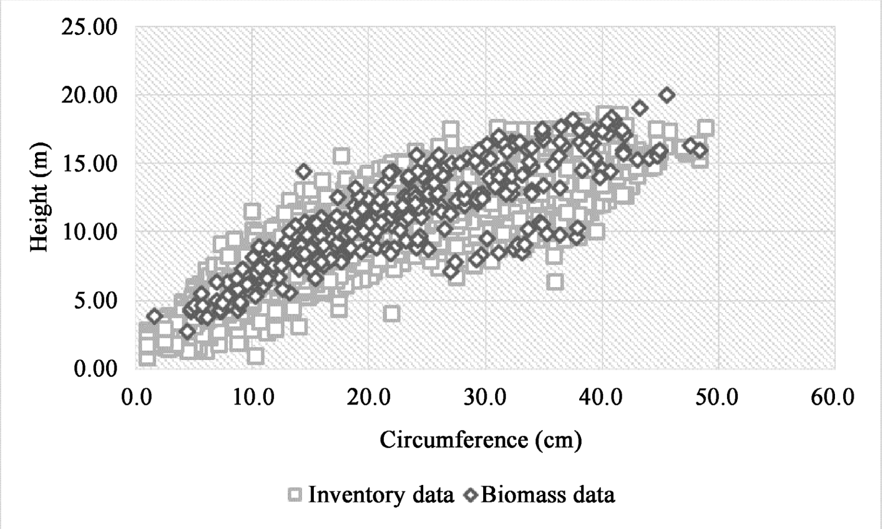

Figure 1. Growth and selection of trees for biomass.

Photo 1. Biomass measurement in the field.

felled on 3 dates (1.5, 2.5 and 3.5 years) and 5,671 circumference measurements on and under the bark along the trees, and masses of wet and dry samples were taken. All statistical analyses and model fits were performed using R software (version 4.4.1). Analyses of variance were performed using the Beta Regression in R procedure. The model-fitting function betareg and its associated class are designed to be as similar as possible to the standard glm function [63] for fitting GLMs. An important difference is that there are potentially two equations for mean and precision and consequently two regressor matrices, two linear predictors, two sets of coefficients.

3. Results

3.1. Distribution of Trunk Biomass in the Tree

The proportion of stem wood biomass in the tree (**Figure 2**), which reached up to 73.06% (±5.75) for clone 18-52 at 1000 stems per hectare under non-limiting fertilization, shows that the denser the stand, the greater its proportion of wood (p-value = 0.019742), regardless of age (p-value > 2.2e-16), clone or fertilization regime. At high densities, the '*E. urograndis*' clones generally had a higher proportion of wood than the 1-41 clone, but this ranking reversed as soon as the density decreased (thinning or planting at 833 stems/ha). Whatever the clone, density or fertilization, the difference in the proportion of wood between the fertilization zones was not significant (p-value = 0.772).

3.2. Distribution of Bark Biomass in the Tree

The proportion of stem bark biomass (**Figure 3**) reached up to 9.14% (±2.91) for clone 1-41 at 2500 stems per hectare under normal fertilization is significant in dense stands, regardless of age, clone or fertilization regime (p > 0.006520). The 'urograndis' clones had a higher proportion of bark than clones 1-41 (p > 1.268e–05) in stands at constant density (833 and 10,000 t/ha) regardless of age and fertilization regime, but changed in 3.5 years old plantations in the direction of 'urograndis' clones < clone 1-41 in thinned stands. The fertilization regime

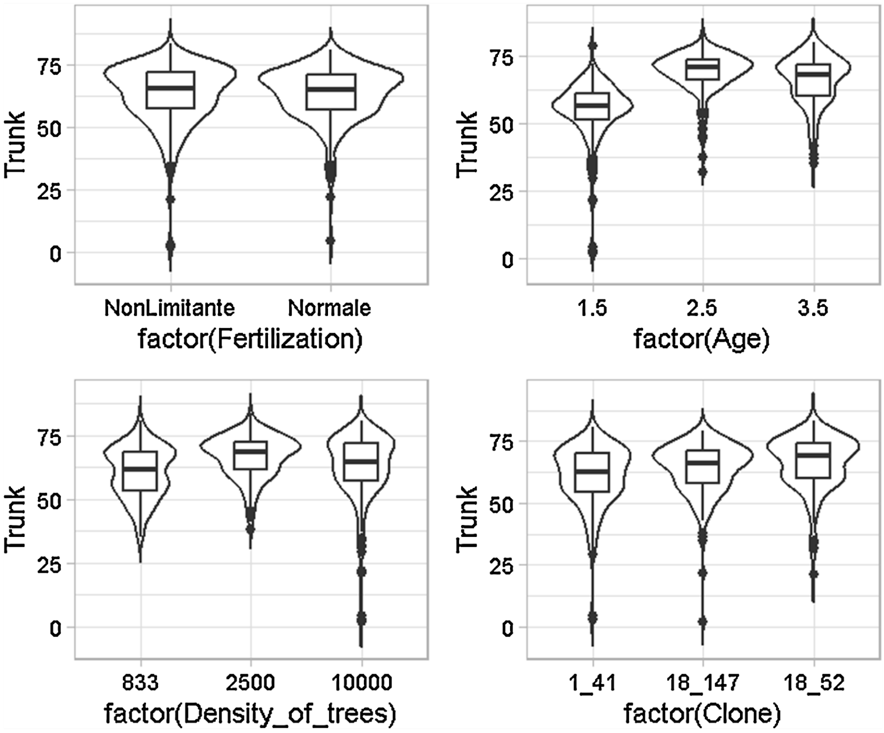

Figure 2. Effect of fertilization, age, density and clone factors in the partitioning of trunk wood biomass.

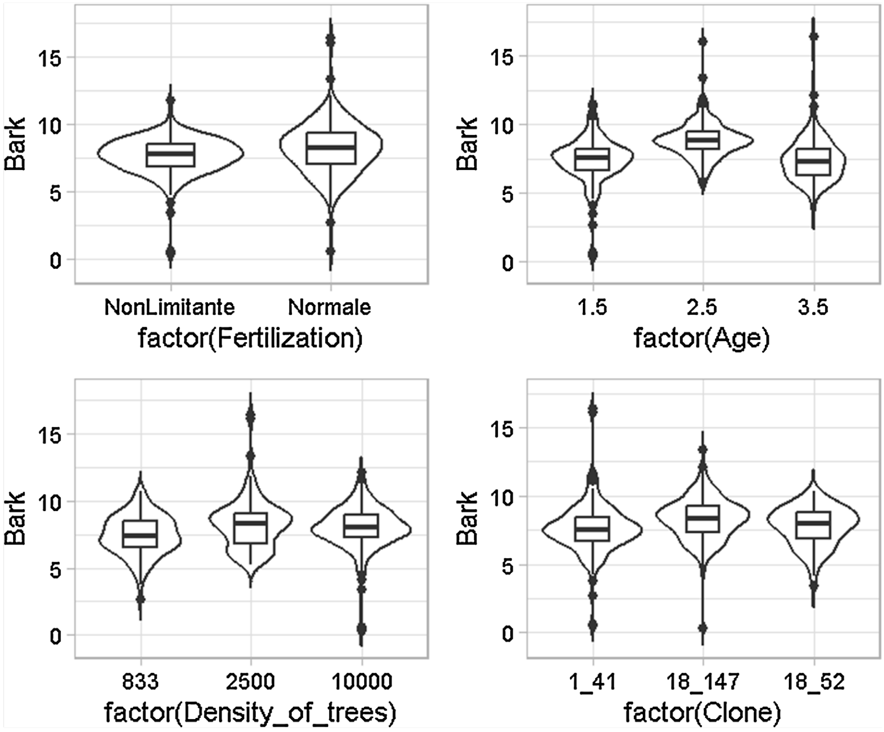

Figure 3. Effect of fertilization, age, density and clone factors on bark biomass partitioning.

generally had no effect, and when it did, it was in the direction of non-limiting fertilization > normal fertilization ($p > 0.000381$).

3.3. Distribution of Biomass of Living Branches in the Tree

The proportion of living branch biomass (**Figure 4**) reached up to 23.90% (±10.49) at low density and with non-limiting fertilization, but the proportions changed significantly with age ($p < 2.2e-16$) and stand density ($p < 1.401e-05$). The denser the stand, the lower the proportion of living branches, regardless of density, clone or fertilization. At 1.5 years, the proportion of living branches of clone 1-41 was greater than that of the '*E. urograndis*' clones, whatever the density and fertilization, and this ranking is reversed from 2.5 years, except in stands with a constant 10,000 stems/ha. With a few exceptions, fertilization had no effect on the proportion of living branches, and when the effect was significant, it was generally in the direction of a higher proportion of living branches in stands with non-limiting fertilization.

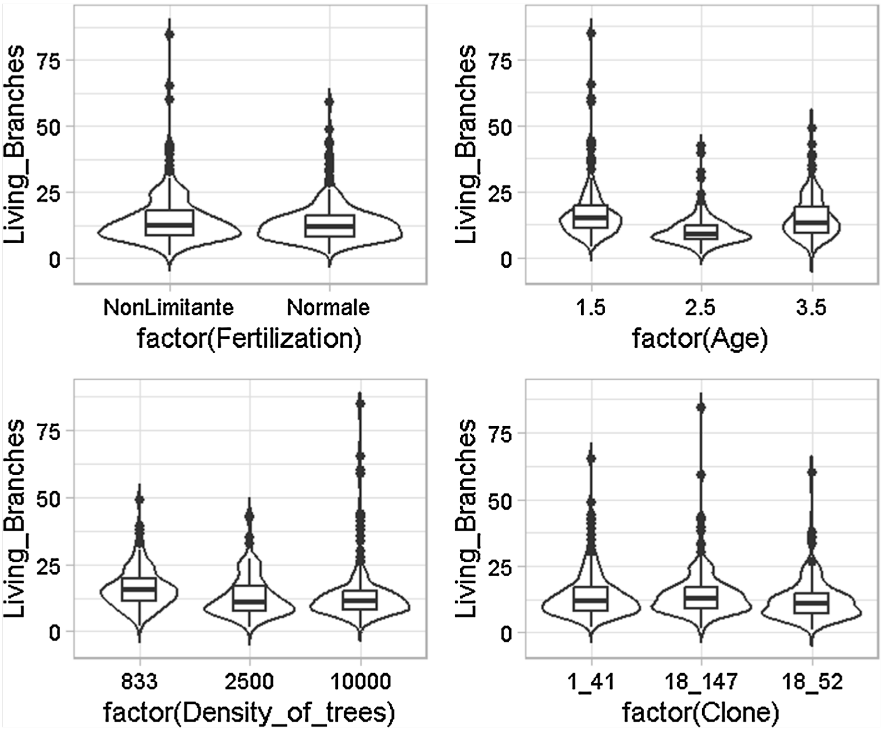

Figure 4. Effect of fertilization, age, density and clone factors in the partitioning of biomass of living branches.

3.4. Distribution of Dead Branch Biomass in the Tree

The proportion of dead branch biomass (**Figure 5**), which reached 9.05% (±2.50) with clone 1-41 under normal fertilization at 833 stems/ha, varied significantly with age ($p < 5.544e-10$), stand density ($p < 0.002488$) and between clones ($p < 3.246e-10$). At 1.5 years, the denser the stand, the greater the proportion of dead branches, whatever the clone or fertilization regime. The ranking then reversed at later ages, with three exceptions (at 2.5 years, clones 18-52 and 18-147 under non-limiting fertilization and at 3.5 years, clone 1-41 under normal fertilization). In general, the pf1 1-41 clones had a higher proportion of dead branches than the *E.*

urograndis clones, which were also significantly different (18-52 ≥ 18-147) regardless of age, density or fertilization. Whatever the clone, density or age, non-limiting fertilization generally resulted in a higher or equal proportion of dead branches, the exceptions being stands with 833 stems/ha and thinned stands with 10,000 stems/ha.

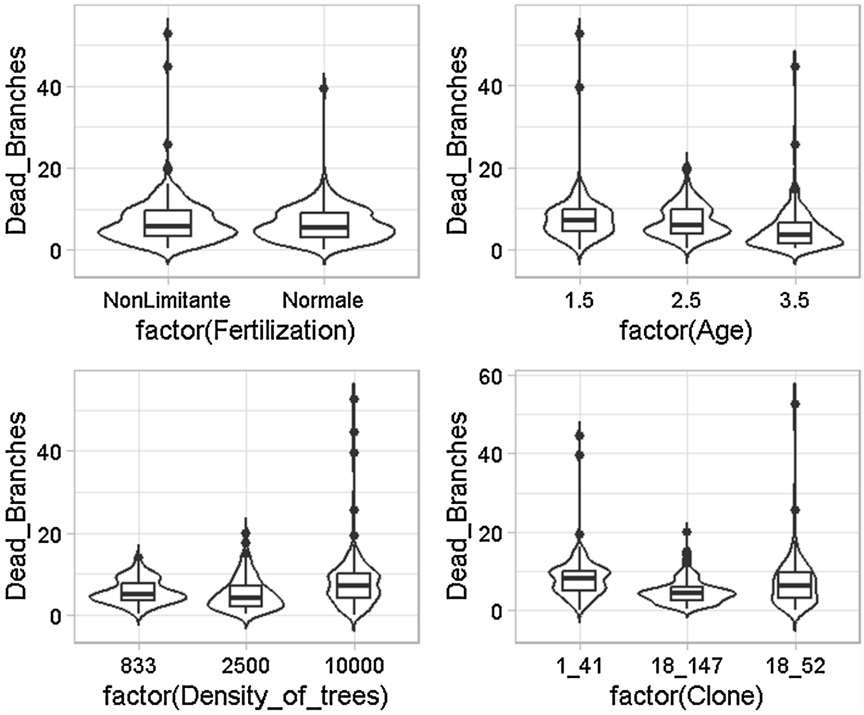

Figure 5. Effect of fertilization, age, density and clone factors on the partitioning of biomass of dead branches.

3.5. Distribution of Leaf Biomass in the Tree

The proportion of leaf biomass (**Figure 6**) reached up to 11.49% (±2.66) with clone 18-147 at 2500 stems/ha under normal fertilization; it changed with age ($p < 2.2e{-}16$), weakly with stand density ($p < 0.019742$) and between clones ($p < 0.005826$). The denser the stand, the lower the proportion of leaves. The proportion of leaves for clones 1-41 was higher than for the 'urograndis' clones in high-density stands and vice versa in low-density stands.

4. Discussion

4.1. Biomass Distribution as a Function of Age

The proportion of stem wood was greater than that of the other compartments, whatever the age, in the direction 1-41 > UG in low-density stands and vice versa in high-density stands. This proportion increased with age. The proportion of bark remained unchanged in all cases, whereas leaves and branches decreased with age. A study by [16] found that in stands of 666 stems/ha aged 8 years, the leaf and bark compartments were also very different (clones 1-41 have 28% more

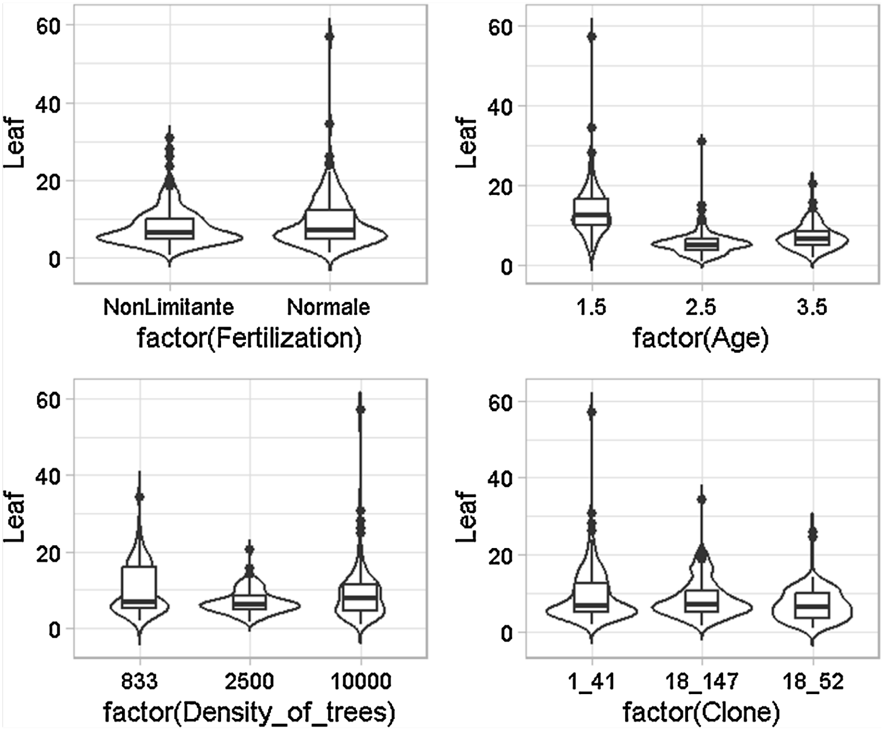

Figure 6. Effect of fertilization, age, density and clone factors on leaf biomass partitioning.

bark and 27% fewer leaves than the '*E. urograndis*' clone) [29]: the annual increase in live branch biomass falls between 2 and 4 years (around 0.15 kg/ha/yr) then increases strongly until the end of the rotation. Leaf biomass was mainly formed during the first year (1800 kg/ha) and continued to increase in the second year (800 kg/ha), then decreased steadily from 2 to 5 years before stabilizing. The result is a considerable increase in the proportion of wood, from 35% of the total above-ground biomass in one year to 80% in 4 years. At the same time, the proportion of leaf and branch biomass fell between 1 and 4 years. Stem wood is the main component of tree biomass. The proportion of stem biomass (with bark) to total tree biomass increased with stand age, while the proportions of branch, foliage and subsoil biomass to total tree biomass decreased with stand age. [64] reported that as trees grow, age-related changes in the tree shape alter the distribution of biomass among tree components. Therefore, the variation in the relative biomass distribution of tree components in our study may have been mainly due to the influence of stand age. These results indicate that stand age modifies biomass distribution. In the present study, we observed an increase in the proportion of stems (with bark) and a decrease in the proportion of crowns (branch and foliage) as stand age increased. This is consistent with other research findings on tree component biomass [52] [65] [66]. The variation in biomass allocation with age can be explained by the strategies that trees use to survive during stand development. In the early periods of growth, the proportions of leaves and roots are critical to the survival of young seedlings and the likelihood that they will survive to the next period of development [47].

4.2. Effect of Fertilization on Biomass Partitioning

The proportion of the various tree compartments, with the exception of bark and living branches, remained high in the non-limiting fertility zone compared with the normal fertility zone, whatever the clone and planting density. Water and nutrient availability may be another factor influencing biomass distribution [35]. Therefore, low nutrient and water availability could be important factors in increasing biomass allocation to roots. One possible explanation is that stands produced much more foliage (*i.e.*, a high LAI) at sites with higher fertilization. If its LAI had been reduced to the same LAI as the poor site, biomass production would probably have been the same. Biomass allocation strategies are linked to the adaptive response of the forest stand to site conditions [67].

4.3. Effect of Competition on Biomass Partitioning

Our results compared with those found by [16]. Do not show strong differences with stands at 833 stems/ha, whatever the clone. Total biomass productivity at 833 stems/ha ranged from 8 to 12.3 tons of dry matter/ha/yr for clone 1-41 and from 18.8 to 22.8 tons of dry matter/ha/yr for clone 18-147 under non-limiting and normal fertilization respectively at 42 months, while it was 13.6 tons of dry matter/ha/yr for clone 1-41 and between 13.5 and 19 tons of dry matter/ha/yr for clone ‘*E. urograndis*’ in stands of 666 stems/ha at 8 years. Productivity in stands at 10,000 t/ha is higher than that at 666 stems/ha for clone 1-41 (+30%) and slightly lower for the ‘*E. urograndis*’ clones (12%). These results suggest that tree biomass distribution is not only controlled by stand age, but that other factors, such as stand density [68] and site condition [69], also have a significant effect on tree biomass distribution. Stand age affected the biomass distribution of tree components. Some studies indicate that stand density also influences the biomass distribution of young oak trees [70] [71] found a significant correlation between stand density and stand age. Furthermore, these authors demonstrated that stand age affects forest biomass not only directly, but also indirectly by affecting forest density.

5. Conclusions

The objective of this study was to gain insight into ecosystem processes in eucalyptus plantations. To this end, the biomass partitioning of different clones was assessed by manipulating the plantation density (10,000 stems per hectare) and fertilization regime (standard or non-limiting) in a factorial design.

The results indicate that fertilization, planting density and clones have an impact on biomass partitioning: better efficiency for stands fertilized before 2 years (in proportion, more wood for fewer leaves), then the reverse (less wood for more leaves after two years); stands with 10,000 plants/ha have in proportion more wood and fewer branches than stands with 833 plants/ha and this in interaction with the clones (reversal of the ranking between clones according to density). The effect of density and clone is also very marked on individual biomass: more biomass individually for trees at 833 stems/ha than at 10,000 stems /ha, and more biomass, whatever the compartment, for the 18-147 at 833 stems/ha. However, in the end, the standing biomass per hectare did not differ between clones, planting density or fertilization regime, due to the different tree densities and differences in size distribution (compensation phenomena).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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