

VARIABILITY IN THE PHYSICO-CHEMICAL PROPERTIES OF WOOD FROM *Eucalyptus robusta* DEPENDING ON ECOLOGICAL GROWING CONDITIONS AND FORESTRY PRACTICES: THE CASE OF SMALLHOLDINGS IN THE HIGHLANDS OF MADAGASCAR

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ABSTRACT

This study set out to determine which environmental factors of growth and silvicultural practices can affect the properties of *Eucalyptus robusta* coppice wood and also to study variability in those properties depending on the factors. Hundred and thirty-five coppice logs aged 2 to 10 years were collected from five zones in the Highlands of Madagascar. Wood density at 12% moisture content was measured by X-ray microdensitometry. Chemical properties, such as the total extractives, Klason lignin and holocellulose contents were predicted using near infrared spectrometry prediction models. The results significantly showed (p -value<0,001) that wood density (543 – 836 kg/m³), total extractives (3,1 – 9,8%) and Klason lignin content (24,6 – 35,3%) increased with age, with the opposite occurring for holocellulose (63,8 – 69,9%). Wood density also varied significantly (p -value<0,001) depending on the zones, which was not the case for chemical properties. The densest woods were found at the hottest zones with less acid soils. Woods were less dense in zones, characterized by high rainfall and a soil rich in nitrogen and organic carbon. The plantation spacing, elevation of the zone and soil texture did not significantly affect wood properties.

Keywords: Climate, *Eucalyptus robusta*, coppice, wood properties, rotation, soil, silvicultural practices.

INTRODUCTION

The fact that the genus *Eucalyptus* adapts to a broad range of environments offers enormous possibilities for producing multi-purpose woods to meet increasing demands worldwide (Hein *et al.* 2012). This makes this genus one of the most widely grown in the tropical and subtropical regions of the world (Gion *et al.* 2011). *Eucalyptus* trees are also fast-growing and usually supply good quality wood and tree shape, which enables multiple uses. Density and chemical properties, such as Klason lignin, and holocellulose contents, along with total extractives, are important characteristics for assessing the quality of wood and informing on its potential uses (Malik and Abdelgadir 2015). According to Gonçalves *et al.* (2004), Thomas *et al.* (2007), Zobel and Buijtenen (2012), these properties vary depending on the growing environment and genetic factors. The environmental factors are particularly the annual mean temperature, annual mean rainfall, elevation, along with soil chemical properties and texture, plantation spacing, and rotation length (Cutter *et al.* 2007, Zobel and Buijtenen 2012).

Wood density varies differently, depending on the regional climate and the species involved. In general,

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woods are denser under growing conditions with higher temperatures and lower rainfall (Drew *et al.* 2017). Anatomically, the adaptation of a tree to climatic factors is reflected in variations in the size and frequency of vessels, and of fibre walls, which consequently affects wood density (Roderick and Berry 2001, Searson *et al.* 2004). In addition, fast-growing trees, such as *E. urophylla* x *E. grandis* hybrid, produce wood with less lignin than slow-growing trees (Makouanzi *et al.* 2017). Wood lignin and cellulose contents are negatively correlated (Trugilho *et al.* 1996) and fast-growing trees are expected to produce wood with more cellulose.

Wood properties are also affected by silvicultural practices (Gonçalves *et al.* 2004). A lower planting density reduces competition for light, nutrients and water, thereby affecting the volume and density of the wood produced. Likewise, soil fertilization affects vessel frequency and fibre wall thickness, hence wood density (Lima *et al.* 2010). In addition, the forestry regime governs wood properties. According to Zobel and Buijtenen (2012), the physico-chemical properties of woods of the same age do not usually display any large differences between coppice and/or high forest management. However, Zbonak *et al.* (2007) found that coppice wood is less dense than that produced from a high forest. Many studies have been carried out on eucalyptus coppicing, but mainly focusing on tree growth. Very few studies have analyzed wood properties with this type of management (Zbonak *et al.* 2007, Zobel and Buijtenen 2012). More specifically for *E. robusta*, studies involving high forest wood have mainly focused on physical and mechanical properties (Carvalho *et al.* 2016, Jiofack-Tafokou 2008) and not on the physico-chemical properties of coppice wood, yet properties such as density greatly influence charcoal quality (Gough *et al.* 1989).

The genus *Eucalyptus* was introduced into Madagascar towards the end of the 19th century (Verhaegen *et al.* 2011). *Eucalyptus* trees then became the most widely used exotic species for reforestation in Madagascar and they can now be considered as naturalized. Plantations for timber or energy wood production, mostly eucalyptus and pine, meet the needs of the population. *Eucalyptus* plantations are estimated to occupy 235000 hectares, and *E. robusta* is the most common species with around 147000 ha (Randrianjafy 1999, Verhaegen *et al.* 2011). Although *E. robusta* has been tested in many tropical and subtropical countries, Madagascar is the only country in the world where it is the most widely planted tree species (Rakotomalala 2015). The plantations are found primarily in the Highlands in the middle of the island (Randrianjafy 1999, Razakamanarivo *et al.* 2012). They mostly belong to smallholders (Ramamonjisoa 1999) and are managed as short-rotation (between 2 and 5 years) coppices, without fertilization or any particular forestry cares (Razakamanarivo *et al.* 2012, Razakamanarivo *et al.* 2010, Rakotomalala 2015). Apart from few studies on forestry management (Verhaegen *et al.* 2011), genetic improvement (Rakotomalala 2015), production in terms of wood volume and energy wood (Razafimahatratra *et al.* 2016, Razakamanarivo *et al.* 2012), the physical and mechanical properties of high forest woods (Rakotovaio *et al.* 2012) and the impact of the stand on soil carbon stocks (Razakamanarivo *et al.* 2010), no study has investigated factors that influence the physico chemical properties of coppice woods. Yet, such knowledge is important for more effective management of *E. robusta* plantations in Madagascar to improve wood quality for various uses.

The purpose of the study was therefore to determine how environmental factors and forestry management methods affect the properties of *E. robusta* coppice wood in the Malagasy context. As the genetic diversity of *E. robusta* in Madagascar is very low (Verhaegen *et al.* 2011), we decided to focus on studying how different ecological growing conditions and cutting frequencies affect the properties of *E. robusta* wood.

MATERIALS AND METHODS

Description of the study zones

Five zones in the area of distribution of *E. robusta* plantations were chosen for the study. They were located in the Highlands of Madagascar (Figure 1). Three sites representative of the zones were selected for each of them.

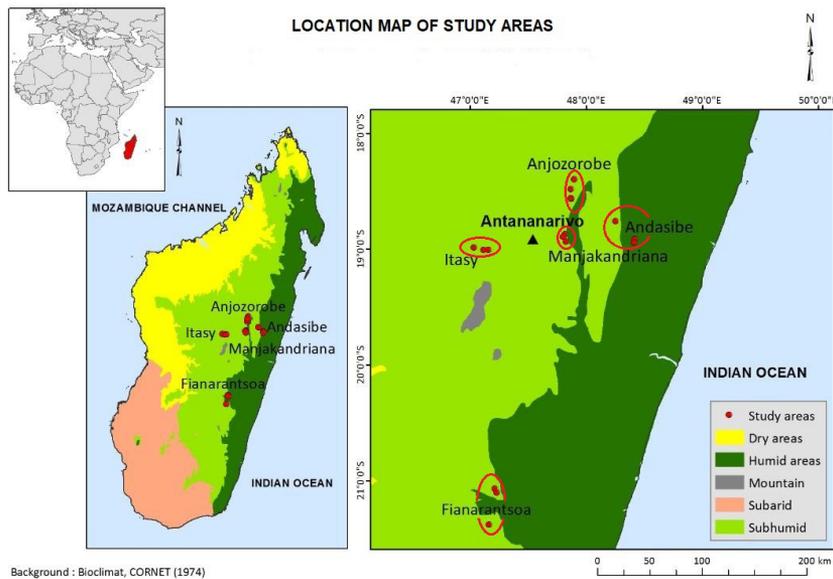


Figure 1: Location of the study zones.

Table 1 lists the characteristics of the study zones according to the environmental factors considered. The study zones differed in terms of elevation, climate and soil texture. Andasibe lies in a humid, lowland region. Anjozorobe, Fianarantsoa, Itasy and Manjakandriana lie in subhumid highland zones. The highest temperature was encountered at Fianarantsoa and the lowest at Manjakandriana. The soils in the 5 zones are somewhat clay-rich and vary in sand and silt rates.

Table 1: Characteristics of each study zone depending on environmental factors.

| Sites | Elevation (m) | Mean annual temperature (°C) | Mean annual rainfall (mm) | Soil texture Sand–Clay–Silt (%) |
|----------------|---------------|------------------------------|---------------------------|----------------------------------|
| Andasibe | 896 - 954 | 19,0 | 1545 | Sandy clay 26 - 35 - 7 |
| Anjozorobe | 1311 - 1387 | 19,1 | 1180 | Clay 10 - 49 - 9 |
| Fianarantsoa | 1096 - 1451 | 20,1 | 945 | Sandy clay 25 - 36 - 7 |
| Itasy | 1364 - 1406 | 19,1 | 1370 | Clay 14 - 46 - 13 |
| Manjakandriana | 1426 - 1457 | 17,6 | 1242 | Sandy clay loamy 26 - 27 - 10 |

Sources: Meteorological service of the Madagascar Ministry of Transport and Meteorology (2007 - 2016).

The environmental factors considered here were elevation, climate (MAT and MAR) and soil properties. The silvicultural parameters were the forestry regime, rotation length and tree density in the plantations.

Soil sampling and analyses

Soil samples were taken at each site from a soil pit (30 cm*30 cm*70 cm), along with 3 auger samples taken around it. The soil texture was determined by sedimentation granulometry using the pipette method (Rzasa and Owczarzak 2013). The finer particles (clay and fine silt) were quantified by decantation. The coarser particles (coarse silt, sand) were separated by dry screening.

The pH was obtained using a solution with a soil/distilled water ratio of 1:2,5 (Conyers and Davy 1988) 0.01 M CaCl₂, and 0.1 M KCl, at dilution ratios 5:1, 2.5:1, and 2:1 solution: soil, were found to be highly correlated over a wide pH range. The regression equations, obtained on a small group of New South Wales soils under strict laboratory conditions, were similar to those reported in comparative studies from Britain (Davies 1971. Organic carbon was measured by the titration method (Walkley and Black 1934) and total nitrogen was measured by quantification on a Kjeldahl continuous flow analyser (SKALAR) (Bradstreet 1954). Available phosphorus was quantified on a spectrophotocolorimeter (Olsen *et al.* 1954) and the cation exchange capacity (CEC) by cobaltihexamine extraction and quantification on an atomic absorption spectrometer (Ciesielski *et al.* 1997).

Making test-pieces

Wood samples were collected from the different coppice-managed *E. robusta* smallholder plantations. For each site in each zone, the suckers were 2 to 10 years old. The age was determined by interviewing the managers. In all, 135 plants were sampled. The plantation spacing differed depending on the stands and the owners, varying from 4m * 4m, to 3m*3m and 3m* 2m.

A stem without any apparent defects was cut from each stump. A log was cut from each stem 1,30 m above the stump. Two 1,5-cm disks were cut from each log. A diametral strip measuring 1 cm wide by 1,7 mm thick was made from one of the disks to assess wood density at a 12% moisture content. The second disk was ground to 4 mm to assess chemical properties (Figure 2).

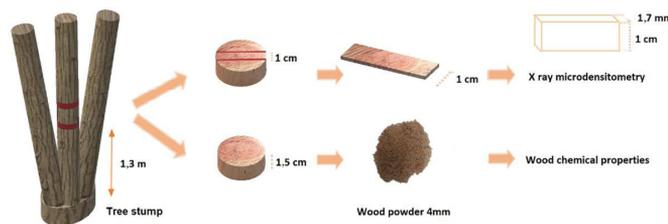


Figure 2: Diagram of the sampling protocol for the characterization of *E. robusta* wood properties.

Wood property measurements

Density

The samples were placed in a climate chamber at 20°C and 65% moisture for 96 h up to stabilization at a theoretical 12% moisture content. The density (d₁₂) of the samples was determined by X-ray microdensitometry on a specific QTRS-01X instrument controlled by QMS Tree Ring System software (Quintek Measurement Systems). For each wood sample, we obtained a density profile along the radius taking measurements every 80 μm.

Wood chemical properties

The chemical properties of the wood, such as extractives (EXT), Klason lignin (KL) and holocellulose

(HOLO) contents were predicted using existing prediction models and near infrared (NIR) spectroscopy spectra measured on the wood samples from the study (Chaix 2012). As for the pre-established models, we used a Bruker Vector 22/N model spectrophotometer. The spectra were measured on the longitudinal surface of all the previously moisture-stabilized samples.

Statistical analyses

Statistical analyses were carried out with the Rstudio version of R software (R Core Team 2017). The relations between environmental factors, silvicultural practices and wood properties were determined with Pearson's coefficient. Some $Y=aX+b$ type linear models were established to show relations between the variables. Variance analyses were used to investigate how the studied factors affected wood properties. The Tukey test was used to determine groups with significant differences at the 5% limit depending on the factors analysed.

RESULTS AND DISCUSSION

Description of wood physico-chemical properties per study zone

The descriptive data for the 12% density and chemical properties of the wood per study zone are presented in Figure 3.

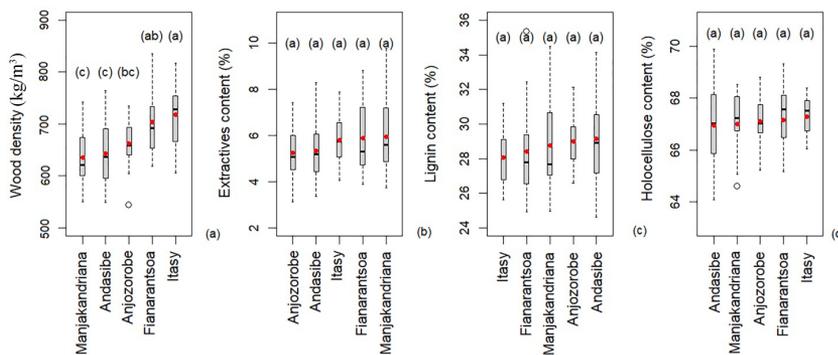


Figure 3: Variability in wood density and chemical properties between and within regions: (a) wood density according to regions, (b) total extractives content according to regions, (c): Klason lignin content according to regions, (d) holocellulose content according to regions.

Density varied from 543 to 836 kg/m^3 and differed significantly between the regions ($p\text{-value}<0,001$). Two groups stood out, with Manjakandriana, Andasibe and Anjozorobe in the first, and Fianarantsoa and Itasy in the second. Based on the factors characterizing the regions, we found no explanation for the formation of these two groups. For example, the Fianarantsoa region was the driest, while the Itasy region was among the wettest.

The extractives, Klason lignin and holocellulose rates varied from 3,1 to 9,8%, 24,6 to 35,3% and 63,8 to 69,9% respectively, but did not differ significantly between the regions ($p\text{-value}>0,05$). These results might be explained by the effects of the different ecological growing factors characterizing each zone, and especially their interactions.

Relations between wood properties, silvicultural practices and environmental factors

The correlations between silvicultural practices, environmental factors and wood properties are described in Table 2.

Table 2: Coefficient of correlation between wood properties and the variables representing silvicultural practices and environmental factors.

| Factors | Wood properties | | | |
|--------------------------|-----------------|-------------------|---------------|---------------|
| | Wood density | Total extractives | Klason lignin | Holocellulose |
| Age of rotation | 0,46** | 0,58*** | 0,72*** | -0,50*** |
| Plantation spacing | -0,11 | 0,01 | 0,10 | -0,06 |
| Zone elevation | 0,15 | 0,13 | -0,12 | 0,10 |
| Mean rainfall (MAR) | -0,18* | -0,15 | -0,07 | 0,05 |
| Mean temperature (MAT) | 0,35** | 0,00 | 0,04 | -0,01 |
| Soil pH | 0,29** | 0,10 | -0,14 | 0,07 |
| Soil nitrogen | -0,35** | -0,02 | 0,14 | 0,01 |
| Soil organic carbon | -0,28** | 0,04 | 0,11 | 0,03 |
| Soil phosphorus | -0,07 | -0,02 | 0,05 | -0,07 |
| Cation Exchange Capacity | -0,13 | -0,17 | 0,11 | -0,04 |
| Clay | 0,15 | -0,03 | -0,01 | -0,03 |
| Silt | 0,13 | 0,12 | -0,1 | 0,08 |
| Sand | -0,17 | -0,03 | 0,06 | -0,01 |
| Wood density | | 0,38** | 0,32** | -0,24* |
| Total extractives | | | 0,65*** | -0,7*** |
| Klason lignin | | | | -0,81*** |

*: significant at 5% limit, **: significant at 1% limit, ***: significant at 0,1% limit.

An analysis of the correlations showed that, out of the factors studied, wood age, MAR and MAT, along with soil chemical properties, such as pH, nitrogen and organic carbon contents, were related to wood density. Only wood age was related to both d12 and the EXT, KL and HOLO contents and therefore appeared to be the most important factor. However, the tree density per hectare, elevation and certain soil properties, such as phosphorus content, cation exchange capacity and texture, did not affect wood physico-chemical properties.

Tree density per hectare had more of an influence on biomass production (Gonçalves *et al.* 2004). DeBell *et al.* (2001) showed for *E. saligna* that a wide spacing (4m * 4m) between trees significantly increased tree diameter, not wood density. Bravo *et al.* (2012) also showed for *E. nitens* that tree spacing as a result of thinning does not affect wood density but tree diameter. Likewise, soil texture governed root development and soil drainage rather than affecting wood properties (Gonçalves *et al.* 2004). In addition, according to Drew *et al.* (2017), variability in wood properties depending on elevation is often associated with the effects of a temperature change. Our results were along the same lines as regards the effect of the mean annual temperature on wood density.

Environmental effect on wood density

Climate effect on wood density

Figure 4 shows the relation between climate and wood density.

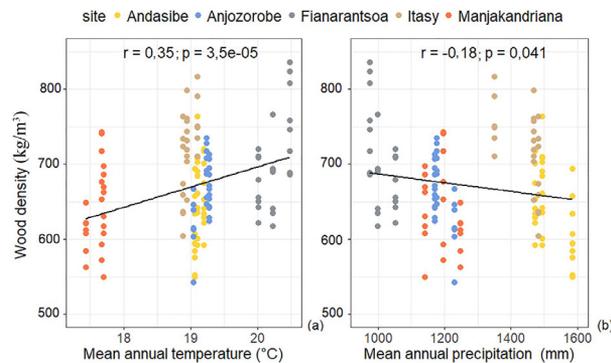


Figure 4: Effect of temperature and rainfall on wood density at the 15 sites considered in Madagascar: (a) wood density depending on the mean annual temperature of the study zones, (b) wood density depending on the mean annual rainfall of the study zones.

Wood density presents some significant differences depending on MAT and MAR (p -value < 0,001). It was positively correlated with MAT and negatively with MAR. In general for eucalyptus wood, wood density has been found to be positively correlated with the temperature of the study zone (Drew *et al.* 2017, Thomas *et al.* 2007). Muneri *et al.* (2007) obtained the same result with *E. dunnii* wood, as did Thomas *et al.* (2007) for *E. camaldulensis*. Temperature affects cambial activity, and thereby the thickness of fibre cell walls and the number and distribution of vessels (Roderick and Berry 2001), hence wood density. A denser wood has fibres with thicker fibre walls, smaller vessels and a lower vessel frequency (Malan 1995). These changes correspond to the adaptation of the tree to heat and water stress. In some warmer regions sap viscosity decreases, making it more fluid (Roderick and Berry 2001). Smaller, or less numerous vessels are better adapted to transporting sap to leaves at higher temperatures (Thomas *et al.* 2007).

As has been presented in the literature, the density of *E. robusta* wood decreases when rainfall increases. Generally speaking, wood produced under water stress is denser (Drew *et al.* 2017). Downes *et al.* (2006), Downes *et al.* (2014) showed that the wood of *E. globulus* increases in response to reduced water availability. Searson *et al.* (2004) found similar results with *E. grandis*, *E. sideroxylon* and *E. occidentalis*, as did Downes *et al.* (2006) for *E. nitens*. Smaller vessels with thicker cell walls are more appropriate for adapting to water stress and resisting embolism risks, and they lead to a higher wood density (Searson *et al.* 2004). It therefore seems that wood from coppices react in the same way as wood from high forest.

Effect of soil chemical characteristics on wood density

Figure 5 shows the relation between certain soil chemical characteristics (pH, organic carbon and nitrogen) and wood density.

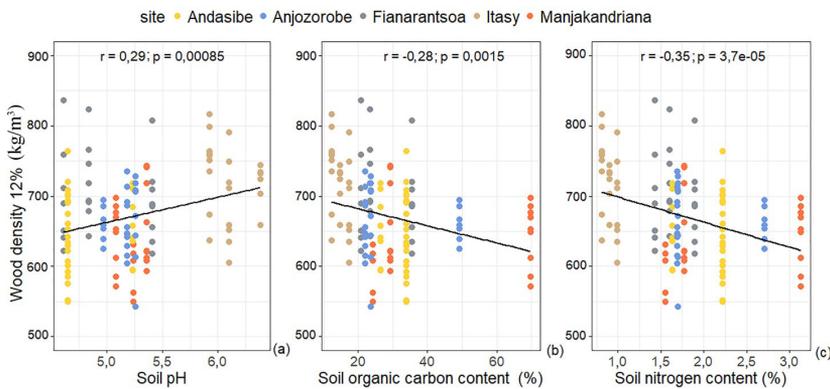


Figure 5: Effects of soil chemical components on wood density for the sites considered in Madagascar: (a) Correlation between wood density and soil pH, (b) Correlation between wood density and soil organic carbon content, (c) Correlation between wood density at 12% moisture content and soil nitrogen content.

Wood density was significantly correlated with the soil pH, nitrogen content (N) and organic carbon content (C). The correlation was positive for pH and negative for the C and N contents. Soil fertility could have an effect on vessel frequency as Lima *et al.* (2010) showed. Thus, the density of hardwood trees is generally lower on more fertile soils, which are conducive to faster tree growth (Cutter *et al.* 2007). Naidoo *et al.* (2007) showed for *E. grandis* that wood density decreases when the soil organic carbon content increases. This leads to an increase in the percentage of wood vessels with thinner fibre walls on an organic carbon-rich soil. Indeed, the soil's water-holding capacity increases significantly with the quantity of organic carbon in the soil (Rawls *et al.* 2003) we used the U.S. National Soil Characterization database and the database from pilot studies on soil quality as affected by long-term management. Regression trees and group method of data handling (GMDH). This reflects the influence of water availability on wood density (Figure 4b).

Some authors found different results for how nitrogen applications affect wood properties. DeBell *et al.* (2001), Downes *et al.* (2014) showed that nitrogen did not have any effect on the wood density of *E. saligna*, *E. globulus* and *E. grandis*. Raymond and Muneri (2000) showed that the effect of nitrogen on the wood density of *E. globulus* varied depending on the site. They also found that the wood density of *E. globulus* was lower on a soil fertilized with nitrogen and phosphorus. Eufrade-Junior *et al.* (2017) showed for *E. urophylla* x *E. grandis* hybrids that wood density increases in response to enhanced nitrogen intake associated with phosphorus and potassium. Thus, the tendency of wood density in relation to soil nitrogen might vary according to the amount applied and depending on the nutrients present or applied with the nitrogen, on the species and on silvicultural practices.

Variability in pH depends on the chemical composition of the soil; a high nitrogen content corresponds to a more acid soil. According to Figure 5c, wood density decreases as the nitrogen content increases. Thus, the less acid the soil is, the higher the wood density will be for *E. robusta*.

Effect of coppice rotation age on wood properties

Figure 6 shows the effect of the rotation length, hence wood age, on the density of *E. robusta* wood and its chemical properties depending on the study zones.

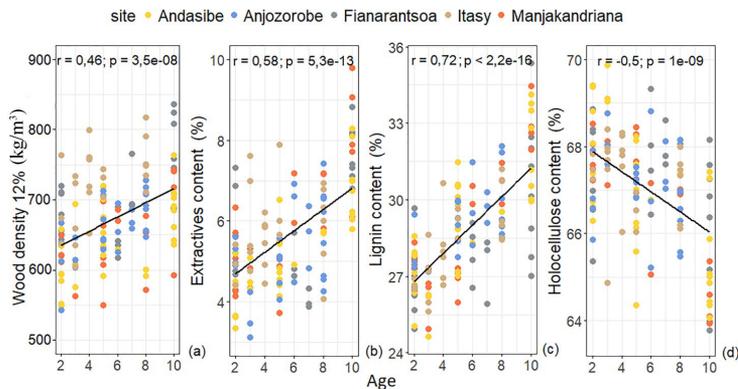


Figure 6: Correlation between the age and properties of *E. robusta* wood: (a) correlation between age and density, (b) correlation between age and extractives content, (c) correlation between age and lignin content, (d) correlation between age and holocellulose content.

Wood density displayed significant differences ($p\text{-value} < 0,001$) depending on the sites and was positively correlated with wood age. *E. robusta* wood became denser with age for all the study zones. Several authors have shown identical results on some eucalyptus species: *E. saligna* from 12 to 48 months (Trugilho *et al.* 1996), *E. grandis* from 2 to 6 years (Sette Jr *et al.* 2012) and *E. urophylla* x *E. grandis* clones from 3 to 7 years (Castro *et al.* 2016). This tendency would appear to come from changes in the cambial meristem and from physiological and mechanical demands resulting from the tree development process (Sette Jr *et al.* 2012). It is reflected in the thickening of fibre walls, notably for mechanical aspects, and a reduction in vessel size (Sette Jr *et al.* 2012) to avoid cavitation, as the distance covered by the sap from roots to leaves is greater.

The total extractives content of wood is positively correlated with age. Severo *et al.* (2006) found that the total extractives content of *E. citriodora* wood tended to be lower in young woods, due to the larger quantity of juvenile wood. One of the characteristics of juvenile woods is their low extractives content as they are still lacking heartwood (Koga 1988). Santana *et al.* (2012) showed similar results on *E. grandis* x *E. urophylla* clones, as did Wehr (1991), during a study on *E. grandis* woods of different ages. The increase in the extractives content in older woods is linked to the wood maturing process, more particularly to duraminization. Extractives, particularly polyphenols, are released during the transition from juvenile wood to mature wood (Trugilho *et al.* 1996).

Klason lignin and holocellulose contents are highly variable depending on the species, the cell layers and even between the different layers of the wall of the same cell. In our study, they were negatively correlated ($r = -0,81$) with each other: the lignin content increased with age and the opposite was the case for holocellulose. Protásio *et al.* (2014) showed the same tendencies on four eucalyptus clones (57 and 69 months old). Hsing *et al.* (2016) showed that the lignin and holocellulose contents of some *E. grandis* x *E. urophylla* clones did not have any clearly defined tendency linked to age. However, Trugilho *et al.* (1996) showed for *E. saligna* that lignin content tended to decrease with age up to 4 years. This was because younger trees tend to have a larger proportion of juvenile wood, which is richer in lignin than mature wood (Koga 1988, Trugilho *et al.* 1996). According to Jankowsky (1979), the juvenile wood period varies depending on the species. It can extend up to 20 years for certain eucalyptus species (Jankowsky 1979). Koga (1988) showed that a trunk can be formed of 85% juvenile wood at 15 years old, whereas it is 10% at 30 years old. The tendency of the lignin content in our study could therefore be explained by the fact that the samples considered mostly consisted of juvenile wood and were therefore richer in lignin.

Consequence of rotation age for production in terms of merchantable wood volume, its density and soil properties

Until now, the optimum *E. robusta* coppice cutting age in Madagascar has been determined based on the

volume of wood produced. Randrianjafy and Deleporte (1995) drew up production tables and proposed optimum ages per site. Yet, it would be interesting to determine the optimum *E. robusta* coppice cutting age taking into account both the increase in wood volume and the variation in basic wood density (Figure 7).

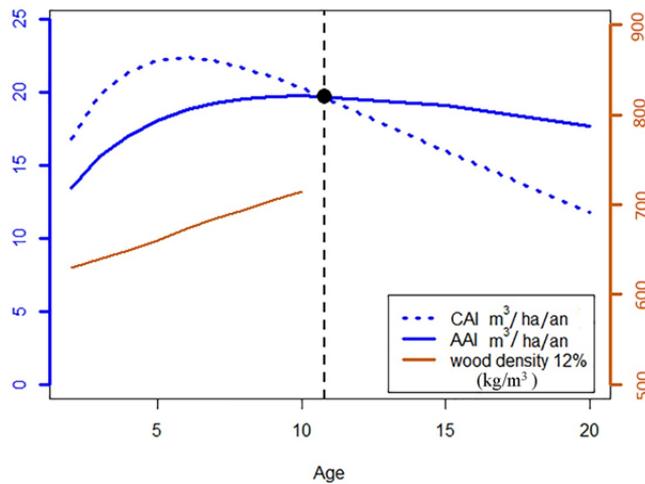


Figure 7: Variability of *E. robusta* wood density and its production in terms of merchantable volume over bark according to age and for an average fertility class (according to Randrianjafy and Deleporte 1995). AAI: (average annual increment in volume): average annual increment in merchantable volume over bark in $\text{m}^3\cdot\text{ha}$, since planting. CAI: (current annual increment in volume): current annual increase in merchantable volume over bark in $\text{m}^3\cdot\text{ha}$; it is the volume produced over a short period (1 year).

For an average fertility class, the current annual increment curve for the merchantable volume of wood per hectare increased up to 5-6 years, decreasing thereafter. The curve for the average increment in merchantable volume of wood per hectare displayed peaks at around 8-9 years. The two curves crossed over in the 11th year, which therefore corresponds to the optimum cutting age for the volume of wood produced. Considering that wood density increases with age, the proposal to cut at 11 years is coherent. Nevertheless, in order to take into account socio-economic aspects whereby *E. robusta* wood is in great demand and the owners often have money problems that prevent them from waiting for a long rotation, the average rotation recommended for *E. robusta* cutting in Madagascar is, in fact, 7 years (Ramamonjisoa 1999). At that age, wood density is around 694 kg/m^3 .

In addition, the rotation age of eucalyptus coppices affects soil physical and chemical properties. The nutrients involved are primarily organic carbon, total nitrogen, exchangeable calcium, exchangeable magnesium and the cationic exchange capacity of the soil (Zhao *et al.* 2014). These nutrients are essential for sucker growth. For instance, the nutrient content of soil decreases after each cutting operation, through exports resulting from coppice logging. Consequently, the more frequent the cutting operations, the more the soil becomes impoverished, leading to weaker sucker growth. In addition, for *E. robusta* in Madagascar, soils are not fertilized between cutting operations. The situation is worsened through the collection of *E. robusta* coppice litter for local domestic energy requirements and fertilizing crop fields.

It can therefore be concluded that the tendency in Madagascar to shorten the coppice rotation age by up to 2-3 years affects not only wood properties, but also those of the soil. The wood produced is less dense, thereby reducing its qualities for use as timber, or for energy purposes. In addition, this type of management reduces soil fertility and, thereby, coppice productivity.

CONCLUSIONS

E. robusta plantations in Madagascar produce denser wood in the hotter regions and on less acid soils. Conversely, wood density is low in wetter zones with soils richer in nitrogen and carbon. Thus, the conditions at Fianarantsoa and Itasy are more suitable for denser wood production, unlike at Manjakandriana and Andasibe. The plantation spacing, elevation of the zone and soil texture do not affect the physico-chemical properties of wood from *E. robusta* trees planted in the Highlands of Madagascar.

The age of wood is the only factor affecting the most important aspects of its chemical composition. The oldest woods have higher extractives and lignin contents, with the opposite being the case for holocellulose. Given the increase in wood volume and its properties required for use as timber or energy wood, the recommended cutting age for *E. robusta* coppices in Madagascar is 7 years old. The current tendency to shorten the coppice rotation length by up to 2 years, and the increase in cutting frequency, have a negative effect not only on the physico-chemical properties of the wood, but also on soil fertility.

A further study is needed to investigate how these silvicultural practices affect the quality and yield of charcoal depending on the physico-chemical properties of the wood. These results provide some important information for greater optimization of production in Madagascar *E. robusta* plantations.

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