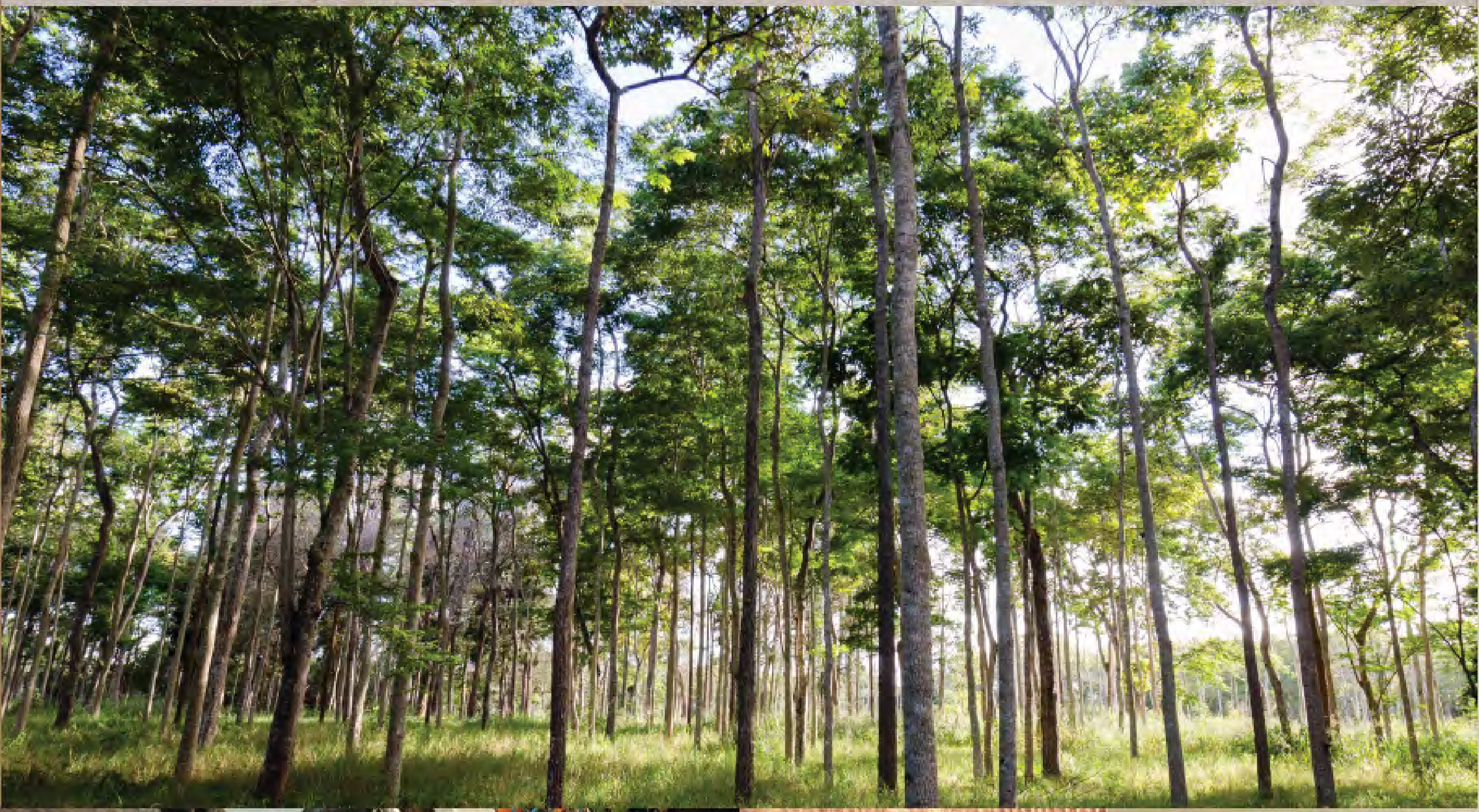
SILVICULTURE AND WOOD PROPERTIES OF NATIVE SPECIES OF THE ATLANTIC FOREST OF BRAZIL

Samir G. Rolim & Daniel Piotto (Editors)



Several researchers have contributed to native species silviculture in the Atlantic Forest. Here, we would like to acknowledge the contribution of two people in particular: Renato de Jesus and Jonacyr de Souza. Renato planned and conducted more than a hundred silvicultural experiments, much of which is portrayed in this book. Jonacyr devoted more than 25 years to measuring all the trees in these experiments.

We extend our thanks to VALE and its employees who work at Vale Nature Reserve in Linhares (ES) for facilitating fieldwork and encouraging this study. This reserve is widely recognized for its contribution to biodiversity conservation and is now making a major contribution to native species silviculture providing data on tree growth and wood quality of Atlantic Forest species. We also thank WRI Brazil, VERENA Project, IUCN Brazil, CIFF, Roberto Waack, Ana Yang and Symbiosis for their valuable support during the writing of this book.

Editors

Silvicultural system with high species diversity

Silvicultural systems for timber production based on mixed plantation of many species, as pictured above, are rare because of the complexity of managing a system where species have different growth rates, cutting cycles, and light and space requirements for growth. However, mixed plantations can ensure that the forest is kept standing without clearcutting, as high species diversity can guarantee successive harvests and bring back functional connectivity, especially in the most degraded landscapes of the Atlantic Forest. It is a system to be targeted for native species silviculture, especially in degraded Legal Reserve areas of the Atlantic Forest.

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Samir G. Rolim & Daniel Piotto (Editors)

EDITORA RUPESTRE

Belo Horizonte

September 2019

preface

Biological evolution has been very generous with the South American continent in expressing its maximum biodiversity. It is estimated that over 15,000 tree species exist in the Brazilian territory. These species evolved under very different climatic and edaphic conditions, from the humid tropics to tropical semi-arid or markedly seasonal regions, seasonally flooded areas, and all the way to more temperate and altitudinal climates. Soil and climatic variability has generated numerous families, genera and species with thousands of variations in all its features. It is highly unlikely that numerous of these distinct traits could not find utility and application for our species, *Homo sapiens*.

However, the model of frontier expansion based on agriculture and livestock since the arrival of Iberian settlers to the present day was based on replacement of native ecosystems with agricultural crops, exotic tree species or pastures. Most of the agricultural research effort in the country over the last 50 years focused on ‘tropicalization’ of crops, grasses and trees, and animal species, all imported from other parts of the world. The relative success of these efforts made Brazil a leading agricultural and forestry power.

Historically, the biome most affected by this development model has been the Atlantic Forest, where just over 10% of the original forest covers remains. Ironically, this biome possibly records the highest diversity of tree species on the planet, registering over 400 different species per hectare in preserved locations in southern Bahia.

Yet, forestry in Brazil relies almost exclusively on only two exotic species - pine and eucalyptus - covering 98% of the total area of plantation forestry. Slowly, this picture begins to change with the cultural and economic valorization of products of our biodiversity, notably of two native tree species - paricá and araucária – though still occupying just over 1% of the area of plantations. This reflects a lack of imagination in designing a tropical mode of development where we actively seek through national science, technology and innovations to harness our unique biodiversity.

Brazil has pledged to reforest 12 million hectares by 2030 as part of its climate change mitigation commitments under the Paris Agreement. To achieve the goal of limiting global warming to less than 2ºC, reforestation can become the main measure of removing billions of tons of carbon dioxide from the atmosphere and storing it in the growing forest not only by 2030, but also throughout the entire length of this century.

This opens up an unprecedented opportunity to implement forestry projects with native species in degraded landscapes. However, native forest species on this scale critically depends on developing scientific studies and field experiments that demonstrate best practices and the financial viability of such endeavors.

Silviculture and Wood Properties of Native Species of the Atlantic Forest of Brazil revisits existing knowledge about practices and results of field experiments of forestry projects with native species in the Atlantic Forest domains, especially in northern Espírito Santo and southern Bahia. The book describes key actors in all sectors of the native species forestry chain. From the necessary research and development, through a series of field experiments, from searching for seeds with genetic diversity to testing with various modes of production, also looking at economic viability and investment needs, and quantifying the carbon sequestration potential and many other economic and environmental benefits that native species silviculture can bring to Brazil and the planet.

This book gives a clear message that the studied and tested modes of silviculture with native species are viable, including agroforestry and restoration systems, pointing out the present and future ways of implementing a modern silviculture based on economic exploitation of species from Brazilian biodiversity, strongly based on science and technology and social participation, bringing in its core not only economic development, but also better quality of life and income for all participants in this effort; in short, sustainable development. The content of this book is rich in information and inspiring for all those who wish to know more about an innovative but quite feasible path to Brazilian forestry and a new forest economy.

Prof. Carlos A. Nobre
April 2018

foreword

I am pleased to commend the timely initiative of the editors Samir Rolim and Daniel Piotto and congratulate them for offering to all of us from the Brazilian forest community the work *Silviculture and Wood Properties of Native Species of the Atlantic Forest of Brazil.* In it is highlighted a set of timber species researched in the extraordinary plantations located in the Reserva Natural Vale, in Linhares, Espírito Santo, Brazil. Although forest researchers have achieved outstanding technical and scientific advances on exotic species introduced in Brazil aiming at supplying raw material for the Brazilian forest industry, the enormous latent qualitative potential of native species, especially those that occur in the Atlantic Forest, cannot be ignored. Its species with timber potential, present in the dense rain forests, in semi deciduous forests, and araucaria forests are significant assets to Brazilian forestry, and devote time to introduce them into the national production process is more than a worthy cause, it is to recognize and value our genetic heritage.

This work, besides focusing on a new vision for the Brazilian forest economy with the participation of native species of the Atlantic Forest as part of a pioneer project, also addresses the theme of their growth and allometry, aiming at the production of wood and biomass for national and international consumption.

Certainly, the experience at Reserva Natural Vale deserves mention as a pioneering and praiseworthy initiative to promote native Brazilian species, but there is still much to do for improving a more effective silvicultural techniques to produce them, to implement a breeding program for the production of higher quality trees, and to provide laboratory conditions for permanent evaluation of the technological characteristics of the wood produced in these plantations.

I am confident that this work will be greatly appreciated by students, professionals, teachers and forest entrepreneurs from around the country.

Prof. Sylvio Péllico Netto
Forest Engineer – UFPR – 1965
April 2018

The book under the title *Silviculture and Wood Properties of Native Species of the Atlantic Forest of Brazil* resulted from a timely idea led by professors Daniel Piotto and Samir Rolim and especially Renato Moraes de Jesus and collaborators who, at a time when everyone was only thinking about plantations and research with fast-growing exotic species, implemented experiments with several native species, that today, almost 40 years later, served as the basis for writing this important work, which certainly brings new knowledge about the researched species.

The Reserva Natural Vale, in Linhares, Espírito Santo, is one of the last well-preserved remnants of the Atlantic Forest biome, thanks to the company's own initiative and the vision of competent and visionary professionals dedicated to planting and caring for native species.

The establishment of permanent plots whose data from successive measurement have already led to important publications; Today, after almost four decades, provided the necessary data for the present work to become reality, involving the participation of numerous authors / co-authors who brilliantly made it available to the general public.

This book contains important input and information on silvicultural aspects, growth and production, dendrometric relationships and analysis involving wood technology, a totally innovative field for the species studied. It also discusses in its first chapter the state of the art of native species silviculture of the important, once vast and lush, Atlantic Forest biome. In its final chapter are presented more detailed studies of some of the main studied species containing unpublished data on growth and wood quality.

Information and research on native species for reforestation such as those contained in this work are rare or at least infrequent. To end this presentation, I, as one of the oldest Forest Engineers in Brazil, congratulate the editors and all authors and coauthors for the outstanding contribution made available to forest science.

Prof. Sebastião do Amaral Machado
Forest Engineer – UFPR – 1965
May 2018

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summary

1. AN OVERVIEW OF SILVICULTURAL SYSTEMS WITH NATIVE SPECIES IN THE ATLANTIC FOREST OF BRAZIL

DANIEL PIOTTO, SAMIR G. ROLIM, FLORENCIA MONTAGNINI AND MIGUEL CALMON

1. Introduction

Strategies aiming to facilitate the recovery of forest cover in degraded tropical landscapes have been based on both the management of secondary forests and the establishment of forest plantations with native and exotic species (Ashton et al., 2001; Kanowski et al., 2005). Despite the high resilience and great contribution of secondary forests to the recovery of tropical landscapes (Chazdon et al., 2016), many of these areas have exceeded ecological thresholds, making the recovery of forest cover difficult (Melito et al., 2017). Because of its history of deforestation and forest degradation, the Atlantic Forest is a clear example of a degraded landscape. Although it has high tree species richness and endemism rates when compared to other tropical forests (Gentry, 1992; Thomas et al., 1998; Myers et al., 2000), after centuries of anthropogenic disturbances, only 12.5% of the original forest cover remains as small fragments dispersed in the landscape (Ribeiro et al., 2009). Estimates indicate that at least one third of Atlantic Forest tree species may be threatened by the high landscape fragmentation and the local extinction of birds and mammals (Silva & Tabarelli, 2000; Canale et al., 2012).

Forest plantations with native species play an important role in promoting sustainable landscapes in tropical regions. Due to their high growth rates, forest plantations may meet a large part of the global and regional timber market demands, decreasing the pressure on areas of natural forest (Sedjo, 2001; Paquette & Messier, 2010). However, the use of native species of high commercial value in plantation-based forestry is still very limited, and the remaining natural tropical forests are still deliberately exploited for the selective extraction of native species of high commercial value.

Silviculture with native tree species is an important wood production strategy, and provides several environmental services, such as the sequestration of atmospheric carbon, conservation of soil and water, maintenance of biodiversity, and recovery of degraded areas (Lamb, 2014). The present chapter presents an overview of silvicultural systems in the Atlantic Forest and indicates the main challenges of developing native species reforestation projects in this biome.

2. Silvicultural Trials with Native Species of the Atlantic Forest

Traditionally, native forest species have always been extracted from natural forests. However, while the supply of native timber species has been decreasing significantly in many tropical regions worldwide, the demand for these timbers is increasing (Sohngen & Tian, 2016). The use of native species in reforestation programs is minimal, and plantations of exotic species predominate both for industrial uses and for rural development projects (Evans & Turnbull, 2004; Lamb, 2014). Native timber extraction from natural forests in the Atlantic Forest was banned by decree at the beginning of the 1990s. Since then, almost all legal native timber consumed in the region is sourced from the Amazon region. As a response to the signing of international climate change treaties, several silvicultural projects were established with the ambitious goal of restoring and reforesting millions of hectares of degraded landscapes. However, the use of native species is still restricted primarily to ecological restoration, with the area occupied by native species plantations being almost insignificant. Until 2016, the area occupied by native species plantations for wood production was a little over 100,000 ha in Brazil, whereas more than 98% of the total planted area in the country was composed of exotic species, such as eucalypt and pine (IBA, 2017).

The use of native species in Brazilian silviculture was initially discussed at the beginning of the 20th century (Andrade, 1941), and the performance of Atlantic Forest native species has been studied since the 1930s. Here, we highlight the studies performed in the states of São Paulo and Paraná (Koscinski, 1934; Gurgel Filho, 1953; 1957) on species from mixed ombrophilous forest (*Araucaria angustifolia* and *Mimosa scabrella*) and the Cerrado and Atlantic Forest (*Stryphnodendron adstringens, Dimorphandra mollis*, and *Pterodon pubescens*).

Several trials with native species were set up since the 1960s, and a summary of these trials was presented in the National Congress of Native Species in 1982. Monteiro et al. (1982), for example, reported the performance of *Araucaria angustifolia* at 14 years of age, and recommended the best provenances for this species. Several provenance and progeny trials had already been established for the native species *Zeyheria tuberculosa* (Viana, 1982), *Dipteryx alata* (Siqueira et al., 1982), *Araucaria angustifolia* (Gianotti et al., 1982), *Myracrodruon urundeuva, Pterogyne nitens, Peltophorum dubium*, and *Machaerium villosum* (Nogueira et al., 1982a). Several trials were also established to test the effects of different spacings in plantations of *Peltophorum dubium* (Coelho et al., 1982), *Centrolobium tomentosum* (Nogueira et al., 1982b), *Ocotea porosa* (Souza et al., 1982), *Cariniana legalis* (Zanatto et al., 1982), and *Myroxylon peruiferum* (Nogueira et al., 1982c). Some mixed plantation trials were also reported at this congress (Nogueira et al., 1982d), and the behavior of pure forest plantations older than 20 years of age that had been established in the 1950s or 1960s was discussed for several species: *Centrolobium tomentosum* (Gurgel Filho et al., 1982a), *Esenbeckia leiocarpa* (Gurgel Filho et al., 1982b), *Peltophorum dubium* (Gurgel Filho et al., 1982c), *Hymenaea courbaril* var. *stilbocarpa* (Gurgel Filho et al., 1982d), *Libidibia ferrea* (Gurgel Filho et al., 1982e), *Balfourodendron riedelianum* (Gurgel Filho et al., 1982f), *Platycyamus regnellii* (Gurgel Filho et al., 1982g), *Aspidosperma polyneuron* (Gurgel Filho et al., 1982h), *Joannesia princeps, Cedrela fissilis, Copaifera langsdorffii, Ocotea porosa, Machaerium villosum*, and *Aspidosperma olivaceum* (Gurgel Filho et al., 1982i).

This summary of the trials performed until the early 1980s shows that experimentation with native species is well established, and several species that had never been used for silviculture presented good growth and adaptation to degraded lands. Experimental plantations were also established in the south of Bahia by Ceplac, with dozens of different native species with timber potential (Vinha & Lobão, 1989), and in the north of Espírito Santo by the company Vale do Rio Doce (Mascarenhas Sobrinho, 1974). In trials run by Ceplac in Porto Seguro, in addition to growth studies on native forest species, studies were also performed to estimate the impact of native forest species cultivation on the recovery of degraded soils (Montagnini et al., 1994, 1995). In the same period, trials with some tree species were also established by the FAO/IBDF in the Bragantina region, state of Pará (Albrechtsen,1975), with some species in the Tapajós Plateau (Yared et al., 1980), and almost 100 trials were established by Embrapa, especially in the state of Paraná (Carpanezzi, 1982). Most of the results of these trials were summarized by P.E. Carvalho in his work over five volumes, which included hundreds of species. Other trials were established in the states of Paraná (Silva & Torres, 1992) and Espírito Santo (Jesus et al., 1992), from which several reports were published with different approaches to native species forestry, especially regarding genetic improvement (Sebbenn et al., 2002; Freitas et al., 2006; Costa et al., 2009). However, the use of native forest species in reforestation projects in the Atlantic Forest is still very limited. This is partially due to both the lack of public and private investment in silvicultural technology for species native to the region, and the absence of lines of credit that encourage farmers to use native species in reforestation projects.

3. Monoculture and Mixed Plantation

The great majority of tropical forest plantations are monocultures of a small number of different species (FAO, 2015). Monocultures dominate forestry systems because they have some advantages relative to mixed plantations, such as the concentration of resources on the growth of a single species, simplicity of seedling production practices, ease of plantation establishment and management, and production of uniform harvests (Evans & Turnbull, 2004). On the other hand, monocultures have been criticized due to their negative impacts on environmental quality, limited provision of environmental services, and because they do not produce a variety of products that were traditionally extracted from native forests by local populations. In Brazil, the two native species most often planted for wood production, *Schizolobium amazonicum* (approximately 90,000 ha) and *Araucaria angustifolia* (approximately 11,000 ha), are grown in monoculture, and make up only 1.27% of the total planted forest area in Brazil (IBA, 2017).

Many studies have shown that the use of mixed plantations, with at least two species, is the most appropriate strategy for the provision of a variety of products and environmental services, such as the protection and conservation of biodiversity, restoration of degraded areas, and increased resilience to climate changes (Keenan et al., 1999; Parrotta & Knowles, 1999; Cusack & Montagnini, 2004; Montagnini & Piotto, 2011; Lamb, 2014). Mixed plantations on a commercial scale are still in their early stages in Brazil. One of the few examples is run by the company Symbiosis, which has approximately 1,000 ha planted with multiple species in southern Bahia. This area is predicted to increase by an order of magnitude over the coming years.

An important advantage of mixed plantations over monocultures is their higher yield. Many recent studies showed a positive relationship between the number of species and yield in native and planted forests, both at a global (Liang et al., 2016) and local scale (Piotto, 2008; Forrester & Pretzsch, 2015). It is widely accepted that the yield of mixed forest plantations will depend on the appropriate selection of species planted in intercropping systems by considering their functional characteristics and ecological interactions, as well as silvicultural aspects.

Trials with extensive data collection for yield comparison between monocultures and mixed forest plantations are rare in tropical regions, because they require a high initial investment and long period of time to obtain results. Rarer still are trials that allow the estimation of competition indices to determine the best combinations of species depending on tree spacing (Kelty, 2006; Vanclay, 2006).

Mixed plantations may have positive or negative effects on tree growth. In an system with two species, when compared to the performance of the same species in monoculture, negative effects are expected when interspecific competition is higher than intraspecific competition. Positive effects can be expected when intraspecific competition is higher than interspecific competition or when one species positively affects the growth of the other (facilitation). In mixed plantation with two or more species, several of these processes may occur simultaneously, and the stand yield will depend on the number of species and interactions between them. In fact, understanding the ecological interactions between the species used in mixed plantations is central to the definition of the best intercropping models. However, literature on ecological interactions in forest plantations is still scarce. The best documented case is the reported positive effect of nitrogen fixing trees on the yield of mixed forest plantations (DeBell et al., 1989; Parrotta, 1999; Binkley et al., 2003; Piotto, 2008; Lamb, 2014). In addition to favoring the growth of other tree species, nitrogen fixing species are adapted to grow in degraded areas and poor soils, which make up a good part of the areas currently available for reforestation in the Atlantic Forest.

New silvicultural systems in the Atlantic Forest should explore the benefits of ecological interactions between different species. Therefore, mixed plantations may play an important role in improving the environment and local livelihoods, increasing forest productivity, promoting additional ecological benefits, and increasing the resilience of production systems to adverse climate conditions.

Figure 1. Pure plantation of *Pterygota brasiliensis* in Linhares (ES), 38 years old. Photo: Flávio Gontijo.

Figure 2. Enrichment plantation of *Dalbergia nigra* in a secondary forest in Linhares (ES), 40 years old. Despite lower growth rates when compared to full sun plantations, the trees present straighter trunks. Photo: Flávio Gontijo.

Figure 3. Mixed plantation with three species, *Paratecoma peroba, Zeyheria tuberculosa*, and *Dalbergia nigra*, in Linhares (ES), 27 years old. Photo: Flávio Gontijo.

Figure 4. Agroforestry System with banana, cocoa, *Hevea brasiliensis* (rubber tree), and *Cordia trichotoma* in Ilhéus (BA), 14 years old. Photo: Daniel Piotto.

4. Enrichment Systems

Traditionally, forestry projects have focused on tree planting on degraded land and in areas that are not apt for intensive agricultural cultivation. Recently, planting in already forested areas has been adopted in some cases for the provision of products and environmental services. Several enrichment techniques with the aim of increasing the wood stock in secondary and overexploited forests have been tested in tropical regions (Ramos & del Amo, 1992; Montagnini et al., 1997; Guariguata, 2000; Rappaport & Montagnini, 2014). Because many commercially important and threatened species are rarely found in secondary forests in very degraded landscapes, secondary forests in these areas have low economic and biodiversity values. To increase the value of forested areas and guarantee that they are not converted to uses other than forest, management alternatives that promote the growth of commercial or threatened species in these areas should be investigated.

The use of enrichment plantations is quite complex, since it requires ecological and silvicultural information on the species that will be used and managed. Knowledge about the shade tolerance of each species to be planted is essential to prescribe thinning, and determine the light levels that should be maintained through canopy opening, to guarantee the full growth of trees, since growth rates tend to decrease after the early years of a plantation (Keefe et al., 2009). Enrichment plantations are recommended for species that are not productive in open areas, such as late-succession species, shade-tolerant species with high timber value, and shade-tolerant species with trunk formation problems in open areas.

Although forest enrichment is traditionally performed in natural forests, some enrichment trials have been performed in forest plantations of exotic species (Ashton et al., 1997; Millet et al., 2013). Similar to natural forests, forest plantations may improve physical and chemical soil characteristics and promote microclimate changes that may favor the establishment and growth of non-pioneer tree species (Keenan et al., 1997; Cusack & Montagnini, 2004; Kaewkrom et al., 2005). Ashton et al. (1997), along with other forest enrichment trials in native forests, showed that many tropical tree species show better performance in non-open areas (Montagnini et al., 1997; Piotto, 2007), indicating the importance of enrichment systems for their cultivation.

In Brazil, there are still few studies on the use of adult forest plantations as habitats for the establishment of non-pioneer tree species. A recent study investigated the restoration potential of 21 native tree species used for the enrichment of rubber plantations in southern Bahia and showed the importance of light availability and management practices to maintain the good performance of the planted species (Rappaport & Montagnini, 2014). However, considering the great extension of eucalypt and pine cultivated areas in the Atlantic Forest, testing enrichment methods with native species in these areas could be an interesting approach.

5. Agroforestry Systems

Many native and exotic tree species are used in silvicultural systems in tropical regions, and practically all current wood production originates from natural forests or silvicultural systems designed exclusively for solid wood production (Wadsworth, 1997; Evans & Turnbull, 2004; FAO, 2015). Although agroforestry systems occupy large areas in tropical regions, little of the potential for high-quality solid wood production and carbon sequestration in these areas is currently utilized (Montagnini & Nair, 2004).

The tree component of agroforestry systems has been traditionally managed to favor associated crops by providing shade, comfortable temperature and microclimate, nutrient cycling, and other services aimed at guaranteeing the productivity of agricultural crops (Ashton & Montagnini, 2000). However, the growing demand for wood forest products and the critical situation of wood reserves in natural forests has created the urgent need for massive reforestation programs to meet the current and future demands for solid wood (FAO, 2015). In addition to forest plantations, plantations intercropped with other crops in agroforestry systems present great potential for wood production (Somarriba et al., 2014). The increasing adoption of agroforestry systems in tropical regions has led to an increase in the number of studies quantifying the growth, yield, and carbon sequestration potential in agroforestry systems with timber forest species (Montagnini, 2017).

In Brazil, several publications promote the implementation of agroforestry systems in different regions: "Agroforestry Manual for the Amazon" (REBRAF; Dubois et al., 1996), "Ecological Restoration with Agroforestry Systems" (Miccolis et al., 2016), and "Agroforestry Manual for the Atlantic Forest" (May & Moreira Trovatto, 2008). The latter, specifically dedicated to the Atlantic Forest, contains general information about agroforestry systems and details about the most widely practiced systems in the Atlantic Forest, including agroforestry homegardens, shaded cocoa and coffee agroforestry systems, banana agroforestry systems, yerba mate agroforestry systems, faxinal systems, citriculture agroforestry, taungya systems, and silvopastoral systems. The establishment and management of agroforestry systems, their financial viability, available agroforestry extensions, and public policies for agroforestry systems in the Atlantic Forest are also discussed, with numerous examples of agroforestry experiences in this region (May & Moreira Trovatto, 2008).

In the Amazon, there are examples of fully consolidated agroforestry systems that have been generating income and other benefits for farmer for decades, such as the Mixed Agricultural Cooperative of Tomé-Açu (Cooperativa Agrícola Mista de Tomé-Açu; CAMTA; state of Paraná) and the Dense and Intercropped Reforestation Project (Reflorestamento Econômico Consorciado e Adensado; RECA; Nova Califórnia, state of Rondonia) (Barros et al., 2009; Oliveira et al., 2016).

Overall, agroforestry systems are already relatively well disseminated in Brazil, and advanced in terms of their applicability and accessibility by farmers. Currently, agroforestry systems have the potential to become one of the main strategies to achieve the recovery goals for degraded areas in Brazil. However, there is still room for the development of tree management, harvesting and exploitation technologies to maximize the production of wood products in agroforestry systems.

6. Restoration Systems

Since the 1980s, planting systems for the restoration of degraded forest areas have been adopted to protect and provide environmental services. In Brazil, there is a high demand for restoration projects in the Atlantic Forest, due to pressure from the civil society and government for the enforcement of environmental legislation. These restoration projects try to establish a high tree species diversity (Rodrigues et al., 2009), usually in open and isolated areas, where it is unlikely for natural secondary forest succession processes to occur.

Many restoration designs were developed over the last 35 years, e.g., the random distribution of native tree seedlings (Biella, 1981), distribution of native species based on the composition of adjacent forests (Joly et al., 2000), and - the most adopted design - distribution of a combination of pioneer and non-pioneer species (Kageyama, 1986; Kageyama & Castro, 1989). The latter assumes that the shade resulting from fast-growing pioneer species will provide adequate conditions for the growth of non-pioneer species.

In practice, the restoration methods promoted in the Atlantic Forest are little adopted by farmers due to the high costs of establishment and maintenance, as well as the lack of direct benefits to farmers and other beneficiaries. One of the alternatives found to enable restoration is to allow economic activity through the exploitation of timber and non-timber products in restored areas (Brancalion et al., 2012; Latawiec et al., 2015). In these systems, exotic species, such as eucalyptus, are usually planted in alternative rows with native forest species, and the exploitation of eucalyptus for up to 6 years generates sufficient income to cover a part of the total cost of restoration. Forestry companies may have great interest in this type of system, which can function as a sort of land leasing strategy, without farmers needing to mobilize their own resources. Examples of these systems are being established in the states of Bahia and Espírito Santo, in partnerships with forestry companies, research institutions, and the Atlantic Forest Restoration Pact. Because the model covers only a part of the costs of restoration, systems that allow the continuous management of timber and non-timber resources should also be studied in areas undergoing restoration, which would guarantee not only the establishment of new areas of restoration, but also their maintenance as forests.

Considering the huge area available for forest restoration, forestry systems using native species, which combine biodiversity restoration with the production of wood and other products in polycyclic systems with successive harvests, have the potential to rehabilitate unproductive areas, promote landscape restoration, provide direct economic return to farmers (including those that are less capitalized) (Lamb et al., 2005; Lamb, 2014), and increase the adoption of native species silviculture.

7. Conclusions

Despite more than a century of forestry in the Atlantic Forest, there is still much to develop in terms of species, production systems, and forest management practices. Forestry in the Atlantic Forest still remains restricted to a small number of exotic species grown in pure plantations. This low species diversity has resulted in a low diversity of products originating from forest plantations. This has promoted the continuous entrance into the market of large amounts of wood from natural forests to meet the demand for solid wood from the main urban centers in Brazil. Furthermore, the silvicultural model currently in place in the Atlantic Forest is the target of constant criticism by the civil society because it does not provide a range of products and environmental services to make it more attractive, which would encourage small- and medium-scale farmers to engage in native species silviculture.

The great challenge of silviculture is to guarantee the provision of forest products and environmental services in a time of global climate change and increasing global hunger eradication and food security efforts. For this, the future of silviculture should be based on increasing the number of forest species planted and the diversity of production systems, including agroforestry and silvopastoral systems. The diversification of production systems and use of native tree species integrated with a landscape management perspective increases the resilience to climate change and may improve the quality of life of local populations. However, a shift in native species silviculture in the Atlantic Forest depends on the support of public and private research institutions to build the necessary knowledge to decrease the risks and increase the economic returns from planting native tree species.

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2. BIOMETRIC MODELS FOR MIXED-SPECIES PLANTATION IN THE NORTH OF ESPIRITO SANTO, BRAZIL

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1. Introduction

There are several mathematical models that describe the ratio between the growth of one part of an organism in relation to that of another part or the whole (Gould, 1966). Tree diameter (D) and height (H) measurements are essential components of descriptions of the physiological aspects, structure, and dynamics of planted or natural forests (McMahon & Bonner 1983), and they are also the basic morphological variables needed for the study of these growth ratios.

Biometric models are used to describe the H:D ratios of trees (Curtis, 1967; Fang & Bailey, 1998; Batista et al., 2001; Feldpausch et al., 2011; Soares et al., 2011; Scaranello et al., 2012; Ré et al., 2015; Mehtätalo et al., 2015; Vibrans et al., 2015), estimate the volume of commercial wood (Scolforo et al., 1994; Batista et al., 2004; Chichorro et al., 2003; Akindele & LeMay, 2006; Rolim et al., 2006; Alegria and Tomé, 2011; Soares et al., 2011; Ré et al., 2015), and quantify the biomass of trees (Nelson et al., 1999; Chambers et al., 2001; Nogueira et al., 2008; Djomo et al., 2010; Chave et al., 2014; Lewis et al., 2013; Lang et al., 2016).

There are many models available in the literature, from very generic models to those specifically designed for sites, forests and species. Generic models, based on tree data from several locations, are the most frequently used. However, such models are sensitive to forest typology, climatic variables, altitude, and soil (Feldpausch et al., 2011; Scaranello et al., 2012; Chave et al., 2014; Vibrans et al., 2015), as well as to the phenotypic plasticity of the same species in different regions (Huang et al., 2000). Thus, generic models are subject to systematic errors that can lead to predictions that vary by more than four times from real values at the locality level, whereas using local models has the potential to reduce the uncertainties affecting predictions and thus reduce errors (Chave et al., 2014).

In foresty, the majority of biometric models have been developed for natural forests or monocultures of the most commonly harvested species, such as eucalyptus, pine, teak, etc. However, there is still a general lack of models for native species in silvicultural plantations (although for exceptions in Brazil see: Tonini et al., 2005; Soares et al., 2011) or even in forest restoration projects (Miranda et al., 2011; Ré et al., 2015). The difficulty in generating models for native species in plantations in the Atlantic Forest of Brazil is related to the relatively limited area that is dedicated to the silviculture of native species when compared to that used for the silviculture of exotic species, as well as to the small number of native species that are used in commercial plantations.

In this study, the data of 168 trees in native species silvicultural plantations in the north of Espirito Santo, Brazil, were used to test models describing the H:D ratio, volume of commercial wood, and aboveground biomass of the individual trees.

2. Methodology

2.1 Study Area

The Vale Natural Reserve covers about 23,000 hectares and is located in the North of Espirito Santo, Brazil. The terrain within the reserve is all located over a similar altitudinal range, mainly between 30 and 60 m. The climate is considered seasonal and the forest vegetation can be classified as a Perennial Seasonal Forest. For the period from January of 1975 to December of 2004, the mean annual rainfall was equal to 1227 mm (standard deviation of ± 273 mm), and the mean annual temperature was 23.3°C, with small variations during the year between 20.0°C and 26.2°C (means of the annual minima and maxima). The mean annual relative humidity was 85.8%, also with small variations during the year between 82.2% and 89.2% (Rolim et al., 2016).

2.2 Data Collection

Several forestry research projects were established from the late 1970s to the early 1990s within a small, approximately 700-ha part of the reserve, which included enrichment plantations (in secondary forests), open-field mixed plantations, and pure plantations. The latter included some experiments that constituted tests of spacing, provenance, and progenies of more than 100 tree species of the Atlantic Forest of Brazil and others tropical countries.

The data used for this study were collected in 2005 and 2006, when 200 trees of 10 species of the Atlantic Forest were cut in these silvicultural plantations, which consisted of 20 trees per species. Thirty-two trees were excluded from analyses for not having satisfactory H:D ratios for silvicultural plantations, which were generally trees with short commercial stem of approximately 3 m height and high dbh (diameter at breast height, at 130 cm height) values, with some trees' dbh up to 30 cm. Such trees would thinned in well-managed silvicultural plantations.

At the cutting date, the 168 trees used in the analyses were of 15 to 30 years of age and had dbh ranging from 5 to 40 cm, with total heights of 3.3 to 24.4 m and commercial stem heights of 1.6 to 17 m. The 10 species were: *Astronium graveolens, Libidibia ferrea, Cariniana legalis, Cordia trichotoma, Joannesia princeps, Pteropcarpus rohrii, Pterygota brasiliensis, Schizolobium parayba, Handroanthus serratifolius* and *Zeyhera tuberculosa*.

The volume of the felled trees were measured by the Smalian method and samples of wood discs were obtained to determine the density of the wood. The methods for collecting these data were described in detail by Vismara (2009). With these data, the models of biomass, commercial volume, and H:D ratio were fitted for all of the species studied.

2.3 Tested Models

The data collected were then used to study hypsometric models (which were used to describe the H:D ratio), commercial volume models, and total biomass models for individual trees (Table 1), most of which were cited in studies by Huang et al. (1992), Kiviste et al. (2002), and Mehtätalo et al. (2015). Two nonlinear volumetric models and five nonlinear models of biomass were tested, from the general formula described in McRoberts & Westfall (2014):

$$Y = \beta_0 \cdot X_1^{\beta_1} X_2^{\beta_2} \dots X_p^{\beta_p}.$$

The volumetric models (with commercial stem height and dbh variables) used were those of Spurr (1952) and Schumacher-Hall (1933), and the biomass models were also basic variations of the volumetric models described by these same studies that contained three predictor variables (total height, dbh, and wood density) individually or in combination (Table 1).

The data used for analyses came from trees of different sizes, and it is common for the variance of such data not to be constant across sizes due to the increasing diameters affecting the distribution of errors in the hypsometric, volumetric, and biomass models. Several methods have been recommended to correct for this heterogeneity of variances (heteroscedasticity), such as data transformation and weighted regression, while maintaining the assumption of error normality (Cunia, 1964; Sprugel, 1983; Carrol & Ruppert, 1988; Parresol, 1999).

However, according to Zuur et al. (2009) it is important for such heterogeneity in the data to be incorporated into the models tested. The use of generalized linear models can do so by allowing model coefficients generated with generalized least squares methods to be estimated, while assuming a distribution of errors of any exponential family and modeling the variance without changing the original scale of the variables (Nelder, 1991), therefore, this is what we did in this study.

All analyses were performed using R software (R Core Team, 2018), wherein the modeling of variance was done with the *varPower* argument of the gnls function (generalized nonlinear least-squares) of the nlme package (Linear and Nonlinear Mixed-Effects Models), originally developed for *S* and *S-Plus* (Pinheiro & Bates, 2000) and adapted for R (Pinheiro et al., 2018). The *varPower* argument represent a power variance function structure with some covariates. The form is: $s^2(v) = |v|^\wedge(2*t)$, where *v* is the covariate and *t* is the estimated coefficient.

2.4 Model Selection

The Akaike information criterion (*AICc*, Hurvich & Tsai, 1989) was used to select the best model. The lowest *AICc* value usually indicates the best model out of all those tested, but other models can sometimes be selected as equally plausible. To take this into account, the difference (Δ_i) between the *AICc* value of each model and that of the best model (i.e. the one with the lowest *AICc* value among the models tested) was calculated. Models with $\Delta_i < 2$ can be considered plausible, and the smaller the Δ_i value, the greater the plausibility of a model; therefore all models should be carefully evaluated based on Δ_i values during the selection of the best one (Burnham & Anderson, 2002).

The Akaike weight, W_i, which is the probability that the model is correct considering all of the models used (Burnham & Anderson, 2002), was also computed for each model. The division of most of the overall weight (which adds to 1.0) between two or more models also provides probabilistic evidence for or against the superiority of the model with the lowest *AICc* and each other model compared.

When more than one model is plausible, the choice among plausible models can be guided by the biological interpretation of model properties, convenience, or personal preferences (Curtis, 1967). However, in any case it is necessary that a good model be parsimonious (i.e. have fewer parameters) and have a good predictive capacity to extrapolate beyond the data used for modeling whenever possible.

Therefore, to select the best model the following

Table 1. Hypsometric, volumetric, and biomass models fitted for ten tree species in silvicultural plantations in the north of Espirito Santo, Brazil. The symbols β_0, β_1, β_2, and β_3 are the coefficients estimated by each model; D is the diameter (cm) at breast height (130 cm); ρ is the wood density in g/cm³; HS is the commercial stem height (m); HT is the total height (m); VS is the stem volume; and AGB is the total aboveground biomass in kg. In hypsometric models, H can be HS or HT.

	Model	Equation
HYPSOMETRIC	Richards (1959, Mitscherlisch I, 1919)	$H = \beta_0(1 - exp^{-\beta_1 D})^{\beta_2}$
	Weibull (1951, Fisher & Tippett, 1928)	$H = \beta_0\left(1 - exp^{-\beta_1 D^{\beta_2}}\right)$
	Monomolecular (Weber, 1891)	$H = \beta_0\ (1 - \beta_2 exp^{-\beta_1 D})$
	Meyer (1940)	$H = \beta_0\ (1 - exp^{-\beta_1 D})$
	Logistic (Verhulst, 1838))	$H = \beta_0 /(1 + \beta_2\ exp^{-\beta_1 D})$
	Hosffeld IV (1822)	$H = \beta_0 /(1 + \beta_2\ exp^{-\beta_1 \ln(D)})$
	Gompertz (1825)	$H = \beta_0 exp^{-\beta_2 \cdot exp^{(-\beta_1 D)}}$
	Naslund (1937)	$H = (D /(\beta_0 D + \beta_1))^2$
	Curtis (1967)	$H = \beta_0(D/(1 + D))^{\beta_1}$
	Power (Arrhenius, 1921)	$H = \beta_0 \cdot D^{\beta_1}$
	Korf (1939)	$H = \beta_0\ exp^{-\beta_1 D^{-\beta_2}}$
	Terazaki (1915, Schumacher, 1939)	$H = \beta_0\ exp^{-\beta_1 D^{-1}}$
VOLUME	V1. Spurr	$V_S = \beta_0 . (D^2 H_S)^{\beta_1}$
	V2. Schumacher-Hall	$V_S = \beta_0 \cdot D^{\beta_1} H_S^{\beta_2}$
BIOMASS	Model 1	$AGB = \beta_0 \cdot (D^2 H_T \rho)^{\beta_1}$
	Model 2	$AGB = \beta_0 \cdot (D^2 H_T)^{\beta_1} \rho^{\beta_2}$
	Model 3	$AGB = \beta_0 \cdot (D^2 \rho)^{\beta_1} H_T^{\beta_2}$
	Model 4	$AGB = \beta_0 \cdot D^{\beta_1} (D^2 H_T\ \rho)^{\beta_2}$
	Model 5	$AGB = \beta_0 \cdot D^{\beta_1} H_T^{\beta_2} \rho^{\beta_3}$

procedures were done in addition to the comparison of *AICc* values: (1) the curve of each model within the range of the analyzed data was examined; (2) the biological significance of the asymptote *b0* was evaluated; and (3) the behavior of the model was evaluated up to the limit of 40-50 cm in dbh, which is an expected maximum limit for the cutting of trees in silvicultural plantations with native species. The interpretation of all results was always made with caution.

3. Results and Discussion

3.1 Hypsometric Models

Many of the hypsometric models tested could adequately describe H:D ratios, since the majority of these models had Δi < 2 (Table 2). For the total height equation, the Naslund model had the lowest AICc and the Hosffeld, Richards, and monomolecular models were all equally plausible, with Δi < 2. For the commercial stem height equation, several models were plausible, with Δi < 1 (logistic, Naslund, Curtis, Weibull, Gompertz monomolecular, Richards and Terazaki), but the Naslund model was selected as the best, had the smallest number of parameters out of these. The Richards and Weibull models are known to be among the most flexible models and are able to accurately estimate heights (Huang et al., 1992; Sharma & Zhang, 2004), including native trees in the Atlantic Forest (Scaranello et al., 2012). These models were able to accurately estimate commercial stem heights when applied in this study, but for the estimation of total height the weight of evidence in favor of the Naslund model was high in this study, which is thus the model we recommend for use in both of these situations (Figures 1 and 2).

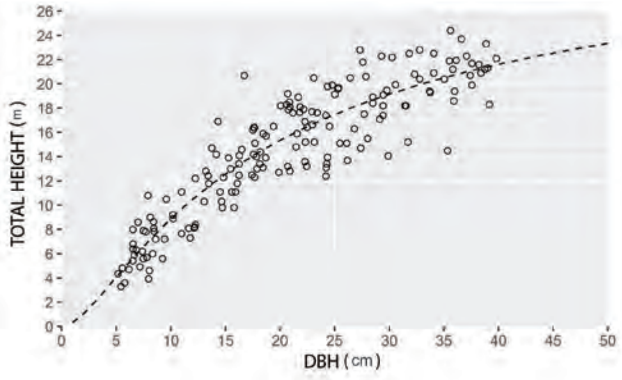

Figure 1. Observed relationship between the dbh and total height of 168 trees, as well as that estimated using the Naslund model, in silvicultural plantations in the Atlantic Forest of Brazil.

Table 2. Estimated coefficients of hypsometric models for silvicultural plantations in the north of Espirito Santo, Brazil, where β_0, β_1, and β_2 are the model coefficients, AICc is the Akaike information criterion, Δi is the difference between the lowest AICc value and that of each model, Wi is Akaike weight, and RSE is the residual standard error. Only models with Δi < 1 (for commercial stem height) and Δi < 2 (for total height) are presented.

Hypsometric	Model	β_0	β_1	β_2	RSE	AIC_c	Δi	*Wi*
Total Height Δi<2	Naslund	0.1749	1.6080		0.743	734.67	0.00	0.312
	Monomolecular	24.6030	0.0535	1.0928	0.738	736.52	1.84	0.124
	Richards	23.6439	0.0648	1.3408	0.743	736.59	1.92	0.120
	Hosffeld IV	28.2218	1.4025	55.6390	0.747	736.68	2.01	0.114
Stem height Δi<1	Logistic	12.0811	0.1630	9.3199	0.350	741.56	0.00	0.131
	Naslund	0.2150	2.5188		0.303	741.68	0.12	0.124
	Curtis	16.6346	12.9661		0.278	741.75	0.19	0.119
	Weibull 3p	13.0604	0.0176	1.3837	0.316	741.78	0.22	0.118
	Gompertz	12.8553	0.1032	2.9960	0.333	742.06	0.50	0.102
	Monomolecular	15.0531	0.0489	1.1273	0.292	742.13	0.57	0.099
	Richards	13.8606	0.0689	1.5974	0.311	742.21	0.65	0.095
	Terazaki	16.0505	11.8678		0.271	742.52	0.96	0.081

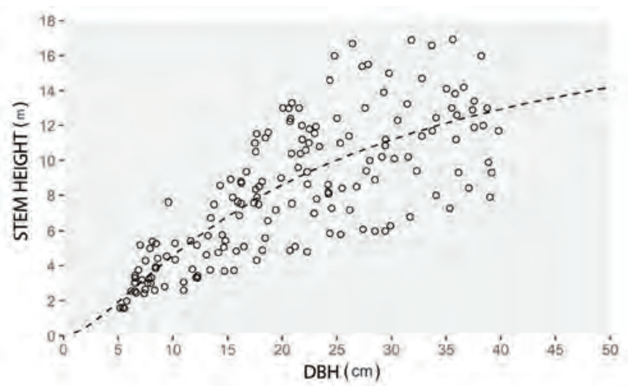

Figure 2. Observed relationship between the dbh and commercial stem height of 168 trees, as well as that estimated using the Naslund model, in silvicultural plantations in the Atlantic Forest of Brazil.

3.2 Volumetric Models

Among the volumetric models tested, the Schumacher-Hall (AICc = -906) model took up 100% of the Akaike weight (Wi) of all models (Table 3), with a much greater weight of evidence thus in favor of this model than the Spurr model (AICc = -821) and without bias. Thus, combining height and dbh variables into a combined variable (Spurr model) did not improve the model, and the Shumacher-Hall model is recommended for use in making volumetric estimates in silvicultural plantations with native species in the north of Espirito Santo (Figure 3) as follows:

$V_S = 1.11 * 10^{-4} * D^{2.0479} * H_S{}^{0.6352}$, where *VS* is the volume of the stem in m^3, *D* the diameter in cm, and *HS* the height of the stem in m.

Table 3. Estimated coefficients of volumetric models for silvicultural plantations in the north of Espirito Santo, Brazil, where β_0, β_1, and β_2 are the model coefficients, AICc is the Akaike information criterion value for each model, Δi is the difference between the lowest AICc value and that of each model, Wi is Akaike weight, and RSE is the residual standard error.

Model	β_0	β_1	β_2	RSE	*AICc*	*Δi*	*Wi*
Schumacher-Hall	$1.110*10^{-4}$	2.0479	0.6352	0.0900	-906.53	0.00	1.00
Spurr	$1.383*10^{-4}$	0.8977		0.1154	-821.26	85.27	0.00

The Schumacher-Hall model has already been tested under the most diverse climatic and soil conditions, and is widely used in forestry to model a wide variety of data, usually with high precision and without bias (Avery & Burkhart, 1983; Leite & Andrade, 2002). For instance, the Schumacher-Hall model had better performance than others when estimating the commercial volume of wood in trees in the African Forest (Akindele & LeMay, 2006; Mayaka et al., 2017), Brazilian Atlantic Forest (Blanco-Jorge, 1982), Amazon Rainforest (Rolim et al., 2006), Brazilian Cerrado (Rufini et al., 2010), *Picea glauca* trees (Morton et al., 1990), *Eucalyptus* plantations (Azevedo et al. 2011; Pereira et al., 2016), *Pinus* plantations (Melo et al., 2013; Thomas et al., 2006; Alegria and Tomé, 2011), *Mimosa scabrella* plantations (Machado et al., 2008), *Tectona grandis* plantations (Vendruscolo et al., 2014), *Tabebuia* trees (Batista et al., 2004), and several Atlantic Forest species (Soares et al., 2011).

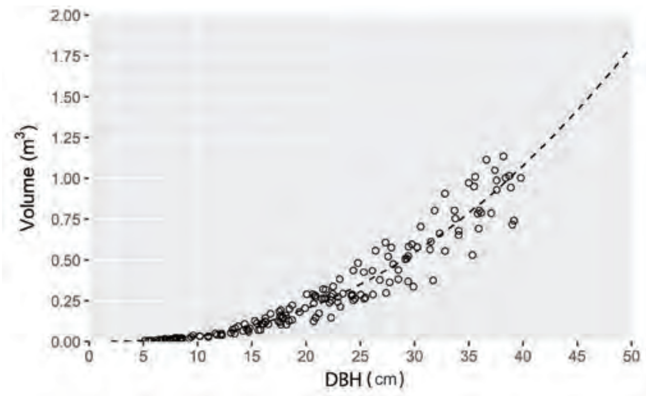

Figure 3. Observed relationship between the dbh and commercial volume of wood of 168 trees, as well as that estimated using the Schumacher-Hall model, in silvicultural plantations in the Atlantic Forest of Brazil.

3.3 Biomass Models

Among the biomass models, only model 5 was found to be plausible, since all others had Δi > 10 (Table 4), and therefore it is recommended to use this model to estimate the aboveground biomass of trees with dbh of up to 40 cm (Figure 4) as follows:

$AGB = 0.1009 * D^{2.2472} * H_T^{0.4333} * \rho^{0.7865}$, where *D* is the diameter in cm, H_T is the total height in m, ρ is the wood density in g/cm^3, and AGB is aboveground biomass in kg.

Table 4. Estimated coefficients of biomass models for silvicultural plantations in the north of Espirito Santo, Brazil, where β_0, β_1 *and* β_2, are the model coefficients, AIC_c is the Akaike information criterion, Δi is the difference between the lowest AIC_c value and that of each model, *Wi* is Akaike weight, and RSE is the residual standard error.

Model	β_0	β_1	β_2	β_3	RSE	*AICc*	Δi	*Wi*
Model 5	0.1009	2.2472	0.4333	0.7865	0.459	1501.29	0.00	0.997
Model 4	0.0749	0.6967	0.6963		0.632	1513.11	11.82	0.003
Model 2	0.0725	0.9479	0.7756		0.737	1540.94	39,65	0.000
Model 1	0.0961	0.9291			0.616	1551.15	49,86	0.000
Model 3	0.0554	0.8635	1.5987		0.738	1733.90	232.61	0.000

Model 5 is a Schumacher-Hall variant with four parameters, including three variables that are considered appropriate for estimating tree biomass: wood diameter, height, and density (Baker et al. 2004; Chave et al. 2014). In rainforests, due to the difficulties of measuring heights, many models are only developed using Dbh data. Although in some cases the introduction of height into the model resulted in minimal improvement in the quality of the model's predictions (Djomo et al., 2010), in others including height significantly improved the model's estimates and decreased the error of its residuals (Li & Zhao, 2013). Additionally, two trees with the same diameter can have different heights, which justifies the use of height as a predictor variable (Nogueira et al., 2008; Picard et al. 2015; Temesgen et al., 2015; Weiskittel et al. 2015). When applied to the data collected from Linhares, Brazil, a very high weight of evidence was found in favor of the use of height and wood density variables in models when comparing those containing these variables to those without them (results not shown), which emphasizes the importance of their use. It is also important to note that, unlike biomass estimates made for rainforests, which have high species diversity and where wood density information is not always available for many species, estimates made in silvicultural plantations require the study of wood density of only a few species; this variable should thus not be neglected in their models. Height is also much more easily measured in silvicultural plantations due to the lower tree diversity and regular spacing of trees, which makes ease to observe the stems and crowns of trees in plantation when compared with those in natural forests.

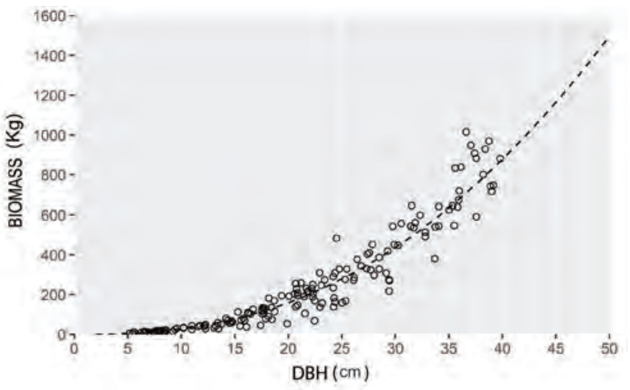

Figure 4. Observed relationship between the dbh and total individual aboveground biomass of 168 trees, as well as that estimated using model 5 (four-parameter Schumacher-Hall variant), for tree biomass in silvicultural plantations in the Atlantic Forest.

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3. DIAMETER GROWTH MODELS FOR 35 ATLANTIC FOREST TREE SPECIES IN SILVICULTURAL TRIALS IN THE NORTH OF ESPIRITO SANTO, BRAZIL

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"*All models are wrong, but some are useful*"[1]

1. Introduction

Growth models explore mathematical relationships between a given tree characteristic, such as diameter or height, and its age, but may also include climate or competition variables. Understanding how a tree grows under each environmental condition has a practical importance for silviculture, since it allows the prediction of the future diameter and potential wood volume of a given tree (Zeide, 1993; Burkhart & Tomé, 2012; Panik et al., 2014). The growth rate of trees can change depending on the life stage (Haggar et al., 1998; Brienen & Zuidema, 2006), and growth behavior can change depending on competition (Gourlet-Fleury & Houllier, 2000; Orellana et al., 2016), light level (Alves & Santos, 2002; Kariuki et al., 2006; Sheil et al., 2006; Adame et al., 2014), rainfall, temperature, soil parameters (Swaine, 1996; Baker et al., 2003; Russo et al., 2005; Calvo-Alvarado et al., 2007; Way & Oren, 2010; Breugel et al., 2011), and genetic variation between individuals (Sebbenn et al., 2000).

The development of growth models has a long history in ecology, and there are many available models to explain tree growth (Zeide, 1993; Kiviste et al., 2002). Due to the different factors affecting growth, models should ideally be developed locally for each region and species. The same species may even present different growth patterns depending on different environmental conditions (Parresol & Devall, 2013). Similar to other tropical regions, growth models for the Atlantic Forest are rare, both for the different regions that compose the biome and the main native species planted for silvicultural purposes (for some exceptions, see: Tonini et al., 2008; Santos et al., 2015).

There are two main methods to obtain data for the development of growth models for planted forests. One is counting and measuring ring thickness in tree trunks, with results highly correlated with tree age (Worbes, 1999; Fichtler et al., 2003; Brienen & Zuidema, 2006). The great advantage of this method is that it can be applied using a single data collection exercise, but also has the disadvantages of not evaluating trees directly in the plantation under management conditions, and of usually being applied to a small number of trees, and are also less reliable in the permanently humid tropics. Periodic growth measurements are another option, which has the great disadvantage of requiring many years of data collection to improve the estimation accuracy; however, this method allows for a better evaluation of the environmental and management conditions at the planting site. Periodical monitoring of plantations for longer than 25 years is rare in the Atlantic Forest. However, in Linhares (ES), a set of silvicultural trials established in 1978 was measured periodically for 25 to 40 years. In the present study, growth results of these trials are presented for 35 tree species native to the Atlantic Forest, and possible factors affecting their performance are discussed.

2. Methodology

2.1 Study area

The Vale Nature Reserve (VNR) includes approximately 23000 ha of Atlantic Forest. It is

1 Box, G.E.P. 1979. Robustness in the strategy of scientific model building. In: Launer, L.R. & Wilkinsom, G.N. (eds.) Robustness in Statistics, pp.201-236, Academic Press.

located in the north of Espírito Santo, on land with little altitude variation, usually between 30 and 60 masl. The climate is considered seasonal, and the forest vegetation is classified as evergreen seasonal forest. Between January 1975 and December 2004, the mean annual rainfall was 1227 mm (standard deviation ± 273 mm) and mean annual temperature was 23.3 °C, varying very little throughout the year (annual mean minimum and maximum temperatures of 20.0 °C and 26.2 °C, respectively). The mean annual relative humidity was 85.8%, also varying very little throughout the year, between 82.2% and 89.2% (Rolim et al., 2016).

In a small part of the reserve, with an area of approximately 700 ha, several silvicultural research projects were established from the end of the 1970s until the beginning of the 1990s, with enrichment plantations in secondary forests; full sun, mixed, and pure plantations (including some spacing trials); and provenance and progeny trials, with a total of almost 100 different tree species native to the Atlantic Forest. Trees were monitored annually, and in some cases every 2 years, beginning when the plantation reached 20 years of age. The plantations were established with different spacings, but most species were planted in monoculture, with 2 × 2 m spacing and 196 trees per plot. All plantations received initial fertilization with 110 and 200 g/pit of single superphosphate for older and younger plantations, respectively.

In general, 20 g/pit of potassium chloride and 30 g/pit of ammonium sulfate were also applied as cover fertilization. Dolomitic limestone was applied sporadically in some experiments (1.5 Mg/ha). Grasses and leaf-cutter ants were systematically and annually controlled, but thinning and debranching were circumstantial, with thinning never performed in some trials.

In the present study, data for 62 tree species were initially analyzed, but several species presented high mortality or very unsatisfactory growth and were discarded from the growth analyses. However, some species with unsatisfactory forestry outcomes due to lack of thinning, irregular stem shape or very slow growth, but with known market value, were analyzed. Species without acknowledged timber value but that may be interesting for other purposes were also analyzed. Models and estimates were obtained for 35 tree species native to the Atlantic Forest.

2.2 DBH Growth Models

The fitness of seven commonly used growth models was tested for each species (Table 1), although with varied mathematical notations (Zeide, 1993; Kiviste et al., 2002; Pretzsch, 2009; Burkhart & Tomé, 2012; Panik et al., 2014). In a sigmoid model, parameter A is the asymptote, or, in our study, the maximum diameter expected under the observed plantation conditions. Models without inflexion points were not used, since according to some authors, they are less biologically likely (Zeide, 1993; Pretzsch, 2009), and the inflection point of a growth curve is of high statistical interest (Goshu & Koya, 2013); however, other authors consider that this has no biological importance (Weymouth et al., 1931). The models were fitted using generalized least squares, where the assumption of normality of errors is extended to include any exponential family (Nelder, 1991). Modeling was performed using function '*generalized nonlinear least-squares' (gnls)* from the '*nlme*' package (*Linear and Nonlinear Mixed-Effects Models*), originally developed for S and S-Plus (Pinheiro & Bates, 2000) and adapted to R (Pinheiro et al., 2018), using R software (R Core Team, 2018). In this case, the variance was modelled relative to the plantation age using the '*varPower*' function, meeting the assumption of error heterogeneity and minimizing the standard error of the model.

The Akaike information criteria (AIC_c; Hurvich & Tsai, 1989) was used to select the best models to explain DBH:Age relationship. The lowest AIC_c usually indicates the best model, but other models may be selected as equally plausible. To take this into account, the difference (Δi) between the AIC_c for each model and the lowest AICc among the tested models was analyzed. Models with Δi < 2 can be considered likely, but the lower the Δi, the stronger the likelihood of a model, and all models should be carefully evaluated for selection. The Akaike weight (Wi) was also computed, which is the probability of a model being the best in a given set (Burnham & Anderson, 2002). The ratio between the weights of different models indicates the likelihood that the model with the lower AIC_c is a better fit to the data than the competitor model.

Table 1. Non-linear growth functions (integral form, yield) commonly used in forest growth modeling, to fit DBH-Age relationship of 35 species native to the Atlantic Forest DBH, 130 cm above ground, Age t in years. A, c, k, are the parameters to be estimated.

Model	Form
Richards (Mitscherlich, 1919)	$DBH = A(1 - exp^{-k\,t})^{c}$
Weibull (Weibull, 1951)	$DBH = A\left(1 - exp^{-k\,t^{c}}\right)$
Logistic (Verhulst, 1838)	$DBH = A\,(1 + c\,exp^{-k\,t})^{-1}$
Gompertz (Gompertz, 1825)	$DBH = A\,exp^{-c \cdot exp^{(-k\,t)}}$
Hosffeld IV (Hosffeld, 1822)	$DBH = A\left(1 + c\,exp^{-k\,Ln(t)}\right)^{-1}$
Korf (Korf, 1939)	$DBH = A\,exp^{-k\,t^{-c}}$
Terazaki (1915)	$DBH = A\,exp^{-k\,t^{-1}}$

When more than one model is being compared, models can be chosen based on the biological interpretation of their properties, convenience, or even personal preference (Curtis, 1967). However, it is always necessary to be careful regarding models with a smaller number of parameters and good predictive ability, extrapolating at least a little beyond the data range used for modelling. Because thinning was not applied periodically and systematically to most of the 35 species studied, the potential for diameter growth was surely underestimated when compared to that of systems that received appropriate thinning (Piotto et al., 2003). In these cases, some studies have deepened growth analyses by separating the dominated and dominant trees (Finger et al., 1996; Santos et al., 2015). A model was therefore constructed for each species, considering only the dominant trees in the plantations, i.e., those that could be harvested considering a final density of approximately 400 trees/ha. This corresponds to 16% of the trees initially established in pure plantations, i.e., 31 of the 196 trees planted with 2 × 2 m spacing. For almost all mixed plantations (72 trees at 3 × 2.5 m spacing), only 21 trees would be necessary to represent a density of 400 trees/ha. However, the absolute value of 31 trees was kept to allow for a good representation of the growth variability, i.e., so that the results for the mixed plantations are conservative. On the other hand, the results were not so conservative for species growing in spacing trials, since the 31 best trees were selected considering all spacings. Growth data considering only the dominant trees should be interpreted with care, since this growth is expected when all forest management practices (including periodic thinning) are applied. However, the results are still conservative, because even when the dominated trees are eliminated from the analyses, they very likely contributed to higher competition during the growth of the dominant trees.

3. Results and Discussion

3.1 Growth Models

Of the seven models tested, the Korf model was selected for 21 species (60%), the Hossfeld IV model for eight species, the Gompertz model for four species, and the Weibull model for two species (Table 2). In several situations, there was more than one competitor model with Δi < 2, which could also be used to fit the tree diameter growth; however, the Korf model was overall much more superior to the remaining models tested. In almost all cases, the Hossfeld IV model competed with the Korf model (both with Δi < 2), and the higher fitness quality of these models was evident when compared to that of more traditional models, especially the Richards model (or Mitscherlich, 1919), one of the most accurate for models for growth estimates (Zeide, 1993); although it was a competitor in some cases, it was not selected for any of the species. The Richards model was probably not very often tested against these models, which seemed to be much more accurate.

The Vacláv Korf model was created in 1939, and is better known in central Europe (Kuzelka & Marusák, 2015). It has been little used for diameter growth, although several studies have recommended it to fit hypsometric curves (Lundqvist, 1957; Zarnovican, 1979; Feng-ri et al., 2000; Vargas-Larreta et al., 2013; Martins et al., 2014; Petrás et al., 2014; Ribeiro et al., 2016). The Terazaki model could have been selected for two species, but it should be noted that the Korf model with parameter c = 1 is a generalization of the Wataru Terazaki model, published in 1915 in a study on *Cryptomeria japonica*. For the species studied in Linhares, decreasing a parameter in the Korf model (making c = 1) did not improve fitness, since in both cases the Korf and the Terazaki models were equally likely, with Δi < 2, and the Korf model was selected because it was more generalized, as previously observed by Petrás et al. (2014). The Terazaki model was also described by Schumacher (1939) and

Michajlov (1943), probably independently (Zeide, 1993; Kindermann, 2016).

The Hossfeld IV model, from 1822, is the oldest known growth model (Zeide, 1993; Kiviste et al., 2002), and has also been found to present good fitness in several cases (Woollons et al., 1990; Ngugi et al., 2000; Kiviste et al., 2002; Bontemps & Duplat, 2012; Donis & Snepsts, 2015). The Korf model presents good statistical properties and predictive ability (Feng-ri et al., 2000), but in some cases, both the Korf and Hossfeld IV models did not achieve convergence or produce a realistic estimate of asymptote A for forest plantations so were discarded. The Weibull (can be attributed to Fisher & Tippett, 1928, according to Bailey, 1980) and Gompertz models are also quite popular and often used to model growth; they were competitors in several cases in Linhares. These models provide good biological interpretation and presented good fitness in several cases (Zeide, 1993; Kiviste et al., 2002), but were usually selected due to the absence of convergence in the Korf and Hosffeld IV models. It should also be highlighted that in several cases the Gompertz model reached the asymptote too early for plantations in Linhares, and should be analyzed with care in the case of forest plantations, even when it is a preferred model, in order to not underestimate growth. Overall, the selected models can be extrapolated safely to estimate the diameters of trees aged 35–45 years; however, for many species, care should be taken when extrapolating for older ages.

3.2 Growth Variation Between Species

Considering only the trees with growth projections for 35 years (n = 29 species, Table 3), a large variation in the estimated mean diameter (19.5–33.4 cm per species) and diameter increase (0.56–0.96 cm/year per species) was observed. In terms of the projected diameters for the fastest growing species from 15 to 25 years (n = 6 species, Table 3), even without genetic improvement, species such as Tachigali vulgaris and Spondias venulosa presented some trees with similar diameter growth to that of eucalyptus at the same age (mean DBH = 35 cm at 15 years of age; Carvalho et al., 2010), but represented an overall lower wood volume because of the high growth in height of the eucalyptus.

Several factors may have contributed to this variation between species throughout the monitoring years of forest plantations in Linhares. Tree growth is directly related to the availability of resources, such as light, water, and nutrients (Binkley et al., 2004); however, except for an initial fertilization, these resources were not supplied artificially to trees (they grew under natural conditions) and will not be discussed here. In addition to the natural evolutionary difference between species, tree growth in plantations is also affected by factors related to genetic variation, thinning, insect attack, infestation by parasitic plants, and drought periods; these factors are briefly discussed below.

3.2.1 Ecological Characteristics of the Tree Species

Growth rates are directly related to the functional characteristics of tree species (Swaine & Whitmore, 1988; Wilson, 1999; Baker et al., 2003; Adame et al., 2014). Whereas some species have functional characteristics that improve resource acquisition and promote fast growth, other species present functional characteristics that improve survival and persistence in environments where resources are scarce. Consequently, in full sun plantations, species with characteristics focused on resource acquisition, such as *Tachigali vulgaris, Parkia pendula*, and *Spondias venulosa*, presented much higher estimated diameters than did other species for the same age. On the other hand, shade-tolerant species that produce dense wood, such as *Paratecoma peroba, Manilkara longifolia, Aspidosperma pyricollum*, and *Handroanthus serratifolius*, showed relatively slow growth (Figure 1).

There are some reports of high growth rates for shade-tolerant species grown under high light availability (Condit et al., 1993). In Linhares, *Cariniana legalis* and *Dalbergia nigra* are good examples of this behavior, as they tolerate shade in their early growth stages, but they both reach centenary age and comprise the canopy of mature forests (Jesus & Rolim, 2005). These two species presented some of the highest diameter growth amongst the 35 studied species.

On the other hand, some species traditionally known for their better growth under direct light presented lower growth rates than did shade-tolerant species. *Pachira endecaphyla* and *Joannesia princeps* presented much lower growth than expected, with very fast asymptotic trends, either stabilizing or growing very slowly after 15 years of age.

Table 2. Growth models (integral form, yield), between DBH (130 cm above ground) and Age (t in years) (K = Korf, H = Hossfeld IV, G = Gompertz, and W = Weibull) selected for each studied species and the respective residual standard error (RSE).

Species		Model	RSE
Amburana cearensis	H	$DBH = 26.11\left(1 + 344.74\ exp^{-2.32\ Ln(t)}\right)^{-1}$	0.62
Aspidosperma pyricollum	W	$DBH = 53.88\left(1 - exp^{-0.0348 \cdot t^{0.7192}}\right)$	0.34
Astronium concinnum	K	$DBH = 23.66\ exp^{-3.99\ t^{-0.8775}}$	0.31
Astronium graveolens	G	$DBH = 39.24\ exp^{-1.81 \cdot exp^{(-0.03925\ t)}}$	1.14
Barnebydendron riedelii	K	$DBH = 47.11\ exp^{-4.20\ t^{-0.5434}}$	0.26
Bowdichia virgilioides	H	$DBH = 83.54\left(1 + 42.02\ exp^{-0.8551\ Ln(t)}\right)^{-1}$	0.44
Cariniana legalis	H	$DBH = 46.40\ exp^{-11.38\ t^{-0.9855}}$	0.90
Centrolobium tomentosum	K	$DBH = 46.43\ exp^{-8.30\ t^{-0.7437}}$	0.30
Clarisia racemosa	K	$DBH = 36.23\ exp^{-4.92 \cdot exp^{(-0.1038\ t)}}$	0.48
Copaifera langsdorffii	G	$DBH = 76.46\left(1 + 190.22\ exp^{-1.2478\ Ln(t)}\right)^{-1}$	0.92
Cordia trichotoma	H	$DBH = 41.27\ exp^{-2.15 \cdot exp^{(-0.0484\ t)}}$	0.88
Dalbergia nigra	G	$DBH = 61.47\ exp^{-3.92\ t^{-0.4838}}$	1.59
Goniorrhachis marginata	K	$DBH = 49.36\ exp^{-5.15\ t^{-0.5634}}$	0.20
Handroanthus serratifolius	K	$DBH = 49.86\ exp^{-4.66\ t^{-0.5405}}$	0.24
Hymenaea courbaril var. *stilbocarpa*	K	$DBH = 47.67\ exp^{-4.08\ t^{-0.5847}}$	0.63
Joannesia princeps	K	$DBH = 44.59\ exp^{-2.32\ t^{-0.3574}}$	0.53
Lecythis pisonis	K	$DBH = 60.82\ exp^{-4.774\ t^{-0.4848}}$	1.39
Libidibia ferrea var. *parvifolia*	K	$DBH = 30.90\ exp^{-4.97\ t^{-0.7867}}$	0.24
Manilkara longifolia	K	$DBH = 25.25\ exp^{-9.59\ t^{-1.0455}}$	0.52
Moldenhawera papillanthera	K	$DBH = 73.09\left(1 + 104.60\ exp^{-1.059\ Ln(t)}\right)^{-1}$	0.81
Myracrodruon urundeuva	H	$DBH = 60.42\left(1 + 20.075\ exp^{-0.9038\ Ln(t)}\right)^{-1}$	0.90
Pachira endecaphylla	H	$DBH = 29.124\left(1 - exp^{-0.0413 \cdot t^{1.3736}}\right)$	0.34
Paratecoma peroba	W	$DBH = 71.15\ exp^{-3.8343\ t^{-0.3558}}$	0.56
Parkia pendula	K	$DBH = 70.98\ exp^{-4.61\ t^{-0.5052}}$	0.62
Paubrasilia echinata	K	$DBH = 40.69\ exp^{-6.03\ t^{-0.6845}}$	0.34
Pterocarpus rohrii	K	$DBH = 81.48\ exp^{-4.48\ t^{-0.4487}}$	0.68
Pterygota brasiliensis	K	$DBH = 89.77\left(1 + 44.28\ exp^{-0.9057\ Ln(t)}\right)^{-1}$	0.29
Senegalia polyphylla	K	$DBH = 77.54\ exp^{-3.935\ t^{-0.3440}}$	0.16
Simarouba amara	G	$DBH = 43.98\ exp^{-2.34 \cdot exp^{(-0.0587\ t)}}$	0.73
Spondias venulosa	K	$DBH = 82.59\ exp^{-2.97\ t^{-0.4292}}$	0.38
Tachigali vulgaris	K	$DBH = 90.41\ exp^{-5.12\ t^{-0.5003}}$	0.21
Terminalia mameluco	H	$DBH = 31.74\left(1 + 168.87\ exp^{-1.6170\ Ln(t)}\right)^{-1}$	1.13
Vatairea heteroptera	K	$DBH = 29.25\ exp^{-5.62\ t^{-0.8561}}$	0.37
Vataireopsis araroba	K	$DBH = 48.59\ exp^{-3.54\ t^{-0.4858}}$	0.81
Zeyheria tuberculosa	H	$DBH = 37.62\left(1 + 19.90\ exp^{-1.13823\ Ln(t)}\right)^{-1}$	0.25

Table 3. List of studied species from silvicultural trials in Linhares, in descending order of mean annual increment in diameter (MAI). Diameter at breast height (DBH [cm]), tree density, and MAI were estimated for the corresponding age in each selected model. All plantations began with 1667 trees/ha, reaching the cited density after periodical thinning (for thinning details see Chapter 5).

Species	Model	Density (n/ha)	DBH (cm)	MAI (cm/ano)	AGE (years)
Spondias venulosa (Engl.) Engl.	Korf	383	32.6	2.18	15
Tachigali vulgaris L.G.Silva & H.C.Lima	Korf	386	32.5	1.30	25
Parkia pendula (Willd.) Benth.	Korf	496	28.7	1.15	25
Pterocarpus rohrii Vahl.	Korf	508	28.3	1.13	25
Pachira endecaphylla (Vell.) Carv.-Sobr.	Weibull	513	28.2	1.13	25
Myracrodruon urundeuva Allemão	Hossfeld	365	33.4	0.96	35
Cariniana legalis (Mart.) Kuntze	Korf	375	32.9	0.94	35
Simarouba amara Aubl.	Gompertz	384	32.6	0.93	35
Pterygota brasiliensis	Hossfeld	388	32.4	0.93	35
Clarisia racemosa Ruiz & Pav.	Gompertz	403	31.8	0.91	35
Dalbergia nigra (Vell.) Allemão ex Benth.	Korf	438	30.5	0.87	35
Joannesia princeps Vell.	Korf	891	21.4	0.86	25
Hymenaea courbaril var. *stilbocarpa* (Hayne) Y.T.Lee & Langenh.	Korf	498	28.6	0.82	35
Zeyheria tuberculosa (Vell.) Bureau ex Verl.	Hossfeld	523	27.9	0.80	35
Cordia trichotoma (Vell.) Arráb. ex Stend.	Gompertz	527	27.8	0.79	35
Bowdichia virgilioides Kunth	Hossfeld	529	27.8	0.79	35
Lecythis pisonis Cambess.	Korf	605	25.9	0.74	35
Vataireopsis araroba (Aguiar) Ducke	Korf	607	25.9	0.74	35
Centrolobium tomentosum Guillem. ex Benth.	Korf	615	25.7	0.74	35
Barnebydendron riedelii (Tul.) J.H. Kirkbride	Korf	620	25.6	0.73	35
Handroanthus serratifolius (Vahl.) S. O. Grose	Korf	642	25.2	0.72	35
Astronium graveolens Jacq.	Gompertz	662	24.8	0.71	35
Goniorrhachis marginata Taub.	Korf	672	24.6	0.70	35
Paratecoma peroba (Record & Mell.) Kuhlm.	Korf	701	24.1	0.69	35
Senegalia polyphylla (DC.) Britton & Rose	Korf	687	24.4	0.70	35
Paubrasilia echinata (Lam.) Gagnon, H.C.Lima & G.P.Lewis	Korf	709	24.0	0.69	35
Amburana cearensis (Allemão) A.C.Sm.	Hossfeld	710	23.9	0.68	35
Copaifera langsdorffii Desf.	Hossfeld	737	23.5	0.67	35
Libidibia ferrea var. *parvifolia* Benth.	Korf	783	22.8	0.65	35
Vatairea heteroptera (Allemão) Ducke	Korf	814	22.4	0.64	35
Moldenhawera papillanthera L.P.Queiroz, G.P.Lewis & R.Allkin	Hossfeld	894	21.4	0.61	35
Terminalia mameluco Pickel	Hossfeld	957	20.6	0.59	35
Manilkara longifolia (Mart.) Dubard	Korf	1018	20.0	0.57	35
Astronium concinnum (Engl.) Schott	Korf	1036	19.8	0.57	35
Aspidosperma pyricollum Müll. Arg.	Weibull	1072	19.5	0.56	35

3.2.2 Influence of Thinning

After plantation establishment and the control of competitor plants and ants, thinning is probably the most important forest management activity. Trees with a competitive disadvantage may die (Peet & Christensen, 1987) or be dominated, since competition with dominant trees results in lower resource availability for growth (Campoe et al., 2013). For example, the mean tree diameter in a plantation of *Cariniana legalis* at 22 years of age without thinning was 7.9 cm (Veiga & Mariano, 1982), but this could have reached approximately 20 cm with appropriate thinning. Trees with a competitive disadvantage in plantations will unlikely be able recuperate their growth rate and reach the dominant trees. Thinning of (dominated or not dominated) trees is, as a rule, essential in maintaining the growth of dominant trees, improving the structural stability of plantations, and improving the stem shape and wood quality of the remaining trees; they are considered an obligatory silvicultural practice in plantations for solid wood production (Cameron, 2002). Thinning increases the space and light availability for the growth of remaining trees and decreases competition for water and nutrients. This usually increases the growth efficiency (especially in diameter), as shown by studies in several regions worldwide (Amateis et al., 1989; Tasissa & Burkhart, 1998; Medhurst et al., 2001; Álvarez-Gonzáles et al., 2002; Piotto et al., 2003; Blevins et al., 2005; Medhurst & Beadle, 2005; del Rio et al., 2008; Kariuki, 2008; Rytter & Stener, 2014; Nogueira et al., 2015). However, in cases where thinning is not performed with the necessary frequency, or when its intensity is very low or very high, trees may not respond positively (Piotto et al., 2003).

In Linhares, the lack of thinning for some species certainly increased competition and decreased light penetration in the plantations. This affected the growth estimates, and they may be considered too conservative for some species with high timber value, such as *Paratecoma peroba, Astronium graveolens, Manilkara longifolia, Paubrasilia echinata*, and *Amburana cearensis*. However, thinning may also have some negative impacts, especially related to higher wind exposure, which may cause damage to trees (Moore & Maguire, 2005). In later stages, when larger trees are removed, thinning may damage the remaining adjacent trees, which should also be felled if the stem is severely affected by the thinning operation.

3.2.3 Influence of Light on Stem Quality

Light availability not only affects growth rates, but may also affect stem shape or tree architecture (Poorter, 1999; Poorter et al., 2006). A bifurcated tree divides resources between two stems instead of concentrating on the growth of only one, and for the vast majority of species, sawn timber production requires the formation of straight stems. In addition,

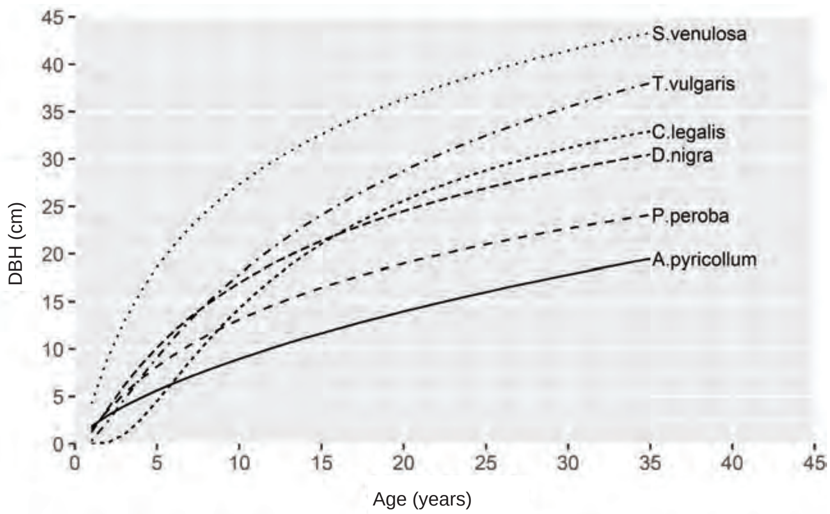

Figure 1. Diameter growth of six tree species native to the Atlantic Forest in forest plantations in Linhares (ES).

for many species, straighter stems are known to result in better wood quality (Allen, 1977; Zobel & Buijtenen, 1989), so that obtaining trees with straight stems is the main goal of forestry for solid wood production.

For the plantations in Linhares, some shade-tolerant species, such as *Manilkara longifolia, Aspidosperma pyricollum*, and *Handroanthus serratifolius*, presented excellent stem shape, even when planted under full sun, but low diameter growth. However, others, such as *Paubrasilia echinata, Clarisia racemosa, Libidibia ferrea*, and *Amburana cearensis*, produced very irregular, tortuous, and/or bifurcated stems. There is genetic variability in the stem shape of individuals of the same species, although this is small in some cases (Cornelius & Mesén, 1997; Sebbenn et al., 2009; Weber et al., 2009; Araújo et al., 2014). However, stem shape probably depends more on the environment than on heritability, and for some species, growth under full sun and a lack of competition may, in itself, produce tortuosity and/or bifurcation.

One of the most important species planted in Linhares (because of its high commercial value) is *Dalbergia nigra*. This species presents a high growth rate in plantations, but high light exposure negatively affects the formation of high-quality and straight stems, whereas low light decreases its growth rate, but results in the formation of straighter stems. Moreover, considering that stem shape can change throughout the lifespan of a plantation (Tasissa & Burkhart, 1998), controlling the amount of light in forest plantations to optimize growth and obtain high-quality stems is probably one of the main challenges in the silviculture of high-value species native to the Atlantic Forest, such as *Dalbergia nigra* and *Paubrasilia echinata*.

3.2.4 Influence of Insects and Parasites

For some species in Linhares, such as *Centrolobium tomentosum* and *Astronium concinnum*, an additional cause of growth stagnation from 12 or 15 years of age were attacks by longhorn beetles of the genus *Oncideres*, which cut new, less lignified twigs for egg laying (“twig girdling”), or attack the main stem of young trees, causing bifurcation (Carvalho, 2003). In Linhares, there are at least 11 species of *Oncideres* (Martins et al., 2016), at least five of which are considered pests of forest species: *O. saga, O. ulcerosa, O. impluviata, O. captiosa*, and *O. germarii* (D. S. Martins, personal communication).

Overall, there is a positive relationship between drought events and potential pathogens, which act in synergy against tree health (Desprez-Loustau et al., 2006), showing the importance of forest pests and pathogens in forest plantations, especially in regions with higher climate seasonality. *Cordia trichotoma* also showed growth problems in pure plantations in Linhares. Attacks by the hemipter *Dictyla monotropidia*, which sucks leaves resulting in leaf fall, have been reported to result in lower tree growth rates due to the increased investment in leaf renovation (Martínez et al., 2012). The occurrence of dry periods, as in the case described below, have also been reported to increase populations of *D. monotropidia*, increasing tree damage (Martínez et al., 2012). This species was not observed in Linhares, and the growth stagnation observed for *C. trichotoma* in Linhares was due to infestation by a parasite plant, commonly known as mistletoe. Several plant species known by this name, especially from the families Viscaceae, Santalaceae, and Loranthaceae, compromise tree growth by fixing themselves to tree branches and trunks, emitting special roots (haustoria) that penetrate the tree bark, and extracting water and nutrients (Arruda et al., 2012). High level of infestation with these parasites is visible on the crown of many of the planted species in Linhares, but *C. trichotoma* seems to be one of the favorite hosts. *C. trichotoma* trees survived without significant growth in diameter for more than 10 years after infestation, but did not resist the severe droughts of 2014 to 2016, and most trees died.

For species that are attacked by insects or parasite plants, pure plantations (with a single species) should be avoided (Piotto et al., 2004), and mixed plantation and low tree density plantations are suggested, at least in drier regions such as the north of Espírito Santo. Some other factors should be highlighted for monospecific plantations. Although the mixed plantation in Linhares are monospecific or mixed with only two species, there are more than 100 species planted in the experimental area, forming a landscape mosaic with a high species diversity. This may have helped to decrease the probability of encounters between pests and hosts, as the more diverse environment, additional habitat for beneficial insects and microbes helped to promote the natural control of pests and diseases in adjacent monospecific plantations (Nair, 2007).

3.2.5 Influence of Drought

Drought may also limit tree photosynthesis and, consequently, growth (Eilmann & Rigling, 2012; McDowell et al., 2013; Timofeeva et al., 2017). Although trees have adaptive strategies to survive dry periods (Santiago et al., 2015), the Northern region of the state of Espírito Santo has been subjected to intense El-Niño periods for the last 30 years (Rolim et al., 2005), a climate event that similarly has resulted in extreme drought in several regions worldwide (Williamson et al., 2000; Aiba & Kitayama, 2002). Mean rainfall in the region is naturally low (approximately 1250 mm, in some years reaching < 1000 mm), with several consecutive months of drought (Rolim et al., 2016). Previous studies have shown that high tree mortality and considerable biomass loss in the natural forests of Linhares were due to drought conditions caused by El-Niño (Rolim et al., 2005). This phenomenon very likely also affected tree growth in the plantations, not necessarily causing tree mortality, but nevertheless decreasing tree growth rates. Further and more detailed studies are needed to confirm this. Following tree harvest, tree growth ring analyses or correlations between diameter growth and climate data may clarify the impact of drought on the growth of the tree species planted in Linhares. It should be highlighted that the high growth rates obtained for some species in the north of Espírito Santo indicate that silviculture in areas with higher rainfall (reduced drought) will probably result in higher yield performances than those reported here.

3.2.6 Research Priorities

Soils: Although many species are not soil-demanding, many respond better to more fertile soils (*Amburana cearensis, Cordia trichotoma, Myracrodruon urundeuva*, and *Zeyheria tuberculosa*) or higher clay content (*Cariniana legalis*) (Silva, 2013). For example, in Linhares, empirical data indicate that the main factor for the lower-than-expected growth observed for *Joannesia princeps*, in addition to the lack of thinning, may have been the slightly more clayey soil; the species grows better in sandy soils. A better understanding of the edaphic characteristics of the areas of natural occurrence for each species is therefore important to help decide the best locations to plant each species. Considering the diversity of species that may have economic interest for silviculture, mapping potential sites for native species silviculture should be a research priority, at least for species with greater silvicultural potential and for which there are already growth data available.

Mixed Plantation: It should also be highlighted that the growth results presented for some species in monospecific plantations are likely conservative, since diameter growth rates are higher for mixed plantations, where two or more species are carefully arranged, than for monospecific plantations (Piotto et al., 2004; Erskine et al., 2006; Kelty, 2006; Petit & Montagnini, 2006; Redondo-Brenes & Montagnini, 2006; Piotto, 2008). In mixed plantations, species also improve the fertility of degraded soils by incorporating large amounts of litter and nutrients into the soil (Aidar & Joly, 2003). Additionally, several species with high timber value, such as *Bowdichia virgilioides* and *Centrolobium tomentosum*, form associations with *Rhizobium* spp., fixing atmospheric nitrogen (Faria et al., 1984). Understanding how tree species may benefit each other is key for a multiple species silviculture with native species. Besides economic gains, it could result in a significant improvement of forest connectivity and restoration of degraded landscapes. This is likely the most complex priority of silvicultural research, since it involves studying different species combinations, with appropriate thinning to avoid competition and achieve the desired light level for each species. Moreover, it requires a long period of time to obtain robust results that can be communicated to interested producers.

Genetic Improvement: There is no doubt that genetic improvement may contribute to potentialize the growth results observed for planted trees without genetic selection. Several tree species present high growth variations between different provenances, indicating a high potential for yield gain (Farias Neto & Castro, 1999; Sebbenn et al., 2000). In Linhares, there was a high intraspecific variation in tree growth, and the selection of superior individuals would be an important step toward improving the growth in future plantations. This stated, it should not be forgotten that silviculture with native species, with the goal of diversifying the landscape and increasing the resilience of plantations to climate change, should prioritize sourcing germplasm from stands with diverse genetic bases. In either case, genetic improvement can be considered a research priority for the next years.

Growth and Wood Quality: The low growth rate of native species has always been one of the reasons for justifying the establishment of exotic species plantations in Brazil. Increased tree growth rates can be achieved through genetic selection, better management practices and adequate fertilization. However, it should be considered that growth rates and wood properties are related, with conflicting reported results (Zobel & Buijtenen, 1989). Some species present a negative relationship between growth and wood density. In others, wood density is not affected by the growth rate, and in rare cases, a small increase in wood density has been observed with an increase in growth rate, as in *Swietenia macrophylla* (Zobel & Buijtenen, 1989; Perera et al., 2012). The relationship between growth and wood quality may also vary with climate, type of wood structure, and wood density class (Zobel & Buijtenen, 1989; Zhang, 1995). For some species with very high wood density, decreasing the wood basic density may even be desirable; however, for species with medium density, it may be a problem, since it can change the product properties, market interest, and economic value. This type of information is not yet available for almost all Brazilian tropical species of commercial interest, opening an important line for future research.

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4. EVALUATION OF THE WOOD QUALITY OF PLANTED NATIVE TREE SPECIES OF THE ATLANTIC FOREST OF BRAZIL

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1. Introduction

Wood quality evaluation is the basis for characterizing forest tree species in terms of their technological properties (physical, mechanical, anatomical, chemical, and energetic), which are intrinsically related to the wood's behavior and use as a raw material for different products or consumer goods.

There are numerous possible uses of wood as a raw material: construction, furniture, floors, window frames, decking, cellulose and paper, energy for the steel industry, charcoal for household or industrial consumption, automotive industry (truck bodies and others), boats, packages, poles, posts, household utensils, pencils, footwear, handicrafts, and others. One or more timber tree species are appropriate for each product, according to their technological quality.

Variations in wood properties are due to differences between trees, species, and factors related to the location where the tree grew, such as rainfall regime, wind, light incidence, slope, fertility, and soil physical and chemical properties.

Cellulose and paper industry technology has developed enormously since it was deemed important to study all variables related to the quality of cellulose pulp in depth. The development of native species silviculture is therefore intrinsically related to the knowledge of wood properties. The technological properties of the wood of several Brazilian native species have already been studied, with available data especially in publications of the Forest Products Laboratory (LPF)/ Ibama (Souza et al., 1997) and Technology Research Institute (IPT) (Mainieri & Chimelo, 1989). However, this characterization was performed using trees harvested in their natural areas of occurrence, with ages that may reach more than 100 years at the time of felling (Fichtler et al., 2003; Andrade, 2015), and it cannot be assumed that the wood properties would be the same if the trees were planted and harvested at between 20 and 40 years of age.

Overall, the wood quality of younger trees is different from that of older trees, and the same species may have different uses depending on the age of harvest. This has been shown for several species from temperate and tropical areas (Zobel & Buijtenen, 1989; Bao et al., 2001; Pelozzi et al., 2012; Pollet et al., 2017); however, very little is known for species from the Brazilian Atlantic Forest (for some exceptions, see Marques et al., 2012; Longui et al., 2017). Understanding the wood properties of planted tree species is essential to recommend the type of use and to help define their market prices.

Therefore, in parallel to growth studies of native tree species in forest trials set in the Vale Nature Reserve (Chapter 2 and Chapter 3), the physical and mechanical wood properties, including anatomical characterization, evaluation of workability in machining processes, and indication of potential uses, were studied. The methodology presented in the present chapter was used in the elaboration of Chapter 5 of this publication.

2. Sampling, tree selection, and primary sawmilling

The evaluation of the wood quality of species native to the Atlantic Forest in the present study began with the selection of trees from 29 species, planted in silvicultural trials in the Vale Nature Reserve. Although growth studies were performed for 35 species, six species could not be felled for wood technology tests due to the lack of legal authorizations.

Figure 1. Felling of selected trees for technological studies in planted forests in the Vale Nature Reserve, Linhares (ES).

Three trees per species were selected based on their growth form and health. Two logs were extracted, measured at 2 m in length from the base of the stem (Figure 1). The logs were taken to the sawmill of the Forest Institute of the Federal Rural University of Rio de Janeiro (Universidade Federal Rural do Rio de Janeiro – UFRRJ) for primary milling using a vertical bandsaw (Figure 2). Planks of 3 cm thick and one central diametral plank of 6 cm thick were produced from each log. The planks were used for workability tests and the diametral planks were used to produce samples for physical, mechanical, and macroscopic anatomical characterization tests.

The wood pieces obtained from the primary milling were air dried until the moisture content was in equilibrium with the ambient humidity, which in many cases was similar to the humidity conditions under which the wood products would be used.

Figure 2.Primary sawmilling of logs using a vertical bandsaw, with 1.20 m diameter wheels and advance/feeding by a semi-automatic feeder.

3. Anatomical characterization

Knowledge about wood anatomy is very important for the determination of wood quality. Regardless of its intended use, the description of the wood anatomical structure may greatly explain the properties and technological behavior of the wood.

For the technological development of industrial cellulose pulp, the anatomical structure, as well as wood chemistry, of *Eucalyptus* and *Pinus* species were studied in depth to determine the best genetic materials. Similarly, the technological behavior of solid wood products can be explained by the anatomical composition of the wood. Variables of wood drying, cutting, finishing, and coating, as well as the relationship of wood with other materials, could make easier or more difficult with different wood anatomical compositions.

The wood mechanical resistance and physical properties are directly correlated with its anatomical structure. Therefore, for a given sample, the denser the anatomical elements, the higher the physical properties, such as wood density.

Until now, the uses of the wood from native species was little studied, and, consequently, anatomical characterizations for the correlation and discussion of wood use and production were scarce. In the present study, wood anatomical characterization was performed through macroscopic analyses (10× magnification) of three planes of wood (cross-sectional, longitudinal tangential, and longitudinal radial). In addition, an overall description of the organoleptic properties of the wood samples is given. Wood samples from all species were deposited in the Xylotheque of the Forest Products Department (FPDw) of the UFRRJ.

4. Physical–mechanical properties

Following primary milling, samples for wood physical and mechanical properties were produced from the 6 cm thick diametral planks (taken from the central part of the logs).

The methodology used was based on Annex B of the ABNT 7190:1997 – Wooden Structures Project Standard, which describes the test methodology for the evaluation of the main wood physical properties and resistance to several mechanical efforts, namely bending, compression, and shearing.

Based on the physical–mechanical properties of wood samples, the uses for wood can be predicted based on the workability, or indicated by tests, such as supporting a load, or being subjected to friction, trampling, the use of tools, or wear from contact with other materials. Given that wood products can be used in the open, where the incidence of humidity and sunlight are constant, or used in protected/closed environments, where humidity and temperature are less variable, both of these conditions need to be tested to indicate differences in wood performance.

Small wood pieces for the main physical–mechanical evaluations were therefore obtained from each evaluated species, with a total of six replicates for each test per sampled tree, and three sampled trees per species. All samples were brought to equilibrium with the ambient humidity by air drying in a covered environment, until they reached a humidity of approximately 12%. The samples were cut from the first log in the stem, which was sectioned from a height of 20 cm up to 2.20 m from the tree base.

The physical–mechanical properties of the wood samples was performed in the laboratories of the Forest Products Department of the Forest Institute of the UFRRJ (Figure 3). The following physical properties and variables were determined and evaluated: apparent density (air dried sample), basic density, volume variation (shrinkage), and anisotropy coefficient. In addition, the following mechanical properties were determined and evaluated: modulus of rupture for static bending strength, shear strength, compression strength parallel to the grain, and Janka hardness (both perpendicular and parallel to the grain).

Wood density has been used for several decades as one of the main wood quality variables. Because the relationship between mass and volume of a given sample or piece of wood is directly affected by its water content, it is extremely important to consider humidity when determining this relationship.

The ABNT 7190:1997 standard method establishes that wood moisture should be 12% on a dry basis (sample fresh weight divided by dry weight) for the determination of wood apparent density, which is the mean moisture value for woodworking under Brazilian climate conditions. Basic density is calculated as the sample dry weight divided by its water saturated volume, i.e., as the ratio between the lowest weight (absolute dry weight) of the sample, and its highest volume (water saturated).

The volume variation and anisotropy coefficient variables are indicators of the wood behavior regarding water gain and loss in response to changes in air humidity or direct contact with water (e.g., rainfall), followed by successive “dryings” (dry periods or without rainfall). These variables may also be related to wood stability, i.e., indicating if a given species will produce wood with higher or lower dimensional stability, which is related to warping, cracks, splitting, and wood deformations, when in use. The volume variation in wood samples was therefore determined as its maximum shrinkage, i.e., as the difference in volume between the saturated and absolutely dry sample, and expressed as a percentage.

The ratio between the tangential and volumetric retraction of a specimen, called anisotropy coefficient (Figure 4), is an important index for the study of retractions, since the higher the anisotropy

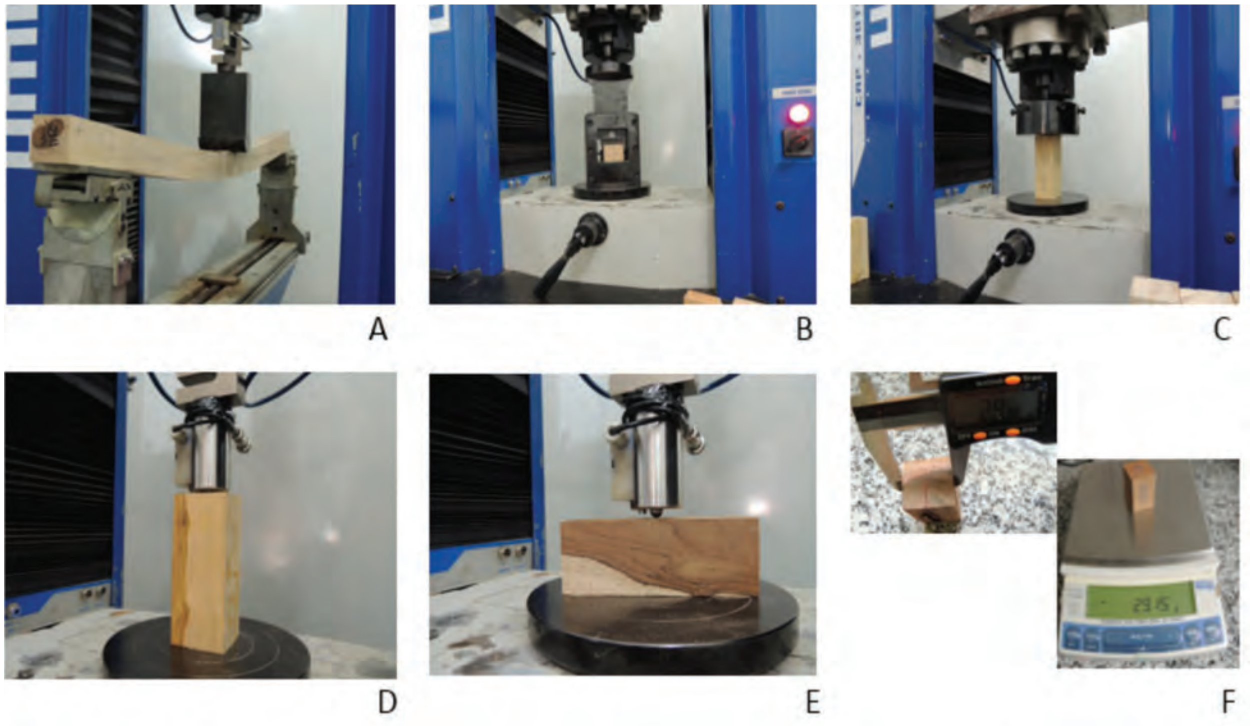

Figure 3.Physical and mechanical study of samples: A) Details of static bending test. B) Details of shear strength test. C) Details of compression strength parallel to the grain test. D) Details of Janka hardness parallel to the grain test. E) Details of Janka hardness perpendicular to the grain test. F) Details of wood physical properties evaluation. Source: photos by the team of the Wood Processing Laboratory (Forest Products Department, Forest Institute/UFRRJ).

coefficient, the higher the probability of cracks, checkingand warping (Oliveira, 1988). Oliveira et al. (1997) used wood anisotropy to evaluate wood quality from forests plantations, and stated that knowing the dimensional instability of wood fibers is important selection criteria for genetic improvement programs.Anisotropy coefficients lower than 1.5 indicate very stable, excellent quality woods, used for fine furniture, frames, and instruments; between 1.6 and 2.0 indicate normal quality woods with low to medium anisotropy, used in products that accommodate slight warping (bookcases, cupboards, and tables); higher than 2.0 indicate low quality wood with medium to high anisotropy, used in products that do not require stability or high quality (construction, packing, pallets) (Nock et al., 1975).

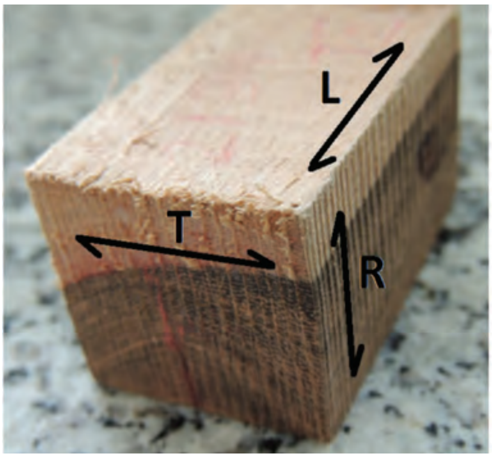

Figure 4. Wood sample showing longitudinal (L), tangential (T), and radial (R) directions. Source: Team of the Wood Processing Laboratory (Forest Institute/ UFRRJ).

5. Machining and workability tests

The evaluation of wood machining processes, workability, and operations related to the surface finishing of wood pieces has not always been considered in wood quality studies. Testing the behavior of wood from a given species worked using a given machine or equipment may give further information about the adequacy of a given genetic material for a certain use or product. Each specific desired end use will demand certain types of wood, and the suitability to the work to be performed by the product will often depend not only on the intrinsic properties of the material, but also on its behavior during processing. This is especially the case in operations that are focused on standardizing batches of wood pieces and improving visual characteristics, as well as taking into account the desired end use, be it either decorative, for construction or for veneers.

To evaluate these variables and factors, samples were produced and subjected to rigorous evaluation by planing, sanding, lateral mortising, through-boring with helicoidal bits (for pins), through- and non-through-boring with flat bits (for hinges), and nailing. The tests were performed according to the American Society for Testing and Materials (ASTM) 1666 D-1666-87 standard method for conducting machining tests of wood and wood base materials, as adapted by the Forest Product Laboratory (LPF)/Ibama (Ibama, 1997).

Wood samples 30 cm long, 12 cm wide, and 2.54 cm thick were produced for each evaluated species from the planks obtained by primary sawmilling of the sampled logs. They were then stabilized to the equilibrium moisture content and tested, as shown in Figure 5.

The results from the machining and workability tests were evaluated visually, according to the ASTM 1666 D-1666-87 standard method. Namely, samples were graded using a scale from 1 to 5, corresponding to *Very Poor, Poor, Fair, Good*, and *Excellent*, for the following properties: planing; through-boring with helicoidal bits of 6 mm, 8 mm, and 10 mm; through and non-through boring with spade bits of 2.54 cm; sanding; and lateral mortising. For nail acceptance, a percentage of acceptance or non-acceptance was attributed, according to the number of nailing operations that generated splitting and/or cracks and severe fiber tearing in the sample.

Defects resulting from machining can be related to the machine type and quality, adequacy of the equipment to work the tree species and its characteristics, and factors related to the anatomical composition and physical properties of the wood. Machining and workability tests are based on standardized operations, in which machines are operated with fixed variables, such as cutting and forward speed, knife angle, sandpaper grain size, and milling cutter and drill characteristics, and aim to evaluate the ease of wood processing, need for special and/or projected equipment depending on the wood composition, and wood adequacy for a specific use or segment, including its processing and final use.

6. Indication of potential uses

Depending on the intended use, wood can be classified as adequate or inadequate, good or bad, and procedures during its processing and/or use can lead to a successful or unsuccessful wood performance. The final quality of a given type of wood or species can therefore be defined with accuracy only if its characteristics and properties are related to its intended use. Based on a deeper technological evaluation and the results of wood property tests conducted during processing, the best uses for each species can be predicted with greater safety.

The main flaws in wood machining can be traced to four basic parameters (Silva et al., 1996): variations in wood properties, characteristics of machinery, characteristics of cutting tools, and the skill/training of the human labor. According to Bet (1999), all of these parameters provide a very useful tool for the quality control of the production process and subsequent determination of use.

The present study tried, with a high level of detail and care, to relate the results obtained for samples of planted trees from 29 native species and provide indications of use that matched the woods' observed properties and characteristics. It should be highlighted that many of these species are being evaluated for this purpose for the first time, whereas other species have a long tradition in the wood market; and some of these have had older or mature trees originating from natural forests evaluated, but not samples from planted trees.

Possible uses were indicated for each species from several wood consumer sections: furniture, floors, frames, construction, utensils, packages, boxes,

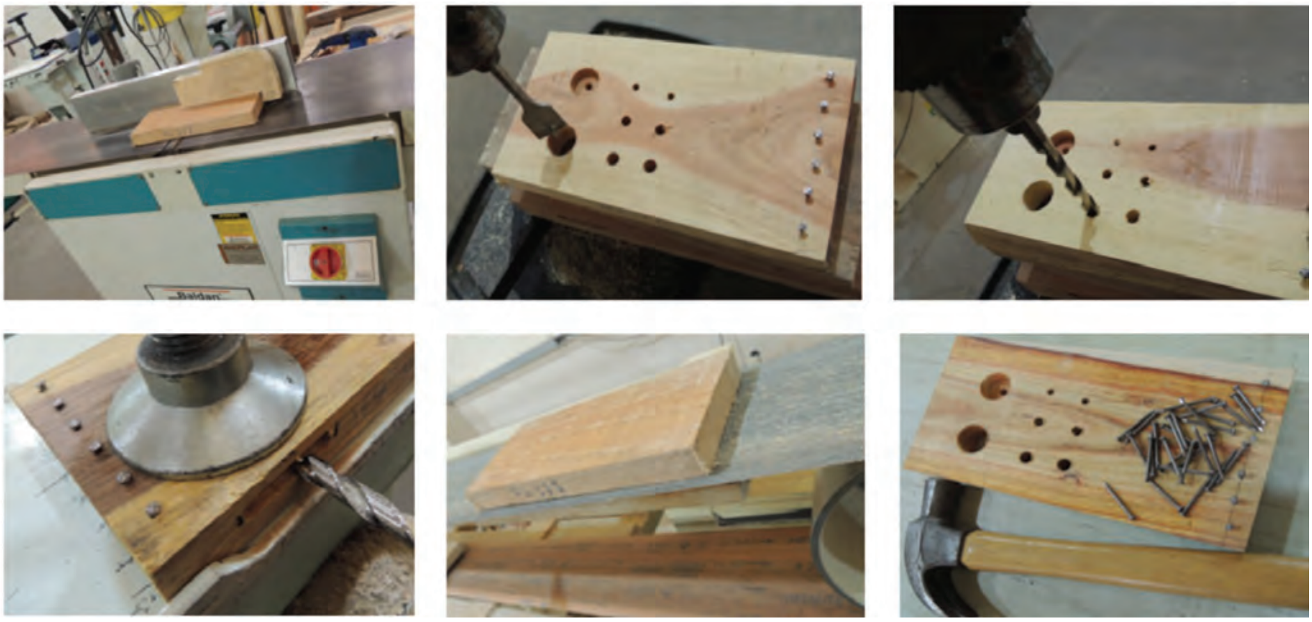

Figure 5. Details of sample production and performance of wood machining and workability tests. Source: Team of the Wood Processing Laboratory (Forest Institute/UFRRJ).

pallets, tool handles, and other small wooden objects. For some of the evaluated species, precautions and/or adaptations for their processing, machining, and finishing were also suggested, since much better results may be obtained using different techniques and materials compared to those used in the standardized tests.

7. Technical data sheets of wood properties, and uses

As a result of the wood quality evaluation of the 29 species native to the Atlantic Forest grown in forest plantations, technical data sheets detailing the wood properties, and uses were created, presenting the results of the tests and their technical interpretations. On the sheets, the following information is presented for each species:

- Description of overall wood properties: color, odor, taste, texture, grain, luster, and special characteristics;
- Macroscopic anatomical description with image of a cross-sectional (10× magnification) and tangential plane;
- Physical properties and relationships - apparent density, basic density, volume variation (shrinkage %), and anisotropy coefficient;
- Mechanical properties - modulus of rupture for static bending strength, shear strength, compression strength parallel to the grain, and Janka hardness both perpendicular and parallel to the grain;
- Workability in planing, boring with helicoidal and spade bits, sanding, lateral mortising, and nailing;
- Image of a sample after the workability tests;
- Indications of wood uses.

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5. GROWTH AND WOOD PROPERTIES OF TREE SPECIES IN SILVICULTURAL TRIALS IN THE NORTH OF ESPÍRITO SANTO

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1. Introduction

Two basic factors are essential to the development of native species silviculture in Brazil: knowledge and improved market information. Native wood species are known to need long production cycles (20–50 years) to reach the minimum diameters considered appropriate for felling (approximately 30–40 cm). The long production cycles and high costs of establishing and monitoring experimental plantations have made comprehensive studies on the performance of almost all Brazilian native species difficult. Although native species silviculture is incipient at the market level in Brazil, it has a long history, and the knowledge accumulated over the last 50 years is not negligible (Chapter 1). However, there has never been considerable and coordinated investment in native species silviculture, and most of the existing knowledge comes from isolated trials that were set-up over 30 years ago by a few institutions, specifically Embrapa, Forest Institute (state of São Paulo - SP), Ceplac (state of Bahia - BA), and Rio Doce Forests (state of Espirito Santo - ES).

Over the last years, there has been a renewed interest in native species silviculture in the whole tropical region of Central/West Asia, Central America, and north Africa (Payn et al., 2015). This renewed interest has been guided by synergies between international conventions on biological diversity (CDB, Legislative Decree no. 2, of 1994), large scale reforestation programs (http:// www.bonnchallenge.org), wood scarcity (Warman, 2014; Buongiorno, 2015), the need to improve landscape permeability (Pirard et al., 2016; Metzger et al., 2017), and to offset carbon emissions (Dewar & Cannel, 1992; Montagnini & Porras, 1998; Marín-Spiotta & Sharma, 2013; Power et al., 2013). The need to attract new investment for native species silviculture is essential not only because of the environmental services resulting from reforestation, but mainly because wood is a valuable asset with growing market demand and prices. Two questions seem to concern those interested in investing in this market:

What wood volume can be produced, and in what timeframe?

What is the wood quality of planted native tree species?

In the present chapter, we present information on the wood production and quality of some of the main native tree species with silvicultural potential in the Atlantic Forest. We hope that this information will help to encourage investments focused on the use of native tree species in commercial plantations, and promote new silvicultural studies on native species from the Atlantic Forest.

2. Methodology

The scientific names and natural distribution ranges for each species were confirmed by consulting the Brazilian Flora project databases (http://floradobrasil.jbrj.gov.br/reflora). Growth data was gathered in a network of permanent plots for the monitoring of forest plantations, established in the Vale Nature Reserve, Linhares. The type of plantation, spacing and tree mortality are described for all species. The photos for all species were obtained from plantations located in the reserve, but some did not correspond to the data for the analyzed plantations. Diameter, height, volume, and biomass values are presented for the age of 35 years, except for some species with shorter cycles, for which they are presented for the age of 15 or 25 years. Equations for diameter growth are presented separately for each species, and the respective methodology is described in Chapter 3. The hypsometric, volume, and biomass models are described in detail in Chapter 2, from which the following equations were selected:

$$H_S = \left(\frac{D}{0.2150\,D + 2.5188}\right)^2$$

$$H_T = \left(\frac{D}{0.1749\,D + 1.6080}\right)^2$$

$$V_S = 1.11 * 10^{-4} * D^{2.0479} * H_S{}^{0.6352}$$

$$AGB = 0.1009 * D^{2.2472} * H_T^{0.4333} * \rho^{0.7865}$$

where ***AGB*** is aboveground biomass in kg/tree, ***Vs*** is stem volume in m^3, D is diameter in cm, ***HT*** is total height in m, ***Hs*** is commercial stem height in m, and ρ is wood density in g/cm^3.

The estimated growth and yield for each species were compared to those found in the literature accumulated over the past decades, and some suggestions and recommendations based on empirical experience are presented for each species.

The stem shape of each tree was evaluated annually in the experimental plantations studied. However, thinnings were performed over time to eliminate individuals presenting tortuous and bifurcated stems. The approach used considers that trees useful for silviculture are those presenting straight and well-formed stems, and that tortuous trees should be eliminated by thinning throughout the trial. We therefore chose to perform a visual evaluation of the remaining trees in each plantation in 2017 or the last year of monitoring in cases where all trees had been eliminated before 2017. The full species variability was therefore not evaluated, but rather the focus was on trees with potential to be harvested, after years of selecting the most suitable trees in the plantations.

For almost all species studied, some trees were felled for analyses of the technological properties of the wood, as presented in Chapter 4.

Finally, the species were divided according to the stem commercial quality and growth rate observed in Linhares, as shown in Diagram 1. This division was based on the data obtained from the permanent plots for the monitoring of forest plantations established in the Vale Nature Reserve, Linhares, but better management conditions may result in improved stems or higher growth rates for the studied tree species.

Some precautions are suggested when interpreting the results:

- Many species presented short commercial stems in plantations because trees were mismanaged, without the application of necessary prunings, or because they were planted in full sun and branched precociously. However, the estimated stem commercial height and volume are presented to show species growth and production potential assuming that the trees were adequately managed, i.e., that the pruning required to reach the height, and consequently volume, estimated by the model will be applied. These cases are explicitly described for each species.

- The growth results obtained in the trials at Linhares can be considered conservative in many cases, since the soils in the area are very sandy with low fertility, and rainfall in the region is unevenly distributed throughout the year and lower than 1250 mm, which is below what can be considered the minimum rainfall threshold for many species. In addition, not all trial trees received thinning at the correct times, and many did not grow as much as they could have. The results obtained are compared to the available literature whenever possible, to help better understand what can be expected in terms of yield for each species, including literature from other regions.

- It is common to compare the volume increase for native tree species with those reached by *Eucalyptus* for cellulose production (6-year cycle, without thinning), which can be higher than 45 m^3/ha/year. However, for a more correct comparison, *Eucalyptus* for wood production should be used as reference (20-year cycle, with thinning), for which the volume increase should be approximately 16 to 20 m^3/ha/year.

- Stem diameter increases are commonly reported for plantations aged 5–15 years. Stem diameter increase usually reaches its maximum at that age, and tends to decrease in older ages. These increases are not constant throughout the life of the tree and should not be used to extrapolate future tree growth when measured for short periods. In the present study, stem diameter increases are presented for trees aged 35 years for most species studied, resulting in an improved understanding of the potential of each species; however, using the stem diameter increase to extrapolate stem diameters for trees aged > 40 years should be avoided;

- It should be highlighted that the present study does not recommended a specific production system for each species. Its aim is only to show the growth and wood quality that can be expected for each species when grown in forest plantations. However, the growth data allows for the evaluation of the potential of different species combinations under different management conditions, by using the wood volume per species based on the proportion of trees in each plot. The best species combinations in terms of growth can therefore be studied, and different production systems can be designed or planned. Production systems range from agroforestry systems with few trees, to mixed plantings that do not require clearcutting or other intensive management for harvesting. The latter can be managed in a continuous polycyclic system, with enough species diversity to recover functional ecological connectivity, especially in highly degraded landscapes of the Atlantic Forest.

- Species for Mixed Plantation
  - Long stems, usually > 8 m, well-shaped and straight or slightly tortuous
    - Species with medium to high DBH growth rates (> 0.75 cm/year)
    - Species with very slow to slow DBH growth rates (< 0.75 cm/year)
  - Short stems, sometimes well-shaped, but usually < 7 m, precociously branched when grown in full sun
    - Species with medium to high DBH growth rates (> 0.75 cm/year)
    - Species with very slow to slow DBH growth rates (< 0.75 cm/year)

Diagram 1: Classification of the tree species studied according to stem quality and growth rate, measured in silvicultural trials in Linhares (ES). The species were classified in terms of their diameter growth since for the great majority of them the expected product from plantations is solid timber used for traditional purposes. The plantation management practices are therefore focused on individual tree diameters instead of total wood volume produced, i.e., for the same volume, it is preferable to have few trees with large diameters than many trees with small diameters.

Cariniana legalis (Mart.) Kuntze **(Lecythidaceae)**

Distribution: Commonly known as jequitibá-rosa, it is distributed mainly in the ombrophilous and seasonal forests of the Atlantic Forest, from the state of Paraná to the state of Alagoas (Smith et al., 2015). It is extensively exploited in the Atlantic Forest, and other species of the same genus are exploited for wood production in the Amazon, as they have high timber values.

Mean Growth and Yield: Growth data was obtained from a mixed plantation with *Handroanthus serratifolius* (ipê-amarelo, n = 72 trees per species) in Linhares, with 3 × 2.5 m spacing. The remaining trees of *C. legalis* at 31 years of age presented excellent shape and health. Mortality was 2% until 17 years of age. The fitted equation to estimate the diameter growth at breast height (DBH) relative to Age (t in years) was as follows:

$$DBH = 46.40\ exp^{-11.38\ t^{-0.9855}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 256 m^3/ha for 375 trees/ha, with a mean DBH of 32.9 cm and stem height of 11.8 m. For this age, the estimated mean annual increment (MAI) in volume was 7.3 m^3/ha/year, MAI in diameter was 0.94 cm/year, and stocked biomass was 216 Mg/ha. The plantation in Linhares presented a period of growth stagnation between 13 and 16 years of age due to the absence of thinning, suggesting that these results could be achived earlier. The DBH growth at 14 years of age in Linhares (DBH = 19.8 cm) was slightly higher than reported for trees growing on purple Latosols in Luiz Antônio (SP) (Sebbenn et al., 2000), São Simão (SP) (Gurgel Filho et al., 1982a), and Paraná (Silva & Torres, 1992). A DBH of 19 cm at 9 years of age was reported for an agroforestry system in Bahia (Matos, 2016). C. *legalis* can be planted in full sun and develop naturally straight stems, but growth and straight stems are favored in mixed plantation, decreasing the need for pruning and promoting growth. In Linhares, the trial was set up on nutrient-poor and sandy Argisols under a climate with low rainfall, and the results obtained for C. *legalis* corresponded to a low-productivity site. C. *legalis* may reach a mean diameter of 39 cm at 30 years of age in more productive soils, with the mean diameter being positively correlated with the soil clay content (Silva, 2013). There are ex-situ conserved populations of C. *legalis* in São Paulo (Siqueira & Nogueira 1992). There are pronounced differences between different provenances and progenies of C. *legalis*, and genetic selection can be expected to increase both DBH and height by 15% (Sebbenn et al., 2000).

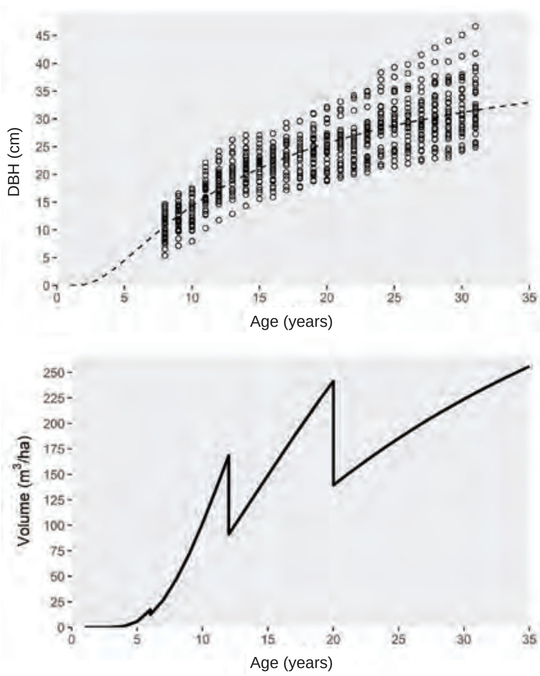
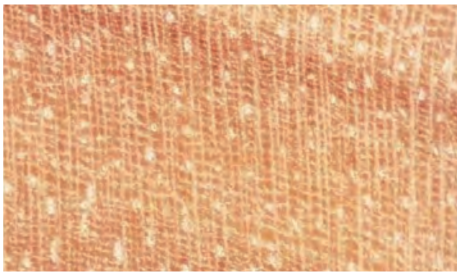


Figure 1. Diameter growth of *Cariniana legalis* grown in a mixed plantation with *Handroanthus serratifolius* in Linhares (ES), and simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 20 years of age.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Slightly distinct heartwood and sapwood, rose-beige heartwood with gray stripes, uncharacteristic odor, indistinct taste, straight grain, fine to medium texture, and little variance in luster.

Macroscopic Anatomical Description:

Axial Parenchyma: only visible under magnification, reticulated. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential planes, little contrast in the longitudinal-radial plane, thin, numerous to very numerous, non-stratified. Vessels: barely visible without magnification, very small to small, numerous, diffuse-porous, solitary and radial multiples (2–3 vessels). Growth Rings: delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.651
Basic density (g/cm³)	0.529
Volume variation (shrinkage %)	12.03
Anisotropy coefficient	1.26
Modulus of rupture for static bending strength (kgf/cm²)	655.36
Shear strength (kgf/cm²)	131.67
Compression strength parallel to the grain (kgf/cm²)	371.44
Janka hardness (kgf) – parallel and perpendicular to the grain	440.00 – 661.67

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Good	Fair	Fair	Fair	Poor	Fair	Good	Excellent	33% accepts; 67% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium density wood. High dimensional stability, no tendency to warp. Medium hardness. Indicated for use in light structures, furniture, frames, utensils, packages, linings, tool handles, and cladding. Good to excellent planing and lateral mortising properties. Difficult boring with both helical and spade bits. Good sanding properties. Fair nail acceptance properties, with most evaluated samples presenting fiber tearing and cracking in the bottom side of the sample.

Pterygota brasiliensis Allemão **(Malvaceae)**

Distribution: Commonly known as farinha-seca or pau-rei. It is distributed in ombrophilous and seasonal forests in the states of Rio de Janeiro, Minas Gerais, Pernambuco, and Espírito Santo, although it is not reported in the latter in the Brazilian Flora project (Esteves, 2015). It is used locally for timber and should be better valued by the market.

Mean Growth and Yield: Growth data was obtained from a spacing trial, where the remaining trees at 27 years of age presented excellent stem shape and good health. Mortality was 4% until 10 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 89.77\left(1 + 44.28\, exp^{-0.9057\, Ln(t)}\right)^{-1}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 254 m^3/ha for 388 trees/ha, with a mean DBH of 32.4 cm and stem height of 11.7 m. For this age, the estimated MAI in volume was 7.3 m^3/ha/year, MAI in diameter was 0.93 cm/year, and stocked biomass was 223 Mg/ha. This was the only studied species for which volume was significantly underestimated by the model, since it presented the highest stem height, and therefore requires its own equation to improve the model's accuracy. Vinha & Lobão (1989) reported a DBH of 14.7 cm at 16 years of age, lower than that observed in Linhares. It is sensitive to a lack of thinning, as was the case for the plantations in Linhares. It grows well in full sun, but despite its excellent natural shape, it presents high growth variability, requiring care in terms of selecting better provenances and adequate thinning. If its production improvement and increase in market value is achieved, this species may become important as a shading plant in mixed plantation (because of its columnar crown) and as a potential wood-producing tree at 25 years of age.

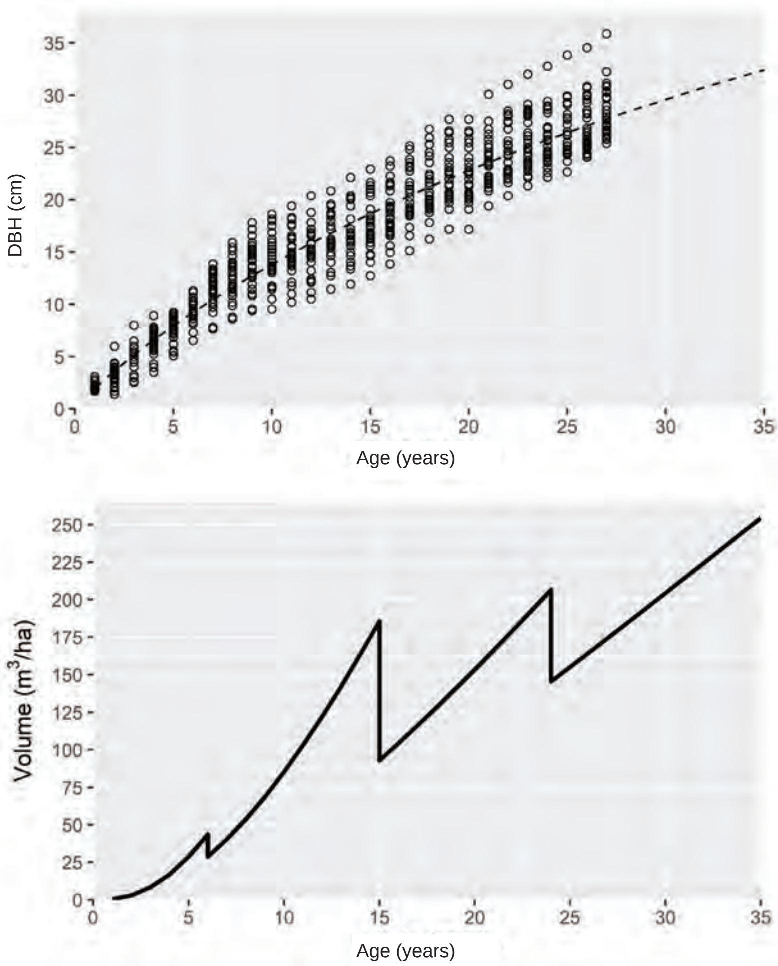
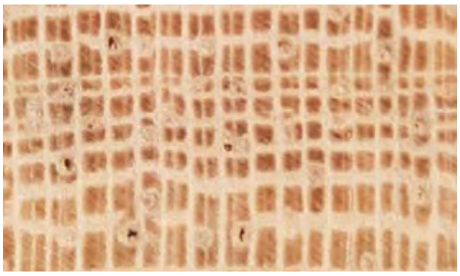


Figure 2. Diameter growth of *Pterygota brasiliensis* in a spacing trial in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 15, and 24 years

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Indistinct white-yellowish heartwood and sapwood, obvious fibrous appearance, uncharacteristic odor, indistinct taste, medium texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, occasionally vasicentric, confluent, and in broad and long bands. Rays: visible without magnification in the cross-sectional and longitudinal-tangential plane, contrast in the longitudinal-radial plane, medium, numerous, and non-stratified. Vessels: visible without magnification, medium, few, diffuse-porous, predominantly solitary, occasionally multiples of two in tangential arrangement. Growth Rings: delimited by fibrous tissue and parenchyma in marginal bands.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.743
Basic density (g/cm^3)	0.553
Volume variation (shrinkage %)	9.01
Anisotropy coefficient	1.72
Modulus of rupture for static bending strength (kgf/cm^2)	758.09
Shear strength (kgf/cm^2)	76.37
Compression strength parallel to the grain (kgf/cm^2)	436.32
Janka hardness (kgf) – parallel and perpendicular to the grain	505.00 – 525.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Fair	Poor	Poor	Poor	Fair	Fair	Good	Fair	14% accepts; 86% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium hardness and density wood. Medium anisotropy. Little tendency to warp and twist. Indicated for use in light structures, furniture, construction, carpentry, cladding, packaging, and utensils. Good to fair planing properties. Poor to fair boring properties with both helical and spade bits. Good sanding and fair lateral mortising properties, and low nail acceptance in most assays performed, demanding specific care, such as pre-boring.

Dalbergia nigra (Vell.) Allemão ex Benth. **(Fabaceae)**

Distribution: Commonly known as jacarandá-da-bahia or jacarandá caviúna, it mainly occurs in ombrophilous and seasonal forests in the state of Bahia, Espírito Santo, Minas Gerais, and Rio de Janeiro (Lima, 2015a). It is the species with the most valuable wood in the Atlantic Forest; and thus has been highly exploited, which almost led to the extinction of its natural populations.

Mean Growth and Yield: Growth data was obtained from a mixed plantation of *D. nigra* with *Paratecoma peroba* (peroba) and *Zeyheria tuberculosa* (ipê-felpudo), with 1.5 × 1.5 m spacing, and two *P. peroba* to two *Z. tuberculosa* and one *D. nigra*. Several thinnings were performed on an irregular basis, and the remaining trees of *D. nigra* at 20 years of age presented well-shaped stems that were slightly tortuous, but with good health. Mortality was 7% until 1 year of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 61.47\ exp^{-3.92\ t^{-0.4838}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 248 m^3/ha for 438 trees/ha, with a mean DBH of 30.5 cm and stem height of 11.3 m. For this age, the estimated MAI in volume was 7.1 m^3/ha/year, MAI in diameter was 0.87 cm/year, and stocked biomass was 241 Mg/ha. The highest growth for *D. nigra* reported by Carvalho (2003) was 17.6 cm at 12 years of age in the Atlantic Forest, which corresponds with the value of 18.7 cm observed in Linhares. Growth in the Ceplac arboretum, located in Bahia, was low, with a DBH of 9.9 cm at 12 years of age (Vinha & Lobão, 1989). A DBH of 17 cm at 9 years of age was reported for an agroforestry system in the state of Bahia (Matos, 2016). Outside its area of origin, in the Amazon, Silva & Canto (1994) reported good growth (17.7 cm at 19 years of age), but with short (3.8 m) and tortuous stems due to very wide spacing and lack of management. Care should be taken with tree borers, which may lead to high plant mortality rates (Jesus et al., 1992). Its heartwood, which is the attractive and valuable part of the wood, takes a long time to form, which warrants the estimation of the best felling age for trees to be 50 years of age, a perfectly acceptable age due to the very high value of the wood. At this age, the tree density will be reduced to approximately 350 trees/ha, but all trees will have a higher percentage of heartwood. It should not be planted in full sun, and produces straighter stems when established as enrichment planting, which stimulates vertical growth and minimizes borer attacks. It should be highlighted that it is sensitive to excessive shading, which may decrease its growth rate.

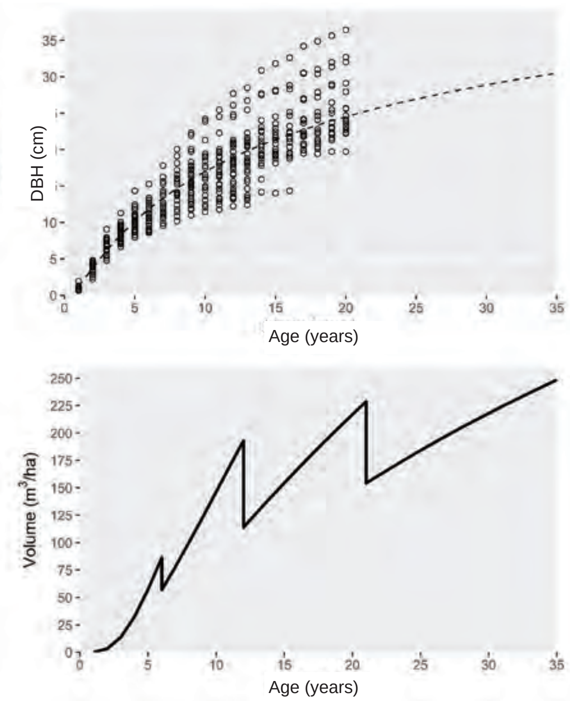
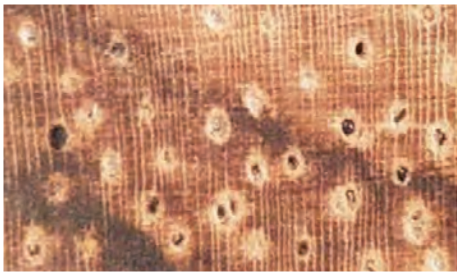


Figure 3. Diameter growth of *Dalbergia nigra* grown in a mixed plantation with *Paratecoma peroba* and *Zeyheria tuberculosa* in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 spacing, with thinning at 6, 12, and 21 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, dark gray heartwood with darker veins, whitish-yellow sapwood, uncharacteristic odor, sweet taste, coarse texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal aliform, vasicentric, and in discontinuous narrow bands. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential plane, little contrast in the longitudinal-radial plane, very thin, few to very numerous, stratified. Vessels: visible without magnification, small, numerous, diffuse-porous, oblique, solitary and radial multiples (2–3 vessels). Growth Rings: delimited by fibrous tissue and discontinuous narrow bands of parenchyma.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.782
Basic density (g/cm³)	0.634
Volume variation (shrinkage %)	12.89
Anisotropy coefficient	1.26
Modulus of rupture for static bending strength (kgf/cm²)	863.79
Shear strength (kgf/cm²)	152.49
Compression strength parallel to the grain (kgf/cm²)	482.92
Janka hardness (kgf) – parallel and perpendicular to the grain	647.67 – 855.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Fair	Good	Fair	Good	Excellent	Good	Good	Excellent	22% accepts; 78% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high hardness and density wood, very low tendency to twist and warp. Indicated for use in structures, decoration (due to the aesthetic beauty of the interaction between the heartwood and sapwood colors), furniture, and utensils. Good planing properties with the grain, with more flaws against the grain. Overall, it is easy to bore, and presents good sanding properties and excellent lateral mortising properties. Low nail acceptance in the heartwood due to high hardness.

Zeyheria tuberculosa (Vell.) Bureau ex Verl. **(Bignoniaceae)**

Distribution: Commonly known as ipê-felpudo or bolsa-de-pastor, it occurs mainly in seasonal semideciduous forests in the southeast region but has also been reported in the state of Bahia and other areas in the Northeast (Lohmann, 2015). Although it is considered a pioneer species that colonizes degraded areas, it has high longevity and some studies indicate that it has timber value, having been historically exploited in the Atlantic Forest (Luz & Ferreira, 1985).

Mean Growth and Yield: Growth data was obtained from a provenance trial in Linhares, with 3 × 2.5 m spacing. The best provenances, from the municipalities of Iconha (ES) and Alfredo Chaves (ES), were selected for analysis (n = 24 trees per provenance). The remaining trees at 23 years of age presented excellent shape and health and good self-pruning. Mortality was 10% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 37.62\left(1 + 19.90\, exp^{-\,1.13823\, Ln(t)}\right)^{-1}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 240 m^3/ha for 523 trees/ha, with a mean DBH of 27.9 cm and stem height of 10.7 m. For this age, the estimated MAI in volume was 6.8 m^3/ha/year, MAI in diameter was 0.80 cm/year, and stocked biomass was 224 Mg/ha. In the state of Bahia, in the Ceplac arboretum, Vinha & Lobão (1989) observed a DBH of 15.2 cm at 17 years of age, lower than that observed in Linhares. However, there was a reported mean DBH of approximately 19 cm at 11 years of age with 4 × 4 m spacing (Carvalho, 2003), higher than that observed in Linhares. The provenance trial in Linhares indicated high variability. It is not demanding in fertile soils but responds better to soils with high fertility and especially in areas with rainfall of approximately 1600 mm, where it may reach a DBH of 30 cm between 25 and 30 years of age. It adapts well to planting in full sun, and usually produces straight stems with good self-pruning, but still requires some pruning. It is interesting for use as a shading plant but does not produce good shade in its initial years, improving after 4 to 6 years when the crown becomes columnar, favoring other species in mixed plantings. In mixed plantings, it cannot be strongly shaded because its stem tends to twist in search of light.

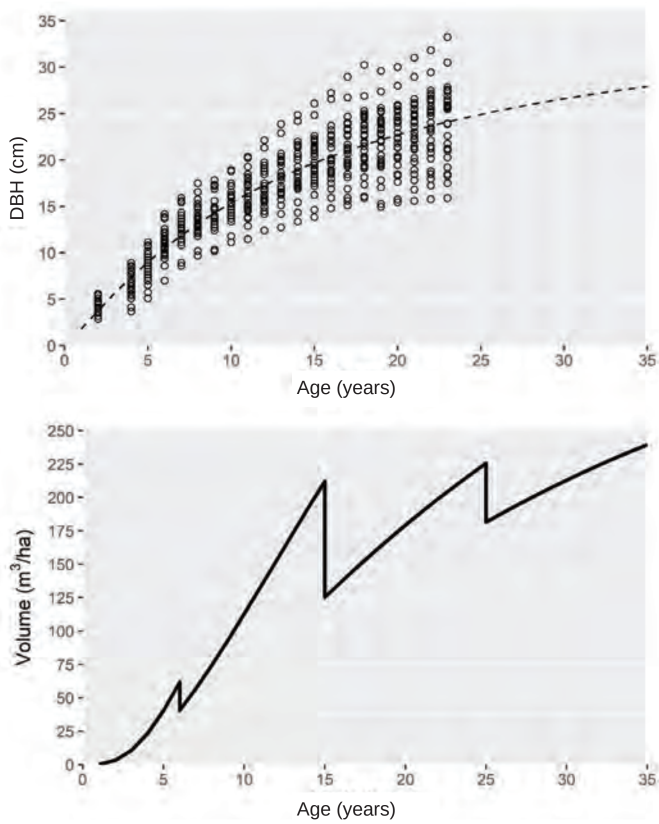
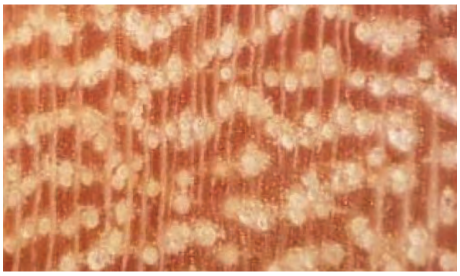


Figure 4. Diameter growth of *Zeyheria tuberculosa* in a provenance trial in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 15, and 25 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, yellowish-brown heartwood and light beige sapwood, uncharacteristic odor, bitter taste, medium texture, interlocked grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: barely visible without magnification, paratracheal vasicentric, confluent, and in marginal bands. Rays: only visible under magnification in the cross-sectional plane and barely visible without magnification in the longitudinal-tangential plane, little contrast in the longitudinal-radial plane, thin, numerous, and stratified. Vessels: only visible under magnification, very small to small, numerous to very numerous, diffuse-porous, predominantly solitary, and tangential multiples (2–3 vessels). Growth Rings: delimited by fibrous tissue and narrow bands of marginal parenchyma.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.795
Basic density (g/cm³)	0.608
Volume variation (shrinkage %)	13.73
Anisotropy coefficient	1.53
Modulus of rupture for static bending strength (kgf/cm²)	831.67
Shear strength (kgf/cm²)	127.99
Compression strength parallel to the grain (kgf/cm²)	155.06
Janka hardness (kgf) – parallel and perpendicular to the grain	623.33 – 736.67

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Good	Fair	Good	Excellent	Good	Excellent	Good	Excellent	50% accepts; 50% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium density and hardness wood. Fair to good stability, no tendency to warp. Indicated for use in light structures, furniture, floors, tool handles, and utensils. Shows good planing properties and fair boring properties with both helical and spade bits. Good sanding properties and excellent lateral mortising properties. Fair nail acceptance, presenting problems in half of the samples evaluated.

Cordia trichotoma (Vell.) Arráb. ex Stend. **(Boraginaceae)**

Distribution: Commonly known as louro-pardo, it occurs on the South edge of the Amazon, in seasonal dry forests in the interior of Central Brazil, and along the whole Atlantic Forest, from the south to northeast (Stapf, 2015). It is a fairly well studied species and is highly recommended due to its high timber value (Harrit, 1991), similar to two other species of the same genus from the Amazon: *Cordia alliodora* and *Cordia goeldiana.*

Mean Growth and Yield: Growth data was obtained from a mixed plantation with *Cariniana legalis* (jequitibá-rosa) and *Bowdichia virgilioides* (macanaíba) in Linhares, with 3 × 1 m spacing. The remaining *C. trichotoma* trees at 18 years of age presented good stem shape, but many trees had compromised health. Mortality was 40% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 41.27\ exp^{-2.15 \cdot exp^{(-0.0484\ t)}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 239 m^3/ha for 527 trees/ha, mean DBH was 27.8 cm, and stem height was 10.7 m. For this age, the estimated MAI in volume was 6.8 m^3/ha/year, MAI in diameter was 0.79 cm/year, and stocked biomass was 186 Mg/ha. Growth in the Ceplac arboretum in Bahia was also lower, with a DBH of 10.5 cm at 15 years of age (Vinha & Lobão, 1989). A mean DBH of 18 cm at 8 years of age, and 16 cm at 10 years of age, were reported in areas managed by Embrapa in the state of Paraná (Carvalho, 2003), much higher than those observed in Linhares. There are ex-situ conserved populations in São Paulo (Siqueira & Nogueira 1992). Good initial growth, until 12 or 15 years of age, was observed in several plantations in Linhares, but from that age on, many trees practically stopped their DBH growth, although they remained alive. The last years of monitoring were not used in the model because of what may be considered growth under compromised health conditions. Two probable causes may explain this.

The first is continuous attack by a leaf-sucking Hemiptera (*Dictyla monotropidia*), resulting in leaf shedding (Carvalho, 2003). This energy investment in leaf renewal results in lower tree growth rates. However, in Linhares, the second - and most likely - cause for growth stagnation was parasitism by mistletoe, which decreases the plant photosynthetic efficiency and respiration rates, affecting DBH growth (Watling & Press, 2001; Cameron et al., 2008; Arruda et al., 2012). Mistletoe infestation was present in almost all pure and mixed plantations in Linhares, and trees only grew well in forest enrichment plantations.

Mistletoe should be controlled by pruning infested branches, and in locations where infestations are likely, low planting densities are recommended (50 - 100 trees/ha), always in mixed stands with other species. It may be planted in full sun, but from a silvicultural point of view, it requires partial shade in the beginning of the plantation to stimulate vertical growth, decrease bifurcation, promote straighter stems, and improve plant health. Care should also be taken with the use of this species due to its high mortality.

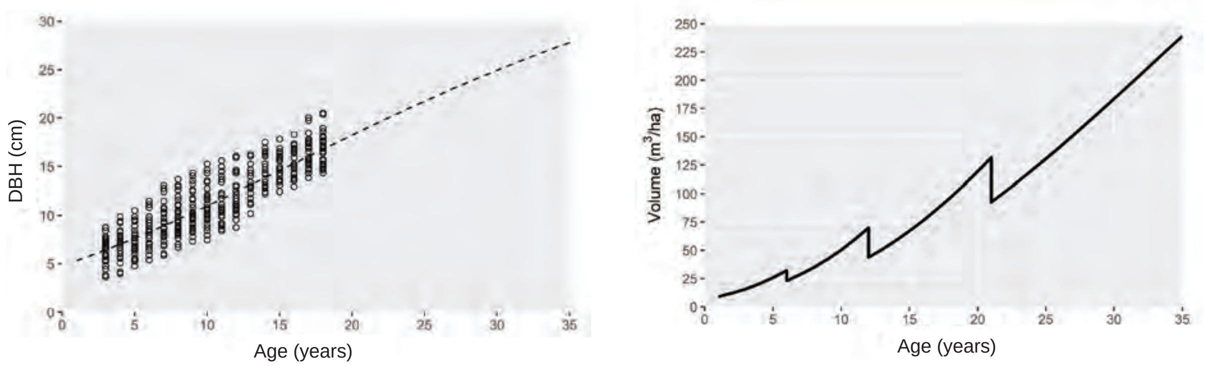
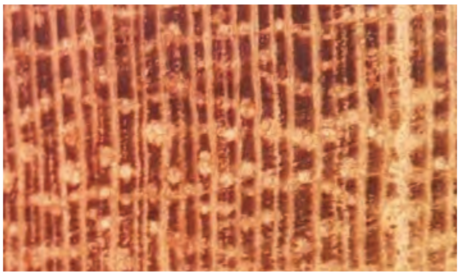


Figure 5. Diameter growth of *Cordia trichotoma* grown in a mixed plantation with *Cariniana legalis* and *Bowdichia virgilioides* in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12 and 21 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, light gray heartwood and beige sapwood, characteristic pleasant odor, slightly pleasant taste, coarse texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, apotracheal diffuse, paratracheal scarce and possibly in marginal band. Rays: visible without magnification in the cross-sectional and longitudinal-tangential planes, strong contrast in the longitudinal-radial plane, medium, very few to few, and non-stratified. Vessels: visible without magnification, small to medium, numerous, diffuse-porous, solitary and radial multiples (2–5 vessels), obstructed by tylosis. Growth Rings: delimited by the vessel arrangement or parenchyma in marginal bands.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.595
Basic density (g/cm^3)	0.480
Volume variation (shrinkage %)	22.13
Anisotropy coefficient	1.15
Modulus of rupture for static bending strength (kgf/cm^2)	619.67
Shear strength (kgf/cm^2)	106.76
Compression strength parallel to the grain (kgf/cm^2)	110.57
Janka hardness (kgf) – parallel and perpendicular to the grain	410.00 – 455.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications										
Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Fair	Poor	Very poor	Poor	Poor	Poor	Good	Good	13% accepts; 87% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium density and hardness wood. Low anisotropy and tendency to warp and twist. Indicated for use in light structures, furniture, posts, frames, tool handles, artisanal goods, and utensils. Good to fair planing properties. Poor boring properties with both helical and spade bits, resulting in fiber tearing and small splinters. Good sanding and lateral mortising properties. Most evaluated samples did not accept nails, presenting fiber tearing and splitting in the bottom side of the sample.

Tachigali vulgaris L.G.Silva & H.C.Lima **(Fabaceae)**

Distribution: Commonly known as tachi-branco it is distributed in the Amazon, Cerrado, and Atlantic Forest, where it mainly occurs in seasonal and ombrophilous forests in the states of Minas Gerais and Bahia (Lima, 2015b). For a long time, it was recommended for charcoal production, which originated one of its common names, “carvoeiro”. It is a currently neglected species, but recent studies have valued its potential for more traditional uses (Orellana, 2015; Faria, 2016), and for shredding and mixing with cement and use in construction (Sousa et al., 2016).

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with 2 × 2 m spacing, where the remaining trees at 25 years of age presented stems with good shape, slightly leaning, and compromised health. Mortality was 13.3% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 90.41\, exp^{-5.12\, t^{-0.5003}}$$

The models showed a trend in growth until 25 years of age, when the estimated volume was 255 m^3/ha for 386 trees/ha, mean DBH was 32.5 cm, and stem height was 11.7 m. For this age, the estimated MAI in volume was 10.2 m^3/ha/year, MAI in diameter was 1.30 cm/year, and stocked biomass was 233 Mg/ha. The growth in Linhares was in agreement with that reported by Carvalho (2003) and Souza et al. (2008), but much lower than the DBH of 30 cm at 9 years of age reported in Tapajós (PA) (Yared, 1990). There is a wide variation in growth between different provenances, with high potential for increases in yield (Farias Neto & Castro, 1999). Because it is not currently marketed, further studies of its wood are needed. However, if its use is popularized, it is one of the tree species in the Atlantic Forest with a high potential for wood production; it has a mean DBH of 30 cm before 25 years of age. The provenance of the plants in Linhares came from the Amazon, and other origins should be tested for the Atlantic Forest, since the DBH is very variable in this species. A great advantage of the use of this species in silviculture, especially in mixed plantations, is that it forms associations with Rhizobium, fixing atmospheric nitrogen and introducing large amounts of organic matter into the soil (Faria et al., 1984; Brienza et al., 2009). It grows well in full sun, and usually produces stems with good shape but that require pruning. It performs well in enrichment plantations in partial shade (Souza et al., 2010).

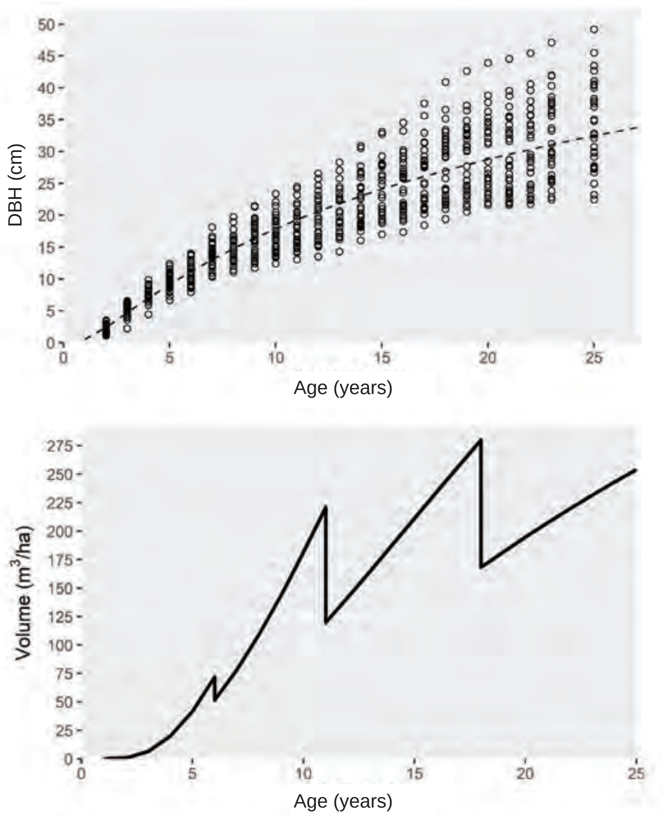
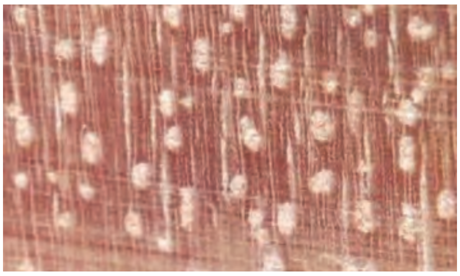


Figure 6. Diameter growth of *Tachigali vulgaris* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation 3 × 2 m, with thinning at 6, 12, and 18 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Indistinct heartwood and sapwood, rose-brown heartwood, characteristic odor, indistinct taste, fine texture, grain irregular, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, paratracheal scarce. Rays: barely visible without magnification in the cross-sectional plane and only under magnification in the longitudinal-tangential plane, without contrast in the longitudinal-radial plane, very thin, numerous, and non-stratified. Vessels: visible without magnification, small to medium, numerous, diffuse-porous, predominantly solitary and radial multiples (2–3 vessels), frequently obstructed by a white substance and tylosis. Growth Rings: delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.711
Basic density (g/cm³)	0.585
Volume variation (shrinkage %)	11.40
Anisotropy coefficient	1.14
Modulus of rupture for static bending strength (kgf/cm²)	509.53
Shear strength (kgf/cm²)	137.54
Compression strength parallel to the grain (kgf/cm²)	523.33
Janka hardness (kgf) – parallel and perpendicular to the grain	476.67 – 621.67

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Poor	Fair	Poor	Poor	Fair	Poor	Fair	Fair	Fair	56% accepts; 44% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium density, good stability, low hardness and low workability wood, with a high generation of defects due to tearing. No tendency to twist and warp. Indicated for use in packages, boxes, and applications that do not require aesthetic appeal. Low durability and resistance to tension. Poor machining properties and workability, demanding great care in the choice of sandpapers, boring bits, and milling cutters. Fair nail acceptance, presenting fiber tearing and splintering in slightly less than half of the evaluated samples.

Joannesia princeps Vell. **(Euphorbiaceae)**

Distribution: Commonly known as boleira, it is distributed in seasonal and ombrophilous forests of the Atlantic Forest in the states of Minas Gerais, Rio de Janeiro, Espírito Santo, and Bahia (Cordeiro & Secco, 2015). It has no tradition of wood production but is indicated for use in carpentry and light structures, being reported to have similar uses to those of *Populus* sp. (poplar) (Carvalho, 2003). It also produces high quality cellulose (Barrichelo & Foelkel, 1975), the oil of its seeds has antibacterial and laxative properties (Sousa et al., 2007), and may be used for the production of a biodiesel additive (Souza, 2008).

Mean Growth and Yield: Growth data was obtained from a progeny trial in Linhares (n = 36 trees per progeny) with 3 × 2 m spacing. The remaining trees at 17 years of age presented stems with good shape and health. Mortality was 0% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 44.59\, exp^{-2.32\, t^{-0.3574}}$$

The models showed a trend in growth until 25 years of age, when the estimated volume was 212 m^3/ha for 891 trees/ha, with a mean DBH of 21.4 cm and stem height of 9.0 m. For this age, the estimated MAI in volume was 8.5 m^3/ha/year, MAI in diameter was 0.86 cm/year, and stocked biomass was 119 Mg/ha. Growth in the Ceplac arboretum in Bahia was also low, with a DBH of 9.0 cm at 10 years of age (Vinha & Lobão, 1989). Carvalho (2003) reported much higher growth rates: DBH values of 20 cm at 10 years of age, and 30 cm at 20 years of age. Gurgel Filho et al. (1982b) reported a DBH of 50 cm at 26 years of age. *J. princeps* therefore has potential for wood production before 20 years of age. It has high growth rates, and the result observed in Linhares can be considered much lower than that expected for this species, probably due to the lack of thinning, both between 3 and 10 years of age and after 15 years of age. Empirical observations in the region also showed better growth in sandier soils than in the soil in Linhares. *J. princeps* is a pioneer species with high longevity. It grows well in full sun, but branches easily and requires pruning. Empirical observations in regeneration areas showed individuals with excellent shape and growth, indicating that it can tolerate shade in enrichment plantations.

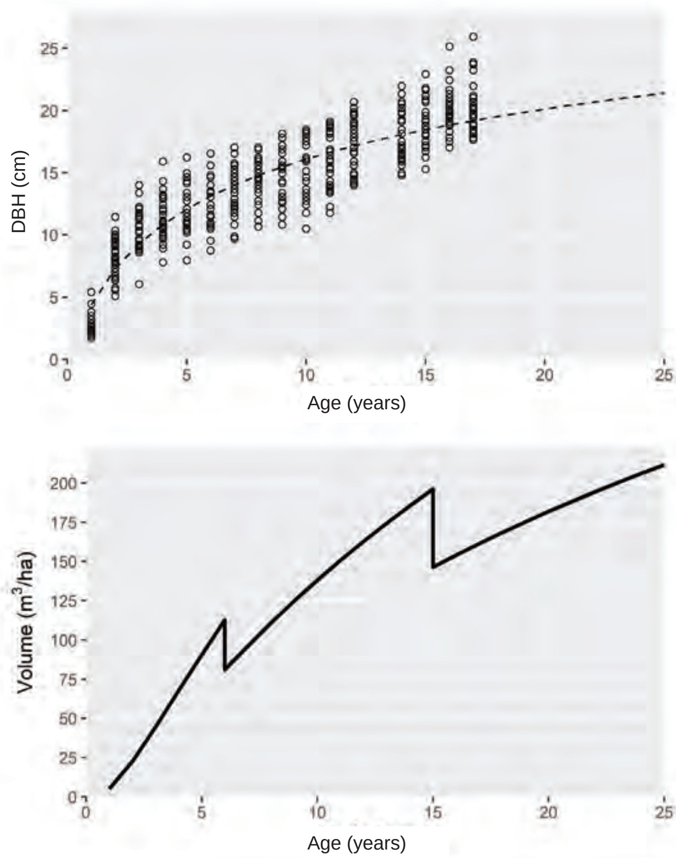


Figure 7. Diameter growth of *Joannesia princeps* in a progeny trial in Linhares (ES), and a simulation of volume production for a 3 × 2 m plantation with thinning at 6 and 15 years.

(Wood properties)

(Cross section, zoom 10×)

Overall Wood Properties: Indistinct whitish-beige heartwood and sapwood, uncharacteristic odor, indistinct taste, medium texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, apotracheal diffuse in clusters forming irregular lines. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential planes, without contrast in the longitudinal-radial plane, thin, numerous to very numerous, non-stratified. Vessels: visible without magnification, medium to large, few, diffuse-porous, predominantly solitary and radial multiples (2–4 vessels). Growth Rings: delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.408
Basic density (g/cm^3)	0.321
Volume variation (shrinkage %)	7.79
Anisotropy coefficient	1.27
Modulus of rupture for static bending strength (kgf/cm^2)	337.50
Shear strength (kgf/cm^2)	49.65
Compression strength parallel to the grain (kgf/cm^2)	208.34
Janka hardness (kgf) – parallel and perpendicular to the grain	123.33 – 210.00

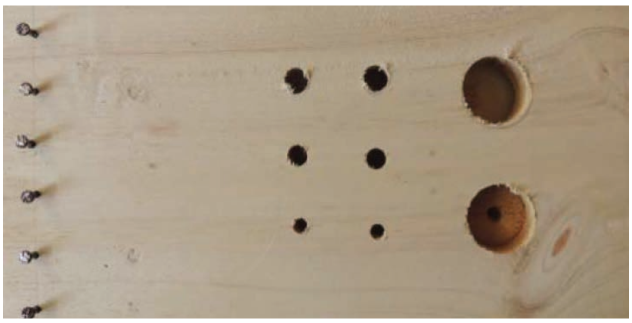
Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Fair	Fair	Poor	Poor	Poor	Very poor	Excellent	Fair	78% accepts; 22% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Wood with low density, low tendency to twist and warp. Indicated for use in non-structural processes, packaging segments, boxes, and cladding that does not require finishing with excellent texture. It can be laminated, and has a low hardness, presenting marks when subjected to light tension. Low physical resistance. Good planing properties only for planing with the grain or fiber orientation. Poor boring properties with both helical and spade bits. Excellent sanding properties, fair lateral mortising properties. Good nail acceptance.



Simarouba amara Aubl. **(Simaroubaceae)**

Distribution: Commonly known as caxeta or marupá, it is distributed throughout the seasonal and ombrophilous forests of Northern, Northeast, and Southeast Brazil (ES and RJ), as well as the Cerrado and Caatinga (Pirani & Thomas, 2015). It is currently exploited in the Amazon, and is one of the most marketed tree species in the state of Mato Grosso (Ribeiro et al., 2016).

Mean Growth and Yield: Growth data was obtained from an enrichment in secondary forest in Linhares (n = 180 trees), with 3 × 3 m spacing. The remaining trees at 33 years of age presented stems with good shape and good health. Mortality was 5% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 43.98\, exp^{-2.34 \cdot exp^{(-0.0587\, t)}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 255 m^3/ha for 384 trees/ha, with a mean DBH of 32.6 cm and stem height of 11.7 m. For this age, the estimated MAI in volume was 7.3 m^3/ha/year, MAI in diameter was 0.93 cm/year, and stocked biomass was 164 Mg/ha. The observed growth in Linhares at 13 years of age (DBH = 15 cm) was similar to that observed in Pernambuco for trees of the same age (Carvalho, 2008). In the Ceplac arboretum in Bahia, the DBH was 30.1 cm at 16 years of age, much higher than that observed in Linhares (Vinha & Lobão, 1989). It usually requires pruning in full sun plantations, but in the studied enrichment trial, shade promoted good stem shape and may also help to prevent insect attacks to the terminal bud, such as those observed in full sun plantations (Albrechtsen, 1975). Growth stagnation was observed between 7 and 12 years of age and between 15 and 20 years of age, probably due to competition with secondary forest and/or excessive shading after the initial years of plantation.

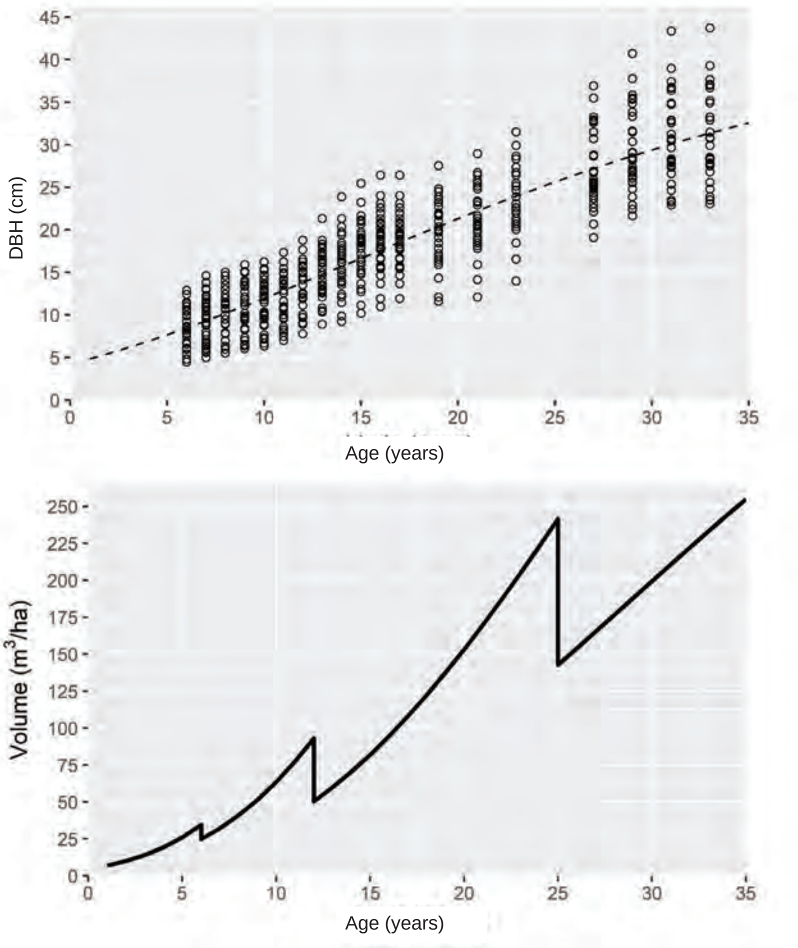


Figure 8. Diameter growth of *Simarouba amara* in an enrichment in secondary forest in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 25 years.

Hymenaea courbaril var. *stilbocarpa* (Hayne) Y.T.Lee & Langenh. **(Fabaceae)**

Distribution: Commonly known as jatobá, it occurs in all Brazilian biomes except the Pampas, and in almost all Brazilian states (Lima & Pinto, 2015). It was highly exploited in the Atlantic Forest and is still exploited in the Amazon region; it is one of the preferred timbers in the market.

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with 2 × 2 m spacing, where the remaining trees at 24 years of age presented good but slightly tortuous stem shape, with good health. Mortality was 7% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 47.67\, exp^{-4.08\, t^{-0.5847}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 242 m^3/ha for 498 trees/ha, with a mean DBH of 28.6 cm and stem height of 10.9 m. For this age, the estimated MAI in volume was 6.9 m^3/ha/year, MAI in diameter was 0.82 cm/year, and stocked biomass was 331 Mg/ha. The diameter growth observed in Linhares was similar to or higher than that reported by Carvalho (2003) for several municipalities in the states of São Paulo and Paraná. Gurgel Filho et al. (1982c) reported a DBH of 19 cm at 27 years of age, which is also lower than that observed in Linhares. Dendrochronological studies in natural forests showed that H. courbaril may take 70 years to reach the estimated DBH of 30 cm for a 35-year-old plantation (Andrade, 2015). Although trees in Linhares presented good stem shape, H. courbaril usually produces shorter and bifurcated stems in full sun plantations, requiring greater attention to pruning management, at least during the first 10 years. Partial shade is necessary to obtain straighter stems and to promote vertical growth. However, it is sensitive to high shading, which may decrease its DBH growth rate and height, as observed by Souza et al. (2010) at 6 years of age in plantations. There are ex-situ conserved populations in São Paulo (Siqueira & Nogueira 1992). It presents high plasticity, occurring in several biomes, which may be one of the reasons for the high variability observed in different plantations. Therefore, great care is required in the selection of mother plants for seed collections.

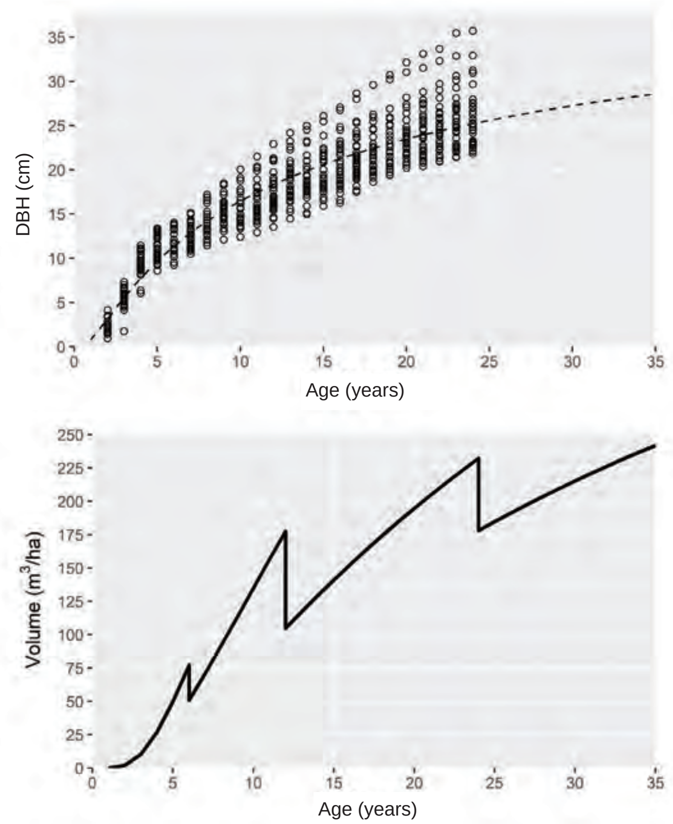


Figure 9. Diameter growth of *Hymenaea courbaril* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 24 years.

Handroanthus serratifolius (Vahl.) S. O. Grose **(Bignoniaceae)**

Distribution: Commonly known as ipê-amarelo, it occurs in seasonal and ombrophilous forests in the Atlantic Forest and Amazon (Lohmann, 2015). It is one of the most valuable species in the current timber market, and is heavily logged in the Amazon.

Mean Growth and Yield: Growth data was obtained from a spacing trial. The remaining trees at 28 years of age presented stems with good shape and health. Mortality was 7% until 6 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 49.86\, exp^{-4.66\, t^{-0.5405}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 229 m^3/ha at 35 years of age for 642 trees/ha, with a mean DBH of 25.2 cm and stem height of 10.1 m. For this age, the estimated MAI in volume was 6.5 m^3/ha/year, MAI in diameter was 0.72 cm/year, and stocked biomass was 265 Mg/ha. In the Ceplac arboretum in Bahia, a DBH of 2.5 cm at 6 years of age was reported (Vinha & Lobão, 1989). At the current growth rate, the mean DBH will reach 30 cm at approximately 60 years of age, with approximately 450 trees/ha, although some individuals reach this DBH at 30–35 years of age. In natural forests, individuals may take approximately 70 years to reach 30 cm DBH (Andrade, 2015). Its high value and recognition in the timber market may justify this long rotation, but its yield is likely to be higher in more fertile soils and areas with higher rainfall. It has high plasticity, and much care is recommended while selecting planting material. Although in the studied monoculture in full sun there was no bifurcation and stems were quite straight, Alencar & Araújo (1980) recommended planting in half-shade to stimulate vertical growth.

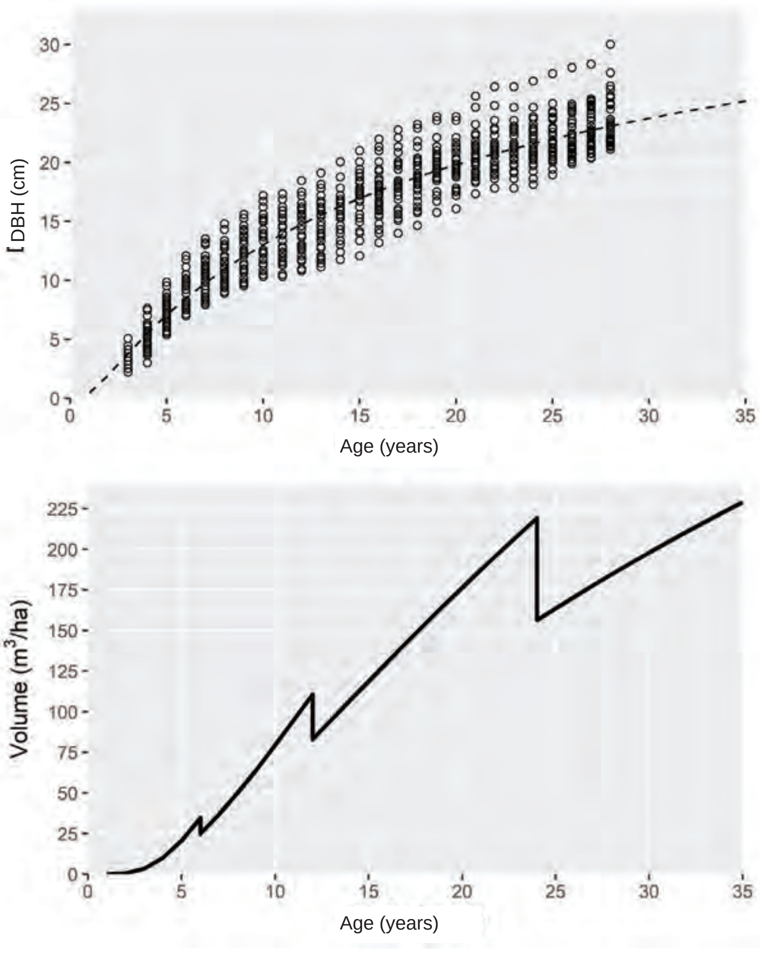
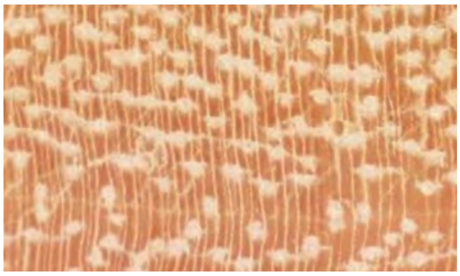


Figure 10. Diameter growth of *Handroanthus serratifolius* in a spacing trial in Linhares (ES), and a simulation of volume production for a 3 × 2 m plantation, with thinning at 6, 12, and 24 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Indistinct yellowish-beige heartwood and sapwood, uncharacteristic odor, indistinct taste, medium texture, interlocked grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, paratracheal vasicentric, aliform, confluent, forming small oblique arrangements occasionally in narrow marginal bands. Rays: only visible under magnification in the cross-sectional plane and visible without magnification in the longitudinal-tangential plane, without contrast in the longitudinal-radial plane, thin, few, stratified. Vessels: only visible under magnification, small, very numerous, diffuse-porous, and solitary and radial multiples (2–3 vessels). Growth Rings: delimited by fibrous tissue and parenchyma rows in marginal bands.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	1.027
Basic density (g/cm^3)	0.799
Volume variation (shrinkage %)	19.14
Anisotropy coefficient	1.35
Modulus of rupture for static bending strength (kgf/cm^2)	782.38
Shear strength (kgf/cm^2)	154.08
Compression strength parallel to the grain (kgf/cm^2)	598.86
Janka hardness (kgf) – parallel and perpendicular to the grain	1113.33 – 1218.33

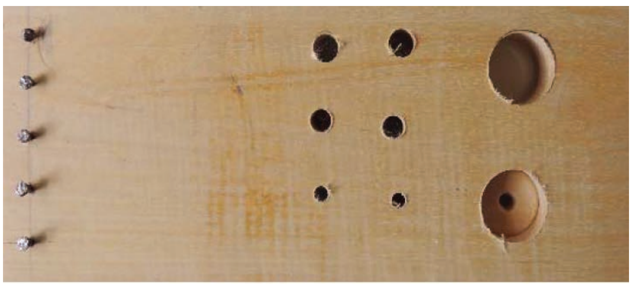
Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Good	Fair	Fair	Fair	Good	Good	Good	Fair	100% does not accept

Assays conducted according to the normative document ASTM 1666:1994

High density and hardness wood. Low anisotropy and little tendency to warp and twist. Indicated for use in structures, construction, stakes and poles, floors, frames, cladding, tool handles, artisanal goods and utensils. Good planing properties. Difficult boring with helical bits and good boring with spade bits. Good sanding and fair lateral mortising properties. Very poor nail acceptance, generating cracks, tearing, and small splinters, especially at the nail exit.



Astronium graveolens Jacq. **(Anacardiaceae)**

Distribution: Commonly known as aderne or guaritá, it is widely distributed in the Atlantic Forest and in some northern states, in seasonal and ombrophilous forests, and the Cerrado (Silva-Luz & Pirani, 2015). It has high-quality wood with high market demand and has been extensively exploited in the Atlantic Forest. Other species of *Astronium* also present high-quality wood: *A. concinnum, A. fraxinifolium*, and *A. lecointei*. The latter, commonly known as muiracatiara, is the main legally marketed species of this genus.

Mean Growth and Yield: Growth data was obtained from a mixed plantation with *Cariniana estrelensis* (jequitibá-branco, n = 72 trees per species) in Linhares with 3 × 2.5 m spacing. The remaining trees of *A. graveolens* at 31 years of age presented good stem shape and good health. Mortality was 22% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 39.24\ exp^{-1.81 \cdot exp^{(-0.03925\ t)}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 227 m^3/ha for 662 trees/ha, with a mean DBH of 24.8 cm and stem height of 10.0 m. For this age, the estimated MAI in volume was 6.5 m^3/ha/year, MAI in diameter was 0.71 cm/year, and stocked biomass was 242 Mg/ha. The lack of more intense thinning between 14 and 19 years of age probably affected tree growth. There are little available growth data for comparison of this species, but due to its high percentage of sapwood (Carvalho, 2003) and low estimated DBH at 35 years of age, this species is likely to require a cycle of at least 45–50 years to achieve a higher yield of high-quality wood. For this age to be reached, at least one more thinning is needed, decreasing the tree density to 440 trees per hectare and resulting in a mean DBH of 30 cm at 50 years of age. Attention should be paid to the high mortality in the initial years of the plantation. It can be planted in full sun; however, from a silvicultural point of view, it requires partial shade, not only to stimulate vertical growth, but also to decrease bifurcation and to produce straighter stems. In a progeny trial, the possibility of a genetic gain in DBH was low due to low heritability (Araújo et al., 2014). There are ex-situ conserved populations of this species in São Paulo (Siqueira & Nogueira 1992).

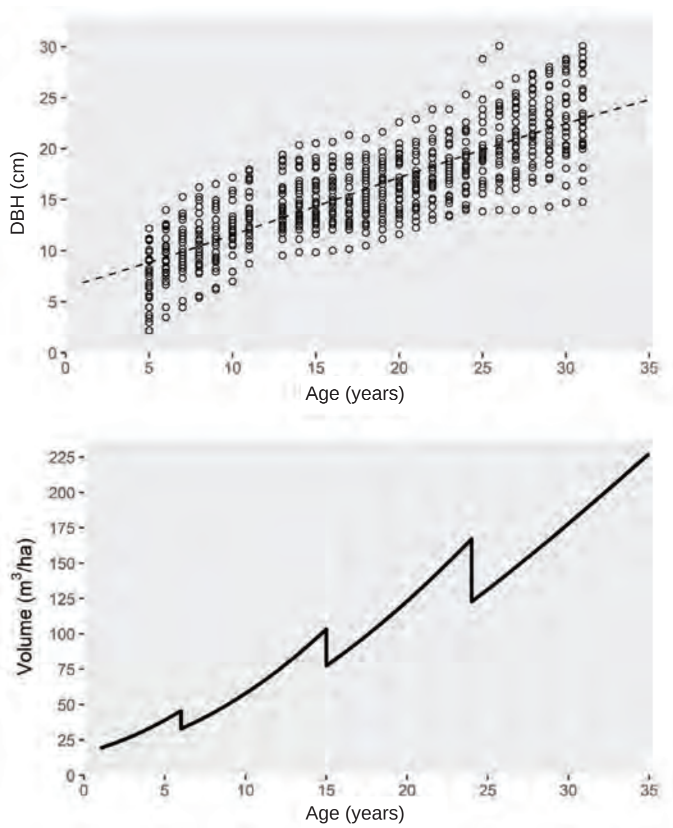
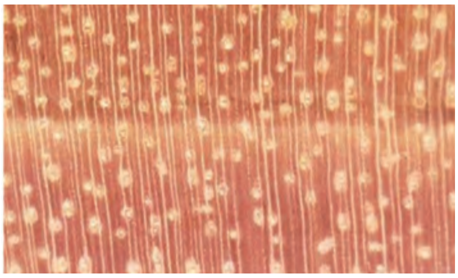


Figure 11. Diameter growth of *Astronium graveolens* in mixed plantations with *Cariniana estrelensis* in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 15, and 24 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, reddish-brown heartwood and light yellow sapwood, uncharacteristic odor, indistinct taste; irregular slightly leaning grain; fine texture, no variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, paratracheal scarce. Rays: visible without magnification in the cross-sectional and longitudinal-tangential plane, without contrast in the longitudinal-radial plane, thin to medium, few to numerous, non-stratified. Vessels: visible without magnification, small to medium, numerous, semi-ring-porous, solitary and radial multiples (2–5 vessels), obstructed by tylosis. Growth Rings: delimited by fibrous tissue and semi-ring-porous

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.847
Basic density (g/cm^3)	0.720
Volume variation (shrinkage %)	6.80
Anisotropy coefficient	1.54
Modulus of rupture for static bending strength (kgf/cm^2)	622.28
Shear strength (kgf/cm^2)	106.94
Compression strength parallel to the grain (kgf/cm^2)	179.50
Janka hardness (kgf) – parallel and perpendicular to the grain	980.00 – 1001.67

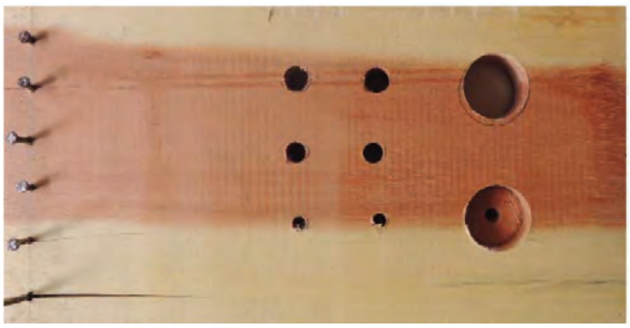
Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Good	Good	Good	Good	Fair	Good	Good	Good	6% accepts; 94% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high density and high hardness wood, with low tendency to twist and warp. Indicated for structural use in construction, frames, furniture and floors. Good lateral mortising properties and good to excellent planing and sanding properties, allowing different cladding. Good boring properties with helical bits and few flaws with spade bits. Presents problems with standard nails available in the market, requiring connecting elements such as higher resistance nails and screws or pre-boring.



Paratecoma peroba (Record & Mell.) Kuhlm. **(Bignoniaceae)**

Distribution: Mainly distributed in ombrophilous and seasonal forests in the states of Bahia, Espírito Santo, and Rio de Janeiro (Lohmann, 2015). It has high-quality wood with high market demand; it has been much exploited in the Atlantic Forest. It should be highlighted that *Paratecoma* is a genus belonging to the family Bignoniaceae, whereas other species commonly known as peroba belong to genus *Aspidosperma* in the family Apocynaceae.

Mean Growth and Yield: Growth data was obtained from a mixed plantation with *Dalbergia nigra* (jacarandá-da-bahia) and *Zeyheria tuberculosa* (ipê-felpudo), with 1.5 × 1.5 m spacing and a ratio of two *P. peroba* to two *Z. tuberculosa* and one *D. nigra*. Several thinnings were performed on an irregular basis, and the remaining *P. peroba* trees at 20 years of age presented slightly tortuous but good stem shape and good health. Mortality was 11% until 1 year of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 71.15\, exp^{-3.8343\, t^{-0.3558}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 224 m^3/ha for 701 trees/ha, with a mean DBH of 24.1 cm and stem height of 9.8 m. For this age, the estimated MAI in volume was 6.4 m^3/ha/year, MAI in diameter was 0.69 cm/year, and stocked biomass was 217 Mg/ha. A DBH of 17 cm was reported for *P. peroba* at 19 years of age in a mixed plantation with eucalyptus (Kageyama & Castro, 1989), similar to that observed in the present study, but the decrease in the DBH growth rate after 15 years of age needs to be elucidated. The lack of more intense thinnings between 14 and 20 years of age probably affected the growth results. To improve performance, the species requires partial shade from the beginning of the plantation, not only to stimulate vertical growth, but also to decrease bifurcation and to form straighter stems. It is a slow-growing species, with rotation cycles predicted at 50 years of age (Coimbra-Filho,1951).

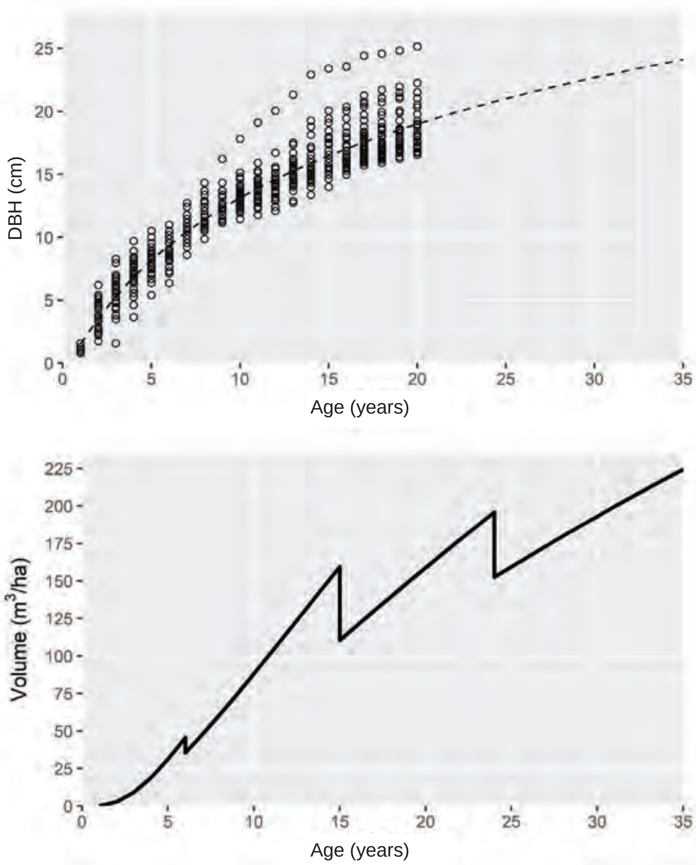
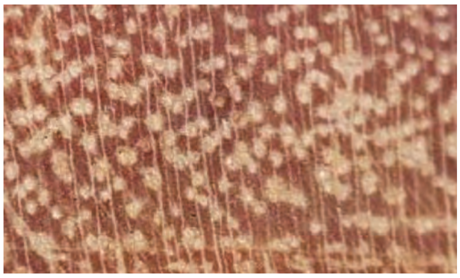


Figure 12. Diameter growth of *Paratecoma peroba* peroba in mixed plantations with *Dalbergia nigra* and *Zeyheria tuberculosa* in Linhares (ES), and a simulation of volume production for a 3 × 2 m plantation, with thinning at 6, 15, and 24 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, yellowish-brown heartwood with darker lines and yellowish-white sapwood, uncharacteristic odor, slightly bitter taste, fine texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, paratracheal scarce, vasicentric and in marginal bands. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential planes, little contrast in the longitudinal-radial plane, thin, numerous, stratified. Vessels: only visible under magnification, very small to small, numerous, diffuse-porous, predominantly solitary and radial multiples (2–5 vessels), obstructed by tylosis. Growth Rings: delimited by fibrous tissue and parenchyma in marginal bands.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.757
Basic density (g/cm³)	0.639
Volume variation (shrinkage %)	14.37
Anisotropy coefficient	1.20
Modulus of rupture for static bending strength (kgf/cm²)	888.38
Shear strength (kgf/cm²)	164.41
Compression strength parallel to the grain (kgf/cm²)	523.13
Janka hardness (kgf) – parallel and perpendicular to the grain	688.33 – 820.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Fair	Fair	Fair	Good	Fair	Good	Good	Good	11% accepts; 89% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high density and hardness wood, very low tendency to twist and warp. Indicated for structural uses, decorative finishes in construction, furniture, floors, and utensils. Good planing properties using peripheral knife planer. Good sanding and lateral mortising properties. Requires care in boring due to its high hardness. Nailing with standard materials is difficult, and the use of connecting elements with higher resistance is recommended.

Terminalia mameluco Pickel **(Combretaceae)**

Distribution: Commonly known as pelada, it occurs in seasonal and ombrophilous forests in the Atlantic Forest in the states of Minas Gerais, Espírito Santo, Bahia, Pernambuco, and Ceará (Marquete & Loiola, 2015). It has been fairly highly exploited in the states of Espírito Santo and Bahia, although it is little known in the market.

Mean Growth and Yield: Growth data was obtained from an enrichment plantation in secondary forest in Linhares (n = 180 trees) with 3 × 3 m spacing. The remaining trees at 33 years of age presented stems with good shape and good health. Mortality was 28% until 6 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 31.74\left(1 + 168.87\, exp^{-1.6170\, Ln(t)}\right)^{-1}$$

The models showed a slow trend in growth until 35 years of age, when the estimated volume was 208 m^3/ha for 957 trees/ha, with a mean DBH of 20.6 cm and stem height of 8.8 m. For this age, the estimated MAI in volume was 5.9 m^3/ha/year, MAI in diameter was 0.59 cm/year, and stocked biomass was 176 Mg/ha. No growth data was found for this species. In the Ceplac arboretum in Bahia, Vinha & Lobão (1989) observed a mean DBH of 11.9 cm at 16 years of age for *Terminalia glabrescens*. At the current growth rate, the mean DBH will reach 30 cm much later than 50 years of age, with approximately 450 trees/ha. The good stem shape could be due to its planting in the forest; however, stems with good shape were also observed in plantations in full sun in Linhares. Attention should be paid to the high mortality in young plantations. Its growth was likely limited by competition and excessive shade in the forest after the initial years of plantation. There were stagnations in growth, especially between 15 and 18 and 21 and 25 years of age.

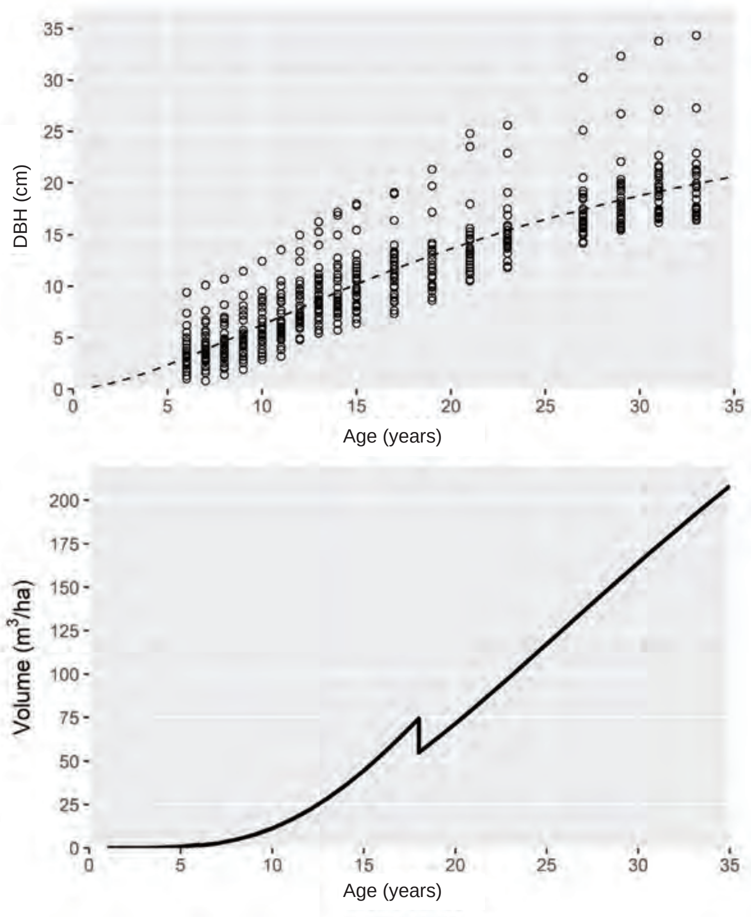
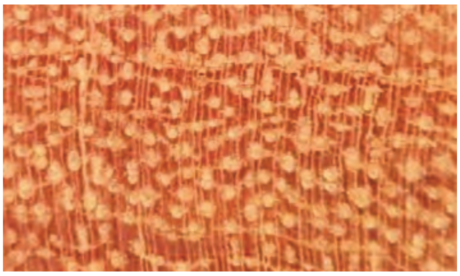


Figure 13. Diameter growth of *Terminalia mameluco* in an enrichment in secondary forest in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6 and 18 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, brownish-gray heartwood and yellowish-light beige sapwood, uncharacteristic odor, indistinct taste, medium texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal vasicentric, aliform losangular, aliform with linear extension, confluent and in marginal bands. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential planes, little contrast in the longitudinal-radial plane, very thin, numerous, non-stratified. Vessels: only visible under magnification, small, very numerous, diffuse-porous, predominantly solitary, tangential, and oblique multiples (2–4 vessels). Growth Rings: delimited by fibrous tissue and parenchyma in narrow marginal bands.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.645
Basic density (g/cm^3)	0.540
Volume variation (shrinkage %)	8.77
Anisotropy coefficient	1.68
Modulus of rupture for static bending strength (kgf/cm^2)	782.46
Shear strength (kgf/cm^2)	109.31
Compression strength parallel to the grain (kgf/cm^2)	489.26
Janka hardness (kgf) – parallel and perpendicular to the grain	500.00 – 715.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications										
Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Good	Fair	Poor	Fair	Fair	Good	Good	Good	100% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high density and hardness wood. Medium anisotropy and some tendency to warp. Indicated for use in light structures, carpentry, furniture, poles, stakes, tool handles, and utensils. Good to excellent planing properties. Fair to poor boring properties with helical bits and fair to good with spade bits. Good sanding and good lateral mortising properties. Difficult nailing, requiring pre-boring or special nails.

Manilkara longifolia (A.DC.) Dubard **(Sapotaceae)**

Distribution: Commonly known as massaranduba or parajú, it is distributed in seasonal and ombrophilous forests of the Atlantic coast, from the state of Paraná to the state of Espírito Santo (Almeida, 2015). Species of this genus usually have a long tradition of being harvested for timber and are currently much exploited in the Amazon. There are taxonomical doubts about the species occurrence in Linhares: it may be a new species (TD Penn. personal communication to the CVRD Herbarium).

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) with 2 × 2 m spacing, where the remaining trees at 25 years of age presented stems with good shape and health. Mortality was 2.5% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 25.25\, exp^{-9.59\, t^{-1.0455}}$$

The models showed slow growth from 15 years of age, with an estimated volume at 35 years of age of 205 m^3/ha for 1018 trees/ha, mean DBH of 20.0 cm, and stem height of 8.6 m. For this age, the estimated MAI in volume was 5.9 m^3/ha/ year, MAI in diameter was 0.57 cm/year, and stocked biomass was 243 Mg/ha. There are no available growth data for comparison, but Manilkara species are usually slow growing. *M. longifolia* presented a DBH of 4.6 cm at 11 years of age in the Ceplac arboretum in Bahia (Vinha & Lobão, 1989). In Linhares, it presented an excellent early growth, with a mean DBH growth rate of 1 cm per year until 15 years of age, when it started to decrease. The lack of adequate thinnings between 14 and 17 years of age may have affected tree growth, and the thinning performed at 17 years of age should have been more intense. An analysis using only the growth data until 14 years of age estimated a DBH of 24 cm at 35 years of age, which is much higher than that observed. This species seems to resume growth at 25 years of age. Another factor that may have affected growth is that some individuals from a similar but smaller species (*Manilkara elata* [Allemão ex Miq.] Monach) may have been mixed into the plantation (personal observation). Planting in partial shade may stimulate vertical growth and ensure a good stem shape.

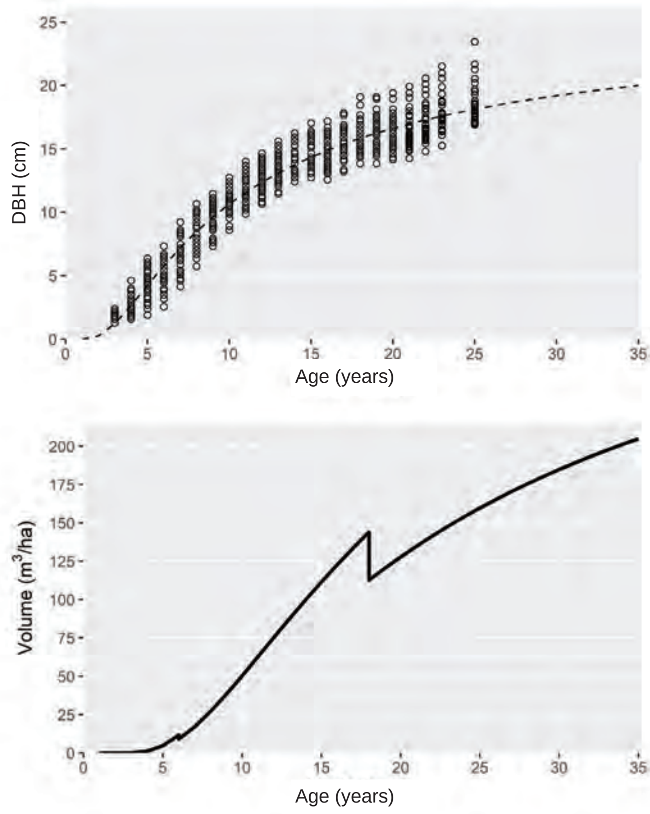
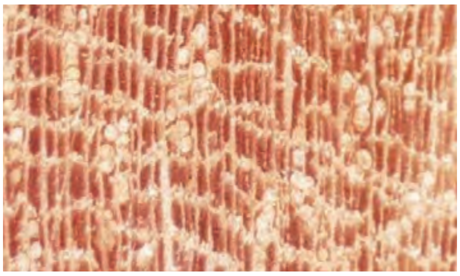


Figure 14. Diameter growth of *Manilkara longifolia* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6 and 18 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, brownish-rose heartwood and lighter sapwood, uncharacteristic odor, indistinct taste, fine to medium texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, apotracheal diffuse in clusters and lines. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential planes, without contrast in the longitudinal-radial plane, very thin, numerous, non-stratified. Vessels: only visible under magnification, very small to small, numerous, diffuse-porous, predominantly radial multiples (2–6 vessels), occasionally solitary, obstructed by tylosis. Growth Rings: delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	1.003
Basic density (g/cm³)	0.829
Volume variation (shrinkage %)	15.47
Anisotropy coefficient	1.69
Modulus of rupture for static bending strength (kgf/cm²)	846.39
Shear strength (kgf/cm²)	99.50
Compression strength parallel to the grain (kgf/cm²)	602.83
Janka hardness (kgf) – parallel and perpendicular to the grain	1018.33 – 1113.33

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Fair	Good	Fair	Good	Good	Good	Good	Excellent	100% does not accept

Assays conducted according to the normative document ASTM 1666:1994

High density and hardness wood, with fair stability and the possibility of warping. Indicated for structural use, or uses that demand high resistance and/or hardness, such as construction, rural construction, floors, and other solid surfaces. May also be used for tool handles and utensils. Difficult planing against the grain or preferential fiber orientation, especially in the heartwood. Fair to good boring properties, good sanding properties, and excellent lateral mortising properties. Difficult nailing, requiring pre-boring or special connecting elements.

Astronium concinnum (Engl.) Schott **(Anacardiaceae)**

Distribution: Commonly known as gonçalo-alves or guaribu-preto, it is mainly distributed in ombrophilous and seasonal forests in the Atlantic Forest, from the south of Bahia to the north of Rio de Janeiro and Minas Gerais, (Silva-Luz & Pirani, 2015). It has high-quality wood with high market demand and has been much exploited in the Atlantic Forest. Other species of Astronium also present high-quality wood: *A. graveolens, A. fraxinifolium*, and *A. lecointei*. The latter is commonly known as muiracatiara and is the main legally marketed species of this genus.

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with 2 × 2 m spacing. The remaining trees at 22 years of age presented stems with good shape but compromised health. Mortality was 2% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 23.66\, exp^{-3.99\, t^{-0.8775}}$$

The models showed a trend for diameter growth stagnation after 15 years, with an estimated volume at 35 years of age of 204 m^3/ha for 1036 trees/ha, mean DBH of 19.8 cm, and stem height of 8.6 m. For this age, the estimated MAI in volume was 5.8 m^3/ha/year, MAI in diameter was 0.57 cm/year, and stocked biomass was 197 Mg/ha. There are little growth data for *Astronium* species, but the growth stagnation observed in Linhares was unexpected. It may have been due to the lack of thinning between 15 and 25 years of age, and to the fact that many plantations of this species in the reserve were attacked by longhorn beetles of the genus *Oncideres* (Jesus et al., 1992; see discussion in *Cordia trichotoma*). This species presents compromised health in some plantations due to parasitism by mistletoe (see discussion also in *Cordia trichotoma*). Carvalho (2010) reported a DBH of 25 cm at 20 years of age in the state of Mato Grosso, which was much higher than that observed in Linhares. Care should be taken when estimating the growth for this species, since the growth model is not robust, but it likely reaches much higher yields than those observed in Linhares. It can be planted in full sun; however, from a silvicultural point of view, it requires partial shade from the beginning of the plantation, not only to stimulate vertical growth, but also to decrease bifurcation, produce straighter stems, and minimize attacks by longhorn beetles and parasitism by mistletoe.

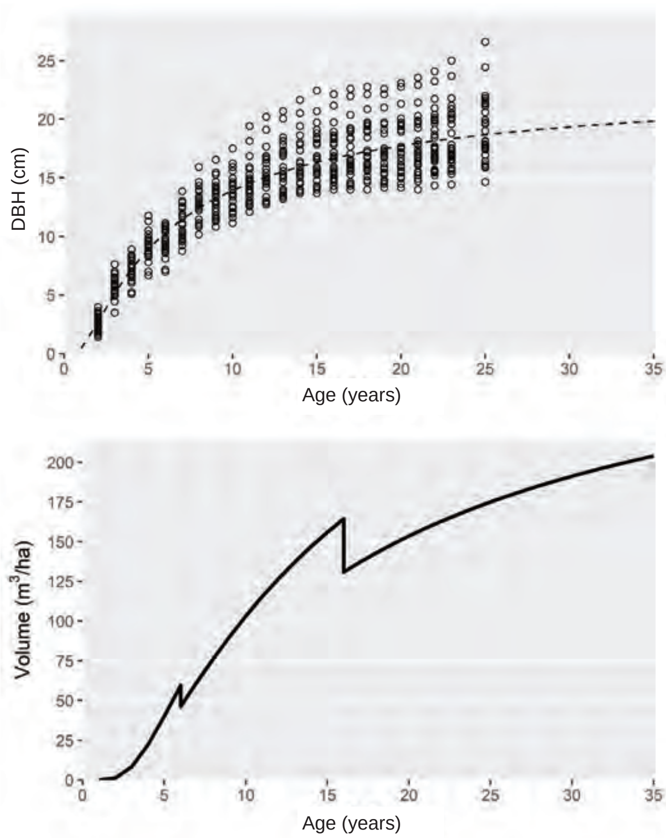
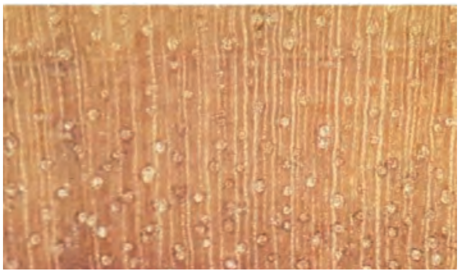


Figure 15. Diameter growth of *Astronium concinnum* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6 and 16 years

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, rose-brown heartwood with darker veins and light yellow sapwood, characteristic odor, indistinct taste, medium texture, straight to irregular grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal scarce and in marginal bands. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential plane, without contrast in the longitudinal-radial plane, thin, slightly numerous to numerous, non-stratified, radial secretion channels. Vessels: only visible under magnification, small to medium, little numerous, diffuse-porous, and predominantly solitary and radial multiples (2–3 vessels). Growth Rings: delimited by fibrous tissue and parenchyma in marginal bands.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.838
Basic density (g/cm³)	0.639
Volume variation (shrinkage %)	14.84
Anisotropy coefficient	1.03
Modulus of rupture for static bending strength (kgf/cm²)	665.39
Shear strength (kgf/cm²)	93.72
Compression strength parallel to the grain (kgf/cm²)	138.73
Janka hardness (kgf) – parallel and perpendicular to the grain	632.00 – 644.00

Assays conducted according to the normative document ABNT 7190:1997

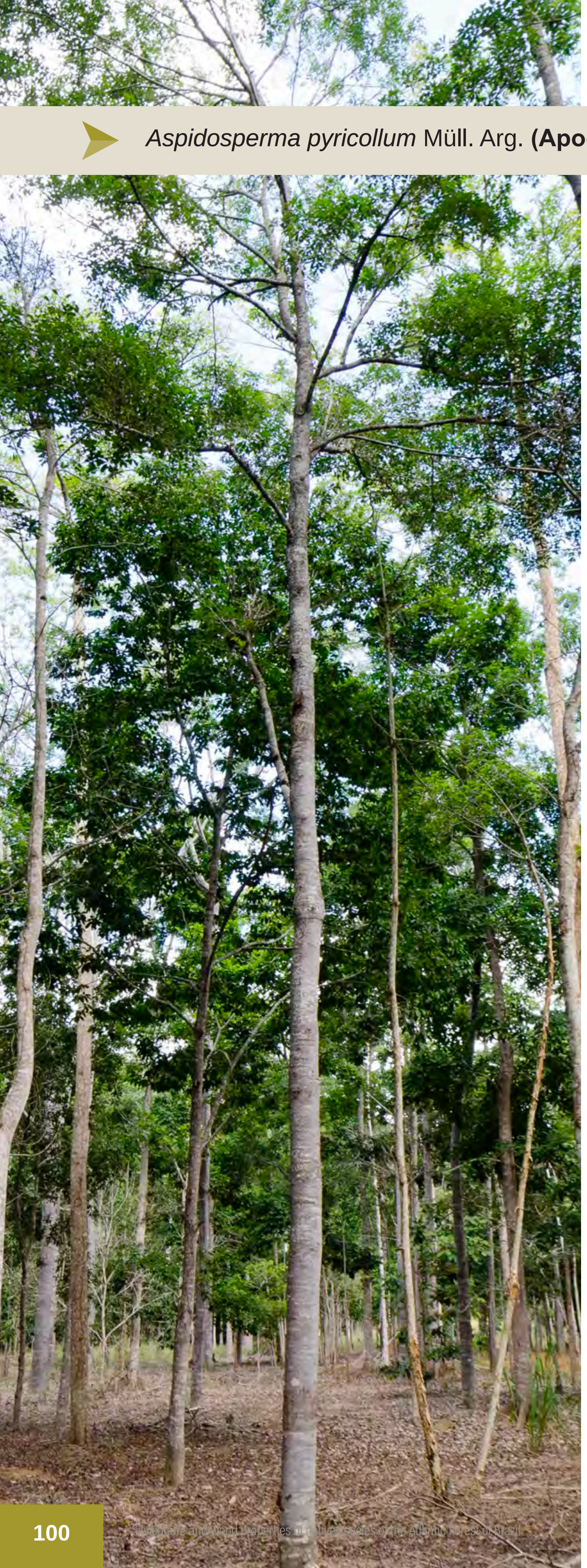
Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Good	Fair	Fair	Fair	Fair	Fair	Good	Good	39% accept; 61% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high density and hardness wood. Low anisotropy and little tendency to warp. Indicated for use in structures, carpentry, rustic furniture, floors, poles, stakes, tool handles, and utensils. Good to excellent planing properties. Fair boring properties with both helical and spade bits. Good sanding and lateral mortising properties. Most evaluated samples presented problems with nailing both in the sapwood and in the darker and reddish heartwood, especially in the bottom side of the sample, where there was splitting, tearing, and small splinters at the nail exit point.

Aspidosperma pyricollum Müll. Arg. **(Apocynaceae)**



Distribution: Commonly known as pequiá-sobre or guatambú-vermelho, it is distributed in seasonal and ombrophilous forests in the Atlantic Forest in the northeast, southeast, and south of the country (Koch et al., 2015). It is one of several species of the genus Aspidosperma that are traditionally valued in the timber market and have been greatly exploited in the Atlantic Forest (Milanez, 1939). In addition, the species of this genus are widely used in traditional medicine because an important alkaloid is extracted from its leaves and bark, and some are being studied for the treatment of fever and diseases, such as malaria and leishmaniasis (Oliveira et al., 2009; Chierrito et al., 2014).

Mean Growth and Yield: Growth data was obtained from a spacing trial. The remaining trees at 22 years of age presented stems with good shape and good health. Mortality was 5% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 53.88\left(1 - exp^{-0.0348 \cdot t^{0.7192}}\right)$$

The models showed a slow trend in growth until 35 years of age, when the estimated volume was 202 m^3/ha for 1072 trees/ha, with a mean DBH of 19.5 cm and stem height of 8.4 m. For this age, the estimated MAI in volume was 5.8 m^3/ha/year, MAI in diameter was 0.56 cm/year, and stocked biomass was 225 Mg/ha. No growth data was found for this species, but its growth is quite slow, as for other species of *Aspidosperma* in general. At the current growth rate, a mean DBH will reach 30 cm at much later than 50 years of age, with approximately 450 trees/ha. Plantations under partial shade may stimulate vertical growth and good stem shape.

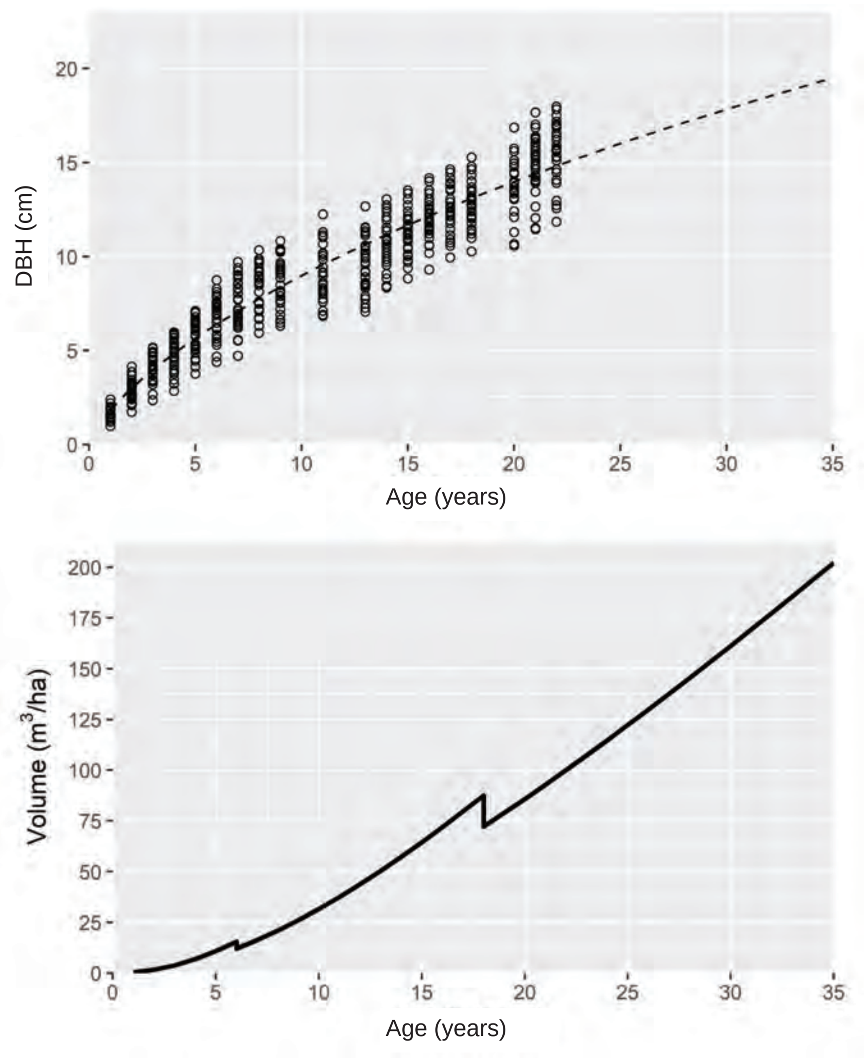
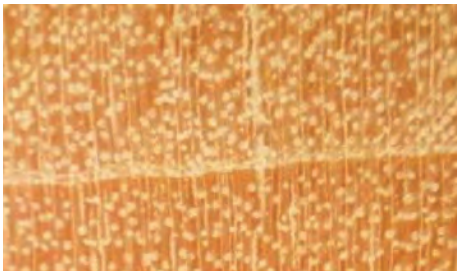


Figure 16. Diameter growth of *Aspidosperma pyricollum* in a spacing trial in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6 and 18 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Slightly distinct heartwood and sapwood, yellowish heartwood and light yellow sapwood, uncharacteristic odor, indistinct taste, fine texture, oblique grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, apotracheal diffuse in clusters and paratracheal scarce. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential planes, without contrast in the longitudinal-radial plane, thin, numerous, non-stratified. Vessels: only visible under magnification, very small, extremely numerous, diffuse-porous, predominantly solitary. Growth Rings: delimited by fibrous tissue.

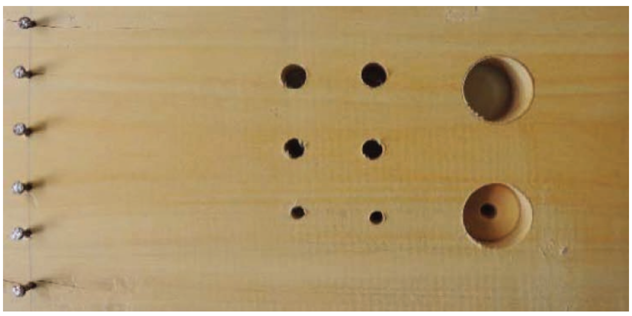
Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.940
Basic density (g/cm³)	0.765
Volume variation (shrinkage %)	16.34
Anisotropy coefficient	1.39
Modulus of rupture for static bending strength (kgf/cm²)	1182.26
Shear strength (kgf/cm²)	167.53
Compression strength parallel to the grain (kgf/cm²)	694.83
Janka hardness (kgf) – parallel and perpendicular to the grain	918.33 – 1135.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications										
Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Fair	Fair	Fair	Fair	Good	Good	Fair	Good	100% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high density and high hardness wood. Low anisotropy and very little tendency to warp and twist. Indicated for use in structures, furniture, solid floors, flooring, cladding, frames, tool handles, and utensils. Good to fair planing properties. Fair boring properties with helical bits and good with spade bits. Fair sanding properties and good lateral mortising properties. All samples evaluated presented problems with nailing, with splitting and cracks, especially at the nail exit point in the bottom side of the samples.



Clarisia racemosa Ruiz & Pav. **(Moraceae)**

Distribution: Commonly known as oiticica or guariúba, it occurs in areas of seasonal and ombrophilous forest in the Atlantic Forest and Amazon (Romaniuc Neto et al., 2015). It is currently one of the most marketed species in the state of Acre (Silva et al., 2015). Its wood is attractive due to its natural yellow color, and has high market acceptance, both for solid timber and veneer.

Mean Growth and Yield: Growth data was obtained from a mixed plantation with *Leucena leucocephala* (n = 72 trees per species) in Linhares with 3 × 2.5 m spacing. The remaining trees at 16 years of age presented short stems, but good health. Mortality was 53% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 36.23\ exp^{-4.92 \cdot exp^{(-0.1038\ t)}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 253 m^3/ha for 403 trees/ha, with a mean DBH of 31.8 cm and stem height of 11.6 m. For this age, the estimated MAI in volume was 7.2 m^3/ha/year, MAI in diameter was 0.91 cm/year, and stocked biomass was 231 Mg/ha. The wood volume was overestimated for the plantation in Linhares, because *C. racemosa* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. The trial ended at 16 years of age due to high bifurcation and mortality rate, but the 31 trees with the highest growth at this age presented a mean DBH of 14 cm, which is quite promising, and was confirmed by the model estimated for 35 years of age. However, Loureiro et al. (1979) reported a DBH of only 5.8 cm at 13 years of age in Manaus, and Alencar & Araújo (1980) did not recommend this species for plantations in the Amazon due to its low growth rate. This species may present periods of growth stagnation in natural forests (Silva et al., 2002), and is little used for plantations. Until its silvicultural properties are better known, it should be included in mixed plantations only at very low tree densities. It is very prone to branching in full sun plantations, and should be planted in partial shade, preferably in enrichment plantations. This may stimulate vertical growth, but does not eliminate the need for pruning, which should be a management priority.

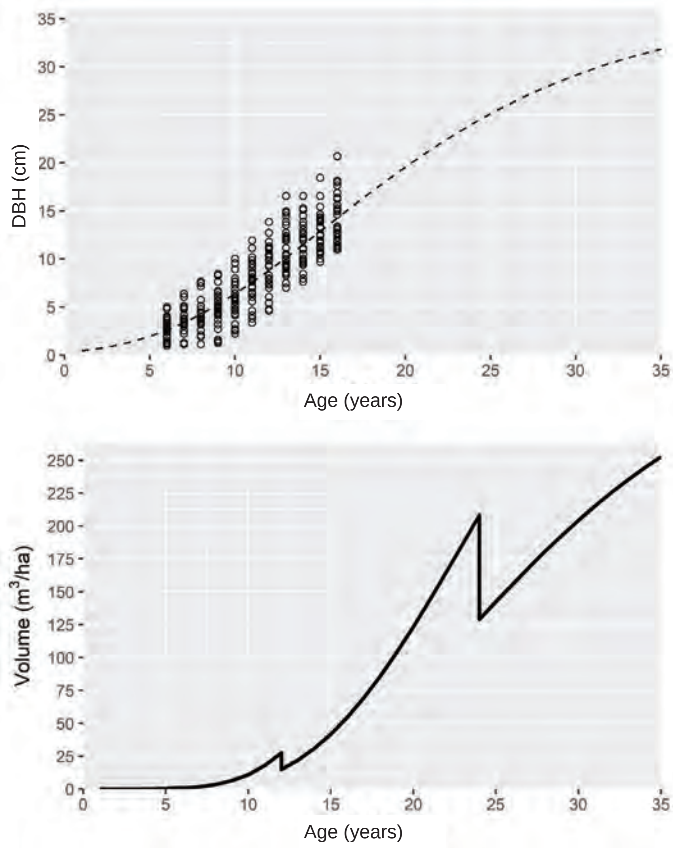
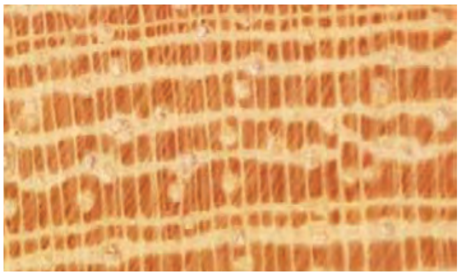


Figure 17. Diameter growth of *Clarisia racemosa* in mixed plantation with *Leucena leucocephala* in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 24 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, strong yellow heartwood with lighter beams, yellowish-white sapwood, uncharacteristic odor, indistinct taste, medium to coarse texture, regular to irregular grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal aliform with linear extension, confluent, occasionally vasicentric and in bands. Rays: visible without magnification in the cross-sectional and longitudinal-tangential planes, contrast in the longitudinal-radial plane, thin, numerous, non-stratified. Vessels: visible without magnification, small to medium, few, diffuse-porous, predominantly solitary and occasionally multiples of two in tangential arrangement. Growth Rings: delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.708
Basic density (g/cm³)	0.587
Volume variation (shrinkage %)	8.76
Anisotropy coefficient	1.12
Modulus of rupture for static bending strength (kgf/cm²)	821.19
Shear strength (kgf/cm²)	117.36
Compression strength parallel to the grain (kgf/cm²)	352.53
Janka hardness (kgf) – parallel and perpendicular to the grain	658.33 – 832.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Fair	Fair	Fair	Fair	Good	Fair	Good	Good	100% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high density and hardness wood, very low tendency to twist and warp, indicated for use in structures, floors, and cladding. It's light and yellowish color permits dyeing and different finishing for decorative uses in furniture, frames, cladding, and utensils. Good planing properties when planing is performed with the grain, with more flaws when cut against the fiber orientation.

Good sanding and lateral mortising properties. Overall, presented some difficulty in boring with both helical and spade bits. Difficult nailing, usually presenting cracks in the nail exit points..

Bowdichia virgilioides Kunth **(Fabaceae)**

Distribution: Commonly known as sucupira-preta or macanaíba-pele-de-sapo, it is distributed in the Amazon, Cerrado, Caatinga, Pantanal, and Atlantic Forest, occurring mainly in seasonal and ombrophilous forests in the states of Bahia, Espírito Santo, Minas Gerais, and São Paulo (Lima & Cardoso, 2015). Large trees of this species in the Atlantic forest are highly exploited due to their high timber value. Its essential oil has activity against several pathogens of the genus *Candida* (Almeida et al., 2006). The other species of the same genus, *Bowdichia nitida*, which occurs exclusively in the Amazon, is also highly valued in the current timber market.

Mean Growth and Yield: Growth data was obtained from a spacing trial, where the remaining trees at 20 years of age presented slightly leaning short stems and good health. Mortality was 26% until 7 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 83{,}54\left(1 + 42{,}02\ exp^{-0.8551\,Ln(t)}\right)^{-1}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 239 m^3/ha for 529 trees/ha, with a mean DBH of 27.8 cm and stem height of 10.7 m. For this age, the estimated MAI in volume was 6.8 m^3/ha/year, MAI in diameter was 0.79 cm/year, and stocked biomass was 255 Mg/ha. The wood volume was overestimated for the plantation in Linhares, because *B. virgilioides* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. Carvalho (2006) reported a DBH of 11.4 cm at 14 years of age in Bahia, which was lower than that observed in Linhares (13.8 cm). In the Ceplac arboretum in Bahia, Vinha & Lobão (1989) observed a DBH of 9.9 cm at 11 years of age, which was also lower than that in Linhares. Ferreira et al. (2016) observed a mean DBH of 17.8 cm at 16 years of age in a restoration plantation with poor and degraded substrate. One great advantage of the use of this species in silviculture, especially in mixed plantations, is that it forms associations with *Rhizobium*, which fixes atmospheric nitrogen (Faria et al., 1984). In homogeneous plantations in Linhares, there was growth stagnation due to the lack of thinning, compromising the overall performance of the species. However, it presented a better stem shape under shade. It is very prone to branching and presents tortuous stems in full sun plantations. It should be preferentially included in enrichment plantations, which may stimulate vertical growth, as can be seen in the photo on the previous page, presenting long, but slightly leaning, stems. However, it still requires periodic pruning, which should be a management priority. Attention should be paid to the high mortality in young plantations. It presents high plasticity, occurring in different biomes, poor soils, and different climates, and great care is required in the selection of provenances for use in silviculture.

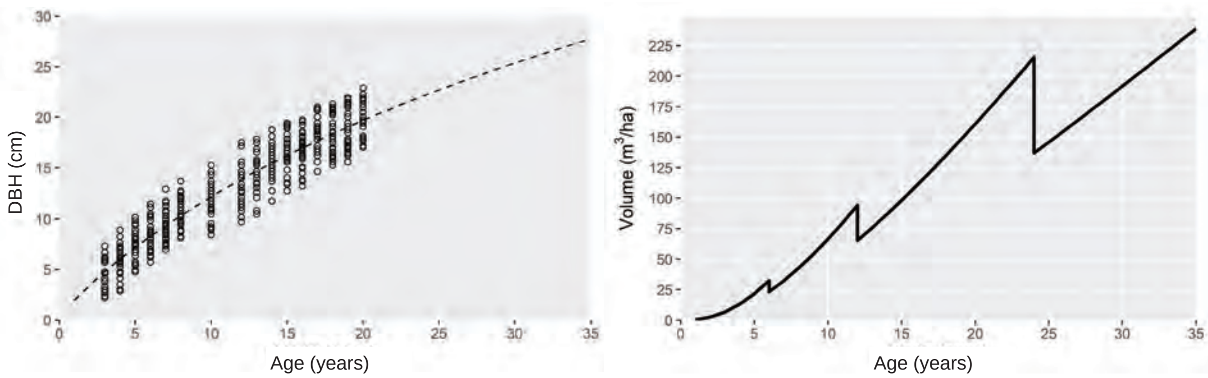
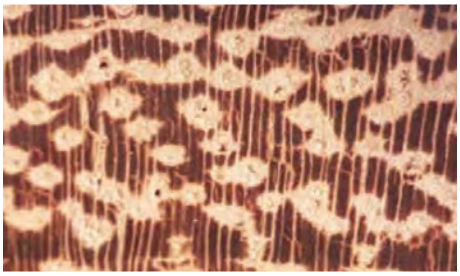


Figure 18. Diameter growth of *Bowdichia virgilioides* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 24 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, dark brown heartwood and yellowish sapwood both with fibrous appearance, uncharacteristic odor, indistinct taste, coarse texture, straight to irregular grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal lozenge aliform, aliform with linear extension, confluent, and occasionally vasicentric and in marginal bands. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential planes, little contrast in the longitudinal-radial plane, thin, numerous, and stratified. Vessels: visible without magnification, medium, numerous, diffuse-porous, predominantly solitary and radial multiples (2–4 vessels). Growth Rings: delimited by fibrous tissue and parenchyma in marginal bands.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.882
Basic density (g/cm³)	0.719
Volume variation (shrinkage %)	17.24
Anisotropy coefficient	1.33
Modulus of rupture for static bending strength (kgf/cm²)	813.07
Shear strength (kgf/cm²)	201.81
Compression strength parallel to the grain (kgf/cm²)	574.56
Janka hardness (kgf) – parallel and perpendicular to the grain	881.67 – 988.33

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Good	Good	Fair	Good	Good	Good	Good	Excellent	29% accept; 71% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high density and hardness wood. Low anisotropy and little tendency to warp. Indicated for use in heavy structures, carpentry, floors, poles, stakes, tool handles, furniture, and utensils. Good to excellent planing properties. Good boring properties with both helical and spade bits. Good sanding and excellent lateral mortising properties. Most samples presented nailing problems, both in the sapwood and in the darker and reddish heartwood.

Parkia pendula (Willd.) Benth. **(Fabaceae)**

Distribution: Commonly known as jueirana-vermelha, it is one of the species presenting disjunction between the Amazon and Atlantic Forest, where it occurs in coastal forests from the state of Espírito Santo to the northeast of the country (Iganci, 2015). It is marketed in the Amazon, but is not highly attractive to the timber market, requiring further studies to increase its value.

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with 2 × 2 m spacing. The remaining trees at 25 years of age presented short, slightly leaning, and tortuous stems, with good health. Mortality was 45% until 5 years of age, due to attack of longhorn beetles of the genus Oncideres. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 70.98\, exp^{-4.61\, t^{-0.5052}}$$

The models showed a trend in growth until 25 years of age, when the estimated volume was 242 m^3/ha for 496 trees/ha, with a mean DBH of 28.7 cm and stem height of 10.9 m. For this age, the estimated MAI in volume was 9.7 m^3/ha/year, MAI in diameter was 1.15 cm/year, and stocked biomass was 173 Mg/ha. The wood volume was overestimated for the plantation in Linhares, because *P. pendula* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. It has one of the highest MAI growth in diameter observed for a timber species in the Atlantic Forest, and has great potential for timber production with thinning at 18 years of age. In the Ceplac arboretum in Bahia, Vinha & Lobão (1989) observed a DBH of 14.9 cm at 16 years, lower than that observed in Linhares. The species can be planted in full sun, but will produce short and leaning stems and very open and wide crowns; this requires great attention to the management of pruning and stem formation, at least during the first 10 years. Partial shade is necessary to obtain straighter stems, preferentially in enrichment plantings, and to stimulate vertical growth, as previously observed in some plantations in Linhares. Attention should also be paid to the high mortality rate due to attacks by longhorn beetles of the genus *Oncideres*.

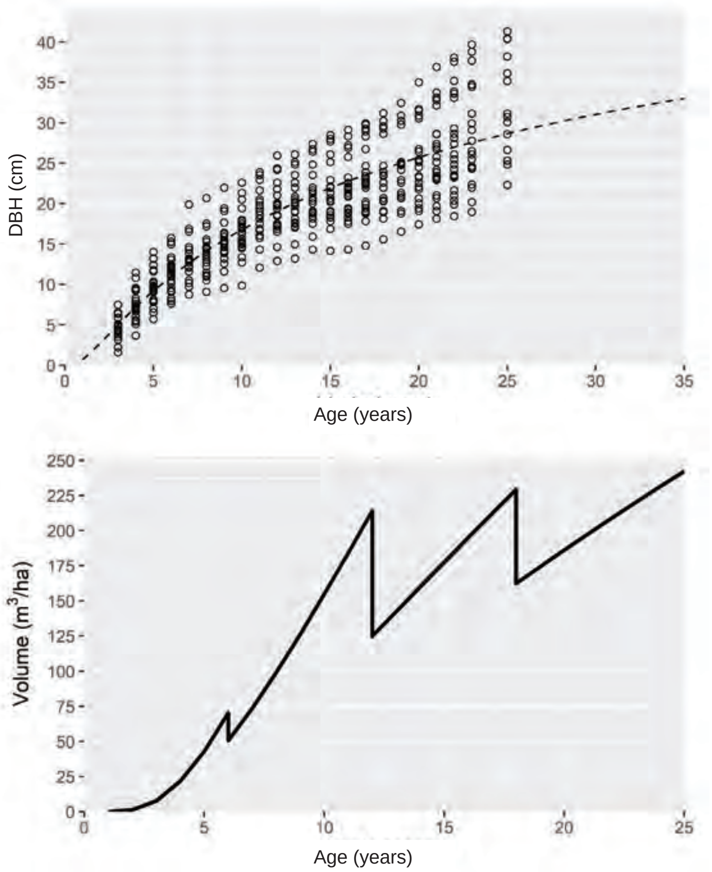


Figure 19. Diameter growth of *Parkia pendula* in a pure plantation in Linhares (ES), and simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 18 years.

(Wood properties)

(Cross section, zoom 10×)

Overall Wood Properties: Indistinct heartwood and sapwood, brownish heartwood with light stripes and yellowish-beige sapwood, uncharacteristic odor, indistinct taste, medium texture, straight to interlocked grain, and variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal aliform losangular, confluent, and occasionally vasicentric. Rays: visible without magnification in the cross-sectional and longitudinal-tangential planes, little contrast in the longitudinal-radial plane, thin, little to very numerous, and non-stratified. Vessels: visible without magnification, medium to large, few, diffuse-porous, predominantly solitary, occasionally multiples of two, and rarely multiples of 3. Growth Rings: indistinct or absent.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.523
Basic density (g/cm^3)	0.430
Volume variation (shrinkage %)	9.10
Anisotropy coefficient	2.05
Modulus of rupture for static bending strength (kgf/cm^2)	420.55
Shear strength (kgf/cm^2)	95.76
Compression strength parallel to the grain (kgf/cm^2)	307.90
Janka hardness (kgf) – parallel and perpendicular to the grain	258.33 – 376.67

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		accept Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Fair	Excellent	Good	Good	Good	Excellent	Good	Excellent	94% accept; 6% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to low density. Medium to high anisotropy and low dimensional stability, with tendency to warp. Low hardness. Indicated for use in packages, boxes, frames, panels, and possibly lamination. Good to excellent planing, sanding, lateral mortising, and boring properties with helicoidal bits. Good boring properties with spade bits. Attention should be paid to the direction of planing, with better results for planing with the grain or fiber orientation. High nail acceptance in most evaluated samples.

Pterocarpus rohrii Vahl. **(Fabaceae)**

Distribution: Commonly known as pau-sangue, it is mainly distributed in seasonal and ombrophilous forests in all Brazilian regions, but also in the Cerrado and Caatinga (Lima, 2015c). It has no history in the timber market, but is used on rural farms in some regions.

Mean Growth and Yield: Growth data was obtained from a pure plantation in Linhares (n = 196 trees), with 2 × 2 m spacing. The remaining trees at 23 years of age presented short slightly leaning stems and good health. Mortality was 15% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 81.48\, exp^{-4.48\, t^{-0.4487}}$$

The models showed a trend in growth until 25 years of age, when the estimated volume was 241 m^3/ha for 508 trees/ha, with a mean DBH of 28.3 cm and stem height of 10.8 m. For this age, the estimated MAI in volume was 9.6 m^3/ha/year, MAI in diameter was 1.13 cm/year, and stocked biomass was 159 Mg/ha. The wood volume was overestimated for the plantation in Linhares, because *P. rohrii* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. This species was not well managed, but it had one of the highest DBH growth observed for any timber species in the Atlantic Forest. There are little growth data available for this species. Carvalho (2008) reported a mean DBH of 10.5 cm in Pernambuco at 13 years of age, which was lower than that observed in Linhares. In the Ceplac arboretum in Bahia, Vinha & Lobão (1989) observed a DBH of 16.4 cm at 16 years of age, which was also lower than that observed for Linhares. It grows well in full sun, but requires pruning. Planting in partial shade may stimulate vertical growth and improve stem straightness.

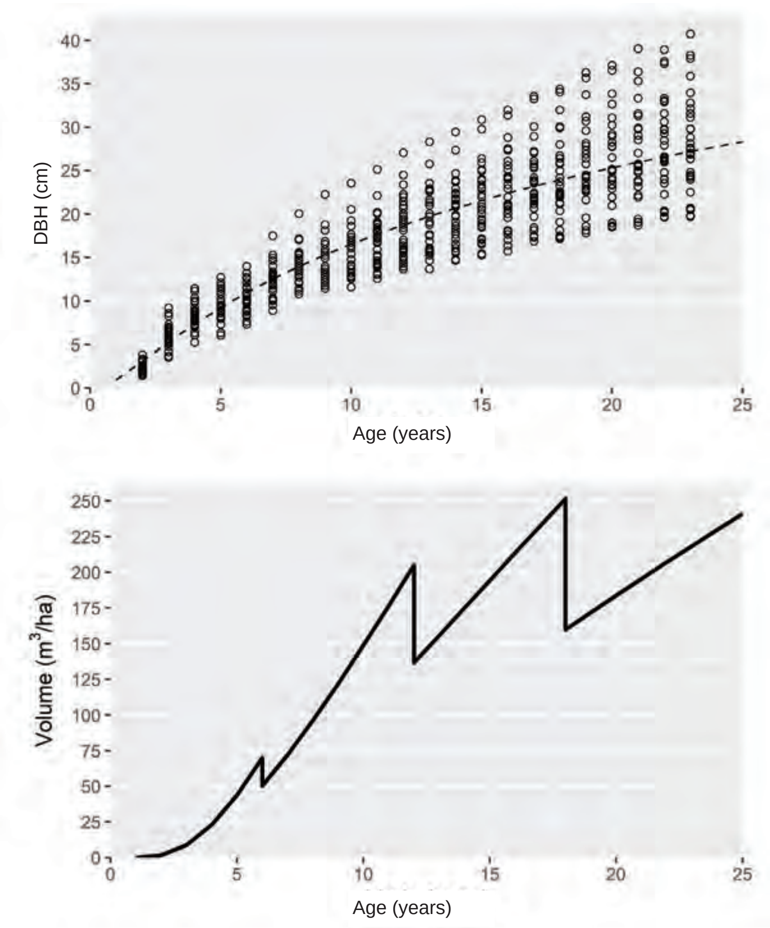


Figure 20. Diameter growth of *Pterocarpus rohrii* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 18 years.

(Wood properties)

(Cross section, zoom 10×)

Overall Wood Properties: Indistinct heartwood and sapwood, light yellow, uncharacteristic odor, indistinct taste, medium texture, straight to irregular grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal aliform with linear extension, confluent, and in lines. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential planes, without contrast in the longitudinal-radial plane, very thin, very numerous, and stratified. Vessels: visible without magnification, small to medium, few, diffuse-porous, and predominantly solitary and radial multiples (2–3 vessels). Growth Rings: delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.479
Basic density (g/cm³)	0.391
Volume variation (shrinkage %)	9.03
Anisotropy coefficient	1.22
Modulus of rupture for static bending strength (kgf/cm²)	521.16
Shear strength (kgf/cm²)	87.08
Compression strength parallel to the grain (kgf/cm²)	365.24
Janka hardness (kgf) – parallel and perpendicular to the grain	270.00 – 420.00

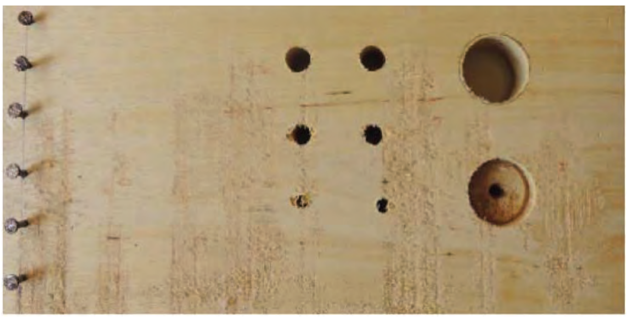
Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Fair	Poor	Poor	Fair	Fair	Poor	Fair	Fair	100% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to low density. Little tendency to warp and twist. Low hardness. Indicated for light use in packages, boxes, possibly lamination, panels, artisanal goods, and utensils. Good to fair planing properties. Poor to fair boring properties with both helical and spade bits. Fair sanding and lateral mortising properties. Very poor nailing properties, causing cracks, tearing, and small splinters especially at the nail exit point, indicating the need for special connecting elements.



Pachira endecaphylla (Vell.) Carv.-Sobr. **(Malvaceae)**

Distribution: One of the species commonly known as paineira, its distribution is limited to the states of Rio de Janeiro and Espírito Santo, in ombrophilous and seasonal forests (Duarte, 2015), with little tradition of popularity in the timber market.

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with 2 × 2 m spacing. The remaining trees at 22 years of age presented short stems with good shape and health. Mortality plus thinning was 63% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 29.124\left(1 - exp^{-0.0413 \cdot t^{1.3736}}\right)$$

The models showed a stagnation in growth between 15 and 25 years of age, with an estimated volume at 25 years of age of 241 m^3/ha for 513 trees/ha, mean DBH of 28.2 cm, and stem height of 10.8 m. For this age, the estimated MAI in volume was 9.6 m^3/ha/year, MAI in diameter was 1.13 cm/year, and stocked biomass was 127 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *P. endecaphylla* presents short stems and needs to be better managed (with appropriate pruning) to reach the estimated height, and consequently volume, estimated by the model. Paineira species in general are fast-growing, and the growth observed in Linhares can be considered lower than that expected for this species. The lack of appropriate thinning from 15 years of age probably had a negative effect on the growth. There are no reports of growth data for this species, but the growth observed was lower than that reported by Carvalho (2003) for species of Malvaceae, such as *Ceiba speciosa*, with DBH values of 33 cm at 20 years of age in São Paulo, and 20–25 cm at 10 years of age in restoration plantations in Paraná. Almost all trees monitored in full sun plantations in Linhares presented short stems, but there are no available data on their growth and stem shape in partial shade. Attention should be paid to the high mortality in young plantations.

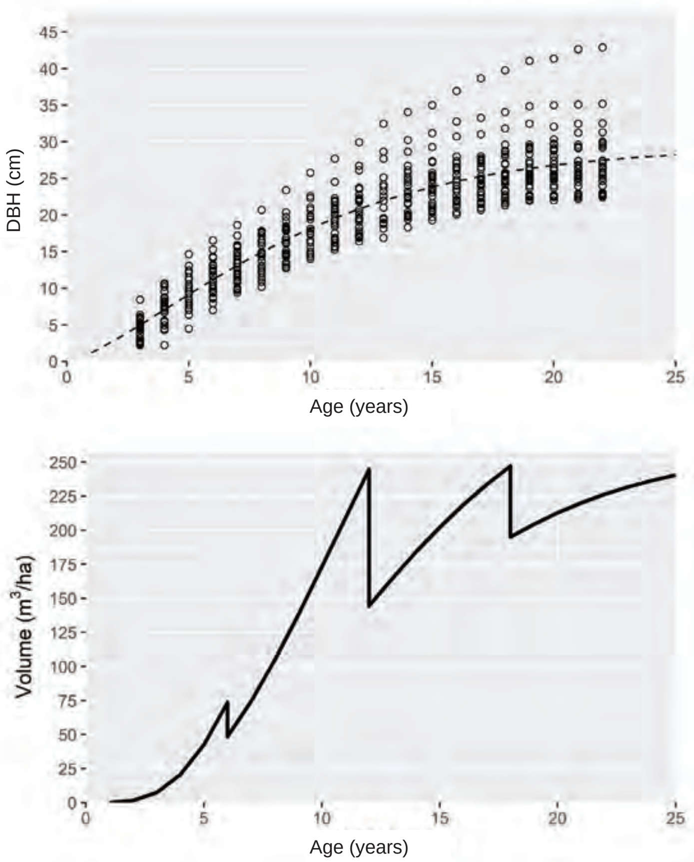


Figure 21. Diameter growth of *Pachira endecaphylla* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 18 years.

(Wood properties)

(Cross section, zoom 10×)

Overall Wood Properties: Indistinct heartwood and sapwood, whitish-beige, uncharacteristic odor, indistinct taste, medium texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: barely visible without magnification, apotracheal diffuse in clusters and in marginal bands. Rays: visible without magnification in the cross-sectional and longitudinal-tangential planes, without contrast in the longitudinal-radial plane, thin, numerous, and non-stratified. Vessels: visible without magnification, medium to large, few, diffuse-porous, predominantly solitary and multiples (2–4 vessels) in radial arrangement. Growth Rings: delimited by fibrous tissue and parenchyma in marginal bands.

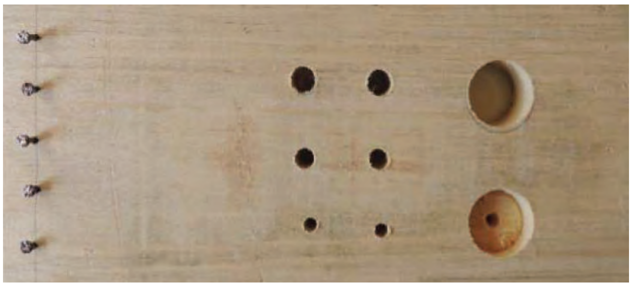
Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.403
Basic density (g/cm^3)	0.293
Volume variation (shrinkage %)	8.49
Anisotropy coefficient	3.50
Modulus of rupture for static bending strength (kgf/cm^2)	339.38
Shear strength (kgf/cm^2)	42.67
Compression strength parallel to the grain (kgf/cm^2)	57.82
Janka hardness (kgf) – parallel and perpendicular to the grain	195.00 – 200.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications										
Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Fair	Fair	Poor	Poor	Fair	Poor	Excellent	Excellent	100% accept

Assays conducted according to the normative document ASTM 1666:1994

Low density and very low hardness. High anisotropy and tendency to warp. Indicated for light use in packages, boxes, possibly lamination, panels, artisanal goods, and utensils. Excellent to fair planing properties. Poor to fair boring properties with both helical and spade bits. Excellent sanding, lateral mortising, and nailing properties.



Spondias venulosa (Engl.) Engl. **(Anacardiaceae)**

Distribution: Commonly known as cajá, it is mainly distributed thoroughout ombrophilous and seasonal forests of the Atlantic Forest in the states of Bahia, Espírito Santo, Minas Gerais, and Rio de Janeiro (Silva-Luz & Pirani, 2015). It has no history in the timber market, but its tasty fruit has traditional local markets.

Mean Growth and Yield: Growth data was obtained from a pure plantation in Linhares (n = 196 trees), with 2 × 2 m spacing. The remaining trees at 24 years of age presented short and slightly leaning stems and good health. Mortality was 34% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 82.59\ exp^{-2.97\ t^{-0.4292}}$$

The models showed a trend in growth until 15 years of age, when the estimated volume was 255 m^3/ha for 383 trees/ha, with a mean DBH of 32.6 cm and stem height of 11.7 m (note that data was collected until 24 years of age; Figure 22). For this age (15 years), the estimated MAI in volume was 17.0 m^3/ha/year, MAI in diameter was 2.18 cm/year, and stocked biomass was 154 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *S. venulosa* presents short stems and needs to be better managed (with appropriate pruning) to reach the height, and consequently volume, estimated by the model. The plantation was not properly thinned from 12 years of age. It is the species with the highest diameter growth rate of all species evaluated in the present study, presenting trees with 30 cm DBH at 10 years of age. Its high growth rate makes the simulation of thinning difficult, an activity to which special attention should be given. The criteria of provenance selection, thinning, and prunings are different for fruit and timber production.

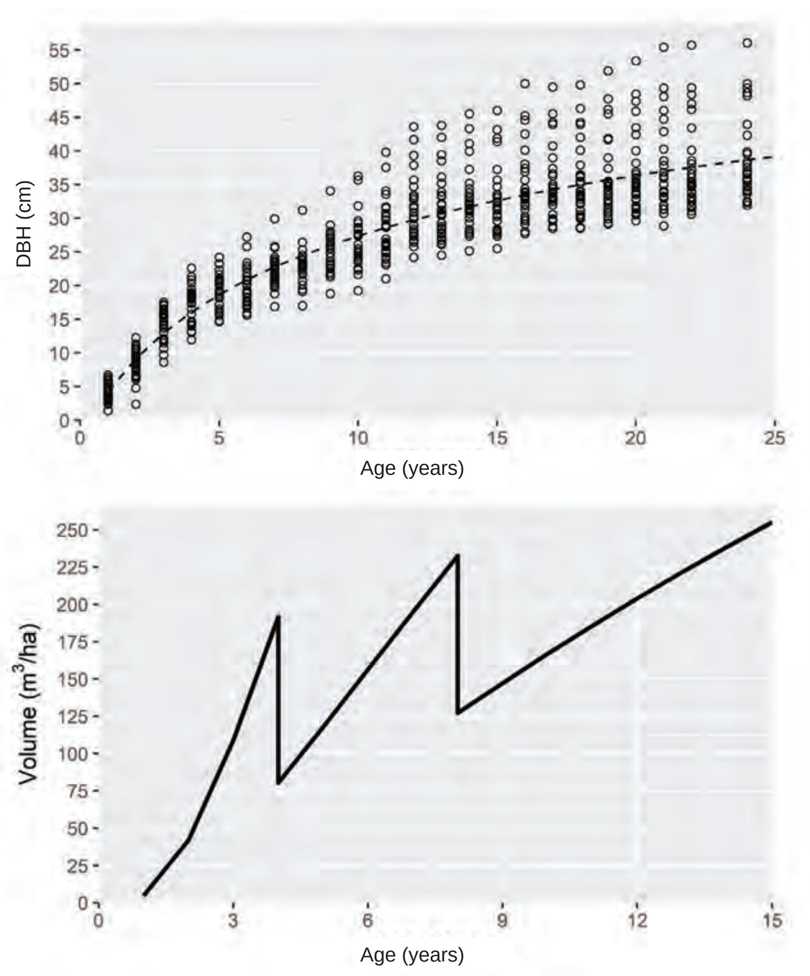


Figure 22. Diameter growth of *Spondias venulosa* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 4 and 8 years.

(Wood properties)

(Cross section, zoom 10×)

Overall Wood Properties: Indistinct heartwood and sapwood, brownish-light beige, uncharacteristic odor, indistinct taste, coarse texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification and paratracheal vasicentric. Rays: visible without magnification in the cross-sectional and longitudinal-tangential planes, little contrast in the longitudinal-radial plane, medium, numerous, and non-stratified. Vessels: barely visible without magnification, small to medium, numerous, diffuse-porous, and predominantly solitary and occasionally multiples of two in radial and diagonal arrangements. Growth Rings: slightly delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.438
Basic density (g/cm^3)	0.345
Volume variation (shrinkage %)	8.65
Anisotropy coefficient	2.21
Modulus of rupture for static bending strength (kgf/cm^2)	656.70
Shear strength (kgf/cm^2)	71.80
Compression strength parallel to the grain (kgf/cm^2)	215.81
Janka hardness (kgf) – parallel and perpendicular to the grain	151.67 – 325.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Good	Poor	Very poor	Poor	Very poor	Very poor	Excellent	Good	95% accept; 5% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Low density, resistance, and hardness. High anisotropy and tendency to warp and twist. Indicated for use in packages, boxes, and utensils. Good planing properties. Very poor to poor boring properties with both helical and spade bits. Excellent sanding and good lateral mortising properties. Very good nail acceptance.

Myracrodruon urundeuva Allemão **(Anacardiaceae)**

Distribution: Commonly known as true aroeira, it is distributed in the Cerrado, Caatinga, Pantanal, and seasonal forests of the Atlantic Forest from the northeast to the south of the country (Silva-Luz & Pirani, 2015), but there are no records of natural forests in the state of Espírito Santo, and the provenance of trees planted in Linhares was Minas Gerais. It is one of the most well-known species in rural areas due to its natural durability.

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with 2 × 2 m spacing. The remaining trees at 22 years of age presented short and slightly tortuous stems with good health. Mortality was 2% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 60.42\left(1 + 20.075\,exp^{-0.9038\,Ln(t)}\right)^{-1}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 257 m^3/ha for 365 trees/ha, with a mean DBH of 33.4 cm and stem height of 11.9m. For this age, the estimated MAI in volume was 7.4 m^3/ha/year, MAI in diameter was 0.96 cm/year, and stocked biomass was 248 Mg/ha. The wood volume was overestimated for the plantation in Linhares, because *M. urundueva* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. Carvalho (2003) reported a mean DBH of 16–20 cm at 20 years of age in the interior of São Paulo, which was lower than that observed in Linhares (26 cm for the same age). It very often occurs in poor and degraded soils but responds well to fertile soils. Its greater silvicultural problem is probably its very tortuous stem and bifurcation (requiring frequent pruning) when grown in full sun, and its introduction into mixed plantations after the initial years is recommended (Gurgel Garrido et al., 1997). In fact, Souza et al. (2015) showed an improved DBH and height at 15 years of age in mixed plantations with 50%–85% of *Croton floribundus*. It can be managed by coppicing, which generates vigorous and high-quality shoots; however, they are sensitive to light. There are ex-situ conserved populations in the state of São Paulo (Siqueira & Nogueira 1992; Canuto et al., 2017), and population studies indicate significant differences between progenies (Freitas et al., 2006), with possible increases in DBH (Canuto et al., 2017). The species has a high natural regeneration ability, which may be beneficial to its management, but care should be taken so that it does not become invasive.

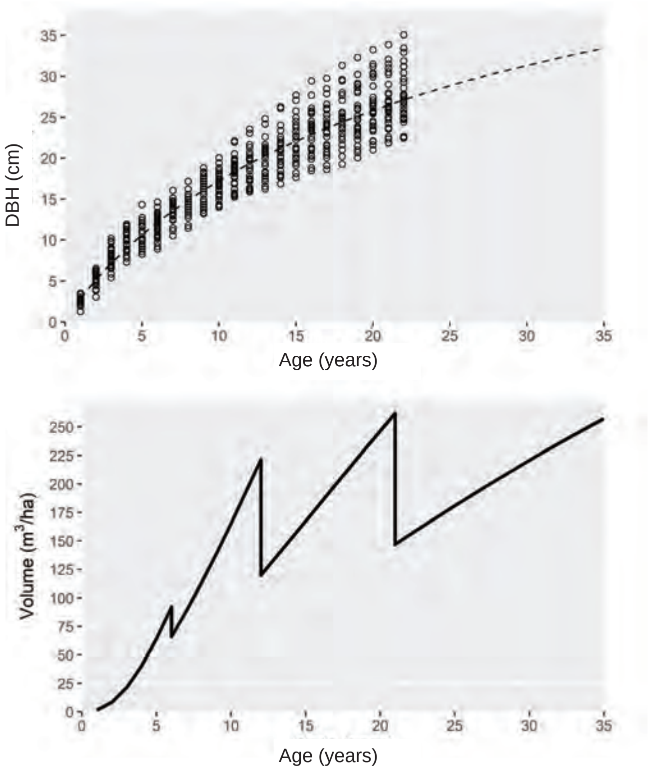


Figure 23. Diameter growth of *Myracrodruon urundeuva* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 21 years.

Lecythis pisonis Cambess. **(Lecythidaceae)**

Distribution: Commonly known as sapucaia-vermelha, it is distributed in seasonal and ombrophilous forests of the Atlantic Forest from the southeast to the northeast of the country, and occurs in the Amazon forest (Smith et al., 2015). It is also interesting as a non-timber species, due to the production of edible nuts with high nutritional and medicinal values, with antioxidant and anti-inflammatory activities (Martins et al., 2016).

Mean Growth and Yield: Growth data was obtained from a pure plantation in Linhares (n = 196 trees) with 2 × 2 m spacing. The remaining trees at 24 years of age presented short stems, but with good shape and health. Mortality was 0% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 60.82\, exp^{-4.774\, t^{-0.4848}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 232 m^3/ha for 605 trees/ha, with a mean DBH of 25.9 cm and stem height of 10.3 m. For this age, the estimated MAI in volume was 6.6 m^3/ha/year, MAI in diameter was 0.74 cm/year, and stocked biomass was 237 Mg/ha. The wood volume was overestimated for the plantation in Linhares, since *L. pisonis* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. If more intensive thinnings had been performed between 8 and 15 years of age, the estimated growth could also have improved. Montagnini et al. (1994) reported a DBH of 13 cm at 14 years of age in the state of Bahia, which was slightly lower than that observed in Linhares (DBH of 15.9 cm for the same age); however, Almeida (1943) reported a DBH of 21 cm at 16 years in the state of Rio de Janeiro, which is much higher. Additionally, in the state of Bahia, the growth in the arboretum of Ceplac was lower, with a DBH of 12.8 cm at 17 years of age (Vinha & Lobão, 1989). Planting under partial shade may stimulate vertical growth, decrease bifurcation, and result in straighter stems, but it is very sensitive to excessive shade, which may decrease its growth.

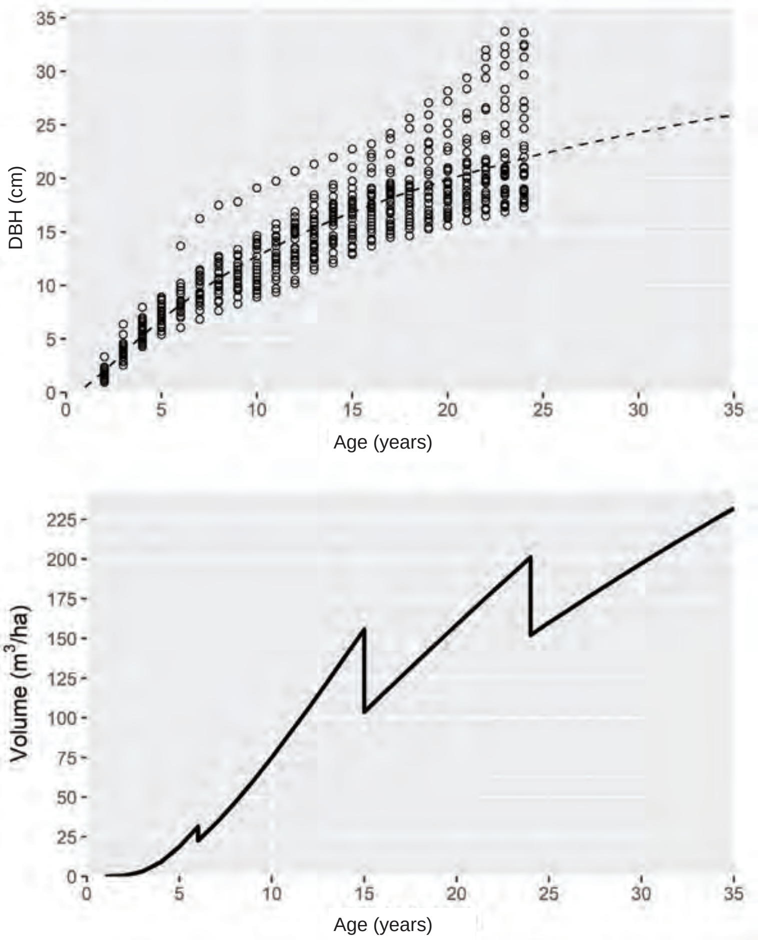
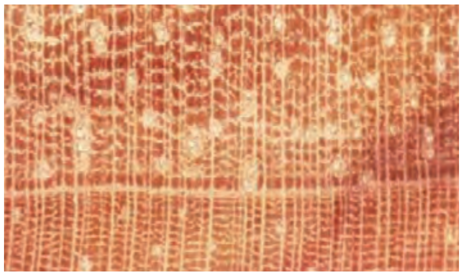


Figure 24. Diameter growth of *Lecythis pisonis* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 15, and 24 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, rose-red heartwood and light yellow sapwood, uncharacteristic odor, taste slightly astringent, medium texture, straight grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, reticulated. Rays: visible without magnification in the cross-sectional plane and only under magnification in the longitudinal-tangential plane, without contrast in the longitudinal-radial plane; thin, numerous, and non-stratified. Vessels: barely visible without magnification, small, few, diffuse-porous, predominantly solitary and radial multiples (2–3 vessels). Growth Rings: delimited by fibrous tissue and the separation of parenchyma bands.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.855
Basic density (g/cm^3)	0.683
Volume variation (shrinkage %)	13.16
Anisotropy coefficient	1.16
Modulus of rupture for static bending strength (kgf/cm^2)	937.42
Shear strength (kgf/cm^2)	129.41
Compression strength parallel to the grain (kgf/cm^2)	533.22
Janka hardness (kgf) – parallel and perpendicular to the grain	786.67 – 871.67

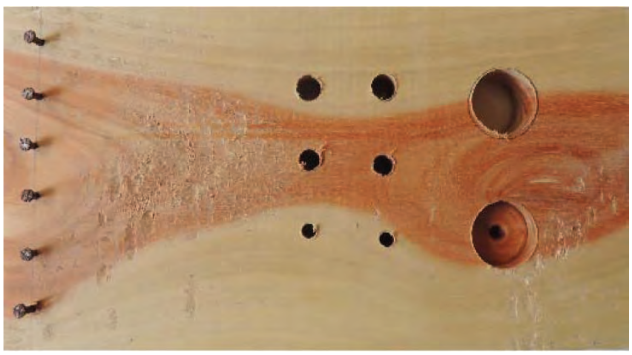
Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Good	Good	Fair	Fair	Fair	Excellent	Good	Good	22% accept; 78% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high density and hardness. Low anisotropy and little tendency to warp. Indicated for use in structures, floors, tool handles, frames, and utensils. Good to excellent planing properties. Good to fair boring properties. Good sanding and lateral mortising properties. Problems with nailing in both the heartwood and sapwood in the upper side of the samples, indicating the need for special care when nailing.



Centrolobium tomentosum Guillem. ex Benth. **(Fabaceae)**

Distribution: Commonly known as araribá-vermelho or putumuju, it occurs mainly in seasonal forests in the Atlantic Forest, from the south of Bahia to the state of Paraná, but also in some areas of ombrophilous forest, in the Cerrado and Caatinga (Klitgaard, 2015). This species, along with other species of *Centrolobium*, such as *C. robustum* and *C. microchaete*, are highly valued and have been extensively exploited in the Atlantic Forest (Bastos, 1952).

Mean Growth and Yield: Growth data was obtained from two mixed plantations, one with Cordia trichotoma (n = 72 trees per species) and one with Astronium graveolens (n = 72 trees per species), due to many plant health problems. The remaining trees at 26 years of age presented short stems and compromised health. Mortality was 6% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 46.43\ exp^{-8.30\ t^{-0.7437}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 231 m^3/ha for 615 trees/ha, with a mean DBH of 25.7 cm and stem height of 10.2 m. For this age, the estimated MAI in volume was 6.6 m^3/ha/year, MAI in diameter was 0.74 cm/year, and stocked biomass was 216 Mg/ha. The wood volume was overestimated for the plantation in Linhares, because *C. tomentosum* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. The estimated DBH for Linhares was similar to the highest reported mean DBH values: 20 cm at 19 years of age (Almeida, 1943), 18.5 cm at 20 years of age (Gurgel Filho et al., 1982d), and a slightly higher 23.3 cm at 20 years for a mixed restoration plantation (Nogueira, 1977). Growth in the Ceplac arboretum in the state of Bahia was low, with a DBH of 6.1 cm at 16 years of age (Vinha & Lobão, 1989). In Linhares, many individuals of *C. tomentosum* decreased their DBH growth rate after 15 years, especially in homogeneous plantations. A likely cause for this were attacks by longhorn beetles of the genus *Oncideres*, which cut new, less lignified twigs (twig-girdling), or cause bifurcation by attacking the main stem of young trees. *C. tomentosum* should be used at low densities in mixed plantations to minimize attacks by longhorn beetles. It presents good self-pruning if it is not attacked. It requires partial shade to develop straighter stems, but it is sensitive to high shade, which may decrease its growth rate. An advantage of its use in silviculture, especially in mixed plantations, is that it forms associations with *Rhizobium*, which fixes atmospheric nitrogen (Faria et al., 1984), and produces large amounts of litter, incorporating other nutrients into the soil (Aidar & Joly, 2003).

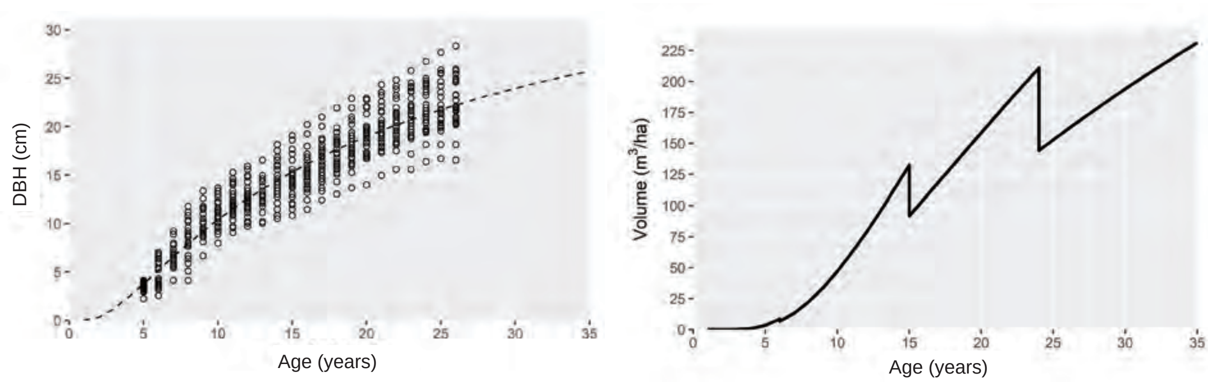
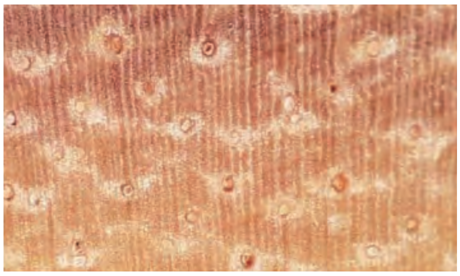


Figure 25. Diameter growth of *Centrolobium tomentosum* in a mixed plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 15, and 24 years.


(Wood properties)


(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, heartwood with yellowish, reddish and whitish veins, whitish-beige sapwood, uncharacteristic odor, indistinct taste, interlocked grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal vasicentric, and aliform losangular and confluent. Rays: only visible under magnification in the cross-sectional and longitudinal-tangential planes, without contrast in the longitudinal-radial plane, very thin, numerous, and stratified. Vessels: visible without magnification, small to medium, numerous, diffuse-porous, and predominantly solitary and in multiples of two in tangential arrangement. Growth Rings: delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.717
Basic density (g/cm³)	0.609
Volume variation (shrinkage %)	8.46
Anisotropy coefficient	1.64
Modulus of rupture for static bending strength (kgf/cm²)	828.29
Shear strength (kgf/cm²)	124.43
Compression strength parallel to the grain (kgf/cm²)	142.06
Janka hardness (kgf) – parallel and perpendicular to the grain	521.67 – 546.67

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Excellent	Excellent	Good	Good	Excellent	Excellent	Excellent	Excellent	22% accepts; 78% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium density and medium to low hardness. Fair to good stability, with little tendency to warp. Indicated for use in light structures, furniture, floors, and utensils, in which its color is valued aesthetically. Excellent planing, boring, sanding, and lateral mortising properties. Fair to poor nailing properties, with tearing and small splinters in the bottom side especially, indicating the need for special connecting elements.

Barnebydendron riedelii (Tul.) J.H. Kirkbride **(Fabaceae)**

Distribution: Commonly known as guaribú-sabão or guaribeiro, it presents a disjunct distribution between the Amazon Forest in the state of Acre and the Atlantic forest in the states of Bahia, Espírito Santo, Rio de Janeiro, and São Paulo (Lima, 2015d). It does not have a great history of popularity in the timber market; however, it is currently exploited in the state of Acre (Silva et al., 2015), and has potential to increase its market value.

Mean Growth and Yield: Growth data was obtained from a pure plantation in Linhares (n = 196 trees) with 2 × 2 m spacing. The remaining trees at 23 years of age presented short, slightly leaning stems and good health. Mortality was 1% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 47.11\ exp^{-4.20\ t^{-0.5434}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 231 m³/ha for 620 trees/ha, with a mean DBH of 25.6 cm and stem height of 10.2 m. For this age, the estimated MAI in volume was 6.6 m³/ha/year, MAI in diameter was 0.73 cm/year, and stocked biomass was 198 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *B. riedelii* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. There are no reports of growth data for this species, but the results in Linhares can be considered promising, considering that the mean DBH was 20 cm at 20 years of age; however, the growth rate decreased from 20 years of age, indicating a long growth cycle to reach a DBH of 30 cm. The lack of adequate thinning from 15 years of age probably affected the growth results. Planting in partial shade may stimulate vertical growth, decrease bifurcation, and produce straighter stems.

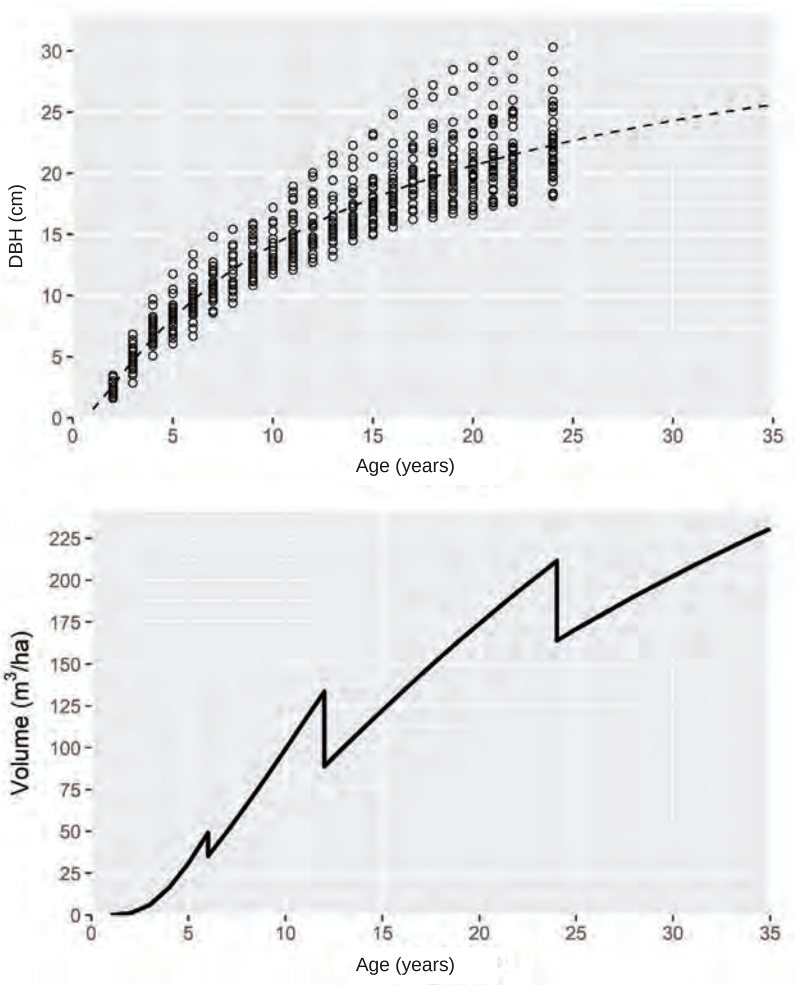
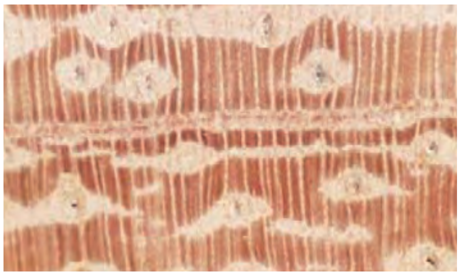


Figure 26. Diameter growth of *Barnebydendron riedelii* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 24 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Slightly distinct heartwood, light brown–rose beige, uncharacteristic odor, indistinct taste, coarse texture, interlocked grain, and variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal aliform losangular, occasionally vasicentric, confluent, and in marginal bands. Rays: few visible without magnification in the cross-sectional and longitudinal-tangential planes, contrast in the longitudinal-radial plane, thin, numerous, and non-stratified. Vessels: visible without magnification, medium, numerous, diffuse-porous, and predominantly solitary and tangential multiples (2–3 vessels). Growth Rings: delimited by fibrous tissue and parenchyma in marginal bands.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.675
Basic density (g/cm^3)	0.545
Volume variation (shrinkage %)	9.08
Anisotropy coefficient	1.52
Modulus of rupture for static bending strength (kgf/cm^2)	452.46
Shear strength (kgf/cm^2)	112.01
Compression strength parallel to the grain (kgf/cm^2)	282.77
Janka hardness (kgf) – parallel and perpendicular to the grain	390.00 – 456.67

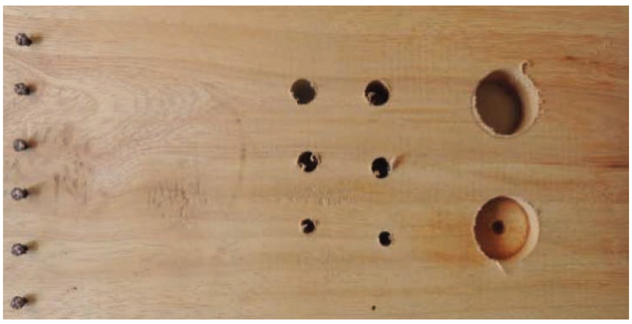
Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Good	Good	Fair	Good	Fair	Fair	Excellent	Good	28% accepts; 72% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium density and low hardness. Low anisotropy and little tendency to warp. Indicated for use in packages, light structures, boxes, frames, panels, cladding, and possibly lamination. Good to excellent planing, sanding, and lateral mortising properties. Difficult boring with both helical and spade bits. Difficulties in nailing for most samples, presenting cracking and fiber tearing in the bottom side of the sample.



Senegalia polyphylla (DC.) Britton & Rose **(Fabaceae)**

Distribution: Commonly known as angico-preto or monjoleiro, it is distributed throughout seasonal ombrophilous forests in all regions of Brazil, as well as in the Cerrado and Caatinga (Morim & Barros, 2015). It has no history of popularity in the timber market, but is used in rural farms in some regions.

Mean Growth and Yield: Growth data was obtained from a pure plantation in Linhares (n = 196 trees) with 2 × 2 m spacing. The remaining trees at 25 years of age presented slightly leaning, tortuous stems and good health. Mortality was 5% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 77.54\, exp^{-3.935\, t^{-0.3440}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 225 m^3/ha for 687 trees/ha, with a mean DBH of 24.4 cm and stem height of 9.8 m. For this age, the estimated MAI in volume was 6.4 m^3/ha/year, MAI in diameter was 0.70 cm/year, and stocked biomass was 261 Mg/ha. Plantations in the state of Acre presented a DBH of 15.5 cm at 5 years of age, which was much higher than that observed in Linhares and Paraná (13 cm at 10 years of age) (Carvalho, 2008). The lack of adequate thinning between 7 and 16 years of age probably affected growth. It bifurcates easily in full sun plantations, but the trees in Linhares presented reasonable shape, which could have been improved with pruning. Planting under shade may help minimize bifurcation and stimulate vertical growth.

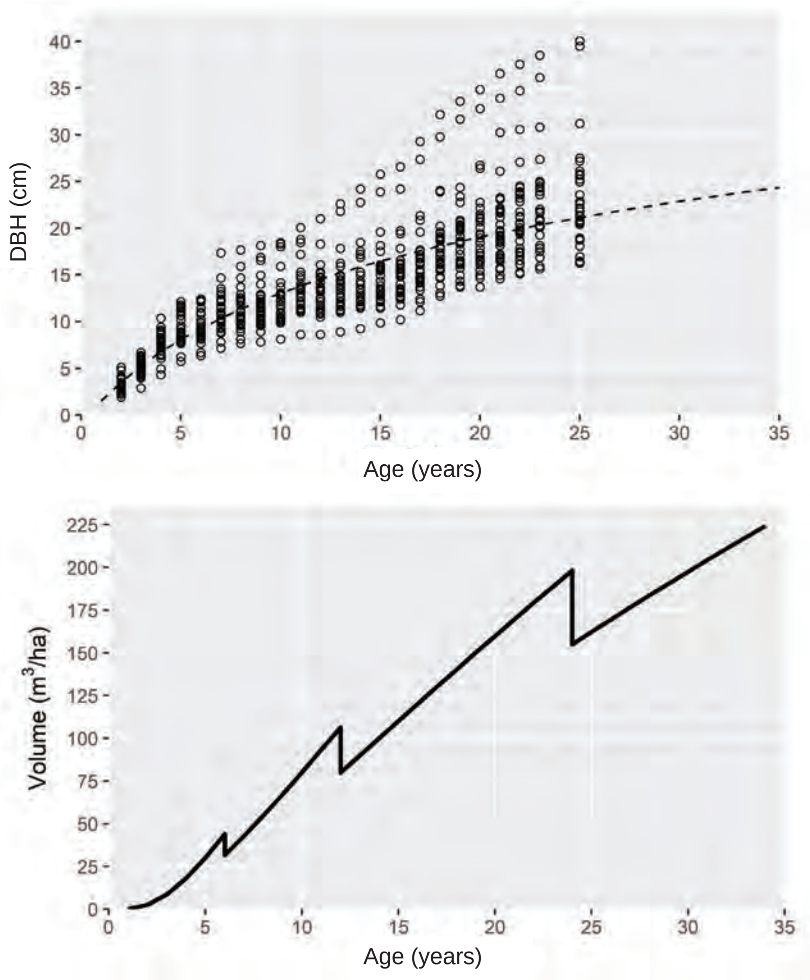
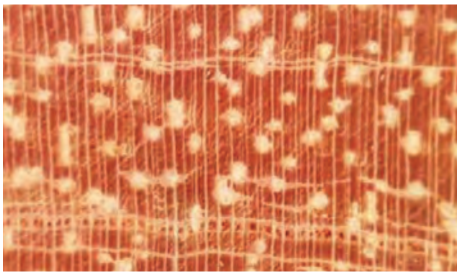


Figure 27. Diameter growth of *Senegalia popyphylla* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 12, and 24 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Indistinct heartwood and sapwood, rose-brown, uncharacteristic odor, slightly astringent taste, medium texture, irregular grain, and variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal vasicentric, aliform with short and narrow extensions, and in marginal narrow and wide bands. Rays: visible without magnification in the cross-sectional and longitudinal-tangential planes, without contrast in the longitudinal-radial plane, thin, numerous, and non-stratified. Vessels: visible without magnification, small to medium, numerous to very numerous, diffuse-porous, and solitary and radial multiples (2–3 vessels). Intercellular axial channels of traumatic origin in tangential series. Growth Rings: delimited by parenchyma in narrow and wide marginal bands.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	1.027
Basic density (g/cm^3)	0.803
Volume variation (shrinkage %)	17.84
Anisotropy coefficient	1.81
Modulus of rupture for static bending strength (kgf/cm^2)	906.47
Shear strength (kgf/cm^2)	145.72
Compression strength parallel to the grain (kgf/cm^2)	625.24
Janka hardness (kgf) – parallel and perpendicular to the grain	913.33 – 1035.00

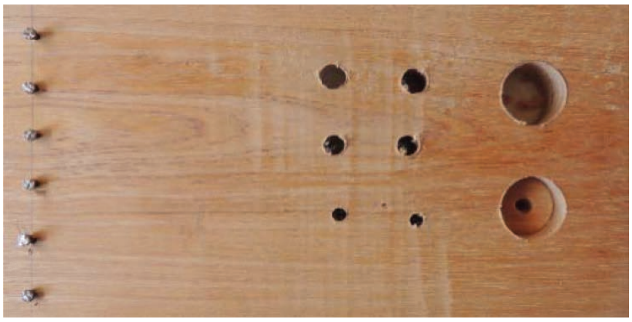
Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Good	Poor	Poor	Poor	Good	Fair	Good	Fair	100% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Moderately high density and high hardness, some tendency to twist and warp. Indicated for use in structures, solid floors, tool handles, and utensils. Good planing properties using a peripheral knife planer. High incidence of fiber tearing when boring with helical bits. Fair to good boring properties with spade bits. Good sanding properties and fair lateral mortising properties. Great difficult in nailing, especially in the bottom side of the samples, demanding care and the use of special connecting elements with higher resistance.



Paubrasilia echinata (Lam.) Gagnon, H.C.Lima & G.P.Lewis **(Fabaceae)**

Distribution: Commonly known as pau-brasil, it occurs in ombrophilous and seasonal forests from Rio de Janeiro to Rio Grande do Norte (Gagnon et al., 2016). It was the first product exploited by Portuguese colonizers in Brazil for fabric dyeing. It is currently considered the best species for the construction of violin bows, probably because the extractives present in the wood have a positive effect on the vibration properties of the bow (Matsunaga et al., 1996). Its natural populations have been greatly reduced, and there is a growing demand for its legally sourced timber.

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with 2 × 2 spacing, where the remaining trees at 24 years of age presented short, tortuous stems and good health. Mortality was 63% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 40.69\ exp^{-6.03\ t^{-0.6845}}$$

The models showed a trend in growth, with an estimated volume of 224 m^3/ha for 709 trees/ha, mean DBH of 24.0 cm and stem height of 9.8 m at 35 years of age. For this age, the estimated MAI in volume was 6.4 m^3/ha/year, MAI in diameter was 0.69 cm/year, and stocked biomass was 257 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *P. echinata* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. In Linhares, a drastic thinning was performed between 2 and 5 years of age (57%), but no prunings were performed, which are essential for the proper management of this species. The lack of adequate thinning between 16 and 22 years of age must have had a negative effect on the species performance. The mean DBH values observed in Linhares at 10, 15, or 20 years were higher than those observed for all other locations where this species was planted (Carvalho, 2003). In the Ceplac arboretum in the state of Bahia, Vinha & Lobão (1989) observed a DBH of 9.2 cm at 17 years of age, which was also lower than that observed in Linhares. However, it reached a mean DBH of 14 cm at 11 years of age in agroforestry systems in Ilhéus, which was higher than that observed in Linhares (Matos, 2016). It is a slow-growing species, but because of its high value it can be used even at low densities, preferentially as an enrichment species, in mixed plantations with 50% shade (Mengarda et al., 2009). It requires long cycles of 40–50 years to reach at least 30 cm DBH. Its populations present large differences in leaflet size and shape, wood color, and growth rates, and could even be different species (H.C. Lima, personal communication). Trees originating from the state of Pernambuco are preferred for bow construction. Due to this high morphological variability, using known provenances is essential to increasing the wood yield and valuation. Attention should be paid to the high mortality in young plantations.

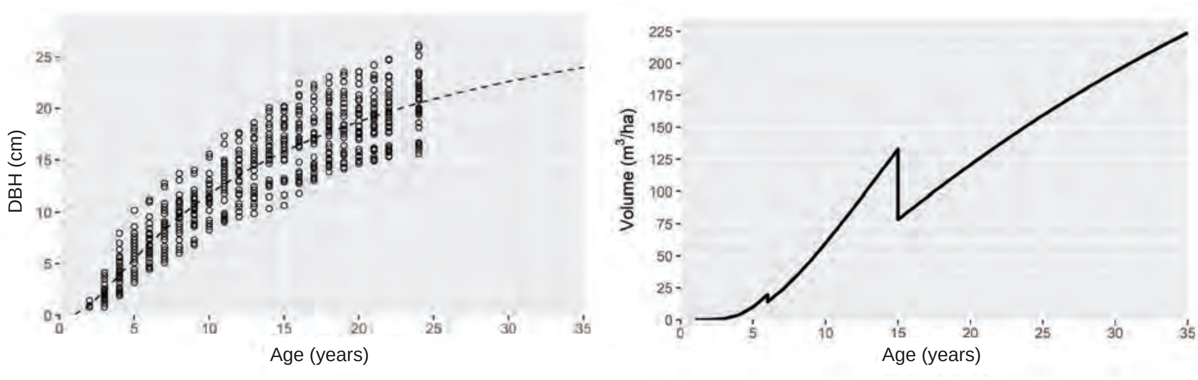
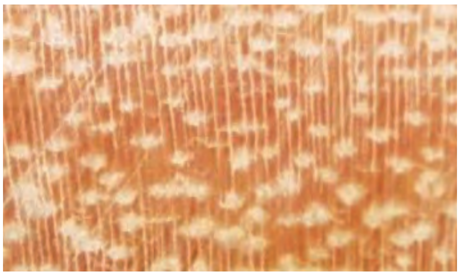


Figure 28. Diameter growth of *Paubrasilia echinata* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6 and 15 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, orange heartwood, whitish-yellow sapwood, uncharacteristic odor, slightly bitter taste, fine to medium texture, straight to irregular grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, paratracheal vasicentric, aliform losangular, confluent, and occasionally in narrow marginal bands. Rays: only visible under magnification in the cross-sectional plane and without magnification in the longitudinal-tangential plane, little contrast in the longitudinal-radial plane, thin, numerous, and stratified. Vessels: only visible under magnification, very small to small, very numerous, diffuse-porous, and solitary and radial multiples (2–4 vessels). Growth Rings: delimited by fibrous tissue and parenchyma in marginal bands.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.973
Basic density (g/cm^3)	0.794
Volume variation (shrinkage %)	13.18
Anisotropy coefficient	1.79
Modulus of rupture for static bending strength (kgf/cm^2)	557.52
Shear strength (kgf/cm^2)	180.21
Compression strength parallel to the grain (kgf/cm^2)	777.38
Janka hardness (kgf) – parallel and perpendicular to the grain	1285.00 – 1500.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Fair	Good	Good	Good	Good	Excellent	Excellent	Excellent	100% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium to high density and high hardness. Good dimensional stability and little tendency to warp. Indicated for use in structures, floors, furniture, and musical instruments. Good to excellent planing, boring, sanding, and lateral mortising properties. Some care should be taken when planing against the grain. Poor nailing properties, requiring special care, with pre-boring and the use of connecting elements of special shape and material.

Amburana cearensis (Allemão) A.C. Sm. **(Fabaceae)**

Distribution: Commonly known as amburana or cerejeira, it is distributed in the Cerrado, Caatinga, and Atlantic Forest biomes, occurring mainly in seasonal forests in the latter (Lima, 2015e). One of the preferred species in the timber market, together with another species of the same genus, *Amburana acreana*, which occurs in the Amazon.

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with 2 × 2 m spacing. The remaining trees at 22 years of age presented short, very tortuous stems and good health. Mortality was 8% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 26.11\left(1 + 344.74\, exp^{-\,2.32\, Ln(t)}\right)^{-1}$$

The models showed growth stagnation after 19 years, with an estimated volume of 224 m^3/ha for 710 trees/ha mean DBH of 23.9 cm, and stem height of 9.8 m at 35 years of age. For this age, the estimated MAI in volume was 6.4 m^3/ha/year, MAI in diameter was 0.68 cm/year, and stocked biomass was 164 Mg/ha. The lack of adequate thinning from 17 years of age probably had a negative effect on growth. The wood volume was overestimated for the plantation in Linhares, because *A. cearensis* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. The highest growth reported by Carvalho (2003), for plants of Paraguay provenance planted in Paraná, was a DBH of 11.4 cm at 9 years of age, which was higher than that observed in Linhares for the same age (8.4 cm). It is very common in poor soils but responds well to fertile soils. It should not be planted in full sun, and it produces straighter stems when planted in enrichment. Engel & Poggiani (1990) recommended planting in 50%–60% partial shade, which still stimulates vertical growth. Even under these conditions, it requires periodic pruning, which should be one of the priorities of its management. It has high plasticity, and requires great care in the selection of provenances for use in silviculture.

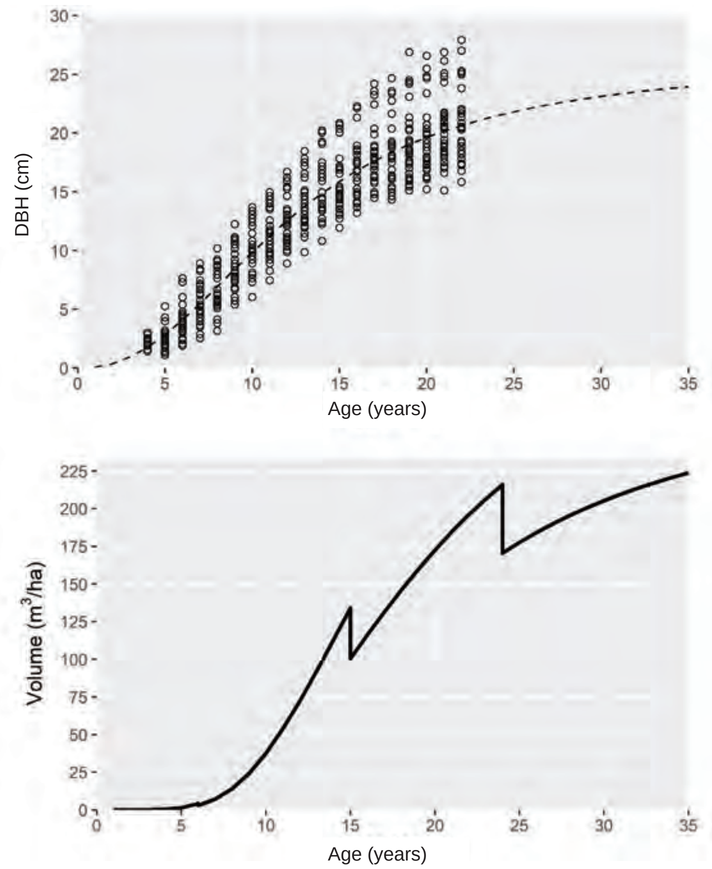


Figure 29. Diameter growth of *Amburana cearensis* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 15, and 24 years.

(Wood properties)

(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, rose-beige heartwood with darker details and whitish sapwood, pleasant characteristic odor, sweet taste, medium texture, irregular grain, and little variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, paratracheal vasicentric, aliform losangular and confluent. Rays: barely visible without magnification in the cross-sectional plane and only visible under magnification in the longitudinal-tangential plane, thin, numerous, and non-stratified. Vessels: visible without magnification, small to medium, numerous, diffuse-porous, predominantly solitary and in multiples of two radials, and occasionally obstructed by a white substance. Growth Rings: indistinct.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.602
Basic density (g/cm^3)	0.447
Volume variation (shrinkage %)	8.91
Anisotropy coefficient	1.49
Modulus of rupture for static bending strength (kgf/cm^2)	455.62
Shear strength (kgf/cm^2)	97.67
Compression strength parallel to the grain (kgf/cm^2)	301.61
Janka hardness (kgf) – parallel and perpendicular to the grain	278.33 – 318.33

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Fair	Excellent	Good	Excellent	Excellent	Good	Excellent	Excellent	100% accepts

Assays conducted according to the normative document ASTM 1666:1994

Medium density and low hardness. Good dimensional stability and little tendency to warp. Indicated for use in light structures, furniture, frames, internal cladding, and utensils. Good to excellent planing, boring, sanding, and lateral mortising properties. Excellent nailing properties, with no problems of fiber tearing or splitting.

Copaifera langsdorffii Desf. **(Fabaceae)**

Distribution: Commonly known as copaíba, it is distributed in seasonal and ombrophilous forests in the Atlantic Forest from the southeast to the northeast of the country, and in the southern edge of the Amazon forest in the states of Rondônia and Mato Grosso (Queiroz et al., 2015). In addition to wood, another important product of this species is its essential oil, which has a high market value in North and Southeast Brazil. Because not all trees produce oil (Rigamonte-Azevedo et al., 2004), some are planted with the aim of wood production and some with oil and eventual wood production.

Mean Growth and Yield: Growth data was obtained from a mixed plantation with *Centrolobium tomentosum* (araribá, n = 72 trees per species) in Linhares, with 3 × 2.5 m spacing. The remaining trees at 31 years of age presented short stems with good shape and good health. Mortality was 32% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 76.46\left(1 + 190.22\, exp^{-1.2478\, Ln(t)}\right)^{-1}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 222 m^3/ha for 737 trees/ha, with a mean DBH of 23.5 cm and stem height of 9.6 m. For this age, the estimated MAI in volume was 6.3 m^3/ha/year, MAI in diameter was 0.67 cm/year, and stocked biomass was 190 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *C. langsdorffii* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. Growth varies widely between different plantations. For example, Nogueira (1977) reported a DBH of 14.7 cm at 20 years of age, which was similar to that observed in Linhares, and Gurgel Filho (1982a; 1982b) reported DBH values of 8.8 cm at 14 years of age and 10.9 cm at 25 years of age, which were lower than that observed in Linhares. The lack of thinning between 13 and 18 years of age probably had a negative effect on growth. There are ex-situ conserved populations in São Paulo (Siqueira & Nogueira 1992). It is very prone to branching in full sun plantations, with many branches, and requires partial shade, preferentially in enrichment plantations, to improve its shape and stimulate vertical growth, as can be seen in the photo on the previous page. Attention should be paid to the high mortality in young plantations.

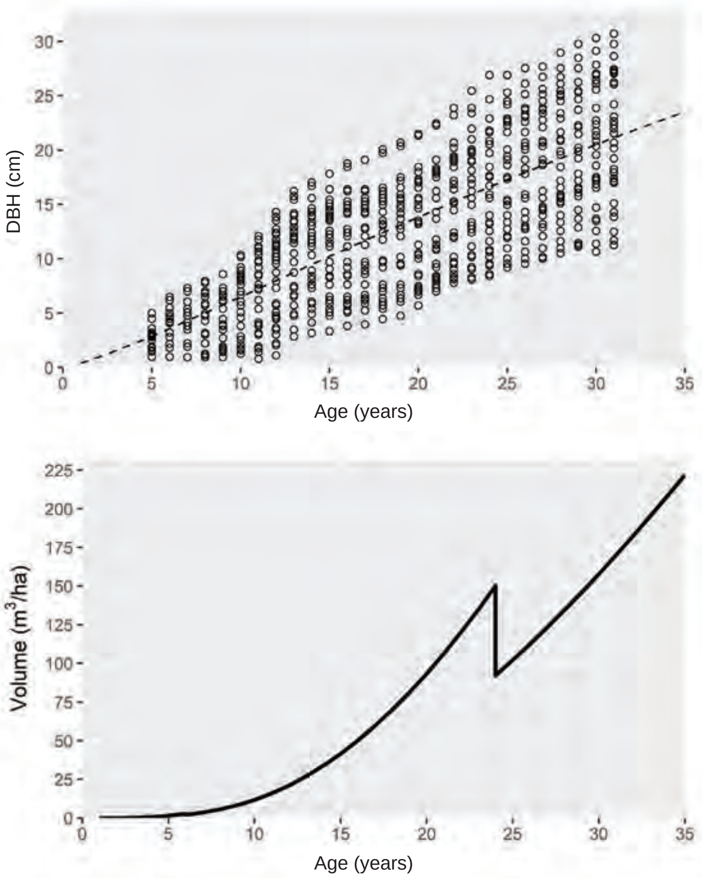
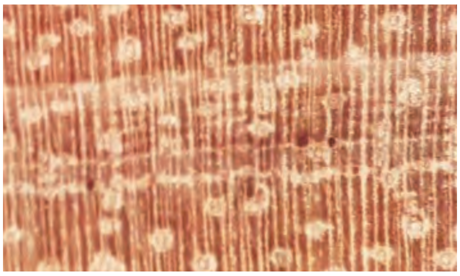


Figure 30. Diameter growth of *Copaifera langsdorffii* in a mixed plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6 and 24 years.

(Wood properties)



(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, brown heartwood with darker rays and grayish-beige sapwood, characteristic odor, slightly astringent taste, medium texture, straight to irregular grain, and variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: barely visible without magnification, paratracheal aliform losangular and in marginal bands. Rays: barely visible without magnification in the cross-sectional plane and only visible under magnification in the longitudinal-tangential plane, contrast in the longitudinal-radial plane, thin, numerous, and unstratified. Vessels: barely visible without magnification, medium, very few to few, diffuse-porous, and predominantly solitary and in multiples of two in radial arrangement; intercellular axial secreting channels, with tangential arrangement, surrounded by parenchyma in marginal bands. Growth Rings: Delimited by parenchyma in marginal bands.

Physical and mechanical properties	
Apparent density (g/cm^3 - air dried sample)	0.669
Basic density (g/cm^3)	0.547
Volume variation (shrinkage %)	9.94
Anisotropy coefficient	1.58
Modulus of rupture for static bending strength (kgf/cm^2)	639.09
Shear strength (kgf/cm^2)	110.33
Compression strength parallel to the grain (kgf/cm^2)	276.73
Janka hardness (kgf) – parallel and perpendicular to the grain	406.67 – 505.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Fair	Poor	Poor	Poor	Fair	Poor	Very poor	Fair	Fair	53% accepts; 47% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium density and hardness. Little tendency to warp and twist. Indicated for use in light structures, furniture, frames, packages, boxes, and utensils. Fair to poor planing properties. Fair to poor boring properties with helicoidal bits and poor to very poor with spade bits. Fair sanding and lateral mortising properties. Approximately half of evaluated samples presented nailing problems, with splitting and tearing of small pieces of wood at the nail exit point.

Libidibia ferrea var. *parvifolia* Benth. **(Fabaceae)**

Distribution: This variety of pau-ferro, also known as giúna, occurs in some areas of seasonal forest in the states of Espírito Santo, Bahia, Pernambuco, and Ceará (Lewis, 2015). Pau-ferro is quite a well-known plant due to its common use in urban afforestation (this and other varieties); however, it is little used as timber, likely because its wood is very hard and difficult to work.

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with 2 × 2 m spacing. The remaining trees at 24 years of age presented short stems and good health. Mortality was 16% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 30.90\ exp^{-4.97\ t^{-0.7867}}$$

The models showed a stagnation in diameter growth after 15 years of age, with an estimated volume of 219 m^3/ha for 783 trees/ha, mean DBH of 22.8 cm, and stem height of 9.4 m at 35 years of age. For this age, the estimated MAI in volume was 6.2 m^3/ha/year, MAI in diameter was 0.65 cm/year, and stocked biomass was 256 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *L. ferrea* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. There are no available data for growth in plantations of this variety, but the variety leiostachya presented slightly lower growth in a restoration plantation than that observed in Linhares (Nogueira, 1977). The variety leiostachya presented a DBH of 18 cm at 27 years of age in a forest plantation in São Paulo (Gurgel Filho et al., 1982e), which was also slightly lower than that observed in Linhares. In the Ceplac arboretum in the state of Bahia, Vinha & Lobão (1989) observed a DBH of 7.1 cm at 16 years of age, which was much lower than that observed in Linhares. This species presented good early growth, but growth stagnated after 15 years, probably due to a lack of thinning. It is very prone to branching in full sun plantations, and should be planted in partial shade, preferentially in enrichment plantations; this may stimulate vertical growth, but the tree still requires pruning, which should be a management priority.

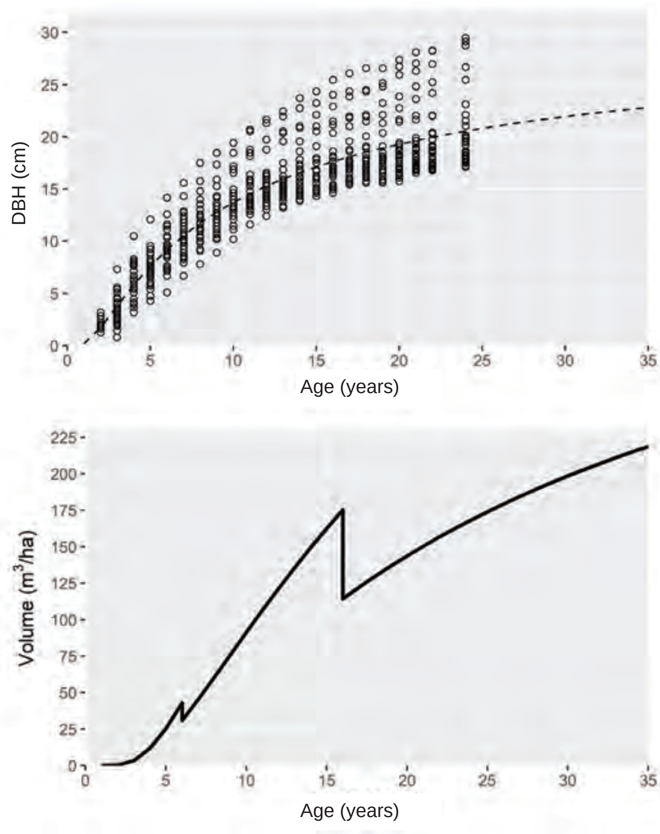


Figure 31. Diameter growth of *Libidibia ferrea* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6 and 16 years.

(Wood properties)

(Cross section, zoom 10×)

Overall Wood Properties: Distinct heartwood and sapwood, dark gray heartwood and light yellow sapwood both with fibrous appearance, uncharacteristic odor, bitter taste, medium texture, straight grain, and variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: visible without magnification, losangular paratracheal aliform, aliform with linear extension, confluent, and in lines. Rays: barely visible without magnification in the cross-sectional and longitudinal-tangential planes, little contrast in the longitudinal-radial plane, thin, numerous, and stratified. Vessels: only visible under magnification, small, numerous, diffuse-porous, and predominantly solitary and in multiples of two in tangential arrangement. Growth Rings: delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	1.080
Basic density (g/cm³)	0.814
Volume variation (shrinkage %)	16.22
Anisotropy coefficient	1.50
Modulus of rupture for static bending strength (kgf/cm²)	779.73
Shear strength (kgf/cm²)	181.65
Compression strength parallel to the grain (kgf/cm²)	358.34
Janka hardness (kgf) – parallel and perpendicular to the grain	1145.00 – 1215.00

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications

Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Good	Good	Fair	Poor	Fair	Fair	Fair	Fair	Fair	100% does not accept

Assays conducted according to the normative document ASTM 1666:1994

High density, good stability, and little tendency to twist and warp. Indicated for construction and structural uses. Can also be used for frames and furniture. Because of its high hardness, it could be used as flooring. Good planing properties with peripheral knife planer, difficult boring, sanding, and lateral mortising. Great difficulty in nailing, with the occurrence of tearing and splintering at the nail exit point, generating cracks. Special connecting elements may be tested and used, and pre-boring may be performed to connect wood pieces.

Moldenhawera papillanthera L.P.Queiroz, G.P.Lewis & R.Allkin **(Fabaceae)**

Distribution: Commonly known as caingá, it is endemic to the Atlantic forest in the state of Espírito Santo (Queiroz, 2015). It is exploited locally in this region, but it is not known in the timber market.

Mean Growth and Yield: Growth data was obtained from a mixed plantation with *Cariniana estrelensis* (jequitibá-branco, n = 72 trees per species) in Linhares with 3 × 2.5 m spacing. The remaining trees of *Moldenhawera papillanthera* at 30 years of age presented short, tortuous stems and good health. Mortality was 29% until 10 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 73.09\left(1 + 104.60\, exp^{-\,1.059\, Ln(t)}\right)^{-1}$$

The models showed a slow trend in growth until 35 years of age, when the estimated volume was 212 m^3/ha for 894 trees/ha, with a mean DBH of 21.4 cm and stem height of 9.0 m. For this age, the estimated MAI in volume was 6.0 m^3/ha/year, MAI in diameter was 0.61 cm/year, and stocked biomass was 192 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *M. papillanthera* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. To improve growth, thinning should have been better applied, especially at 12 and 25 years of age. At the current growth rate, the mean DBH will reach 30 cm after 50 years of age, with approximately 450 trees/ha. It is very prone to branching and produces tortuous stems in full sun plantations. Planting in partial shade may stimulate vertical growth, decrease branching, and produce straighter stems, but it still requires artificial pruning, which should be a management priority. Attention should be paid to the high mortality in young plantations.

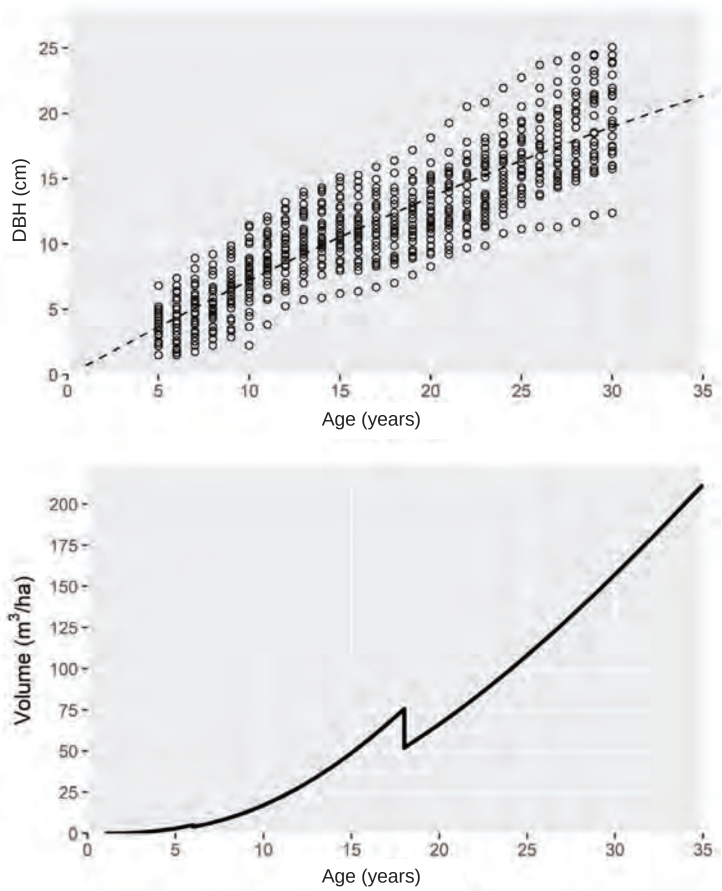
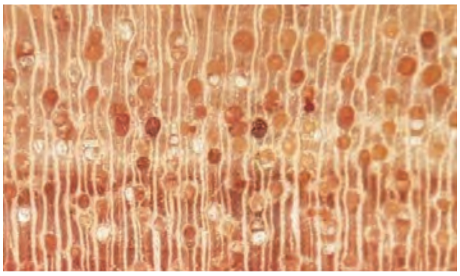


Figure 32. Diameter growth of *Moldenhawera papillanthera* in mixed plantation with *Cariniana estrellensis* in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6 and 18 years.


(Wood properties)


(Cross section, zoom 10×)

Overall Wood Properties: Slightly distinct heartwood and sapwood, light brown heartwood and light beige sapwood, characteristic odor, indistinct taste, straight grain, medium texture, and variance in luster.

Macroscopic Anatomical Description:
Axial Parenchyma: only visible under magnification, paratracheal scarce. Rays: visible without magnification in the cross-sectional plane and only visible under magnification in the longitudinal-tangential plane, without contrast in the longitudinal-radial plane, thin, numerous, and non-stratified. Vessels: visible without magnification, medium, little numerous, diffuse-porous, and solitary and radial multiples (2–3 vessels). Growth Rings: delimited by fibrous tissue.

Physical and mechanical properties	
Apparent density (g/cm³ - air dried sample)	0.703
Basic density (g/cm³)	0.590
Volume variation (shrinkage %)	10.20
Anisotropy coefficient	1.93
Modulus of rupture for static bending strength (kgf/cm²)	729.05
Shear strength (kgf/cm²)	109.84
Compression strength parallel to the grain (kgf/cm²)	421.01
Janka hardness (kgf) – parallel and perpendicular to the grain	538.33 – 586.67

Assays conducted according to the normative document ABNT 7190:1997

Workability and use indications									
Planing		Boring with helical bit (through-hole)			Boring with spade bit (10mm)		Sanding	Lateral mortising	Nail acceptance (%)
With	Against	6 mm	8 mm	10 mm	Through-hole	Non-through-hole			
Excellent	Good	Excellent	Good	Good	Poor	Fair	Good	Excellent	28% accepts; 72% does not accept

Assays conducted according to the normative document ASTM 1666:1994

Medium density and hardness, medium to high anisotropy, and low dimensional stability, with tendency to warp. Indicated for use in light structures, furniture, frames, utensils, packages, linings, tool handles, and cladding. Good to excellent planing, lateral mortising, and boring with helical bits. Poor boring properties with spade bits. Good sanding properties. Fair nailing properties, with fiber tearing and small cracks at the nail exit point in most samples.

Vataireopsis araroba (Aguiar) Ducke **(Fabaceae)**

Distribution: Commonly known as angelim-amargoso, it occurs in some areas of ombrophilous and seasonal forests in the states of Minas Gerais, Bahia, Rio de Janeiros and Espírito Santo (Cardoso, 2015b). It is the only species of the genus *Vataireopsis* in the Atlantic Forest, but all three species of this genus in Brazil have high timber values (Lima, 1980). Overall, all species marketed as angelim are very well accepted in the market due to their natural wood patterns (Nahuz et al., 2013).

Mean Growth and Yield: Growth data was obtained from a pure plantation in Linhares (n = 196 trees) with 2 × 2 m spacing. The remaining trees at 23 years of age presented short, tortuous stems and good health. Mortality was 55% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 48.59\ exp^{-3.54\ t^{-0.4858}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 232 m^3/ha for 607 trees/ha, with a mean DBH of 25.9 cm and stem height of 10.3 m. For this age, the estimated MAI in volume was 6.6 m^3/ha/year, MAI in diameter was 0.74 cm/year, and stocked biomass was 266 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *V. araroba* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. There is no available data for growth for this species, but the results in Linhares can be considered promising, considering that the average DBH was 21 cm at 20 years of age. However, from 20 years of age, the growth rate was slow, indicating a long growth cycle for this species to reach a DBH of 30 cm. However, the lack of adequate thinning after 16 years of age probably affected growth. It is very prone to branching in full sun plantations; it should be planted in partial shade, preferentially in enrichment plantations. This may stimulate vertical growth, but would still require artificial pruning, which should be a management priority. Attention should be paid to the high mortality in young plantations.

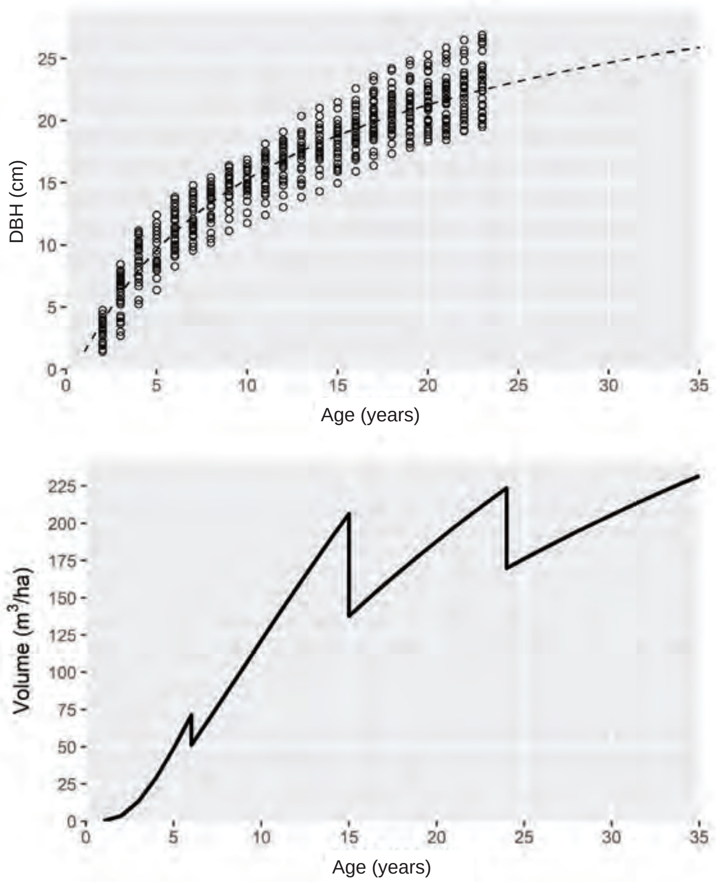
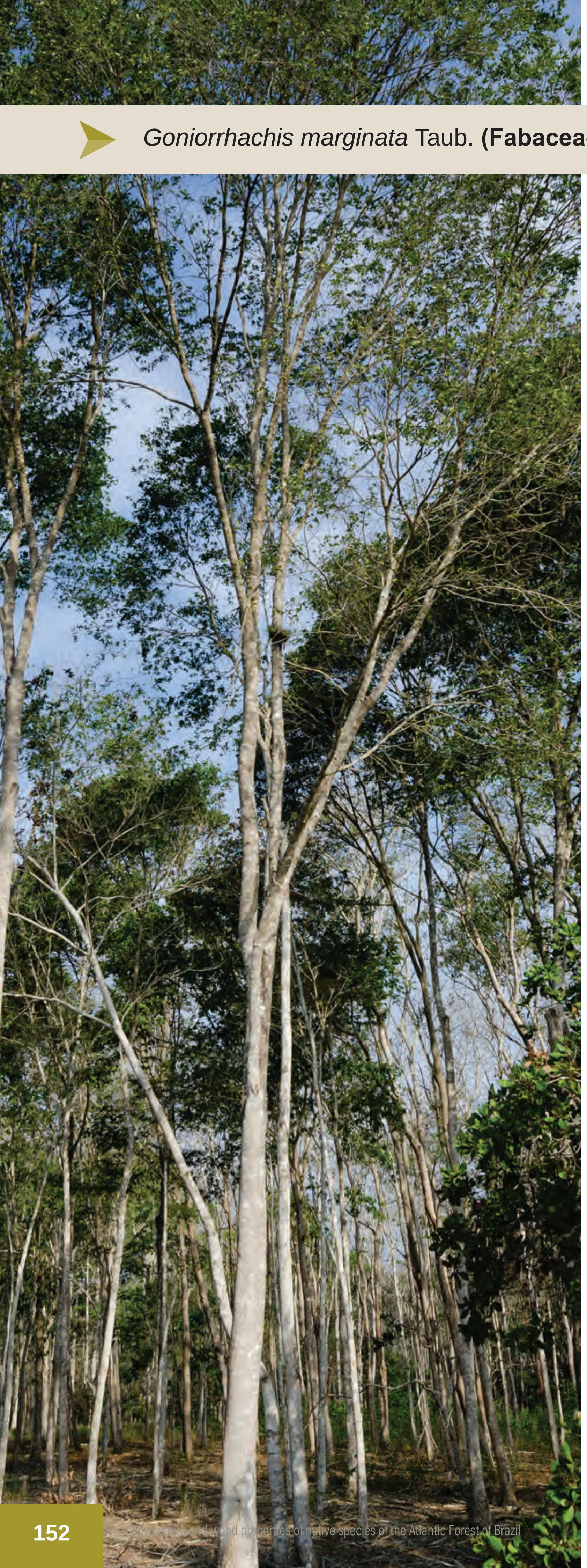


Figure 33. Diameter growth of *Vataireopsis araroba* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 15, and 24 years.

Goniorrhachis marginata Taub. **(Fabaceae)**



Distribution: Commonly known as guaribú amarelo or itapecurú-amarelo, it occurs in areas of seasonal and ombrophilous forests in the Atlantic Forest in the states of Minas Gerais, Espírito Santo, Bahia, Sergipe, and Alagoas (Lima, 2015f). It has been highly exploited in its occurrence areas; it presents excellent quality (similar to roxinho [*Peltogyne* sp.], and is considered to have exceptional rot resitance (Mattos-Filho, 1965).

Mean Growth and Yield: Growth data was obtained from a pure plantation in Linhares (n = 196 trees) with 2 × 2 m spacing. The remaining trees at 23 years of age presented short, tortuous stems and good health. Mortality was 13% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 49.36\, exp^{-5.15\, t^{-0.5634}}$$

The models showed a trend in growth until 35 years of age, when the estimated volume was 227 m^3/ha for 672 trees/ha, with a mean DBH of 24.6 cm and stem height of 9.9 m. For this age, the estimated MAI in volume was 6.5 m^3/ha/year, MAI in diameter was 0.70 cm/ year, and stocked biomass was 270 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *G. marginata* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. No growth data was found for this species. The data for Linhares indicates that it may reach a mean DBH of 30 cm after only 50 years. It is very prone to branching in full sun plantations; it should be planted in partial shade, preferentially in enrichment plantations, which may stimulate vertical growth. This would still require artificial pruning, which should be a management priority.

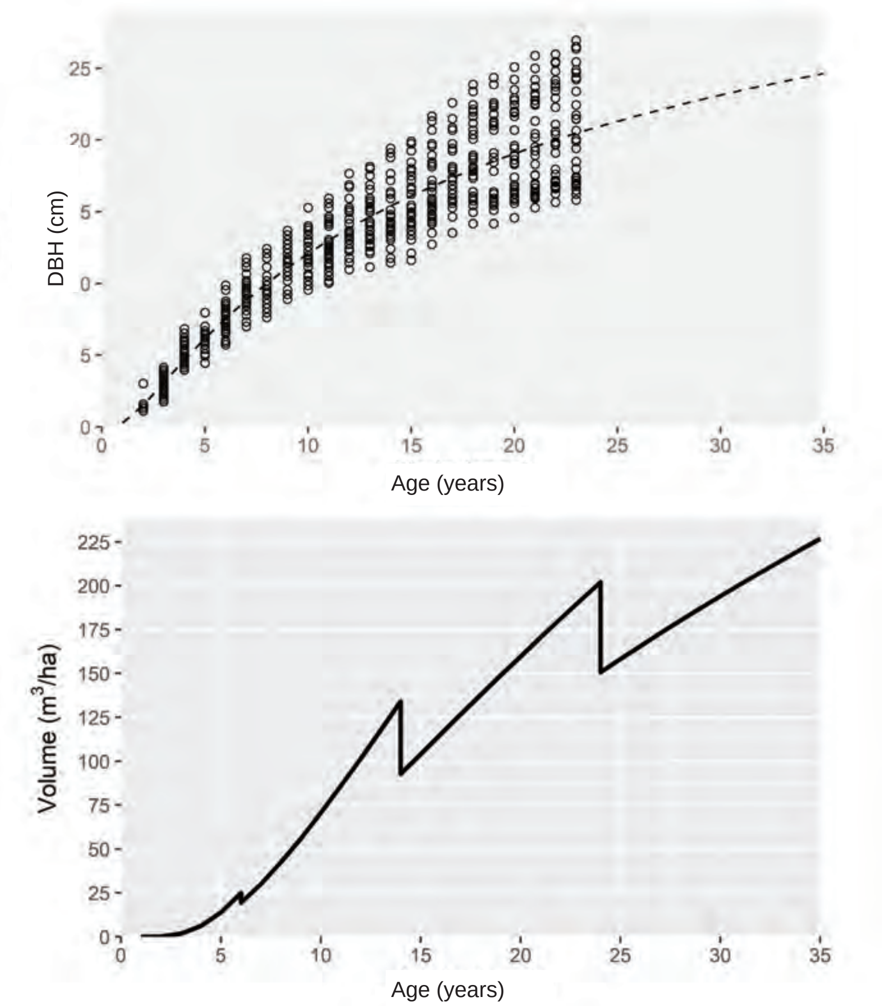


Figure 34. Diameter growth of *Goniorrhachis marginata* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6, 14, and 24 years.

Vatairea heteroptera (Allemão) Ducke **(Fabaceae)**

Distribution: Commonly known as angelim-aracuí, it occurs in the Atlantic Forest from the state of Paraná to the states of Sergipe and Alagoas (Cardoso, 2015a). It is one of the species of the genus *Vatairea* in the Atlantic Forest. Overall, all species marketed as angelim are very well accepted in the market due to their natural wood patterns (Nahuz et al., 2013).

Mean Growth and Yield: Growth data was obtained from a pure plantation (n = 196 trees) in Linhares with spacing 2 × 2 m. The remaining trees at 22 years of age presented short, tortuous stems and good health. Mortality was 17% until 5 years of age. The fitted equation to estimate the DBH relative to Age (t in years) was as follows:

$$DBH = 29.25\, exp^{-5.62\, t^{-0.8561}}$$

The models showed a slow trend in growth until 35 years of age, when the estimated volume was 217 m^3/ha for 814 trees/ha, with a mean DBH of 22.4 cm and stem height of 9.3 m. For this age, the estimated MAI in volume was 6.2 m^3/ha/year, MAI in diameter was 0.64 cm/year, and stocked biomass was 240 Mg/ha. The wood volume was overestimated for the plantation in Linhares because *V. heteroptera* presents short stems and requires better management (with appropriate pruning) than that applied in Linhares to reach the height, and consequently volume, estimated by the model. There are no available growth data for this species, being that the data for Linhares indicate that it may reach a DBH of 30 cm after only 50 years. However, the lack of adequate thinning from 15 years of age probably affected the diameter growth. It is very prone to branching in full sun plantations; it should be planted in partial shade, preferentially in enrichment plantations, which may stimulate vertical growth. This would still require artificial pruning, which should be a management priority.

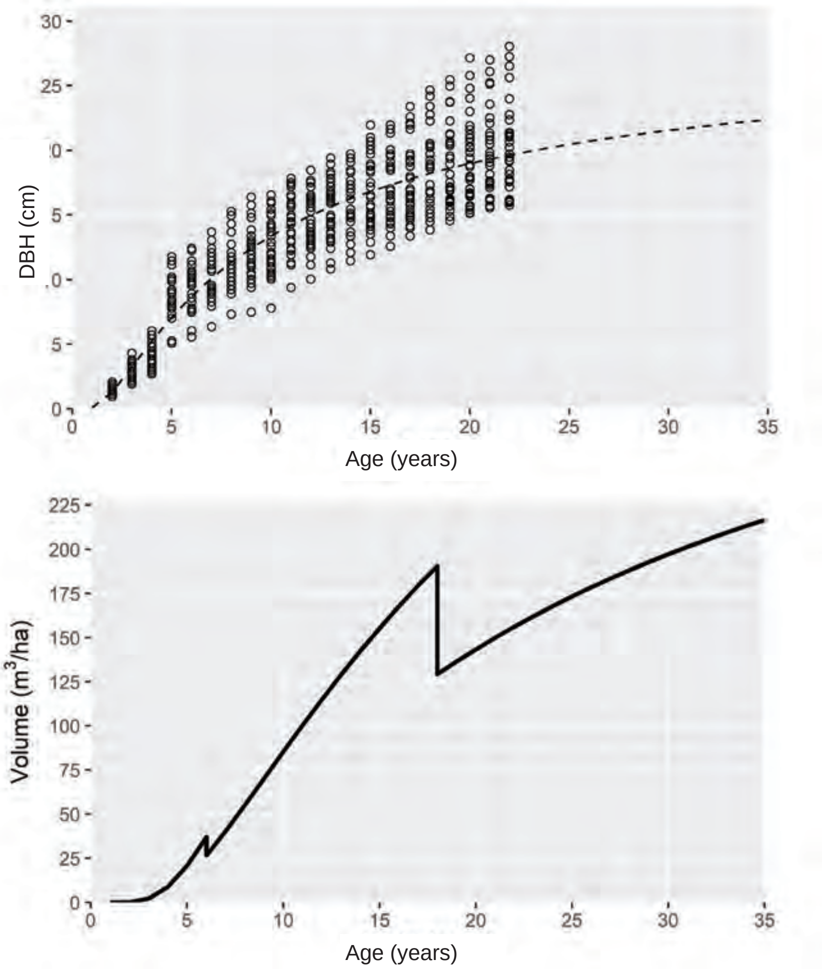


Figure 35. Diameter growth of *Vatairea heteroptera* in a pure plantation in Linhares (ES), and a simulation of volume production for a plantation with 3 × 2 m spacing, with thinning at 6 and 18 years.

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