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Preface

Mixed Plantations of Eucalyptus and *Acacia mangium*

We indicate this book to foresters, entrepreneurs in forestry, producers of wood, cellulose or other forest sub-products, agricultural engineers, agronomists, biologists, people working in Environmental Conservation and Natural Life Preservation, as well as the graduate and post-graduate students in these areas and socio-economic planners.

Here, we present a compilation as complete as possible on research, themes regarding eucalypt plantations, especially when in consortia with leguminous tropical trees. Such mixed stands generally can be productive and economically viable and are ecologically sustainable and favorable for the social-economic guarantees of rural workers and entrepreneurs. Eucalypt is one of the most cultivated forest trees in Brazil. However, most of the time, it is produced as monoculture and needs continuous fertilizer applications, including nitrogenous compounds, to maintain productivity. These plantations, usually propagated by vegetative means, as clones, receive criticism from various sectors of society for their low genetic diversity. Among forest producers, the main concern is the high susceptibility of homogeneous stands to abiotic and biotic stress. In consequence, during the last decades, several research teams all over the tropical countries have been investigating changes in the eucalypt management system to provide a more attractive and sustainable activity, achieving economic gains and diminishing its environmental impacts. Our proposal is mostly restricted to the Brazilian research experience on this topic, with special consideration of the need to diminish the use of industrial products as fertilizers and pesticides, but valuating soil health, biological gains, and ecosystem services.

Considering those prerequisites, it becomes easy to answer the main question of the first chapter: "Why mixed forest plantations?" Our response is as follows: "Because, when comparing all investigated management systems, this one is socially more advantageous and benefitting the rural entrepreneur economically, besides its high sustainability."

Considering some of these advantages, we want to present the main line of thought of the sequence of the book chapters. Thus, regarding growth and productivity of the trees, the most outstanding combination is *Eucalypt* in consortium with *Acacia mangium,* an exotic species, already known for its expressive productivity. Although, in biology, one always gets some variation, the best responses occur with mixed plantations in deep and sandy soils of low fertility, with a hot and rainy climate, which corresponds to most of the Brazilian regions used for eucalypt production.

The main reason for these superior results is that most legumes present a natural association with soil bacteria, generically known as rhizobia, which nodulate the roots of these trees and have a high potential of fixing atmospheric nitrogen, transforming it into ammonia in the root nodules. The forthcoming fixed nitrogenous compounds cycle throughout the whole tree and generally are exported and divided with other plants in their neighborhood. During litterfall, some of the fixed N reaches the soil causing its enrichement in N. The symbiotically fixed N can supply nitrogen needs of all plants, at the same time retaining nutrient reserves for the next tree rotation. Thus, the enriched soil in C and N turns the nutrient cycling much more dynamic.

Chapters 5–10 are all dedicated to discussing biological aspects of this kind of management, providing us with a constant increase in knowledge on the most adequate strategies to be applied to better soil health and plant growth. The perfect functioning of the soil as producer correlates directly with the size and diversity of the soil bacterial community structure, with each plant recruiting in its rhizosphere the most helpful bacteria, with functions of mineralizing the soil organic matter, acting on enzymes related to plant nutrition and on biological control of pathogens, among others. Right thereafter, we present the processes inherent to biological N fixation (BNF), selection of the most adequate rhizobial strains, and the transfer from soil to plant or from plant to plant mediated by mycorrhizal fungi, having a synergic interaction with BNF. Mycorrhizal fungi transport all kinds of nutrients to plants but are more active regarding the ones with slow mobility in soil, as phosphorus (P). Here, it is important to highlight another trait of *Eucalyptus* and *Acacia*: both host plants form symbioses with both kinds of mycorrhiza, the arbuscular (AM) and the ectomycorrhiza (ECM), which is exceptional among plants, that normally associate only with one kind of mycorrhiza, if at all.

Following the chapters, we now come to the important contribution of insects and other soil invertebrates to soil health, nutrient cycling and organic matter decomposition, showing how they influence the plants and how they become affected, in numbers and diversity, besides the influence of the climate. Right afterwards, there follows a chapter on bio-indicators of soil health, showing many recent results on the extreme relevance of the microbiological phenomena and the innumerable ecosystem services derived from the ecologically correct management, with benefits to soil, plants, and workers, still contributing to economic gains.

Chapter 11 discusses the problems that may derive from the introduction of exotic possible biological species into any ecosystem different from its origin, which resides in its invasiveness, sometimes causing severe ecological and economic problems, a phenomenon that has been occurring regarding specimens of plants and animals of most categories. Although most of our researchers did not perceive such behavior regarding *A. mangium*, we feel ethically compromised to tell what a few other researchers have reported, and it is always worthwhile to use prevention and caution in such situations. Generally, however, our experience says that the danger of this species becoming invasive should be neglected, when being used adequately. We belief that invasiveness may only occur in open lands and not when used in forests.

Chapter 12 presents the use of Brazilian leguminous trees to substitute *A. mangium*. So far, the best choice has always been this species (*A. mangium*), and it is the only one about which we have already compiled a great amount of experimental reports and practical experience, as well in Brazil as in many other countries. The approval of employing this species was almost unanimous by all researchers or farmers who had the opportunity of following its performance in the field, and for many decades.

Nevertheless, nothing impedes to test other species, as, for example, the national leguminous trees, which are available in great numbers. Maybe in the future, we can select some of them, which present the same advantages or are even better in such a consortium, as indicated by the author of this chapter, one of the very few scientists who worked in this area.

Finally, all this information is complemented by the last chapter, which describes the Brazilian legal structure and presents the regulations for the exploration of forests, either Eucalypt plantations in monoculture or in consortia, which we hope, will help the interested people to make the best choices on this activity.

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José Leonardo de Moraes Gonçalves is full professor in the Department of Forest Sciences at the University of São Paulo. He has undertaken extensive research on soil fertility, site preparation, and plant nutrition, focusing on the tropical and subtropical eucalyptus and pine plantations, including genotypic adaptation and phenotypic acclimatization of plantations in regions with high water, thermal, and nutritional stresses. Ecosystem management and sustained production of wood and non-wood products from planted forests always were among his main objectives, having been a pioneer in forest research with minimum tilling in the early 1990s. He has edited three books and published more than one hundred scientific articles in journals of wide dissemination and international impact. He supervised 25 masters, 24 doctors, and 5 post-doctorates.

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Chapter 1
Why Mixed Forest Plantation?

Ranieri Ribeiro Paula, Ivanka Rosado de Oliveira, José Leonardo de Moraes Gonçalves, and Alexandre de Vicente Ferraz

1.1 Introduction

Although relevant to Brazilian gross domestic product (GDP), forest plantations currently occupy only a small fraction of Brazilian land with 9.8 million hectares (Bacha 2008; IBGE 2017). Approximately 96% of these lands are occupied by monocultures of species of *Eucalyptus* (75.2%) and *Pinus* (20.6%), and only a few forest species occupy another 400,000 hectares (IBGE 2017). These plantations have expanded over the past 30–40 years on land abandoned by agriculture and livestock, especially in the Atlantic Forest (South, Southeast, Coastal area of Bahia), Cerrado (Southeast, Midwest, and North), and Pampa (South) (Gonçalves et al. 2013; IBGE 2017).

Pastures planted with "African" grass occupy at least 80 million hectares in tropical regions of Brazil, and at least half of those are considered degraded (Boddey et al. 2004). Additionally, current estimates by the Brazilian Government indicate that 4.5 million ha of permanent preservation areas of native vegetation need to be recovered throughout Brazil. In addition, approximately 7.2 million ha of legal reserve should be recovered mainly in the Amazon, 4.8 million ha in the Atlantic

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Forest, and 3.7 million ha in the Cerrado—Brazilian savannah (Soares-Filho et al. 2014; Brazil 2017). Public policies are foreseen in the National Plan for the Recovery of Native Vegetation for the recovery of at least 12 million ha until 2030 (Brazil 2017).

The expansion of highly productive monospecific forest plantations faces several challenges. Species are recommended for a given site according to edaphoclimatic adaptation, productivity, quality of wood, and resistance to pests and diseases, among others. In the case of *Eucalypt*, higher wood yields (e.g., annual average increment >40 m^3 ha^{-1} $year^{-1}$) have been achieved by integrating improved genetic material, suitable edaphoclimatic conditions, and good silvicultural practices (Gonçalves et al. 2013). However, breeding programs exist only for a limited number of species, notably *Eucalyptus*, *Corymbia*, *Pinus*, and *Hevea*, and for commercial fruit trees. Several potential native and introduced tree species for forest plantations with economic purposes have little or no level of genetic improvement (Carvalho 2003).

Most of the soils located in the tropical and warm subtropical portions are generally deep and well drained, with high acidity and low fertility, mostly classified as Oxisols and Ultisols (Gonçalves et al. 2013; Guerra et al. 2014). The chemical, physical, and biological characteristics of soils intended for forest plantations will be increasingly limiting as plantations occupy lands degraded by agriculture and livestock. The availability of water is in most cases the main limiting factor for forest production, since other edaphic factors can be overcome through mechanization and fertilization (Stape et al. 2010; Gonçalves et al. 2013). The availability of water may be a limiting factor for the expansion of highly productive forest plantations in the regions with predominance of the tropical and subtropical climates, whose dry season varies between 3 and 7 months. Moreover, the effects of climate change on forest plantations need better understanding. The mortality induced by lack of water in native and exotic trees has been detected in several regions of the world, including Brazil (Laclau et al. 2013; Rowland et al. 2015). To minimize the risks of tree mortality due to water shortage, it is indicated to plant species that are adapted and efficient in the use of resources (Gonçalves et al. 2013). The impacts of highly productive trees and plantations on water resources need to be well understood to promote the sustainable expansion of plantations (Christina et al. 2011; Nouvellon et al. 2011).

Nitrogen is a nutrient commonly limiting the productivity of forest plantations with non-nitrogen-fixing species (Gonçalves et al. 2003; Rennenberg et al. 2009; Laclau et al. 2010; Bouillet et al. 2013; Gonçalves et al. 2013). Although N is naturally available in the soil through the mineralization of organic matter, this is reduced in degraded soils because of the low content and quality of the organic matter (Gonçalves et al. 2003). And availability of N is conditioned by the microbial activity that is regulated by soil moisture content (Rennenberg et al. 2009; Voigtlaender et al. 2019). Nitrogen fertilizer application in forest plantation may be recommended according to organic matter concentrations in soil (Gonçalves 1995). For example, values of 60 kg ha^{-1} and 30 kg ha^{-1} of total nitrogen are indicated for commercial plantations of *Eucalyptus* and *Pinus*, respectively, when the concentration of soil organic matter is less than 1.5%. These amounts decrease to 20 kg ha^{-1} if the concentration of soil organic matter is higher than 4%. For native species of Brazil with a medium and high nitrogen demand 50 kg ha^{-1} of total nitrogen is recommended (Gonçalves 1995). The production and use of N fertilizers involve environmental risks of water pollution and greenhouse gas emissions, as well as being increasingly costly for Brazilian planters due to the fluctuation of the dollar and the influence of the value of oil (Galloway 1998; Dias and Fernandes 2006).

A growing scientific interest in the establishment of more biodiverse forest plantations has been observed around the world and Brazil (Paquette and Messier 2010; Brancalion et al. 2012; Bouillet et al. 2013; Del Río et al. 2016; Dai et al. 2018; Marron and Epron 2019). These plantations may involve only trees and/or trees with agricultural crops and/or livestock pastures. The call for the establishment of mixed forests is mainly associated with the possibility of higher productivity and greater provision of products (e.g., wood for multiple uses, non-timber forest products, fibers, and proteins) and ecosystem services (e.g., soil and water conservation, carbon storage, wildlife feeding). Mixed forest plantations involving N_2-fixing legume species and non-N_2-fixing species such as eucalypt have been proposed to increase productivity and ecosystem services in regions with N-deficient soils (Balieiro et al. 2002; Chaer et al. 2011; Bouillet et al. 2013; Santos et al. 2016; Voigtlaender et al. 2019; Marron and Epron 2019). Tree legumes inoculated with specific bacteria can fix most of the N demanded for growth and transfer the fixed N to the soil and plants in companion, as detailed in Chap. 6. Results of research in Brazil testing intercropped *Eucalyptus* sp. with *Acacia mangium* (Fig. 1.1) increased the nutrient cycling rate, contributing to the soil a large amount of N from the biological nitrogen fixation (FBN) in only one crop rotation (Santos et al. 2016; Voigtlaender et al. 2019), as detailed in Chap. 3.

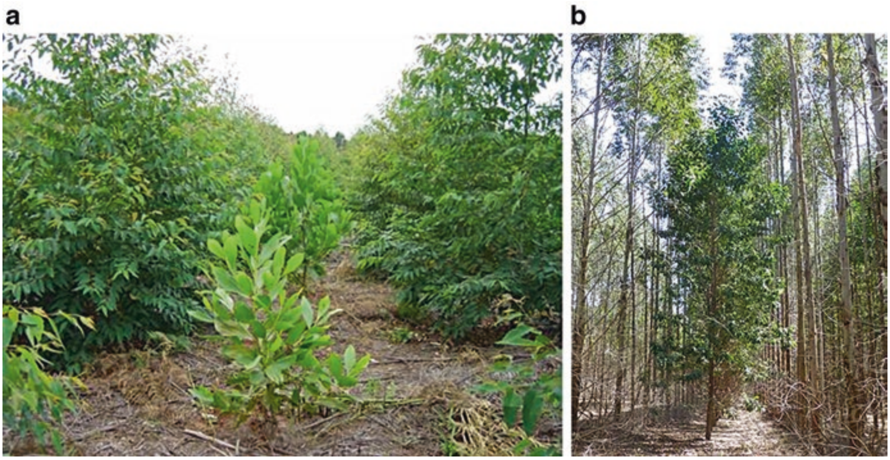

Fig. 1.1 Mixed forest of *Eucalyptus grandis* and *Acacia mangium* at spacing of 3 m by 3 m (proportion 1:1): (**a**) 5 months and (**b**) 30 months after planting, at the Experimental Station of Forest Sciences of Itatinga, São Paulo, Brazil

In a recent meta-analysis, Marron and Epron (2019) showed that mixed forest plantations involving at least equal proportions of N_2-fixing and non-N_2-fixing species are generally more productive than monospecific plantations when established in sites with low productive capacity. In these sites, poorer in nutrients or water, positive interactions (e.g., facilitation and complementarity) over negative ones (e.g., intraspecific competition) are expected to prevail. Sites with lower growth resource limitations tend to favor fast-growing species more adapted, leading to greater intraspecific competition (Kelty 2006; Forrester et al. 2006; Bouillet et al. 2013). Thus, the zoning of the productive capacity of the forest sites is a necessary measure for the best use of the sites destined to the mixed and monospecific plantations. Even when yield is not increased the benefit of long-term sustainability and other ecosystem services should be considered (see the Chap. 10).

The choice of the right species to minimize the effects of site quality also is important. According to authors such as Gonçalves et al. (2003) and Kelty (2006), the success in terms of production and ecosystem service delivery is obtained more easily by combining species that differ in growth rates, in growth resource requirements, and in the form they obtain resources. The combination of these functional characteristics of the species is necessary to promote a better capture of the resources to maximize nutrient cycling and the recovery of degraded soils in Brazil (Gonçalves et al. 2003).

1.2 Socioeconomic Benefits

The increase in forest cover promoted by forest plantations with economic objectives and recovery of ecosystem functions is an urgent need pointed out by several authors (Ab'Sáber et al. 1990; Machado and Bacha 2002; Bacha 2008; Brancalion et al. 2011; Chaer et al. 2011; Guerra et al. 2014; Soares-Filho et al. 2014; Brazil 2017). There are numerous public and private actions in the Brazilian forestry production and conservation program aimed at the sustainability of the development of this sector: for example, the ABC Plan (Low Carbon Emissions Agriculture), and the Native Vegetation Protection Law (Law 12.651, of May 25, 2012), which defines the proportions of areas for protection of native vegetation and for forestry, agriculture, and livestock in rural properties, as well as the process of restoration of native vegetation in degraded areas. More recent legislation, called National Policy for the Recovery of Native Vegetation, was created to promote the revegetation of Brazilian biomes with mixed forest plantations and agroforestry. Moreover, other initiatives involving nongovernmental organizations, such as the Atlantic Forest Restoration Pact, bring new approaches to reconcile restoration of the biome with economic returns (Brancalion et al. 2011; Amazonas et al. 2018).

One of the great novelties of the Law 12.651 is the possibility, according to pre-established criteria, in mixing a 1:1 proportion of exotic and native species including fruit trees, in the legal reserve area (i.e., forest area of rural property intended for forest management and biodiversity conservation). This mechanism allows the formation of mixed multipurpose forests, as well as reduction of planting costs. Another relevant aspect is the legal reserve having a minimum area set at 20% in relation to the total size of the property for all regions of the country except the Amazon. In the Amazon region, legal reserve areas range around 80% (forest region), 35% (Cerrado region), and 20% (general field region). Chapter 13 details the Brazilian legal framework of multifunctional mixed forest plantations.

Mixed forest plantations provide a greater diversity of products and ecosystem services than monospecific forest plantations (Bouillet et al. 2013; Del Río et al. 2016; Dai et al. 2018; Voigtlaender et al. 2019). The mixture of two species with high timber value, with one being a N-fixer, has been the model most studied and recommended by researchers working with forest for timber production (Forrester et al. 2006; Bouillet et al. 2013; Del Río et al. 2016; Marron and Epron 2019). Pairs of mixtures of fast-growing exotic species such as *Eucalyptus* sp. or *Pinus* sp. with legumes such as *Acacia mangium* or *A. mearnsii* have the potential to offer a wide range of products in the same area, including timber, firewood, coal, tannins, resins, and essential oils. Such mixtures also contribute with the addition of ecosystem services, including the reduction of surface runoff and consequent more water infiltration, carbon sequestration, and biological fixation of N, culminating in the reduction of nitrogen fertilization use (see also Chap. 10).

Forest plantations carried out by companies on their own area or via forest out grower schemes use high-technology equipment with variation of techniques in function of the terrain slope (Malinovski et al. 2006; Gonçalves et al. 2013). The use of heavy machinery (e.g., tractors and harvesters) during planting and harvesting has restrictions because of local topography, and the alternatives for harvesting machinery in steep areas are even more expensive. Among the main limitations for the establishment of mixed forests with high technology, we cite the increase in the operational cost during harvesting. This limitation may not occur in plantations carried out in slope areas where cutting is done primarily by chainsaws. Moreover, the increase in the cost of harvesting in steep areas, in comparison to flat areas, may render unfeasible forest plantations with low value added (e.g., firewood and charcoal). Under these conditions, the planting of mixed forests with species of higher value, such as fruit trees or trees for seed production, noble wood, resins, and latex, among others, would be an interesting alternative.

The increase in income generated by the supply of both timber and non-timber products and ecosystem services (e.g., water increase, conservation of plant and animal diversity) could be much higher with mixed plantations with a greater diversity of species (Brancalion et al. 2012). Forestry production participated in the economy of 87% of Brazilian municipalities in 2017; 77.3% of revenue generation was derived from forestry (e.g., logs, firewood, and charcoal) and 22.7% from vegetable extraction (e.g., fruits, nuts, waxes, latex, resins) (IBGE 2017). Mixed forest plantations are an alternative to land use by small- and medium-sized producers who are interested in obtaining multiple forest products, and to increase ecosystem services on their properties (Brancalion et al. 2012; Brazil 2017). Species of the families Fabaceae, Myrtaceae, Arecaceae, and Lecythidaceae, among many others, can function both as a source of income and as a source of food for the fauna. Mixed plantation composed of groups of trees capable of producing wood, fruits, nuts, and extractives planted side by side allows to maintain a forest cover of sloping areas for a long term and, in this way, could reduce the surface runoff of water after rain events, and promote the infiltration of water into the soil (Gonçalves et al. 2003).

One of the main barriers to planting for restoration of native ecosystems is the high costs involved in establishment and maintenance. In some projects, high mortality may occur due to the attack of ants and competition with grasses. For example, the costs of establishment and maintenance during the first 2 years after planting native forests of the Atlantic Forest can exceed 5000 USD per hectare. These costs may be even higher if farmers request access to technical assistance, since seedlings and manpower are limited. Alternatives proposed to reduce costs of planting by generating more revenue include the mixing of *Eucalyptus* species for wood production with a relatively high-diversity (about 20–30) native species (Amazonas et al. 2018).

1.3 History of Mixed Plantations

Since the 1940s, several native and exotic forest species have been tested to select the most suitable ones for monospecific plantations. In Brazil, monocultures of *Eucalyptus* and *Pinus* have stood out in relation to native species, showing faster growth and good wood quality for multiple uses. Mixed forest plantations have been planted mainly with the objective of recovering degraded areas and restoring ecosystems (Kageyama and Castro 1989; Rodrigues et al. 2009). These plantations were planned according to the logic of ecological succession observed in natural forests, mixing groups of native and exotic species each one with different requirements for growth resources and lifetimes. The species used have little or no genetic improvement and the productivity of these types of plantations is not an important factor to consider. The use of mixed plantations for timber production is not very common in the practice of forest companies and producers.

In the last 30 years, several experiments about mixed plantations have been established in Brazil. These plantations were tested in experimental fields installed in different regions of the country in partnership with national and international research institutes and universities. Mixed forest plantations with fast-growing species with economic value, especially *Eucalyptus* × *Acacia mangium*, have recently been tested. The first experiment with *A. mangium* was set up in 1979 by EMBRAPA (Brazilian Agricultural Research Company) (Tonini et al. 2010). In 1985 the first plantation of *Acacia mangium* for genetic improvement was established and, in 1993, EMBRAPA Agrobiology established the experimental plantations that later culminated in the pioneering research center in studies of recovery of degraded areas with fast-growing leguminous species (Franco and Faria 1997; Macedo et al. 2008; Chaer et al. 2011).

From 1989 to 2000, there was a cooperation between Brazil and Germany in the studies of *A. mangium* in the North of Brazil with the project "*Studies of Human*

Impact on Forests and Floodplains in the Tropics." In 1995, the project "*Soil and Climate Zoning for the planting of fast-growing tree species in the Amazon*" was created. This project was financed under the "Pilot Program to Conserve the Brazilian Tropical Forest." The aim was to contribute to the reduction of deforestation rates in the region supplying the market with timber from areas with less legal restrictions instead of using native forests (Balieiro et al. 2018). The network of experiments was established in several units of EMBRAPA, in the states of Amazonas, Pará, Amapá, Acre, Rondônia, and Roraima. Different clones of *Eucalyptus* and *Acacia mangium* seedlings and several native species were tested.

In the last 10 years, Brazil, in cooperation with 34 countries, as France, the United States, Germany, Australia, Congo, the Netherlands, South Africa, China, Colombia, and Cuba, has developed studies specifically with *Acacia mangium* (Balieiro et al. 2018). In cooperation with the research institute CIRAD UMR Eco&Sols (La Recherche Agronomique pour le Développement), the thematic project "*Ecological intensification of eucalypt plantations by the association with nitrogen fixing tree legumes*" was approved by the Research Support Foundation of the State of São Paulo and its French counterpart, the "*Intensification écologique des écosystèmes de plantations forestières. Modélisation biophysique et évaluation socio-économique de l'association d'espèces fixatrices d'azote*," which was financed by the French National Research Agency. This project included a network of experiments installed in the southeast region, covering three states of Brazil, Minas Gerais, Rio de Janeiro, and São Paulo. The results showed that there were gains of biomass in the mixed plantations compared to *Eucalypt* monoculture when under favorable climatic conditions (hot and humid climate) for the development of *A. mangium*, low soil fertility and low water restrictions (Bouillet et al. 2013). This network of experiments has been recently expanded (since 2015) in two other Brazilian states, Tocantins and Mato Grosso. Previous studies were conducted in the Congo with similar edaphoclimatic condition as observed in the northern part of Brazil, showing a great productivity of these plantations and indicating a high potential of the eucalypt-acacia association (Bouillet et al. 2013). Chapter 2 details the studies about mixed forest plantation growth at different sites and under diverse silvicultural management.

1.4 Major Combinations of Species Already Tested in Practice and Potential

There are only few studies testing the growth of native species in mixed plantations compared to monocultures with the same species (Carvalho 1998, 2003; Machado and Bacha 2002). Carvalho (1998 and 2003) indicated the success of some of these studies to minimize the risks of pest attacks, such as the mixture of species of the Meliaceae family, as *Cedrela fissilis* and *Cabralea canjerana*, with other native or exotic fast-growing species to reduce the attacks of the cedar borer (*Hypsipyla* *grandella*). According to this author, species with reduced requirement of light at young age and with a large canopy when associated with fast-growing species generate stands with higher growth and straighter stem. For example, *Aspidosperma polyneuron* trees mixed with *Grevillea robusta* showed a straighter stem and 41% higher height growth than in monoculture after 16 years. Other timber species with good performance in mixed forest plantations, highlighted in Carvalho's bibliography, include the non-legumes *Cordia trichotoma, Prunus brasiliensis, Talauma ovata, Laplacea fruticosa, Luehea divaricata, Patagonula americana,* and *Tabebuia heptaphylla,* and the legumes *Anadenanthera peregrina var. falcata, Parapiptadenia rigida, Peltophorum dubium, Piptadenia gonoacantha, Piptadenia paniculata,* and *Sclerolobium paniculatum.* Additionally, potential species for timber indicated for mixed forest plantations are *Apuleia leiocarpa, Caesalpinia leiostachya, Enterolobium contortisiliquum, Hymenaea courbaril, Machaerium scleroxylon*, and *Pterogyne nitens* (Carvalho 1998). Planting of yerba mate (*Ilex paraguariensis*) in southern Brazil has been done in monoculture. In a literature review, Baggio et al. (2008) verified that there is great potential to associate this species with other natives of the southern region of Brazil, including leguminous N_2 fixers, with relevant economic gains in small properties.

The mixture of fast-growing species, including the N_2-fixing ones, has been tested in recent years in Brazil (Balieiro et al. 2002; Coelho et al. 2007; Bouillet et al. 2013; Santos et al. 2016; Soares et al. 2018). Mixed-species plantations of *Eucalyptus* and N_2-fixing *Pseudosamanea guachapele* with a 1:1 proportion were established in 1993 in the municipality of Seropédica, Rio de Janeiro state, Brazil (Balieiro et al. 2002). The authors showed that mixed stands had higher biomass production than pure plantations of each species, and despite the 10% less biomass of eucalypt in mixed than in pure stands, the efficiency of nutrient use of eucalypt increased in the consortium.

In São Paulo state, Brazil, a combination of five leguminous native trees, *Peltophorum dubium*, *Inga* sp., *Mimosa scabrella*, *Acacia polyphylla*, and *Mimosa caesalpiniaefolia*, and one exotic species, *Acacia mangium*, was tested with *Eucalyptus grandis* (Coelho et al. 2007). Each species was planted in monocultures and in consortium with *E. grandis* in commercial spacing (3 m × 3 m). The leguminous trees were planted between the plants of *E. grandis* in alternating rows with a 1:1 proportion. The study showed that interspecific competition between *E. grandis* and legumes is greater than intraspecific competition until the age of 24 months. Among the species studied, *A. mangium* was the one that best resisted to the competition with *E. grandis*.

Studies have indicated that higher yields occur mostly in mixed plantations with species of *Eucalyptus* sp. and *Acacia mangium,* and in monospecific *Eucalyptus* sp., under tropical climate (Bouillet et al. 2013). In regions of subtropical climate, mixed forest plantations of *E. grandis* and *A. mangium* are less productive than pure plantations of *E. grandis*. One of the main concerns of these authors is the high competition capacity of *E. grandis* on *A. mangium* in places where climatic conditions are optimal for the development of eucalypt and suboptimal for acacia. The same behavior was not observed in mixed plantations of the same species in an experiment in Congo (Bouillet et al. 2013). In this case, mixed plantations produced more biomass than eucalypt monocultures because they were embedded in areas characterized by nutrient-poor soils (e.g., sandy soils, deep soils, leachate), and warm and humid climates, but with low water limitation. These conditions are favorable for the growth of *A. mangium* but not optimal for eucalypt trees. Similar soil and climate conditions are found in the Brazilian Cerrado and transitional areas with the Amazon rainforest (e.g., Mato Grosso, Tocantins, and Roraima states). Santos et al. (2016) investigated the consortium between *Eucalyptus grandis* × *E. urophylla* and *A. mangium* in the municipality of Seropédica, Rio de Janeiro state, in a region with N-deficient soils and favorable climate for acacia. They also found a higher productivity of mixed plantings compared to pure eucalypt plantations.

The mixture with a 1:1 proportion of *Eucalyptus* spp. and *Acacia mearnsii* has been tested mainly in the southern part of Brazil. *A. mearnsii* has been more successful than *A. mangium* in facing eucalypt competition in this region. For example, the wood production of *A. mearnsii* in mixed stands with *E. globulus* was 77% of the production found in monospecific stand. In contrast, eucalypt wood production in the mixture was only 36% of the production found in monocultures (Soares et al. 2018). Mixed stands of *A. mearnsii* with *Eucalyptus* sp. presented similar production to monocultures (Vezzani et al. 2001; Soares et al. 2018), besides improving the nutritional status of soil and eucalypt trees (Vezzani et al. 2001).

Recent studies have suggested the use of eucalypt in consortia with many native species (20–30), in order to promote the restoration of ecosystems linked to the economic return from the sale of timber (Amazonas et al. 2018). Native species, including N-fixing legumes, established in mixture between eucalypt lines had their growth affected by eucalypt regarding their growth rates in three experimental sites with tropical climate without a dry season. The authors highlight the high capacity of interspecific competition of eucalypt and native species, reaching 75% of the basal area of pure eucalypt plantations, although with only 50% of tree density.

The planting of N_2-fixing trees is necessary for reclamation of degraded lands by agriculture and livestock or more severe situations such as mining. In a recent review, Chaer et al. (2011) described several successful studies using N_2-fixing legumes for land reclamation. The main objective of these plantings is the recuperation of the soil or substrate to provide colonization of new species in the future. A major concern today is the degraded soils of the Cerrado and Amazon region. Studies have shown that pastures cover about 62% of the deforested area of the Brazilian Legal Amazon, representing 335,700 km^2, and that the states with the highest incidence of pastures occur in Mato Grosso, Pará, and Rondônia (Almeida et al. 2016). According to EMBRAPA, half of this area is degraded, 30% is moderately degraded, and only 20% is in good condition. An alternative to recover degraded areas and improve the region's economy is through the insertion of intercropped plantations with fast-growing N_2-fixing legumes and eucalypt. The introduction of mixed acacia and eucalypt plantations is an alternative for the recovery of degraded areas and can increase the economy of small- and medium-sized farmers (Griffin et al. 2011).

1.5 Final Remarks

Brazil has millions of hectares of lands where forest plantations should be used to promote both economic and environmental gains. Forest covers promote important ecosystem services with emphasis on soil protection against erosion, silting of watercourses, and improvement of water infiltration.

Monospecific forest plantations with non-N_2-fixing species require higher fertilizer inputs and may have limited productivity on degraded soils with low nutrient and water availability. The environmental benefits of monospecific forest plantations may be more limited in these regions.

Mixed forest plantations involving the mixture between N_2-fixing and non-N_2-fixing trees have been highlighted as the most promising to sustain and/or increase the productivity of forests in regions limiting for development of monocultures. These more biodiverse plantations may be composed of two or more species used for different purposes, such as timber and non-timber products, soil protection in steep land, and recharge area of the groundwater, besides the recovery of degraded soils.

The introduction of the N_2-fixing species into eucalypt plantations, for example, is associated with improved nutrient cycling, especially nitrogen, with the addition of hundreds of kilograms of nitrogen via litterfall, root turnover, pruning of branches and leaves, and crop residues. Lower yields sometimes found in mixed forest plantations relative to monocultures are balanced by the increase in long-term sustainability.

There is need to broaden the debate on the ecosystem benefits of mixed forest plantations in relation to monocultures. Several species are promising for the composition of these more biodiverse forests, but little is known about the combinations and the edaphoclimatic conditions that permit to maximize the gains of the mixture.

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Chapter 2
Growth Patterns at Different Sites and Forest Management Systems

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2.1 Introduction

Associating biological nitrogen-fixing trees (NFT) with non-nitrogen-fixing trees can increase biomass production of plantations (Bouillet et al. 2013; Santos et al. 2016). Nitrogen provided by biological fixation is likely the main reason for mixed-forest plantations with N_2-fixing trees being more productive than non N_2-fixing monocultures, since N plays an important role in the plant metabolism, soil-microbial activity, and cycling of other macronutrients that foster the forest growth. Hence, the introduction of N_2-fixing species in fast-growing eucalypt plantations could be a management strategy in sites where eucalypt growth is limited by N availability (Stape et al. 2010; Koutika et al. 2017; Tchichelle et al. 2017).

Decades of eucalypt breeding in Brazil, associated with adequate fertilizer inputs and weed control, have made the seedlings and clones in Brazilian plantations much more productive than N_2-fixing tree species. Therefore, the competition between eucalypt and N_2-fixing species in this scenario has differed largely from patterns observed in less productive eucalypt plantations (Laclau et al. 2008).

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The management practice aiming to supply the nutritional demand for N fertilization in eucalypt plantations has been achieved by the introduction of *Acacia mangium* in Brazilian forest plantations (Voigtlaender et al. 2012; Voigtlaender et al. 2019). Future studies seek to consolidate the increase of the productive potential of acacia in order to improve its competitiveness in terms of wood production with eucalypt in mixed stands as well as conciliate both trees' growths. Therefore, two issues are of great importance: (1) to find the best arrangements (additives and replacement designs) between trees and (2) to obtain improved acacia genetic materials that match the site conditions and woody product of interest.

Thus, it is necessary to consider that the productivity of tree plantations is a function of supply, capture, and efficiency of resources (Richards et al. 2010). In this sense, to unravel the competition for light, water, nutrients, and effects of intra- and interspecific competition on biomass partitioning between tree components (Le Maire et al. 2013) becomes fundamental, since these are the main processes influencing tree growth in mixed-forest plantations.

Our objective in this chapter is to gather a large number of data obtained in the last decade regarding above- and belowground mixed-forest growth in Brazil and to give insights into the main drivers influencing the development of *Eucalyptus* and *Acacia mangium*, including soil and climate conditions, silvicultural management, and species interactions. Additionally, we intend to provide important information for a wide range of land managers, from small farmers producing firewood to large commercial forestry companies focused on timber or pulp production, looking for sustainable mixed-forest systems.

2.2 Soil and Climatic Conditions on Stand Growth of Mixed-Forest Plantations

Climatic characteristics play a key role on the aboveground biomass production of mixed-forest plantations relative to monoculture. Acacia is well suited for the hottest and most humid sites (Atipanumpai 1989; Krisnawati et al. 2011) and, for this reason, its productivity can vary greatly according to solar radiation intensity, vapor pressure deficit, and water availability. Acacia has not been studied thoroughly for breeding characteristics as has the eucalypt, and does not offer many genotypes (hybrids, clones, genetic material) that could better adapt to specific sites. However, eucalypt has a broad option of genetic material (species and hybrids) provided by several decades of eucalypt breeding, offering different kinds of genetic materials that can be chosen to match certain climatic and edaphic conditions of each site (Gonçalves et al. 2013), in order to maximize the growth and yield of these plantations.

Although acacia has not yet achieved an exponential breeding potential, it has attracted great attention due to its physiological ability to fix atmospheric nitrogen, which benefits the soil-plant system. In the last decade, studies on the growth