Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations

José Leonardo de Moraes Gonçalves [a,*], Clayton Alcarde Alvares [b], Antonio Rioyei Higa [c], Luciana Duque Silva [a], Acelino Couto Alfenas [d], James Stahl [e], Silvio Frosini de Barros Ferraz [a], Walter de Paula Lima [a], Pedro Henrique Santin Brancalion [a], Ayeska Hubner [a], Jean-Pierre Daniel Bouillet [f,a], Jean-Paul Laclau [f,a], Yann Nouvellon [f,g], Daniel Epron [f,h]

[a] USP, Universidade de São Paulo, ESALQ, Departamento de Ciências Florestais, CEP 13418-900 Piracicaba, SP, Brazil
[b] Instituto de Pesquisas e Estudos Florestais (IPEF), Piracicaba, SP, Brazil
[c] Universidade Federal do Paraná, Curitiba, PR, Brazil
[d] Universidade Federal de Viçosa, MG, Brazil
[e] Klabin, Telêmaco Borba, PR, Brazil
[f] CIRAD, UMR 111, Ecologie Fonctionnelle & Biogéochimie des Sols & Agro-écosystèmes, F-34060 Montpellier, France
[g] USP, Universidade de São Paulo, Departamento de Ciências Atmosféricas, IAG, CEP 05508-900 São Paulo, Brazil
[h] Université de Lorraine, UMR INRA-UL 1137, Ecologie et Ecophysiologie Forestières, Faculté des Sciences, Vandoeuvret-les-Nancy, France

ARTICLE INFO

ABSTRACT

Organized forestry in Brazil began in the late 1960s, stimulated by a government policy which subsidized afforestation programs from 1967 to 1989 to develop an internationally-competitive wood-based industry, managed by the private sector. Currently, planted forests in Brazil total about 6.9 million ha, from which 4.9 million ha is planted with eucalypt (around 25% of world plantation), 1.6 million ha with pine, and 0.42 M ha with other species. Roundwood consumption of forest plantations totaled 170.1 million m^3 in 2011, eucalypt plantation accounted for 80.6% of this total.

Most eucalypt plantations are managed in short rotations (6–8 years) and are established in regions with water, nutritional and frost stresses of low to high degrees. The mean annual increment is 40 m^3 ha^{-1} $year^{-1}$ roundwood, ranging from 25 to 60 m^3 ha^{-1} $year^{-1}$ depending on the level of environmental stress. Improving natural resources use efficiency by breeding and matching genotypes to sites and using appropriate site management practices is a key challenge to sustain or increase productivity.

The wide range of eucalypt species and hybrids with different climatic and edaphic suitability associated with the easy propagation by seeds and cloning allow the adaptation of plantations to various tropical and subtropical regions in Brazil. The possibility of using eucalypt wood in a range of purposes has led large and small enterprises to establish eucalypt forests for multiple uses. The desirable characteristics in association with the accumulated knowledge on eucalypt silviculture encourage the use of this genus in most plantations. The most important factors in the selective process for a genotype are wood characteristics, productivity level, susceptibility to pests and diseases, drought tolerance, especially in tropical regions (frost free), and frost tolerance in subtropical regions (mostly without water deficit). In regions with pronounced seasonality and moderate to long drought periods, the planting of hybrid genotypes predominates, propagated by cloning. Under subtropical conditions, the planting of single species predominates, propagated by seed. Clonal plantations with interspecific hybrids have been fundamental for eucalypt adaptation in regions under water and nutritional stresses. Given the rapid advances in eucalypt breeding, regarding adaptation to water stress and resistance to diseases and pests, and the adoption of clonal propagation techniques, genotypes are rapidly becoming obsolete and are replaced by more productive ones after harvesting. Thus, the replanting of crops has become a common procedure after the second half of the 1990s in Brazil.

This paper describes the basic requirements for integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in eucalypt plantations.

* Corresponding author. Tel.: +55 19 3301 1732; fax: +55 19 2105 8601.
E-mail address: jlmgonca@usp.br (J.L.M. Gonçalves).

1. Background of eucalypt plantations

Brazilian forestry can be divided into two main periods, before and after the 20th century. It was started as native silviculture with the experience of reforestation of Tijuca Forest (Rio de Janeiro) in 1862, which aimed to restore the Atlantic Forest in sites formerly used for coffee plantations (Silva, 1870). This was an important milestone because it was the first successful reforestation throughout Americas. This period was marked by traditional forestry that was ruled by values of conservation and ecology, until then practiced in the northern hemisphere. Only native species were used, regeneration was based on natural methods, where clearcuts in large areas, intensive site preparation and application of fertilizer were not practiced (Ferreira, 1989). In this period, the first batch of eucalypt seeds coming from Montevideo, Uruguay arrived in Brazil (Azevedo, 1874). Eucalypt plantations were quickly widespread in the states of Rio de Janeiro, Sao Paulo, Parana and Rio Grande do Sul, mainly used as urban forestry and hedgerows for farms. Although the government had encouraged the search for eucalypt acclimation at that time, there was no success, because the works were very widespread and not properly coordinated.

The first coordinated research studies of eucalypt forestry started in early twentieth century, more specifically in 1904, in the municipality of Jundiai, and in 1909 in the municipality of Rio Claro (Andrade, 1909), both in Sao Paulo state. These early

studies were funded by the Paulista Railway Company and coordinated by Edmundo Navarro de Andrade. By 1919, the seed orchard of Rio Claro had turned out 123 species of *Eucalyptus*, which were studied for seedling production, soil preparation, alignment and spacing of planting, pruning, thinning, harvesting, coppicing, diseases, pests, productivity, and uses of wood (Andrade, 1961). This phase marks the birth of scientific forestry and intensive forestry in Brazil.

Until the 1930s, the plantations had as main objectives to grow up species with proper timber to supply the demands of firewood used as fuel for locomotives and sleepers for railways, which were in plain expansion in Brazil. The annual planting of eucalypt was about 1000 ha yr^{-1} (Andrade, 1923). Some years later, based on the results of early experiments comparing native species with eucalypts cultivated in Jundiai and Rio Claro, it was concluded that species of *Eucalyptus* should be planted on a commercial scale (Andrade, 1928, 1936). Shortly afterwards, the planted area increased to about 25,000 ha yr^{-1} (Reis, 1948). Since 1950s started the establishment of large plantations for the production of charcoal in São Paulo (Alvares, 2011). Over the same period, the pulp and paper industry adopted eucalypt as the main source of raw material (Lemos, 2012).

It was from the 1960s that Brazilian forestry had a big boost. Between the 1960s and the 1980s, the forestry sector was encouraged to develop forest plantations by a governmental policy that granted tax incentives (Law n. 5106, 2 September 1966, giving tax incentives to afforestation). In the beginning, about 37,000 ha yr^{-1} were planted with *Eucalyptus* (Bastos, 1961), and at the end of period of tax incentives, about 270,000 ha yr^{-1} (Fig. 1a). Productivity was relatively low ranging from 10 to 30 m^3 ha^{-1} year^{-1} (Ferreira, 1992; Campinhos, 1999). High rate of segregation caused by uncontrolled hybridizations, major changes in vigor and wood quality showed that the seed sources were not adequate. Consequently, the phenotypic variability of the most planted species, namely *Eucalyptus grandis* (over 70% of the planted area), *Eucalyptus urophylla* and *Eucalyptus saligna* were very large (Ferreira, 1992). Tomazello (1976) obtained remarkable findings in identifying the high canker resistance at an individual level of these species. The author also found that trees with gummed-bark like (smooth) were the most resistant. These findings constituted one of the basic guidelines for the clonal multiplication of superior individuals (Ferreira, 1992). Seeking productivity increase and wood quality improvement, new species and new provenances of *Eucalyptus*, such as *E. grandis* (Coff's Harbour, Australia), and *E. urophylla* (Timor and Flores, Indonesia) were introduced. The introduction of *E. grandis* (Coff's Harbour) provenance occurred after the visit of Professor LD Pryor to Brazil (Pryor, 1971). At that time, the ecological zoning of exotic species (Golfari, 1974), the selections of superior site-specific provenances and progenies in addition to the establishment of areas of improved seed production played a critical role. Concurrently, in 1979, the first clonal plantations were established in the State of Espirito Santo (Ferreira, 1992). All these advances led the area of eucalypt plantations to surpass that of pine plantations (Fig. 1a) by the end of the 1970s.

The following period, 1980–2000, was marked by the consolidation of the Brazilian forest sector, involving mainly breeding programs, productivity increases, expansion of cropped areas, diversification of the use of products, increase of competitiveness and concerns with social and environmental issues (ABRAF, 2012). New eucalypt populations emerged from interspecific crosses, especially between *E. grandis* and *E. urophylla* seeking segregation of individuals with high productivity and desirable wood quality (Lemos, 2012). Superior individuals planted on commercial scale in various regions were selected by cloning techniques. In addition to forest improvement, there was significant advance of
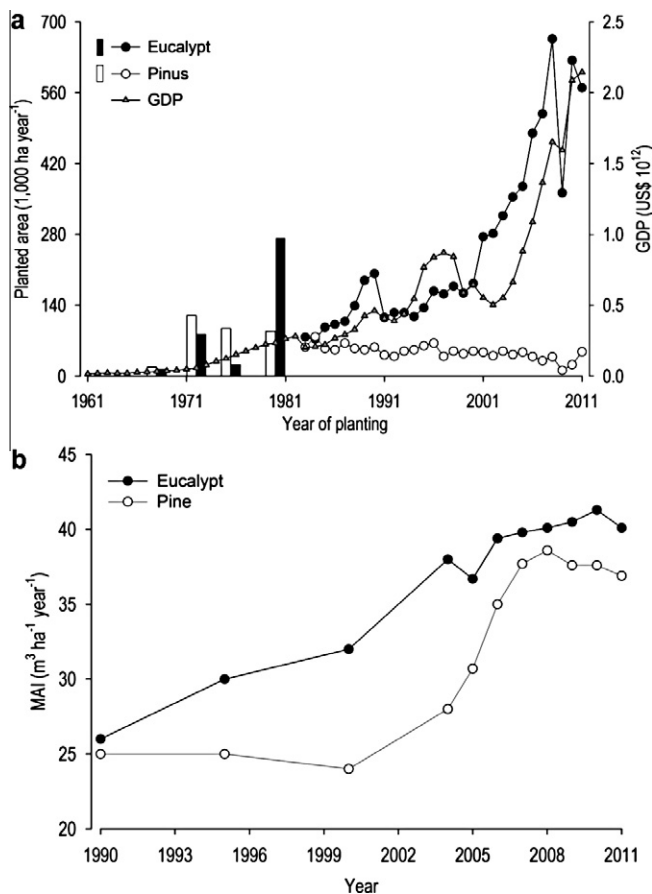

Fig. 1. (a) Annual planted area with pine and eucalypt, and the Gross Domestic Product since 1961; (b) mean annual increment (roundwood with bark) of eucalypt and pine plantations since 1990. Planted areas was compiled from data published by Andrade (1923, 1928, 1936), Reis (1948), Bastos (1961), Ferreira (1989), BRACELPA (2004) and information obtained from Brazilian Association of Forest Plantation Producers (ABRAF). GPD data are from World Bank (http://data-bank.worldbank.org/data/home.aspx). The mean weighted productivity was computed as a function of planted area (ABRAF, 2012).

silvicultural practices, especially regarding production of high-quality seedlings, use of minimum tillage, integrated control of weeds, pests and diseases, judicious fertilization recommendation, and effective control of forest fires (Gonçalves et al., 2008). Thus, at the beginning of the 21st century, mean annual increments exceeded 30 m^3 ha^{-1} year^{-1} roundwood (Fig. 1b).

Between the 1980s and late 1990s, there was a decrease followed by the stabilization of the annual planted area of eucalypts (Fig. 1a), mainly due to the end of tax incentives in 1986. Such was the mark of a new phase in the history of intensive forestry in Brazil (Moratori, 2008). Forest companies allocated large investments for the maintenance of stands, invested in new plantations and consolidated associations and cooperatives with public universities for the development of science and technology (Lemos, 2012).

The current status of the Brazilian forest sector, since the year 2000, is characterized by the consolidation of Brazil as a major international player of the planted forest sector. This phase has been characterized by the expansion of planted areas and the consolidation of the technological development of the sector, which has been accompanied by a rapid GDP growth in Brazil (Fig. 1a). The importance for society of eucalypt plantations and related industry can be measured by assessing some main indicators, for instance, roundwood production and consumption. It is estimated that the potential roundwood production of pine, eucalypt and teak amounts to around 255.4 million m^3 yr^{-1}. From this amount, 76.5% corresponds to eucalypt, 23.1% pine, and teak accounts for only 0.4% of the total production. The major part of the potential eucalypt production is concentrated in the Southeast (59.3%), in view of the significant number of pulp and paper mills and metallurgy charcoal companies in this region. In 2011, the roundwood consumption of forest plantations totaled 170.1 million m^3, 80.6% corresponded to eucalypt plantation productions. The pulp and paper sector stood out as the main consumer (36.1% of total),

followed by the industrial firewood (26.3%), the wood industry (18.8%), the charcoal sector (10%), reconstituted panels (7.4%), treated wood (0.9%) and others (0.6%). Except for firewood, charcoal and industrialized wooden panels, which operate in the domestic market, other products are preferably aimed at foreign markets. A significant volume of secondary products (furniture, paper, flooring, frames, iron and steel, etc.) is also exported, underscoring thus the importance of the international market for the forest sector. The key trends for the forest sector in the short and mid terms are: (i) increase forest plantation area; (ii) consolidation of "new forest frontiers"; (iii) partial replacement of pine plantations for eucalypt in the southern and southeastern regions; (iv) development of new markets (products and businesses, such as bio-refineries and bio-energy) (ABRAF, 2012).

2. Location of plantations

In 2011, Brazil's total area of forest plantations growing eucalypt and pine covered 6.5 M ha, being 74.8% planted with eucalypt (Fig. 2) and 25.2% with pine. Part of the pine plantations are being replaced by eucalypt. During 2005–2011, the area planted with pine reduced by 189,593 ha (−1.8% p.a.). The area cropped with other forest species such as *Acacia mearnsii*, *Acacia mangium*, *Hevea brasiliensis* (Rubber tree), *Schizolobium amazonicum* (Parica) and *Tectona grandis* (Teak), account for more than 421,588 ha, representing 6.0% of the total area of planted forests (ABRAF, 2012).

The largest eucalypt plantations are found in the southeastern region (56%), especially in the states of Minas Gerais and São Paulo (Table 1). Large plantations can also be found in the northeastern region (17%) in the state of Bahia; in the southern region, mainly in the state of Parana, in the central-western region (11%), mainly in the state of Mato Grosso do Sul, and in the northern region (5%)
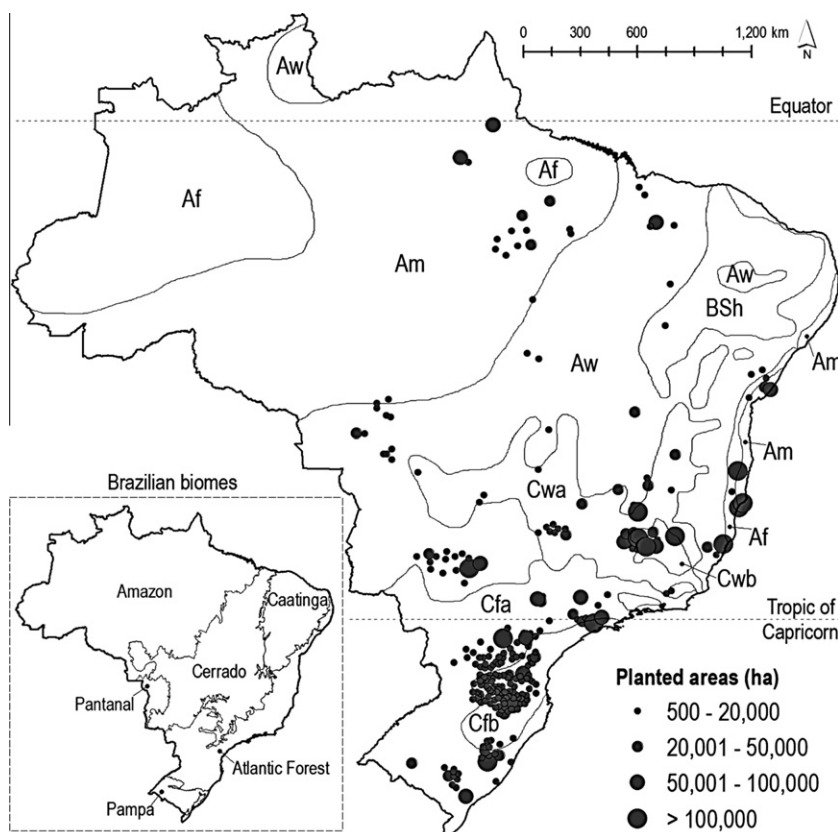

Fig. 2. Distribution of eucalypt plantations and different natural biomes in Brazil (modified of ABRAF (2012)). For description of climate types see Table 2.

Table 1
Planted area of eucalypt in 2011, order and suborder, texture, local topography and extension of the soils in different Brazilian regions.

Region	Planted area		Soil				
	1000 ha	% Total	Order and suborder	Texture	Topography[a]	Planted area	
						1000 ha	% Region
Southeast	2640	54.2	Oxisols	Sand clay loam to clayey	Flat to undulating	1499	56.8
			Ultisols	Sand clay loam (A-hor)/sand clay to clay (B-hor)	Undulating to hilly	598	22.7
			Inceptisols	Clay loam to clay	Rolling to hilly	387	14.7
			Entisols				
			Orthents	Clay loam to clay	Hilly	118	4.5
			Psamments	Sand to loam sand	Flat to gently sloping	38	1.4
Northeast	800	16.4	Oxisols	Sand clay loam to clay	Flat to undulating	254	31.7
			Ultisols	Loam sand to sand clay loam (A-hor)/sand clay loam to clay (B-hor)	Undulating to rolling	400	50.1
			Entisols				
			Psamments	Sand to loam sand	Flat to gently sloping	64	8.0
			Inceptisols	Clay	Hilly	54	6.8
			Oxisols (plinthic)	Clay loam	Flat to gently sloping	27	3.4
South	573	11.8	Inceptisols	Clay	Hilly to steep	225	39.3
			Ultisols	Sand clay loam (A-hor)/sand clay (B-hor)	Undulating to hilly	131	22.9
			Oxisols	Sand clay loam to clay	Undulating	128	22.3
			Entisols				
			Orthents	Clay loam	Hilly to very steep	54	9.3
			Psamments	Sand	Flat to gently sloping	6	1.0
			Alfisols	Sand clay loam (A-hor)/clay (B-hor)	Flat to undulating	29	5.1
Midwest	659	13.5	Oxisols	Sand clay to clay	Flat to undulating	313	47.5
			Entisols				
			Psamments	Sand	Flat to gently sloping	289	43.7
			Orthents	Clay	Hilly	5	0.7
			Ultisols	Sandy clay loam (A-hor)/clayey (B-hor)	Undulating to rolling	34	5.2
			Inceptisols	Clayey	Hilly to steep	13	1.9
			Alfisols	Loam sand (A-hor)/clay (B-hor)	Flat to gently sloping	6	0.9
North	201	4.1	Oxisols	Sand clay loam to clay	Flat to undulating	127	63.0
			Ultisols	Loam sand (A-hor)/sand clay loam (B-hor)	Undulating to rolling	43	21.5
			Entisols				
			Psamments	Sand	Flat to gently sloping	19	9.4
			Orthents	Clay loam	Hilly to very steep	9	4.3
			Oxisols (plinthic)	Sand clay loam	Undulating	4	1.8

[a] Topography: 0–2% flat, 2–5% gently sloping, 5–8% undulating, 8–16% rolling, 16–30% hilly, 30–45% steep, and >45% very steep (Soil Survey Staff, 1993).

in the state of Amapa (ABRAF, 2012). The largest concentration of forest plantations occurs in the south and southeast of Brazil where the main industries of pulp, paper, wood panels and steel are located. However, due to current and high land prices in consolidated markets of the southern (Parana and Santa Catarina) and southeast regions (São Paulo), Brazilian forestry is advancing to other regions called the 'new forest frontiers', as it has already been observed in the last 3 years in the states of Mato Grosso do Sul, Maranhão, Piauí and Tocantins.

Closely related to rainfall and temperature conditions and climate seasonality, the major biomes where eucalypt plantations were established are the Atlantic Forest (60%), the Cerrado (Brazilian Savannah) with 21%, the Amazon Rainforest (10%) and the Pampa (lowland grasslands) with 7% (Fig. 2). Caatinga biome (Steppe-like savannah) comprises only 1% of eucalypt plantations. Previously, grassland and agricultural crops occupied most of the area.

The eucalypt plantations established in lands belonging to industrial companies have been decreasing over the last few years, and in 2010, they represented approximately 73%. Plantations in leased and fostered areas doubled in the last 5 years. In 2010, 12% of plantations were established on leased lands and 15% in forest outgrower scheme. In this model of relationship with landown-

ers, the industry aims to ensure timber supply, reduce the amount of equity capital in fixed assets, promote supportive programs for employment generation and increase the local income (ABRAF, 2012).

3. Edaphoclimatic and physiographic characterizations

3.1. Climate

The climatic classification of Köppen (1936) has been effective in distinguishing the different climatic types and subtypes that occur in Brazil, which have close correlation with the recommendations of eucalypt genotypes and forest productivity. According to this classification, where are the eucalypt plantations, two climate types occur, tropical and subtropical, which are subdivided into seven subtypes: fully humid tropical (Af), monsoon (Am), humid tropical with dry winter (Aw), fully humid subtropical with hot summer (Cfa), fully humid subtropical with temperate summer (Cfb), humid subtropical with dry winter and hot summer (Cwa), humid subtropical with dry winter and temperate summer (Cwb). In the Amazon Forest, Af and Am subtypes predominate, in the Cerrado, Aw and Cwa subtypes, and in the Atlantic Forest, Cfa, Cfb, Cwa and Cwb subtypes (Fig. 2 and Table 2).

Environmental stresses notably hamper productivity. In climates with marked seasonality, such as the climatic subtypes Aw, Cfb, Cwa and Cwb, productivity is highly variable. Effects of water stress are more typical in Aw and Cwa, and thermal stress (mainly frost) in Cfb and Cwb. Water stress is not observed in Af and Cfb. In Aw and Cwa, due to rainfall badly distributed among the seasons, water stress is medium to high. In Cfb and Cwb, average temperatures, and thus evapotranspiration, are lower, because of highlands (Table 2). The most severe water stress occurs during periods of Indian summers, when there are 2 or more weeks of drought in the middle of the rainy season, especially if average temperatures are high.

The first eucalypt plantations were established in temperate zones of Southeastern and Southern states. In recent decades, the plantations have expanded to more tropical regions of the Northeast and Central-West, especially in Am and Aw climates. In these regions of inexpensive land but with a dry season with high water stress, the major challenge is to obtain new genotypes adapted to these warmer and xeric conditions.

3.2. Soil and topography

An estimate of the major Brazilian soil and topography types used for eucalypt plantations was performed using several sources of spatial and tabular data (Table 1). Data for each area was adopted from ABRAF (2012). The area mappings of plantations in the states of Sao Paulo (IF, 2002) and Minas Gerais (Scolforo et al., 2008) were arranged in a single database. These states are the largest eucalypt planters, accounting altogether for 51.5% of the total planted area. The remaining area (fourteen other states) was joined in tabular information for municipality-based forest plantations (IBGE, 2011). Orders and suborders of soils were obtained from the pedological map of Brazil (IBGE, 2001). Such map is classified according to the Brazilian soil taxonomy (EMBRAPA, 2006), which was converted to the US soil taxonomy (Soil Survey Staff, 1993). The map of clay content produced by Silva et al. (2011) was used as information source of clay content. The map of clay content was interpolated by the kriging method of 5500 Brazilian soil profiles. Using a geographic information system, Alvares et al. (2011b) compiled a digital elevation model from Shuttle Radar Topography Mission (SRTM) (Farr and Kobrick, 2000) in its current fourth version (Jarvis et al., 2008). Simple geoprocessing techniques (Ormsby et al., 2010) were used to perform intercepts of clay contents between the map of eucalypt plantations and the pedological map, and the slope map to elaborate Table 1.

The wide variability of soils and topography reflects the broad range of the planting area as well as the action and the dominance of various factors and processes for soil formation (Tables 1 and 2). Generally, the most weathered and developed soils (oxic B horizon) are under very active climatic and biotic conditions, as in the case of tropical and subtropical humid lands that are located in the landscape at more stable positions, flat to undulating topography. Moderately developed, less weathered soils (argilic B horizon) are formed at less stable topography (undulating to rolling). Soils less developed than the previous ones (cambic B horizon) are formed in rolling to very steep topography. Poorly developed soils are commonly found in very unstable topography.

Oxisol is the main soil order occupying almost half of the land used for eucalypt plantations (47.9%). This soil type is found in all regions, but especially in the Southeast, in São Paulo and Minas Gerais states. It is deep, with well-differentiated horizons and low texture gradient. Due to the advanced stage of weathering and intensive leaching process, the predominant clays are kaolinitic and oxidic (gibbsite, goethite and hematite). The cation exchange capacity is lower than 13 cmol$_c$ kg^{-1} clay (after correction for carbon), fertility and content of minerals with low resistance to weathering are low. The particle size distribution is finer than sandy loam (loamy to clayey texture). Usually, the soil mass has a porous massive aspect with strong aggregation of particles into granules, occurring, less frequently, subangular blocky soil-structure. In the South of Sao Paulo state, Alvares et al. (2011a) studied soils of wide areas of eucalypt plantations and found high variability of physical and chemical characteristics of Oxisols and recommended specific management of the soil. Small areas (0.7%) of Plinthic Oxisols with sandy clay loam texture and undulating topography are planted in the north.

Ultisols also appear as an important soil used for eucalypt plantations, with 1.2 M ha (25.5%), mainly southeastern, northeastern and southern Brazil. They are deep to shallow, well to poorly drained, with significant illuviation of clay from the surface horizons to the B horizon, evidenced by the textural gradient (erosion susceptibility increases with the textural differences). Special care related to soil management should be taken when A horizon is sandy and B horizon is clayey, which commonly occurs in areas with steep slope. The B horizon usually has faces of peds with shiny waxy sheen, and it has medium fertility.

Approximately 0.68 M ha (14%) of eucalypt plantations are grown in Inceptisols, mainly in the southeast and south. They are moderate to well drained, shallow, rarely deep, with pedogenic development little pronounced. The contents of easily weathered primary minerals are greater than 4%, being common the presence of rock fragments. Their texture ranges from clayey loam to clayey. Physical constraints (permeability, depth, water retention) limiting eucalypt production are generally found, without necessarily being economically unfeasible. Commonly, Inceptisols are of medium to high fertility.

The little developed soils, such as Lithic Orthent and Entisols develop on sands (Psamments) present A horizon overlying rock or C horizon. Orthent has low depth, but high clay content and generally medium to high fertility. There are approximately 185,000 ha (3.9%) cultivated mainly in the southeastern and southern states. The topography is strongly tilted, ranging from hilly to very steep. Most lands covered by Orthent have physical characteristics unfavorable to eucalypt development and are located in areas of permanent preservation of natural vegetation. Psamments are mostly cultivated in the central-western region, in flat to gently sloping topography. In the State of Rio Grande do Sul, there are extensive areas of Alfisols cultivated in flat topography and high texture relation. These soils usually have sandy clay loam (A-hor)/clayey (B-hor) texture. In many places, plantations show effects of anoxia in these soils.

4. Genetic adaptation

Three phases characterize the eucalypts culture in Brazil, under tree breeding perspectives.

The first phase was from eucalypt introduction at the beginning of last century by Navarro de Andrade to supply firewood poles and railway sleepers until the advent of fiscal incentives for reforestation in the late 1960s. At this stage, the large-scale eucalypt plantations were restricted to Sao Paulo state. The main species were *E. grandis*, *Corymbia citriodora*, *Eucalyptus camaldulensis*, *E. saligna*, *E. urophylla* (known then as *E. alba*). The second phase, with fiscal incentives, lasted until the 1980s and was characterized by the expansion of planted areas using species such as *E. grandis*. The use of seeds from selected origins, such as Coffs Harbour, Australia, generated in seed production areas (SPA's) brought significant gains in productivity in the state of Sao Paulo. However, eucalypt plantations established in other regions using seeds selected for the Sao Paulo state showed problems of adaptation to biotic factors

Table 2
Main characteristics of the climate, topography and soil of the planted areas with eucalypts.

Attribute	Tropical[a]			Subtropical[a]			
	Af Fully humid	Am Monsoon	Aw Dry winter	Cfa Oceanic, fully humid, hot summer	Cfb Oceanic, fully humid, temperate summer	Cwa Humid, dry winter, hot summer	Cwb Humid, dry winter, temperate summer
Native vegetation	Atlantic Forest (small area)	Amazon Forest	Cerrado (Brazilian Savannah) and Atlantic Forest	Atlantic Forest (mostly) and Cerrado	Atlantic Forest	Atlantic Forest	Atlantic Forest
Region	Northeast (coastal)	North (eastern part)	Midwest (mostly) and Northeast (western)	South and Southeast (southern most)	South and Southeast (highlands of coast)	Southeast	Southeast (interior highlands)
Mean annual rainfall (mm year^{-1})	2000–3000	1500–2000	1000–2000	1500–2500	1500–2500	1000–1500	1000–1800
Mean annual temperature (°C)	24–26	24–26	21–25	16–20	13–17	20–22	18–20
Dry season (no. months with less 50 mm rainfall)	None	Short (≤3)	Medium to high (3–7)	Short (≤2)	None	Medium (≤3–5)	Short (≤3)
Occurrence of frost	None	None	None	Light and frequent	Severe and frequent	Light and infrequent	Moderate and infrequent
Main topography[b]	Gently sloping to undulating	Gently sloping to undulating	Flat to undulating	Undulating to steep	Rolling to steep	Gently sloping to hilly	Rolling to hilly
Main soil class	Ultisols and Oxisols	Ultisols and Oxisols	Oxisols, Quartzipsamments and Ultisols	Inceptisols, Ultisols, Oxisols and Alfisols	Inceptisols and Ultisols	Oxisols and Ultisols	Ultisols and Inceptisols
Main soil characteristics (depth, texture, structure, fertility)	Very deep (>2 m), clayey, blocklike, very firm to extremely firm, hard to very hard, dystrophic	Very deep (>2 m), clayey, blocklike, very firm to extremely firm, hard to very hard, dystrophic	Very deep (>2 m), loamy and sandy, spheroidal, very friable, soft, dystrophic	Deep (>1 m), loamy to clayey, blocklike to spheroidal, very firm to friable, hard to slightly hard, dystrophic	Deep (>1 m), clayey, blocklike, firm to very firm, moderately hard to hard, dystrophic	Deep (>2 m), loamy to clayey, spheroidal, friable, soft, dystrophic	Deep (>1.5 m), clayey, spheroidal to blocklike, friable to firm, soft to slightly hard, dystrophic
Soil properties	High water-holding capacity (WHC), poorly aerated, slow to medium drainage, acidic, poor supply of plant nutrients (SPN)	High WHC, poorly aerated, slow to medium drainage, acidic, poor SPN	Medium and low WHC, moderate and well aerated, medium and rapid drainage, acidic, poor SPN	Medium to high WHC, moderate to poorly aerated, medium to slow drainage, acidic, medium SPN	High WHC, poorly aerated, slow to medium drainage, acidic, medium to excellent SPN	Medium to high WHC, well aerated, medium to rapid drainage, acidic, poor SPN	High WHC, moderate to poorly aerated, medium to rapid drainage, acidic, medium SPN

[a] Types and subtypes according to the climatic classification of Köppen (1936).
[b] Topography: 0–2% flat, 2–5% gently sloping, 5–8% undulating, 8–16% rolling, 16–30% hilly, 30–45% steep, and >45% very steep.

such as trunk canker caused by the fungus *Cryphonectria cubensis* and abiotic factors, such as drought periods.

Field observations and research showed that these problems could be largely solved using clones of interspecific hybrids, such as *E. urophylla × grandis* ("urograndis"), leading to the current third phase. The first hybrids were selected in plantations originated from seeds of natural hybrids, spontaneously generated by contamination of seed collection areas. The Simple Recurrent Selection (SRS) was used thereafter as a breeding strategy based on controlled pollination. Later, after the occurrence of heterosis in interspecific crosses be showed (Coterill, 1997; Resende and Resende, 2000), the Reciprocal Recurrent Selection (RRS) became one of the largely used strategy to generate hybrids. Several breeding strategies may be used, however the RRS Selection of parents and Generation of Intermediate Hybrid (RRS-G-IH), proposed by Resende and Higa (1990), is one of the most suitable because it leads to greater genetic gain per time unit, and superior intermediate hybrids before the RRS cycle is completed. The RRS-G-IH is based on the selection of parents of either species or populations, on hybrid progeny tests and on recommendations of the parents themselves (a pollen mix) to generate a new hybrid population. The intermediate hybrids (IH) are obtained by crossing parents with high General Ability for Hybridization (GAH) that had not been previously crossed, during the generation of hybrid progenies. This new population of hybrids is obtained concurrently with the recombination of the parents; therefore it is a process of obtaining new hybrids before a new RRS cycle (Fig. 3).

The interspecific hybridization is a quick and efficient method to obtain gains in genetic improvement of eucalypt species, with significant and direct impact on forest-based industry. The search of complementary technological traits in the wood characteristics, namely tolerance to biotic and abiotic stress and manifestation of the heterozygosis as observed in several hybrids, is the main way

to produce superior individuals with higher growth, adaptation and wood quality (Assis and Mafia, 2007). The use of clones, rather than seedlings originated from seeds, allows the transfer of the total genetic variance, which includes the additive variance and the variance due to the dominance effects (Zobel et al., 1982). This procedure results in maximum genetic gains regarding wood productivity, wood quality properties and resistance to biotic and abiotic factors. Clones from hybrids are more advantageous than seedlings of single species, because they can combine silvicultural traits such as wood quality and adaptability (Table 3).

According to Assis and Mafia (2007), the most important eucalypt species to generate hybrids resistant to drought are found in the Exertaria section from northern Queensland, Australia (*E. camaldulensis*, *Eucalyptus tereticornis* and *Eucalyptus brassiana*). For sites where frosts are frequent, the recommended species for hybrid generation are: *Eucalyptus viminalis*, *Eucalyptus badjensis*, *Eucalyptus benthamii*, *Eucalyptus smithii* and *Eucalyptus dunnii*. In practice, subtropical species of eucalypts exhibit low rooting capacity, making it difficult to use them as pure species. Therefore, it is recommended to cross them with species that have good rooting capacity.

The hybrid *E. grandis × urophylla* is not fully adapted to very warm and humid climates as in northern Brazil (Amazon region) in particular due to leaf diseases (Hardiyanto and Tridasa, 2000). Creating highly productive eucalypt material remains a challenge in northern Brazil where growth rates are still far lower than in south-eastern Brazil (Souza et al., 2004; Demolinari et al., 2007; Behling et al., 2011). *Eucalyptus pellita* (F. Muell.) is one of the most promising species for eucalypt breeding programs in humid tropics (Harwood et al., 1997; Brawner et al., 2010). This species is native to northern Queensland (Australia) and southern New Guinea and is resistant to to many tropical pests and diseases (Guimarães et al., 2010). It is largely used in Indonesia for pulpwood production (Leksono et al., 2006; Brawner et al., 2010) and could be used for hybridization with *E. urophylla* (Vigneron and Bouvet, 2000).

In addition to improvements of plantation productivity and wood quality, rooting ability, resistance to drought, frost and diseases, research is also being conducted to increase orthotropism (stem straightness) and resistance to wind. There are some risks associated to clonal forestry, mostly related to the restricted genetic base of plantations. Most commercial clonal forests do not follow recommendation from theoretical studies, which have shown that clonal plantations should deploy at least 40 different clones (Brishir and Roberds, 1999). Another aspect is the need of continuous investment in breeding programs to generate new clones. In general, a new clone takes at least 12–16 years to be generated and approved for commercial use. It is recommended that, on average, a new clone should be introduced every year. Currently in Brazil, most of the breeding programs to generate new clones are developed by pulp and charcoal private companies. Breeding for solid wood products is less developed. The use of transgenic genotypes
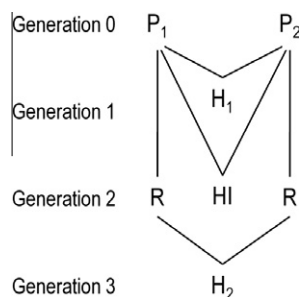

Fig. 3. Simplified scheme of RRS-G-IH: Reciprocal Recurrent Selection (RRS) with recombination of the parents themselves and use of Intermediate Hybrid (IH) between two selections cycles. Where: P_1 and P_2 = parents from populations 1 and 2; H_1 and H_2 = new hybrid populations; IH = intermediate hybrids; R = recombined parents generated from crossing within each population.

Table 3
Relative quality of *Eucalyptus* species traits which may be combined in the interspecific hybrids: VG = very good; G = good; R = regular; I = intermediate; ? = without information.
Source: Santos et al. (2008).

Species	Growth	Rust resistance	Rooting	Canker	Drought resistance	Frost resistance	Wood density	Screened yield	Lignin	Hemicellulose
E. grandis	VG	I	G	I	R	R	R	I	I	I
E. urophylla	G	I	VG	VG	I	R	I	I	R	I
E. camaldulensis	R	VG	VG	VG	VG	R	VG	R	R	R
E. tereticornis	R	VG	G	VG	VG	R	VG	R	R	R
E. robusta	I	VG	VG	VG	I	R	VG	R	R	R
E. resinifera	I	VG	VG	VG	I	R	VG	R	R	R
E. pellita	I	VG	VG	VG	I	R	VG	R	R	R
E. dunnii	I	I	R	R	R	G	G	G	G	R
E. benthamii	VG	G	R	?	R	VG	R	R	R	I
E. globulus	R	I	R	?	I	G	VG	VG	VG	VG

is also being studied in Brazil. Herbicide resistance and reduction or modification of lignin content and composition may be achieved through transgenesis. However, the availability of genetic material resistant to pests and diseases or adapted to frost and drought conditions in Brazil will take a while to occur.

5. Matching species/hybrids to sites

The wide range of eucalypt species and hybrids with different climatic and edaphic aptitudes associated with the easy propagation by seeds and cloning allow the adaptation of plantations to various tropical and subtropical regions in Brazil. The possibility of using eucalypt wood for a range of purposes has stimulated the establishment of forests for multiple uses by both large and small enterprises (Table 4). The desirable characteristics in association with the accumulated knowledge on eucalypt silviculture encourage the use of this genus in most plantations even more.

The most important selective factors for a genotype allocation are wood characteristics, productivity level, susceptibility to pests and diseases, drought tolerance, especially in tropical regions (frost free), and frost tolerance in subtropical regions (mostly without water deficit).

Under tropical conditions, in regions with pronounced seasonality and moderate to long drought periods, the planting of hybrid genotypes predominates, propagated by cloning. Under subtropical conditions, the planting of single genotypes predominates, propagated by seed (Tables 4 and 5). Clonal plantations with interspecific hybrids have been fundamental to adapt eucalypt in regions with water and nutritional stresses. Clones from hybrids are more advantageous in relation to seed-originated seedlings of pure species, because they can combine silvicultural traits such as wood quality and site adaptability (Tables 3–5). Therefore, cloning is essential for the fixation of desirable genotype combinations and hybrid vigor as it allows obtaining homogeneous forest products and maximization of selection (Fonseca et al., 2010).

Genotypes propagated by cloning, due to the small genetic diversity, are little plastic relatively genotypes propagated through seeds. Hence, they have a higher risk of genotype-environment incompatibility (Gonçalves et al., 2011). Thus, the specific allocation of a genotype to a site should be well tested, based on field and laboratory tests. The use of clones in forest-based enterprises is the result of extensive investments in research and pilot plantations in regions with different edaphoclimatic characteristics (Higa and Silva, 2008). Given the rapid advances in eucalypt breeding, regarding adaptation to water stress and resistance to pests and diseases, and the adoption of clonal propagation techniques, genotypes rapidly become obsolete and are replaced by more productive ones after harvesting. Thus, the replanting of crops became a common procedure after the second half of the 1990s in Brazil, while coppice was more frequent before (Fonseca et al., 2010).

Under subtropical conditions in regions with hot summer and good rainfall distribution, Cfa climate type, with no more than a month of water deficit, and light and frequent frost, the most recommended genetic materials are the hybrid E. urophylla × grandis (urograndis), E. grandis, E. urophylla, E. saligna and C. citriodora. If the summer is temperate, Cfb climate type, which occurs in southern Brazil and high-altitude areas of the southeast, the species E. dunii, E. benthamii and E. saligna are used (Tables 2 and 5). E. dunii tolerates moderate frost and E. saligna tolerate mild frost, so they should be planted in the higher quotas of the terrain. In areas of lower quotas, middle third of the slope and lowlands, where frost is severe and frequent, it is recommended to use E. benthamii. If the summer is mild and the winter is dry, Cwb and Am climate types, with low water stress (i.e., a water deficit of 50–100 mm year^{-1}, according to the soil water balance proposed by

Thornthwaite and Mather, 1955), it is recommended to plant the hybrid E. urophylla × grandis, E. grandis and E. urophylla. Among these three species, E. grandis is the most sensitive to water stress, and should be planted in deeper and clayey soils. E. dunii presents problems of seed propagation (late flowering) and cloning (poor rooting).

Still under subtropical conditions, if there is moderate water stress (100–200 mm year^{-1}), which occurs in regions with hot summers, the hybrids, in order of increasing drought tolerance, E. urophylla × grandis, E. grandis × camaldulensis (grancam), E. urophylla × camaldulensis (urocam), and the pure species E. urophylla, E. camaldulensis and E. tereticornis are most suitable. The hybrids propagated by cloning and more specifically related to edaphoclimatic adaptation, are the most planted. This flexibility of options allows obtaining yields similar to those in low water stress conditions (Table 5). The E. urophylla × grandis is the genetic material most planted in Brazil, since its edaphoclimatic adaptation is compatible with the regions where the largest plantation areas are located.E. urophylla has high adaptability to several regions and has been widely hybridized with E. grandis, aiming to obtain materials tolerant to droughts and resistant to eucalypt canker. Although E. urophylla and E. camaldulensis present some favorable traits in common, E. camaldulensis has greater resistance to drought and higher wood density than E. urophylla as well as more alleles of importance for hybridization. In regions where E. urophylla is adapted, it has a higher volumetric growth than E. camaldulensis. Generally E. urophylla adapts to a wider range of environments than E. camaldulensis (Tables 4 and 5). Both species are good sources of rust resistance, although the intraspecific variability requires preliminary assessment for resistance by means of inoculations under controlled conditions (Fonseca et al., 2010).

When there is high water stress (200–400 mm year^{-1}), typical in tropical conditions, Aw climate type, with warm and dry winter, the hybrids are the most recommended genotypes. Among them E. grandis × camaldulensis, E. urophylla × camaldulensis, E. tereticornis × brassiana and E. urophylla × tereticornis are highlighted. It is also recommended the use of pure species E. camaldulensis, E. tereticornis and E. brassiana (Tables 2 and 5). Most areas with these climate conditions are located in the central-western and northeastern regions (western), where the "new forest frontiers" are found. There is not much knowledge of abiotic and biotic interactions of genotypes with the site. Above 400 mm year^{-1} of water deficit eucalypt plantations are not economically viable.

Gava and Gonçalves (2008), Alvares (2011) and Gonçalves et al. (2012) evaluated the effect of different physical and chemical soil attributes on wood quality and productivity of E. grandis and E. grandis × urophylla plantations for cellulose production in several sites at the Western Plateau of the State of São Paulo, with ages ranging between 6.0 and 7.0 years. Four soil types, with texture ranging from sandy to very clayey were found. They found high relationship between MAI and several attributes of soil, mainly clay content, which was directly related to the amount of soil plant-available water content (Fig. 4; see also Marsden et al., 2012, this issue). Gava and Gonçalves (2008) found that basic wood density did not changed at different soil types, total lignin content decreased and holocellulose content and screened cellulose yield increased exponentially as soil clay content increased (until about 350–400 g kg^{-1} of clay). The wood extractives content was not affected by soil attributes.

6. Root configuration depending on water and nutrient stresses

Traits of the eucalypt and its outstanding success to thrive in harsh environments reflect the evolution of a particularly strong adaptation where water and nutrients are limited. There are a

Table 4
Characteristics of wood, main uses, susceptibility/resistance to pests and diseases and sprouting capacity of species and hybrids commonly used in plantations (short rotation 6–8 years).

Species/hybrids	Wood density (g cm^{-3})	Lignin content (%)	Main uses	Susceptibility/resistance		Capacity of sprouting[a]	
				Pests[b]	Diseases[c]	Stump survival	Vigor of shoot
Corymbia citriodora	0.72–0.75	22–25	Sawnwood, fuelwood, charcoal, treated wood	Susceptible to bluegum psyllid (BGP); tolerant to redgum lerp psyllid (RGLP), bluegum chalcid (BGC) and bronze bug (BB)	Susceptible to *Cylindrocladium* leaf spot; resistant to canker and very resistant to rust; susceptible to *Armillaria* root disease (ARD)	Low to medium	Low to medium
E. benthamii	0.48	24–25	Pulpwood, sawnwood, treated wood, firewood	Susceptible to BGP	Very resistant to rust and canker	Low to medium	Medium
E. camaldulensis	0.60–0.70	28–32	Pulpwood, sawnwood, charcoal	Susceptible to several species of psyllid; very susceptible to RGLP, BB and BGC	Susceptible to leaf spot of *Mycosphaerella* (LSM) (several species); resistant to very resistant to rust and canker; susceptible to ARD	Medium to high	Medium to high
E. dunnii	0.44–0.52	22–23	Pulpwood, sawnwood, treated wood, firewood	Susceptible to BGP and BB	Resistant to rust; very resistant to canker; susceptible to LSM (several species)	Low to medium	Medium
E. grandis	0.42–0.48	24–26	Pulpwood, fuelwood, sawnwood, panel, treated wood, charcoal	Very susceptible to BB; susceptible to BGC; tolerant to RGLP	Susceptible to very susceptible to rust and canker; susceptible to LSM (several species)	Low to medium	Low to medium
E. saligna	0.46–0.52	24–27	Pulpwood, sawnwood, panel	Very susceptible to BB and BGC; tolerant to RGLP	Good sources of resistance to rust; very susceptible to canker; susceptible to LSM (several species)	Medium to high	Medium to high
E. tereticornis	0.60–0.65	30–32	Pulpwood, sawnwood, panel	Very susceptible to RGLP, BGC and BB	Susceptible to LSM (*M. marksii* and *M. molleriana*); resistant to very resistant to rust; resistance to canker varies from very susceptible to highly resistant	Medium to high	Medium to high
E. urophylla	0.48–0.56	27–29	Fuelwood, charcoal, treated wood, pulpwood	Very susceptible to RGLP; susceptible to *Eucalyptus psyllid* (*C. spatulata* and *B. occidentalis*); tolerant to BGC	Good sources of resistance to rust and canker; susceptible to LSM (several species)	High	High
E. camaldulensis × grandis	0.47–0.49	29–31	Pulpwood, fuelwood, firewood, charcoal	Very susceptible to BGC; susceptible to BB and RGLP	Susceptible to canker	High	High
E. urophylla × globulus	0.51–0.54	23–25	Pulpwood	Unidentified occurrence in the plantations	Resistant to rust and *Teratosphaeria* spp.	Medium to high	Medium to high
E. urophylla × grandis	0.48–0.52	26–29	Pulpwood, charcoal, fuelwood, panel, sawnwood, treated wood	Susceptible to RGLP and BB	Good sources of resistance to rust and canker; susceptible to LSM (several species)	Medium to high	Medium to high
E. urophylla × tereticornis	0.53–0.64	28–35	Fuelwood, pulpwood, charcoal	Very susceptible to RGLP	Susceptible to leaf spot of *Cylindrocladium pteridis*	High	High

This table was compiled from data published by Higa and Sturion (1991), Ferreira (1992), Pereira et al. (2000), Fonseca et al. (2010), and information obtained from forest companies associated to Forestry Science and Research Institute (IPEF, Brazil).

[a] Stump survival: high (>90%), medium (80–90%), low (<80%), mainly dependent on the genetic characteristic of the species/hybrid and environmental conditions. Generally, the greater the water deficit, the lower is the capacity of sprouting. If survival is low, it is not recommended use coppice system.

[b] Pests: bronze bug (*Thaumastocoris peregrinus*); bluegum chalcid (*Leptocybe invasa*); redgum lerp psyllid (*Glycaspis brimblecombei*); *Eucalyptus* psyllid (*Ctenarytaina spatulata* or *Blastopsylla occidentalis*); bluegum psyllid (*Ctenarytaina eucalypti*).

[c] Diseases: *Eucalyptus* rust (*Puccinia psidii*); basal canker (*Diaporthe cubensis*); *Eucalyptus* leaf disease (*Mycosphaerella*); *Armillaria* root disease (*Armillaria luteobubalina*).

Table 5
Climate type, mean annual rainfall, temperature and actual evapotranspiration, dry season, the main species and hybrids recommended for planting and expected average productivity (roundwood with bark) of the planted areas with eucalypts.[a]

Type climate	Mean annual rainfall (mm year^{-1})	Mean annual temperature (°C)	Mean actual evapotranspiration (mm year^{-1})	Dry season		Species/hybrid[c]	Mean annual increment (m^3 ha^{-1} year^{-1})
				Number of months	Water deficit[b] (mm year^{-1})		
Cfa, Cfb	1500–2500	13–20	500–1000	0–2	0–50	EUG, Egr, Eur, Esa, Cci, Edu, Ebe, EUG	35–60
Cwb, Am	1000–1800	18–20	800–1100	2–3	50–100	EUG, Egr, Eur	35–45
Cwa, Aw	1000–1800	20–24	1000–1200	3–4	100–200	EUG, Eur, EGC, EUC, Eca, Ete	35–45
Aw	1100–2000	24–26	1100–1500	4–6	200–400	EGC, EUC, ETB, Eca, Ete, Ebr, EUT	25–35
As, BSh	700–1500	23–27	600–1000	>6	>400	Planting is not feasible	

[a] This table was prepared based on information obtained from foresters who work for companies associated with the Institute of Forest Research and Studies, Brazil, and information presented by Fonseca et al. (2010) and Silva (2008).

[b] According to the soil water balance proposed by Thornthwaite and Mather (1955).

[c] Egr = *E. grandis*; Esa = *E. saligna*; Eur = *E. urophylla*; Cci = *Corymbia citriodora*; Ete = *E. tereticornis*; Ebr = *E. brassiana*; Ebe = *E. benthamii*; Edu = *E. dunnii*; EGU = *Eucalyptus urophylla × grandis* (urograndis); EGC = *E. grandis × camaldulensis* (grancam); EUC = *E. urophylla × camaldulensis* (urocam); ETB = *E. tereticornis × brassiana*; EUG = *E. urophylla × globulus*; EUT = *E. urophylla × tereticornis*.
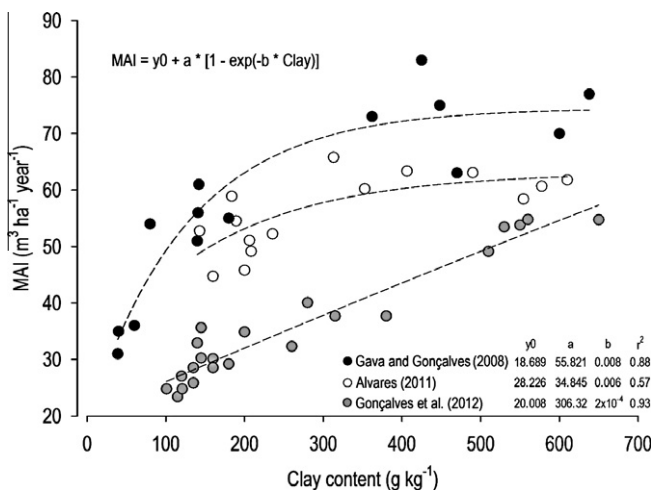

Fig. 4. Relationship between increases in mean annual increment (MAI) of roundwood and clay content (0–20 cm layer) for three sites of eucalypt plantations in Sao Paulo state.

number of attributes of tree roots that influence the ability of the tree to compete for soil resources in regions of small availability of water, nutrients, air, growing space (Gonçalves and Mello, 2004; Florence, 2007). The attributes include the structure of the root system, the distribution of fine roots, the seasonality of growth, and the physiological ability to take up water and nutrients (Comerford et al., 2006).

The root structure and growth are important attributes genetically controlled by the species and individual—an evolutionary response to maintain the competitive ability in sites with specific characteristics (Florence, 2007). In general, mechanisms and processes that enable a plant to cope with periodic, severe, water deficit in the soil involve a tradeoff to the plant in terms of reduced growth potential (Gonçalves and Mello, 2004).

The eucalypt root system has high relationship with the site quality. This may be expressed through the root: shoot ratio of the plant, or a tendency to develop a strong tap root according to water stress. The tree root configuration may be modified according to site conditions (soil moisture, depth, texture and structure, stoniness, hard horizons, etc.) (Jacobs, 1955; Krejci, 1986; Gonçalves and Mello, 2004). This has high variability in terms of species and hybrids. Species and hybrids that express different degrees of drought tolerance show differences in the root structure. Tap root depth, vertical and lateral distribution of roots, particularly fine feeder roots play a significant role in determining adaptation

to site. Species or hybrids exhibiting low drought tolerance produce a large number of medium and fine lateral root in the surface soil horizons, but not a deep and strong tap root, and the root systems show a small response or do not respond at all to dry soils. Moreover, highly-drought tolerant species produce vigorous and deep tap roots, and sinkers emerging from the laterals towards the base of the tube in a dry soil. The ability of the genotype to rapidly develop a strong, deeply descending root system in a dry soil is undoubtedly an important adaptive feature in drought conditions (Krejci, 1986; Gonçalves and Mello, 2004; Florence, 2007).

In eucalypt plantations established in coastal regions of Brazil, in clayey cohesive Ultisols with physical impediments like fragipan and iropan, under high water stress, species and hybrids more tolerant to droughts are those that produce the more vigorous tap roots associated with the capacity to explore cracks by sinkers. For the genotypic adaptation of eucalypt in these edaphoclimatic conditions, the development of specific equipment and techniques specific for deep subsoiling (80–120 cm) was fundamental (Stape et al., 2002; Souza, 2002).

Most total root length of eucalypt plantations consist of fine roots, and mainly established in the upper section of the soil profile (Gonçalves and Mello, 2004). It is not only the distribution of fine roots in the soil profile that contributes to the adaptation of a genotype to its environment, but also the root dynamics. Fine root productions exhibit strong seasonal variations (Laclau et al., 2004; Mello et al., 2007; Thongo-M'Bou et al., 2008). When edaphoclimatic conditions are favorable, there is rapid production of fine roots, from recent assimilates or from carbohydrates and nutrients stored in thicker roots (Ford and Deans, 1977). In times of increased water availability and soil temperature, the production of fine roots is accelerated, boosting shoot growth (Teskey and Hinckley, 1981; Hendricks et al., 1993; Joslin et al., 2001; Mello et al., 2007). There is continual death and replacement of fine roots (Thongo-M'Bou et al., 2008). Observations of the root system at anytime provide only a static view of the system. The dynamic view is much more valuable, particularly when it includes the turnover of fine roots during the year, the soil exploration rate by roots, and the times of the year when root systems are most active (Mello et al., 2007; Jourdan et al., 2008; Laclau et al., 2010a,b). A more dynamic root system is more effective to explore a large soil volume and maximize access to water and nutrients.

The senescence of fine roots can be accelerated by stressful conditions due to seasonal variations in temperature, soil water status, injuries to canopy (defoliation, parasitism), hormonal changes, among others. Thus, fine roots are ephemeral components and have a turnover rate comparable to leaves; therefore, it is expected similar response patterns of these components to environmental factors (Lyr and Hoffmann, 1967; Gonçalves and Mello, 2004).

Strong correlations between leaf and fine root biomass have been observed in eucalypt plantations (O'Grady et al., 2005; Laclau et al., 2008) and are suggested by theories linking organ structure and function (Magnani et al., 2002). Moreover, in a forest stand, specific and interspecific competition between individuals play a preponderant role in the root growth process (Florence, 2007). The root growth rate differs between species; however, maximum growth occurs in most tree species in early summer (December and January). The way root activity responds to environmental factors may influence the relative capacity to adapt to water deficit.

Gonçalves (1994) studied at 18 stands of *E. grandis* (mean age = 5.6 years) the distribution of fine roots (diameter ⩽3 mm) in profiles of loamy and clayey Oxisols (OXS) and Quartzipsamments (QTZ). In the three clayey OXS and productive sites, fine root density (FRD) decreased exponentially from 0.57 g dm^{-3} to 0.04 g dm^{-3} and in the three sandier soils and less productive sites, FRD decreased exponentially from 1.13 g dm^{-3} to 0.09 g dm^{-3}, from the upper to the bottom layer, respectively. The mean annual increment of roundwood was linear and negatively correlated to FRD at 0–10, 50–100 and 100–150 cm with coefficients of correlation increasing with the depth of the soil layer. The higher FRD in OXS than in QTZ and a strong correlation between productivity and FRD were associated to adapting mechanisms of trees to drought periods in the upper soil layers, when deeper layers become the main water supply.

In another study of root distribution, Mello et al. (1998) found that a 4.5 years-old stand of *E. grandis* × *urophylla* (a highly productive clone) exhibited a five time lower fine root length (diameter <1 mm) in the forest floor than a stand of *E. grandis* (seedlings of average productivity) at the same age (5500 versus 25,200 km ha^{-1}). By contrast, the length of fine roots in the soil profile was higher for the highly productive hybrid than for the stand of *E. grandis* (91,400 versus 53,100 km ha^{-1}). They found large seasonal FRD variations between the three genotypes studied. The most productive clone of *E. grandis* × *urophylla* was a genotype more plastic to seasonal changes of water content in the soil, than the seedling stand of *E. grandis*. In dry and cold winters, FRD of the most productive clone was higher in upper soil layers (down to 30 cm deep), and during the rainy summer, FRD was higher in layers below 30 cm. There was no significant difference between genotypes with respect to the cumulative length of fine roots in the soil profile sampled in the winter. About 70% of roots were found within the upper 30 cm. Differently, in the summer, the cumulative distribution of fine roots of the superior clone was quite different than that found in the winter, when only 30% of fine roots were found within the upper 30 cm of soil, i.e., in the summer, the roots of this genotype were distributed more homogeneously in the soil profile. Root distribution throughout the soil profiles was not significantly different for the other genotypes. This large seasonal variation in FRD for the superior clone shows its great capacity to adapt to adverse environmental conditions, which constitutes a major factor in its superiority towards other genotypes. In the summer, period of high metabolic activity, when water demand is very high, trees of this clone increase FRD in depth to a large amount of water, and therefore more nutrients dissolved in soil solutions. On the other hand, in the winter, with the slowed tree growth, FRD in deeper layers is reduced. These results show the importance of morphological plasticity of FRD as an adaptive strategy to drought periods and nutritional stress. A similar behavior was also found in *E. grandis* stands studied by Mulligan and Sands (1988). The higher morphological plasticity of the superior clone partly explains the higher productivity of this genotype in large plantations under different edaphoclimatic conditions. There is a clear and efficient "feedback" mechanism of the root system when environmental conditions change (Adams et al., 1989).

The fine root turnover in 9-year-old *E. grandis* stands grown in a loamy OXS and in a QTZ was evaluated by Mello et al. (2007). On each soil type, the experimental area was divided into three plots that corresponded to the following time sequence: mature forest before harvesting, after harvesting in the summer and after harvesting in the winter. Fine roots (diameter <3 mm) were sampled by sequential coring. There was a significant seasonal difference in fine root density (diameter <1 mm) at 0–10 cm in OXS (2.3 and 4.4 cm cm^{-3}) and QTZ (5.7 and 8.2 cm cm^{-3}), in the winter and summer, respectively. Fine root dynamics were significantly reduced after harvesting, mainly in the surface layer in both soils. An approx. 50% decrease in FRD was observed 60 days after harvesting in the two soil types. Seasonal variations in FRD over 2 years were markedly influenced by rainfall distribution. The peak in root growth coincided with periods of high rainfall, and fine root growth correlated negatively with drought periods. The regrowth of fine roots after harvesting was synchronized with requirements for water and nutrients by the coppicing stands. A similar pattern was reported for eucalypt plantation in Congo and root growth reduction was likely driven by the whole plant water status that affects photosynthetic carbon uptake rather than a direct effect of local soil water status on root activity (Thongo-M'bou et al., 2008).

The relationship between the vertical extension of shoots and roots throughout plant growth reflects their strategies to explore the environment and depends on the development of fine roots. Aiming to compare the vertical velocity of the above- and below-ground exploration of the environment by eucalypt plantations established in a deep OXS, Christina et al. (2011) showed that the root front depth was accurately predicted at 85% of the average tree height for stands up to 20 m high, in the absence of any physical or chemical barrier. Early vertical tree growth was fast above and below ground, reaching 10.4 m high and 9.2 m deep at 1.5 years of age, and 19.2 m high and 15.8 m deep at 3.5 years of age. The root front and height growth followed a similar pattern until 42 months of age, when roots reached the vicinity of the water table. From the age of 42 months onwards, the root front depth did not increase further. Tree height and root front growth velocities peaked at 0.59 and 0.55 m month^{-1} respectively 9–10 months after planting, and decreased steadily thereafter. Fast root front displacement might provide a competitive advantage to fast-growing species in forests established in deep soils, particularly if there is water deficiency. This pattern indicated that active water withdrawal extended down to high soil depths during dry periods, starting in the second year after planting. The decrease in water content in the soil at a depth of 10 m from 43 to 56 months after planting showed that water was withdrawn very deeply at the end of stand rotation.

7. Silvicultural practices used to alleviate the biotic and abiotic stresses

7.1. Soil preparation

During site preparation, plant residues can be burned or mixed with surface soil, e.g. by conventional plowing, or retained on soil surface between the planting rows or the planting spots. Until the late 1970s, silvicultural practices regarding residue management and soil preparation followed a typically agronomical pattern, as windrowing and/or residues burning and intense turning of the topsoil. This was the sole recommendation for large forest plantations, regardless of climate, soil type and genotype. The need to reduce soil erosion, nutrient output and costs has led to a progressive increase in the use of minimum cultivation practices, including slash and litter retention, during the last decades in Brazil (Gonçalves et al., 2008). The minimum cultivation system prescribes the

maintenance of plant residues (litter and harvest residues) on the soil, followed by soil preparation in planting rows or pits. The first pilot projects on a commercial scale were established in 1989 in eucalypt plantations in the municipality of Itatinga, São Paulo state, (Zen et al., 1995). In a study conducted in 2002, about 72% of forest plantations were established in minimum cultivation system (Gonçalves et al., 2002). Currently, it is estimated at over 85% of the plantations are established in this system.

Soil preparation can help overcome the limitations of water resources for eucalypt stand during the dry season in two ways. The first is due to the increase of rainfall infiltration, reducing runoff, thus increasing the water reserve in the soil. The second refers to the increase of soil effective depth when there are layers of physical impediment (Gonçalves et al., 2002; Stape et al., 2002). The increased infiltration is favored when compacted or hardened layers are disrupted, especially when crop residues are kept on the soil surface. Experiments established as part of a CIFOR research network (Bouillet et al., 2000; Gonçalves et al., 2000; O'Connell et al., 2000; Sankaran et al., 2000; du Toit et al., 2000; Xu et al., 2000; Laclau et al., 2010a,b; Versini et al., 2012, this issue) indicate that the presence of different amounts of litter and logging residues on the soil surface increase eucalypt productivity at different levels related to some extent to water and nutrient availability. Residue retention in some sites increased water and nutrient status. This was associated with reduced losses of nutrient and organic matter and the maintenance of crucial soil physical properties such as porosity and thereby permeability, root growth, infiltration, and aeration (Gonçalves et al., 2002; Stape et al., 2002; Xu and Dell, 2002).

For soils with textural gradient, the subsoiling of the upper sublayer of B horizon also tends to increase water infiltration. Regarding the increase in soil effective depth, certain hardened layers are susceptible to disruption by the roots only when wet (fragipans), while constituting constriction points of root growth. More cemented layers are impenetrable even when wet (plinthites) and directly affect water status during dry seasons. The hardened layers, when situated at top layers, may cause poor soil drainage, resulting in very wet conditions during the rainy season. Accordingly, the disruption of these layers promotes plant growth in rainy seasons by eliminating water excess and allowing better soil aeration for growing roots (Gonçalves et al., 2002; Stape et al., 2002).

The most commonly used implements in managed areas in minimal cultivation systems are the ripper (work depth >30 cm) and the pit digger. The latter is used on very steep slopes (heavily undulated and mountains) (Silva et al., 2002) or where there are many physical obstacles to using the ripper, such as in areas under intercropping with many thick stumps. On steep slopes higher than 30–35% of slope (depending on the irregularity of the terrain), mechanical soil preparation is not feasible, thus it is restricted to the manual opening of planting holes (20 cm × 20 cm × 20 cm). The operational yields obtained with the ripper are higher than those using a pit digger (Gonçalves et al., 2008).

7.1.1. Friable soils

The potential response to soil preparation is smaller in friable soils (coarse texture or oxide-rich), with a direct relationship with water and nutrient status. The good physical conditions of the soil allow its preparation any season of the year (Gonçalves et al., 2004). This soil condition favors winter forest establishment (accomplished during the driest and coldest season of year) and has become a common practice in the south-eastern region. Likewise, it allows soil preparation and planting in periods of Indian summer, followed by post-planting irrigation for the first 2 weeks to ensure field adaptation of the seedlings, until root systems are well established in the soil (Gava, 2002; Gonçalves et al., 2002).

The reduction of bulk density through soil preparation in the planting row or hole leads to fast root growth and, consequently, increases fertilizer use efficiency through greater use of water and nutrients by adjacent seedlings (Gonçalves et al., 1997). Even in friable soils, soil preparation ensures faster growth of juvenile roots, which experience lower physical soil resistance, resulting in energy saving and increased radial and longitudinal growth (Gava, 2002). Rapid seedling establishment increases its competitive capacity to survive under water and nutrient stress, besides providing greater protection to the soil. In flat and slightly undulating terrain, soil preparation consists of ripping up to 30–40 cm depth. When large amounts of residues are found on the soil, ripping is possible (2.5–3.5 m interrow spacing) down the slope (gradient between 12% and 35%) with low risk of erosion. In this case, ripping must be performed during low rainfall periods (fall, winter and spring) and, preferably, with ripping furrow interruption every 20 m (Gava, 2002; Gonçalves et al., 2002; Silva et al., 2002). Regarding soil hardening and compaction, the ripping depth is usually 30–35 cm and the planting hole opening, either manual or mechanical, is limited to 25–30 cm. These depths may sometimes increase, depending on soil bulk density (Gonçalves et al., 2008).

7.1.2. Cohesive soils

Cohesive soils occur in some coastal areas in the northeastern region. They show serious physical and chemical restrictions due to high rainfall variability (monthly and interannually). Therefore, silviculture can become unviable if soil preparation is not properly planned and managed (Souza, 2002). For a similar amount of rainfall, soils of higher effective depth or clones with higher root penetration capacity tend to be more productive. Nutritional restrictions are overcome by fertilizer application. For the decision-making process on soil preparation, rainfall rate and root depth reaching the layer of physical impediment need be considered (Souza, 2002; Stape et al., 2002). In areas where rainfall is higher and evenly distributed, the ripping depth is lower. If the soil has a fragipan or hardpan between 50 and 80 cm, the ripping depth will be in the range 60–90 cm; should the layer with physical impediment be above 80 cm, the ripping depth may reach 110 cm.

These soils should be prepared during the wet season to facilitate implement penetration and provide seedlings a long period for root growth. Since soil preparation is performed in planting rows, 3.0–3.5 m spacing, the interrow topsoil should undergo preparations. At more compact soils, a harrow is applied (20–30 cm depth) in order to help root elongation. The operation is carried out 10–20 months after planting, early or late in the rainy season, with wet soil (above 50% permanent wilting point) and when canopy cover can prevent direct impact of rain to the soil. Therefore, a good relationship between soil preparation effect and effort required is achieved (Stape et al., 2002; Sasaki et al., 2007).

7.1.3. Growth response to 'minimal cultivation'

Gonçalves et al. (2004) conducted an experiment to assess the effect of site management practices of minimal and intensive soil cultivation on plant growth, soil fertility, nutrient cycling and nutrition of a E. grandis stand. The climate of the area is of the Cwa type, i.e. mesothermic with dry winters. The average annual precipitation of the area is 1579 mm, 57% of which occurring between December and March. The soil type of the area is classified as a typical Oxisol, loamy (200 g kg^{-1} clay), dystrophic. Different soil preparation and residue management resulted in pronounced growth effects. The treatment in which all residues were retained on soil surface showed the highest growth at 6.4 years of age. The lowest growth occurred when all residues were removed. Removal of bark and slash caused a reduction in productivity of 40 m^3 ha^{-1} (14.5%) of stem volume. When compared to the treatment in which all residues were retained and that in which all res-

idues were removed, the reduction reached 101 m^3 ha^{-1} (36.5%). Therefore, these results corroborate the important role that residues play on productivity of low-fertility soil. Results from other CIFOR network sites of low-fertility soils in Australia (O'Connell et al., 2000) and Congo (Bouillet et al., 2000) also showed similar trends. Furthermore, in the same treatments, Silva et al. (1997) found that weed occurrence was much lower when residues were maintained on soil surface, obstructing, therefore, the germination of weed seed bank in the soil.

For two sites with high water deficit and cohesive soils on the northern coast of Bahia, Stape et al. (2002) reported the results of a trial conducted to evaluate the effect of soil preparation and fertilization on clonal stands of the hybrid *E. grandis* × *E. urophylla*. The soil of one site was classified as a loamy red-yellow Oxisol (100 mg kg^{-1} clay in A horizon and 150 mg kg^{-1} in B horizon), plane relief, and the sum of bases was 1.3 cmol$_c$ kg^{-1} in the A horizon. The soil of the other site was classified as a red-yellow Ultisol with loamy/clayey texture (180 mg kg^{-1} clay in the A horizon and 300 mg kg^{-1} in the B horizon), plane relief, and the sum of bases was 4.3 cmol$_c$ kg^{-1} in the A horizon. Trees in the first site showed good growth until the third or fourth year, when high mortality of trees was caused by water deficit during the dry season. Until this event, all treatments in the Ultisol grew better than in the Oxisol. Thus, in the most fertile soil, while water availability was not limiting, tree growth was little influenced by soil preparation regardless of residue burning or fertilization. In the dry season, there was great mortality of trees in all treatments, leading to the living tree biomass in the fourth year in the Oxisol to surpass that in the Ultisol. The largest mortality in Ultisol was attributed to less effective rooting depth, where B horizon is very cohesive, causing greater water stress to trees. Ripping at 60 cm along the planting rows (3 m between rows) was not enough to develop adequate rooting structure to resist drought.

7.2. Stocking

Defining the initial spacing for eucalypt plantations is essential because it determines the amount of natural resources available for each tree growth. Spacing greatly affects production, moreover, it has several implications regarding silvicultural, technological and economic aspects, as it influences growth and survival rates of trees, crown and branch amount, wood quality, bark amount, age of harvesting as well as harvesting processes and forest management, and therefore, production costs of eucalypt plantation (Leite et al., 1997; Leles et al., 2001; Gonçalves et al., 2004).

Closer spacing promotes faster development of the leaf area index (LAI), which increases light interception and photosynthesis: conversion efficiency is regulated by water and nutrient supply. The dynamics of LAI can be used to characterize pre- and post-canopy closure of developmental stages of eucalypt plantations (Landsberg and Waring, 1997), which are affected in different ways by silvicultural practices. During the pre-closure phase, trees tend to be more responsive to cultivation, fertilizers and weed control, while soil erosion tends to be greater (Gonçalves and Mello, 2004). After canopy closure, intraspecific competition for resources becomes strong. In many studies of *Eucalyptus*, the age at peak LAI coincides with the highest rate of biomass production (Ryan et al., 1997). Species with denser crowns, such as *E. grandis*, *E. urophylla*, *E. saligna* and *E. pellita* are more responsive to spacing variations than less dense crowns, like *E. camaldulensis*, *E. tereticornis*, *C. citriodora* and *E. brassiana* (Gonçalves and Mello, 2004). This behavior is directly associated with the intraspecific capacity of species to compete for light, water and nutrients (Florence, 1996; Gonçalves and Mello, 2004).

Consumption and water use efficiency are greatly affected by tree spacing. In an experiment conducted in the municipality of Santa Bárbara, southern region in Brazil, Leite et al. (1999) assessed the internal rainfall, evapotranspiration and soil water status (Typical Clayey Oxisol) cropped with *E. grandis* (32–38 months old), with stand densities ranging from 500 to 5000 ha^{-1} plants. The canopy rainfall interception (18–21%) increased linearly with higher stocking (due to higher LAI), while evapotranspiration rates were not affected. Soil moisture was higher with lower stocking, highlighting the important role spacing plays in the efficient use and management of soil water status. The results showed that consumption and water use efficiency are higher in wider spacing, mainly because of lower rainfall interception by the canopy in closer spacing, where water is lost by evaporation.

Biomass allocation to different parts of the tree is significantly affected by spacing (Gonçalves and Mello, 2004). For example, Bernardo et al. (1998) observed in wide spacing of stands of *E. urophylla* and *E. pellita* that there was a reduction in the ratio between stem biomass and total biomass, due to increased biomass allocation to leaves and roots. In stands of *E. camaldulensis*, the authors observed increased biomass allocation to growth roots wider than 2 mm, in detriment of stem biomass production. The different responses to spacing regarding production and partitioning of photoassimilates may occur because of site quality, with regard to water, nutrient and light status (Gonçalves and Mello, 2004). The higher is water and nutritional shortage, the greater is allocation of photoassimilates to root growth (Reis et al., 1985; Mello et al., 2007).

The distance between trees (spacing), or the number of trees planted per hectare (stocking), is one of the most important silvicultural decisions for the establishment of an eucalypt plantation. The choice of planting density depends on edaphoclimatic conditions of the site, requirements of the timber market and the many purposes of the plantation. For many years, seedling plantations were established using stocking ranging from 2200 to 1600 trees ha^{-1} (3.0 × 1.5–2.0 m spacing), which anticipated loss rates up to 10% due to mortality and poor growth of some trees (Stape et al., 2001). In drier regions of Brazil, water availability can impose serious limitations to forest growth and reduce stocking. For instance, in some plantations in the Brazilian northeast, the initial densities of 1600–2500 trees ha^{-1} can decrease to 900–1000 of living trees ha^{-1} at 7 years of age (Gonçalves et al., 1997). The use of highly-productive clones, the potential to reduce harvesting costs with the production of larger trees, and the lack of water in some sites may result in a reduction of the initial stocking to 800–1100 trees ha^{-1} (3.0 × 3.0–4.0 m). Under these conditions, the acceptable mortality rate is lower than 5% in order to ensure stockings over 1000 trees ha^{-1} for pulpwood and 800 trees ha^{-1} for sawnlog (Stape et al., 2001). Wide spacing may also be used in water catchments to increase water yield in the site (Lima et al., 2012). Higher stocking will increase mean annual increment and shorten the time to the maximum. As a general rule for a given rotation length, higher stocking leads to higher total biomass production per unit area, but lower biomass per tree.

Observing Fig. 5, concerning the production of roundwood of six clones of *E. grandis* and *E. saligna* under increasing stocking – 8 years of age (Stape et al., 2001), allows to conclude that there is not a point for ideal spacing, but a range. Within this range, there is compensation for the growth rate, without major changes in productivity.

7.3. Application of fertilizers

There are significant yield gains in response to fertilization in most eucalypt plantations in Brazil (Barros et al., 2004; Gonçalves et al., 2008). Regardless of weather conditions, the magnitude of the response depends on the nutritional demand of the genotype and on the availability of soil nutrients. Especially in soils with low fertility, continuous nutrient removal by crops consecutively
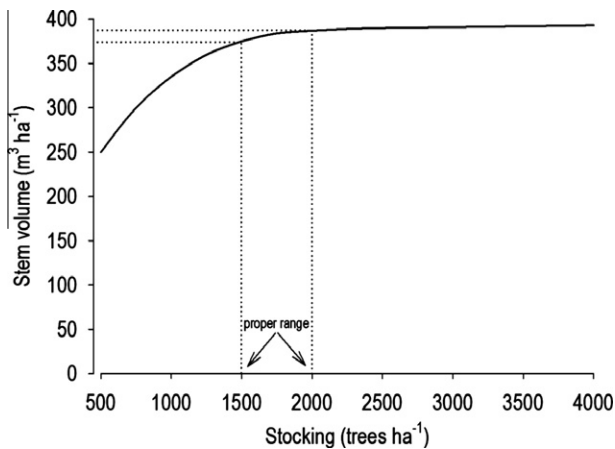
Fig. 5. Average volumetric production (8 years old), of six *E. grandis* or *E. saligna* clones in Sao Paulo state with increasing initial stocking densities (Stape et al., 2001).

increases the potential response to fertilizer application (Gonçalves et al., 1997, 2008; Laclau et al., 2005, 2010a,b). Gains in productivity attributed to mineral fertilizers are quite variable and high, but in general, they represent at least 30% to 50% on average (Gonçalves, 2011).

Although continuous fertilization throughout crop rotation can be used to maximize tree growth, recent results showed that forests adequately fertilized at early stages, which produced an adequate canopy structure at 2 years of age, are highly efficient in using nutrients through the biogeochemical cycles, becoming little responsive to further fertilization (Stape et al., 2004; Laclau et al., 2010a,b). Since investments in fertilizers are relatively high for most forest producers, fertilization should be combined with other silvicultural practices to reduce fertilizer demands in the short or long-term. In eucalypt plantations established in soils with high seasonal water stress and low fertility, techniques of minimum cultivation have played an essential role to mitigate water and nutrient stress to plants. When plant residues are kept on the soil and surface layers are not tilled, soil moisture and structure are preserved making the process of transferring water and nutrients to the roots more effective and, therefore, increasing the potential response to fertilization (Gonçalves et al., 1997; Gonçalves et al., 2002, 2008).

Before LAI peak is reached, responses to fertilizer are very common (Cromer et al., 1995; Herbert and Schonau, 1989; Gonçalves et al., 2004; Laclau et al., 2010a,b). When a response to fertilizer occurs, increased rates of nutrient uptake lead to an LAI increase, which can prolong leaf retention and increase photosynthetic efficiency (Cromer et al., 1995; Binkley et al., 2004; Laclau et al., 2009). Increased nutrient uptake also affects partitioning in eucalypt stands by increasing allocation to foliage in detriment of roots, reducing the root: shoot ratio (Bouillet et al., 2002; Mello et al., 2007; Laclau et al., 2010a,b). After canopy closure, internal and external nutrient cycles become more important, as light and water become more limiting due to intraspecific competition (Grove et al., 1996; Gonçalves et al., 2000, 2008; Laclau et al., 2010a,b).

Nutrient cycling reduces tree dependence on net nutrient supply from soil reserves. Mobile nutrients (namely N, P and K) are redistributed in the plant increasing efficiency for biomass production. Biogeochemical cycles lead to a smaller dependence of eucalypt plantations on nutrient reserves in the mineral soil at the end of the rotation, through intense recycling processes of retranslocation, foliar leaching and litter decomposition (Laclau et al., 2003, 2010a,b; Barros et al., 2004; Gonçalves et al., 2008).

Nutrient requirements by the plant depend on its growth rate and the efficiency that it converts the absorbed nutrients into biomass. Using information from different genetic materials, ages, silvicultural techniques and locations in Brazil, Santana et al. (1999) found that correlation coefficients between eucalypt trunk biomass and macronutrient content ranged from 0.76 to 0.96 ($p < 0.01$). The highest values found were for P and K, respectively. Differences in nutritional efficiency among forest species (Moraes et al., 1990; Gonçalves et al., 1997), and even among provenances and hybrids of eucalypt (Gonçalves et al., 2008) have been verified. Different genetic materials can present differences in the efficiency of nutrient acquisition from the soil and/or in the use of nutrient uptake in the production of stem dry matter or any other product that is taken from the forest (Barros et al., 2004). The interaction between the genotype and the environment is an important factor that must be taken into account to optimize fertilizer prescriptions in forest plantations.

Nutritional stages of a eucalypt stand can be divided into before, during, and after canopy closure. Understanding these stages and nutrient cycling is essential for the adequate planning of fertilizer application (rate, method, and time). Fertilizer recommendation should preferably be adjusted at regional level to the most representative species and soil types, based on field experimentation, and should allow optimization of financial returns. Fertilization is performed during the initial stage of eucalypt establishment, from the planting to canopy closure (1–2 years of age, depending on growth rate). The most frequent and most significant responses to fertilizers in Brazil are to P, K and B. Only in special cases, responses to N and Ca have been reported, while responses to other nutrients are rare. Normally, for sandy and water-deficient soils, responses to fertilizers are more common (Gonçalves et al., 2008; Gonçalves, 2011).

Gonçalves et al. (2008) proposed classes of expected responses and recommendations for N–P–K fertilization of eucalypts based on soil organic matter and clay contents, resin-extractable P, and exchangeable K. The recommendations for N are 60, 40 and 20 kg ha^{-1} depending on whether soil organic matter concentrations are 0–20, 21–50 and >50 g kg^{-1}, respectively. The authors considered that organic matter and clay contents, besides relating to the availability of N, P and K, directly affect potential productivity through water status. The extreme rates of N, P and K are of 60, 70 and 120 kg ha^{-1}, respectively. Normally, in average rotations of 7 years, up to 2 Mg ha^{-1} of lime, 60–80 kg ha^{-1} of N, 60–80 kg ha^{-1} of P$_2$O$_5$, 140–160 kg ha^{-1} of K$_2$O, 1–5 kg ha^{-1} of B are applied, depending on local water deficit, and 1 kg ha^{-1} of Cu and Zn. Fertilizers are applied in synchrony with plant growth and, therefore, the nutrients are rapidly uptake.

Phosphorous doses can be thoroughly applied at planting, since this nutrient is little movable and relatively little soluble. N and K doses should be divided into one or two surface applications. It is recommended to apply 1/3 of the doses of N and K in the first surface application and the remaining, in the other applications (Gonçalves et al., 2008). Doses of up to 50 kg ha^{-1} of N and K$_2$O may be applied thoroughly in one single surface application, once risks of leaching are low (Maquère et al., 2005; Laclau et al., 2010a,b). In the application at planting, aiming to boost seedlings growth and, therefore, their competitive potential against weeds, it is recommended to apply close of the seedling, in a continuous bead in furrow at subsoiling or in lateral little pit from 10 kg ha^{-1} to 15 kg ha^{-1} of N and K$_2$O (Gonçalves et al., 2008).

Regarding the direct effect of mineral fertilization on the plant physiology, K applications may considerably increase water use efficiency by the eucalypt, which is a critical factor to boost its productivity in water-deficiency regions. Almeida et al. (2010) evaluated the effect of fertilization with K in plantations of *E. grandis* in a loamy Oxisol (200 g kg^{-1} clay). The transpiration rates in the

treatments that received K applications were, on average, 20% higher than the control, at 36 months of age. On the other hand, the amount of transpiration per unit of leaf area was lower in the treatment that received K applications (0.62 mm day^{-1} m^{-2}) in relation to the control (0.96 mm day^{-1} m^{-2}). Therefore, although the fertilization increased water consumption, there was a significant gain in wood productivity and water use efficiency. Moreover, K fertilization increased plant resistance to rust (*Puccini pisidii* Winter). In this experiment, Laclau et al. (2009) compared leaf traits and tree growth in treatments without K fertilization and with the application of 116 kg ha^{-1} of K. Young leaves were tagged 9 months after planting to estimate the effect of K fertilizer application on leaf lifespan. Leaf mass, specific leaf area and nutrient concentrations were measured every 28 days until the last tagged leaf dropped. K fertilization increased the above-ground net primary production cumulated over 3 years after planting from 4.48 to 8.74 kg DM m^{-2}. K fertilization increased average lifespan of leaves from 111 to 149 days, and the stand biomass mainly through the enhancement in LAI since growth efficiency (defined as the ratio between woody biomass production and LAI) was not significantly modified. At harvest (7 year-old), above-ground net primary production was still twice higher in the fertilized plots compared to the unfertilized one and stemwood biomass was 130% higher (Epron et al., 2012).

Recent studies have shown that fertilizer prescription in eucalypt plantations in Brazil are well calibrated and that the greatest limitation to additional productivity gains is related to water deficit. For example, in an experimental research network, Stape et al. (2010) examined the potential growth of clonal *Eucalyptus* plantations at eight locations in southeast and northeast Brazil by manipulating the supply of nutrients and water. With no fertilization or irrigation, mean annual increments of roundwood were about 28% lower (33 m^3 ha^{-1} year^{-1}) than yields achieved with current operational rates of fertilization (46 m^3 ha^{-1} year^{-1}). Fertilization beyond current operational rates used by the companies did not increase growth, whereas irrigation raised growth by about 30% (to about 62 m^3 ha^{-1} year^{-1}). Higher water supply increased growth and also delayed by about 1 year the point where current annual increment and average annual increment intersected, indicating the influence of year-to-year climate variations in optimal rotation periods.

Among micronutrients, B has caused the largest productivity limitation in Brazilian eucalypt plantations. The factors that lead a plantation to B deficiency are: (1) soils highly weathered, deep and permeated, above all those originated from sedimentary rocks, coarse texture and low in organic matter content; and (2) long periods of water deficiency. Main symptoms, namely growth reduction and dieback, usually appear in the first year of growth, starting during the onset to the middle of the dry season and extending until the rainy season. It can also occur during the second and third years of tree growth, but with reduced severity. This effect is related to the occupation of larger soil volumes by the root system and B biogeochemical cycling, which is intensified after canopy closure. Susceptibility to B deficiency is quite uneven among eucalypt species. Surprisingly, among the most sensitive species are some of the most productive under water stress, e.g. *C. citriodora* and *E. camaldulensis*. Some causes, acting alone or in combination, that lead to B deficiency are: (1) among the commercial species, these are the most tolerant to, and planted under, water stress; (2) they commonly have a low rate of litter decomposition, which restricts biochemical cycling; and (3) their root systems have intense vertical exploration of the soil profile, with little horizontal exploration by fine roots, which limits B acquisition from SOM mineralization (Gonçalves and Valeri, 2001; Gonçalves et al., 2008). Besides the application of fertilizers, the problem of B deficiency has also been prevented or solved with the use of improved genetic materials (Gonçalves and Valeri, 2001).

In regions of low to moderate water deficiency (lower than 100 mm), it is recommended the application of 2–3 g of B per eucalypt plant. If water deficiency is high (greater than 100 mm), it is recommended to apply 4–5 g of B per plant. Among the best B sources, ulexite partially acidified stands out, because it has been largely tested and shown excellent results. It is recommended to make the application concomitantly with the first surface fertilization (Gonçalves, 2011).

Responses to Fe, Mn, Cu and Zn are rare, and these micronutrients have great availability in soils, predominantly, oxidic and acidic used in eucalypt plantations (Gonçalves and Valeri, 2001). Responses tend to be more common after several forest rotations, mainly in areas never fertilized with micronutrients. Commonly, one cannot assure that there will be a response to a given micronutrient, however, depending on edaphoclimatic conditions, it is recommended to apply them as prevention. Zn and Cu are applied as maintenance fertilizers, preventing or restoring removals that have occurred during harvesting of forest products, besides edaphic losses. This does not increase fertilization costs very much, given that the minerals are applied at small quantities. Alternatively, in fertilization at planting, micronutrients may be applied in form of *Frited Traced Elements*. There are formulations especially designed for eucalypt plantations (Gonçalves, 2011).

7.4. Weed control

Eucalypt plantations are very sensitive to weed competition at earlier stages of growth. A reduction in plant survival and growth may result from competition for light, water and nutrients, because weeds use larger volumes of soil than young tree seedlings (Gonçalves and Barros, 1999). Wood production and economic benefits of managing weeds during establishment have been widely demonstrated for eucalypt plantations (Zen, 1987; Pitelli and Marchi, 1991; Toledo et al., 2000, 2003; Tarouco et al., 2009). Competition for water can be intense as indicated by stomatal conductance measured in contrasting weed control treatments (Silva et al., 2000; Lima et al., 2003). However, once established, trees may be able to uptake water in deeper soil layers than most annual herbaceous species.

The edaphoclimatic conditions of the site significantly affect the competition between eucalypt and weeds. Toledo et al. (2000) carried out a study to evaluate the effects of control and coexistence of *Brachiaria decumbens* and *Spermacocea latifola* on the growth of *E. grandis* × *urophylla* clones in the municipality of Três Lagoas, central-western Brazil. The predominant climate in the region is Aw, with average annual rainfall of 1300 mm, actual evapotranspiration of 1200 mm and temperature of 23.8 °C. The dry season lasts 4–6 months with 200 mm of water deficit. The treatments consisted of different periods of weed-eucalypt coexistence initiated during the planting and continued until 364 DAP (days after planting). Eucalypt plants grown in a coexisting environment with weeds, during 364 days, had a mean diameter and height 71% and 68% lower, respectively, compared to eucalypt plants grown in weed-free plots. The tree diameter began to be significantly affected by the weed community after 14 days of coexistence, and the height, after 28 days. The plants did not suffer reduced growth when they were kept in weed-free plots from 28 until 140 DAP (Fig. 6a). After this age, shading caused by canopy closure and litter accumulation prevented weed growth.

In a site of wetter and colder climate, Tarouco et al. (2009) determined the interference periods of weeds on the growth and development of a clone of *E. grandis* × *urophylla* in the municipality of Cerrito, southern Brazil. The predominant climate in the region is Cfa, with average annual rainfall of 1400 mm, actual
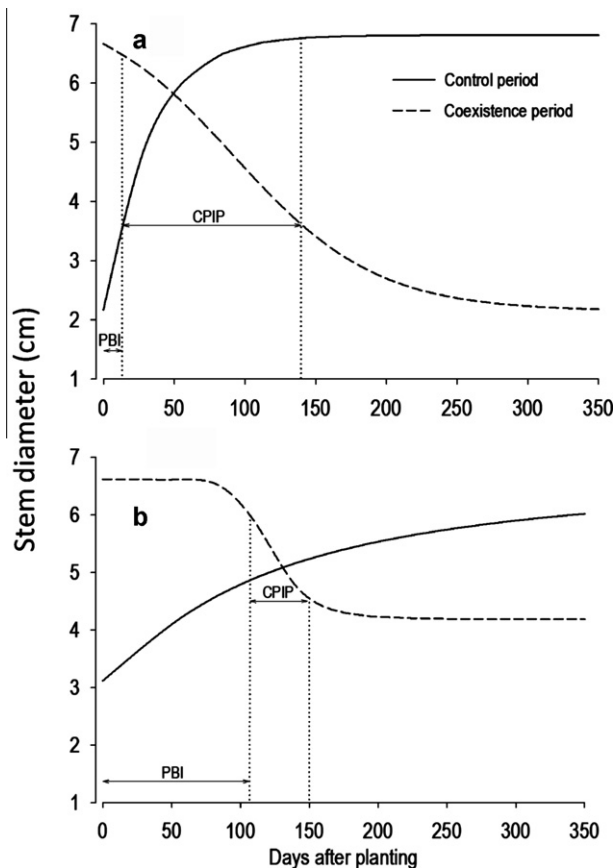
Fig. 6. Change in stem diameter (10 cm above ground) of *Eucalyptus grandis × urophylla* clone under different climate conditions and periods of weed coexistence initiated at planting and continued until 350 days after planting: (a) site located in the municipality of Três Lagoas, central-western Brazil (4–6 months with 200 mm of water deficit); (b) site located in the municipality of Cerrito, southern Brazil (1–2 months with less than 40 mm of water deficit). Where: PBI = period before weed interference; CPIP = critical period of weed interference prevention.

evapotranspiration of 800 mm and temperature of 17.8 °C. The dry season lasts 1–2 months with less than 50 mm of water deficit. The main weed species were *Lolium multiflorum*, *Brachiaria fasciculata* and *Cynodon dactylon*. Differently from the previous study, the diameter of eucalypt tree was significantly affected by the infesting weed community only after 107 days of coexistence, from then on the competition between eucalypt and weeds caused a reduction of up to 61% of the stem diameter in relation to control. The eucalypt did not suffer growth reduction when kept in a weed-free plot from 107 to 150 DAP (Fig. 6b), i.e., in this study, with lower water deficiency and temperatures lower than those found by Toledo et al. (2000), eucalypt-weed competition occurred at a later age. Therefore, weed control starts later in colder and wetter sites than in warmer and drier ones. Overall, in eucalypt plantations, given the edaphoclimatic conditions, the first weed control procedure starts 15–60 DAP, and other interventions occur up to 150 DAP.

Weed control prior to planting eucalypt, both in areas of afforestation and replanting in the system of minimum cultivation of the soil, is essential for the removal of weeds that vegetatively propagate and for the reduction of their seed bank (Gonçalves et al., 2004). The procedures are usually carried out combining mechanical and chemical methods, using total-action herbicide (non-selective), such as glyphosate. During the planting of forest stands, most eucalypt production systems in Brazil apply pre-emergence herbicides at a 1-m strip on the crop row. The main pre-emergence herbicides include oxyfluorfen, sulfentrazone and isoxaflutole (Christoffoleti, 2008). After planting, the post-emergence control

of weeds is performed by spraying herbicides. In the application, special care must be taken to avoid the drift to leaves and stems of the cultivated plants because it can cause phytotoxic effects of reduced growth (Salgado et al., 2011).

The spread of weeds in cultivated area is another important factor that influences the level of interference between the weed community and the eucalypt plantation, mainly because of the proximity of weeds to the eucalypt rows. Normally, well-spaced plants can further develop their individual competitive potential. Despite the negative competitive effects of weeds, their potential benefits for nutrient conservation (Silva et al., 1997), erosion reduction, biodiversity, and N fixation (Nambiar and Nethercott, 1987) should be highlighted. Optimizing the positive and negative effects of weeds may allow the use of partial weed control techniques in eucalypt plantations (Gonçalves et al., 2004). Toledo et al. (2003) examined the width effect of a vegetation control strip in hybrid eucalypt *E. grandis × urophylla*. The authors tested strip widths of 0–1.5 m in each side, maintaining them for 12 months free of weed competition. Twenty-two months after planting, in a site previously used as pasture, the average diameter at breast height (DBH) of trees, in the treatments where weed control was applied in strips between 1.0 and 1.5 m, was 9.0 cm, about 100% higher than that obtained with weed control used in strips of 0–0.5 m. Twenty-seven months later, the DBH in the larger control strips was 12 cm, about 25% higher than that obtained in the narrow control strips. These results show that the differences between control strips decreased with age, indicating a reduction of the competitive power of weed. The authors concluded that the minimum control strip width should be at least 100 cm in each side of eucalypt rows in order to keep the crop free of weed interference, i.e., in plantations with 3-m spacing between tree rows (the most common spacing), a 1-m strip could be used without weed control. In practice, maintaining this narrow strip with weeds can be a difficult operation, because the spray bar with non-selective herbicide would need to run twice, instead of once (usual procedure), in narrow strips beside the rows, in the middle of space between rows. However, in plantations established with wider planting space (e.g., ⩾4 m between rows), situated in regions with mild or no dry season, maintaining strips of weeds between tree rows is highly recommended and commonly practiced. Still according to Toledo et al. (2003), in the second treatment, there was no response to weed control, because it was established in a site previously cropped with eucalypts where weed abundance had been greatly reduced during the preceding rotation.

8. Minimizing risks of diseases

Until the 1970s, eucalypt plantations covered a relatively small area in Brazil, concentrated in São Paulo and Minas Gerais states, and were considered disease-free. Thereafter, the expansion of plantations to regions susceptible to infections; the use of more productive genotypes without prior knowledge of their resistance; the implementation of new management techniques and successive stand rotations in the same area have favored the incidence of diseases, caused by endemic or accidentally introduced pathogens (Alfenas et al., 2009). The following diseases should be highlighted: eucalypt cancker (*Chrysophorte cubensis*), eucalypts rust (*Puccinia psidii*), leaf blights and defoliation (*Cylindrocladium* spp., *Rhizoctonia* spp. and *Xanthomonas axonopodis*), bacterial wilt (*Ralstonia solanacearum*), ceratocystis wilt (*Ceratocystis fimbriata*), eucalyptps die-back (*Erwinia eucalypti*), and *Quambalaria* stem girdling and leaf spot (*Quambalaria eucalypti*).

Environmental conditions favoring infections and the inheritance of resistance mechanisms are critical issues for an efficient disease control. *P. psidii* infects juvenile plant organs, either in

the nursery or in the field and has great occurrence in Brazil. However plants taller than 3–4 m are not infected in the field. The optimal condition required for the establishment and development of this pathogen is leaf wetness over 6–8 h and temperatures between 18 and 25 °C. Similarly to *P. psidii*, *C. fimbriata* wilt is observed throughout Brazil at an optimum temperature for infection of 26 °C. The eucalypt canker caused by *C. cubensis* is epidemiologically important in regions with mean temperature $\geqslant$23 °C and annual rainfall $\geqslant$1200 mm. *Cylindrocladium* leaf blight, caused by *C. pteridis*, may also limit growth of highly susceptible *Eucalyptus* genotypes in warm and humid regions (Alfenas et al., 2009).

The heterogeneity of seedling stands and the incidence of canker in the 1970s led to the adoption of the eucalypt cutting technique, as a global disease control tool. About one million ha of Brazilian eucalypt plantations consist of only 362 clones from pure species or interspecific hybrids, mainly *E. grandis* $\times$ *urophylla*, with 10–34,000 ha/clone/company (TF Assis, personal communication). Despite the risks inherent to homogeneous plantations, cloning is a powerful tool for the commercial propagation of superior genotypes, resistant to diseases.

It is essential to ensure a regular flow of new clones with different genetic backgrounds, including contrasted silvicultural and technological characteristics of commercial interest. It is crucial to carry out systematic monitoring of diseases in nurseries and in fields, including clonal and progeny trials. Forest breeding programs are conducted for the mid and long-term, and it is then essential to identify disease resistant parents as most Brazilian forest companies do (Fonseca et al., 2010). Besides, selection of resistant genotypes is needed to understand the genetic basis of resistance as well as the variability in pathogen populations, since new races of pathogens may overcome resistance.

9. Minimizing risks of pests

The expansion of *Eucalyptus* in Brazil was followed by infestation outbreaks of some native insect species, which have become key pests to the activity, requiring investments in prevention and control. The most important pests that have occurred since the beginning of commercial eucalypt plantations in the country are leaf-cutting ants, termites, caterpillars and defoliator beetles. However, most of them have been efficiently monitored and controlled with use of chemical and biological insecticides (Wilcken et al., 2008).

In the last decade, the occurrence and establishment of exotic pests from Australia in many Brazilian states were indentified, namely the redgum lerp psyllid (*Glycaspis brimblecombei*), bronze bug (*Thaumastocoris peregrinus*) and eucalyptus gall wasp (*Leptocybe invasa*) (Costa et al., 2008; Barbosa et al., 2010). Despite control measures, these pests have spread widely, compromising the improvement of several *Eucalyptus* species, especially in regions of defined drought season, such as the Cerrado region and northeast of Brazil.

Control strategies for these exotic pests are based on Integrated Pest Management, using the classic biological control, importing and releasing natural enemies, pesticides and assessing resistant genetic material. Studies have investigated the effectiveness of introduced natural enemies from other countries and the results show that the control of redgum lerp psyllid is partly satisfactory, depending on the site location and year season. Currently, rates of nymph parasitism achieved by *Psyllaephagus bliteus* (Hymenoptera: Encyrtidae) range 25–94% (Wilcken et al., 2011). This large variance is associated to temperature effects on the lifespan of the parasite in the field that is reduced at temperatures above 26 °C (Daane et al., 2005). Monitoring systems using sticky traps

are important to evaluate the occurrence of redgum lerp psyllid and their natural enemy population's levels in several Brazilian states. Furthermore, stick traps are being used to detect *T. peregrinus* and *Leptocybe invasus*. This method of monitoring is essential to evaluate pest population dynamics under the influence of abiotic factors, as well as to establish control strategies.

In 2010, the exotic parasite *Cleruchoides noackae* (Hymenoptera: Mymaridae) was introduced in Brazil from Australia for biological control of *T. peregrinus*. The current studies aim to investigate the possibility of multiplication of egg parasitoids in laboratory and to establish methodology for creating a biological control program (Bubola et al., 2010). Research to determine the efficacy in controlling *T. peregrinus* is still incipient, but until long-term sustainable management of this pest is achieved intervention with insecticides is one solution. Experimental tests are under way to evaluate doses of systemic and contact pesticides and biological products (*Beaveria bassiana* and *Metarhizium anisopliae*) (Soliman et al., 2010). Recent studies aim to select strains of these fungi for control new pests, with great potential for the control of bronze bug in laboratory conditions. (Lorencetti et al., 2011). Studies with chemical products have also been conducted in nursery and field conditions for *L. invasus* and it is still the only alternative for controlling this pest, once the introduction of its natural enemies has not been performed.

Plant resistance is another important method employed for pest control. However, breeding programs specific for pest resistance, as those developed for eucalypt diseases, are still in their infancy. For the control of redgum lerp psyllid, a protocol to evaluate the susceptibility or resistance of eucalypt clones in laboratory conditions has been developed. This has been the single case that forest companies incorporate this methodology and field evaluations to select resistant material. *Eucalyptus* species that belongs to the subgenus *Symphyomyrtus*, Exsertaria section (e.g., *E. camaldulensis*, *E. tenenticornis*, *E. brassiana*) are susceptible to redgum lerp psyllid. Species from other section are resistant, except *E. urophylla*. In Brazilian eucalypt plantations with *E. camaldulensis*, records show tree mortality ranging from 30% to 95%, after 3 years of infestation. High infestations in *E. urophylla* plantations have also been observed, as well as in several *E. grandis* $\times$ *urophylla* hybrids plantations mainly in the last 2 years. The hybrid clones tested by forest companies after the introduction of redgum lerp psyllid in 2003 have shown a gradient response to pest attack, with some genotypes highly resistant and others considered susceptible. The high pest adaption capability to the new genotypes developed has been demonstrated (Wilcken, 2011).

For gall wasp, high susceptibility was found in plantation of *E. camaldulensis* and their hybrid clones, affecting tree development until the second year, reducing growth afterward and losing apical dominance. The best option to control this pest is the breeding to develop resistance, despite the time necessary to develop resistant clones. That is because chemical and biological methods have some restrictions, due to the requirements established by forest certification systems regarding to the use of chemical insecticides, and scarcity of studies on the rearing natural enemies as well as difficulties to obtain permission to introduce them in Brazil (Costa et al., 2008).

Control measures have been studied and carried out, but their application generally takes time, especially when the focus is on biological control, due to reduced environmental impact and forestry certification requirements. Furthermore, in light of difficulties to protect the country from the introduction of new exotic pests, the development of resistant genotypes will be hard. In the next years, it is crucial to increase the inspection levels of products and people entering the country from risky areas. Moreover, it is important to avoid the use of susceptible materials, and to use genetic modified organism techniques to incorporate resistant genes

in *Eucalyptus* to create resistant traits to new pests (Wilcken, 2011).

10. Eucalypt management in subtropical regions

Eucalypt plantations with species adapted to subtropical climate have gained prominence over the last 5 years in southern Brazil. Over this period, the areas planted with forests in this region have increased by 12%, of which 53% with *Eucalyptus* species (ABRAF, 2012). Most of this increase occurred in regions subject to the occurrence of frost. Records show the occurrence of 15–40 frosts per year, usually causing considerable damage to plants, affecting wood quality and productivity. The risk of frost damage is compounded by the wide range in daily temperature. In some cases, during the day, the temperature reaches 20/30 °C and drops to −5 °C or less at night. Special silvicultural practices are needed in these areas, since frosts are common during the winter. Traditionally forest companies in southern Brazil, especially in Paraná and Santa Catarina states, use *Pinus* species primarily in most of their plantations and *Eucalyptus* species secondarily. This condition is highly favorable since the *Pinus* species have high growth rate and are considered much more tolerant to frost damage. However, few landowners visualize the need to use silvicultural techniques different from those used for the establishment of pine plantations to properly manage eucalypt plantations.

Since the 1980s, several *Eucalyptus* species have been introduced in southern Brazil. Among them, the *E. dunnii* and *E. viminalis* showed good adaptability to freezing conditions. On the last 10 years, *E. benthamii* also showed high frost tolerance and has readily become one of the preferred species for plantations. In tests for species selection performed in the province of Hunan – China, where the minimum temperature averages in the coldest month range between 3 and 8 °C and the absolute minimum temperature reaches around −6 to −10 °C, the *E. benthamii* was considered particularly indicated (Mujiu et al., 2003). Similar results were reported by Hesheng et al. (2003), who found that *E. benthamii* tolerated minimum temperatures of −8 °C, followed by 7 days of temperature below 0 °C.

Currently, there are plantations of frost-resistant clones of *E. benthamii* and *E. dunnii* with 35 and 42 m^3 ha^{-1} year^{-1} roundwood of mean annual increment, respectively (Klabin Corporation, personal communication). For the selection of new genetic material with higher pulp productivity, hybridizations are being performed to obtain genotypes resistant or tolerant to frost, pest and diseases, and with high quality wood (Resende and Assis, 2008).

To establish highly productive subtropical eucalypt plantations, it is necessary to adopt more advanced technology, since these plantations demand more resources and are more sensitive to environmental stresses than pine plantations. On the other hand, they respond readily to forest management. A positive interaction between intensive silviculture and well-adapted species require the complementary effect of planning and management, before, during and after planting, such as edaphoclimatic zoning, planting season and silvicultural practices (site preparation, weed control, fertilizer application).

The application of correct zoning requires the study of variations in the relief, soil and microclimate, adjusting the species to each location, according to their frost tolerance. More cold tolerant and/or resistant species are planted in the lower portions of the slope and on the south face, where frosts are more intense. So, the stand compartments are always composed by different species. In the lower slopes, *E. benthamii* and *E. viminalis* are planted and in the upper slopes, species less frost resistant such as *E. dunnii*. These combinations are recommended in areas of altitudes ranging from 500 to 1000 m above sea level in southern Brazil. They present fast

initial growth potential and high tolerance to frost damage (EMBRAPA, 1988; Oliveira, 1988; Higa et al., 1997). The establishment of eucalypt plantations is not recommended in the highlands of southern Brazil, at altitudes above 1200 m, where is common the occurrence of very severe frost, the relative humidity is very high and predominate hydromorphic soils unsuitable for eucalypt growing.

In areas highly susceptible to frost damage in southern Brazil, the planting in the spring was found as the most appropriate. In spring, the occurrence of frost is minimum. Plantations established during this season will have enough development to survive the arrival of the next cold season, which starts in April. The selected species planted under those recommendations survive with minimum or no frost damage.

Frost resistance is positively correlated with tree size, and is therefore enhanced by silvicultural practices that promote rapid growth of trees after planting (e.g. weed controls and application of fertilizer). *Eucalyptus* species growing in subtropical climate and soil conditions of southern Brazil have shown a high response to P and K fertilization (Laclau et al., 2009; Stahl, 2009; Epron et al., 2012). There are several research projects in progress seeking information on the physiological responses of eucalypts to higher rates of fertilizers, such as potassium chloride. The hypothesis is that the higher uptake of nutrients by eucalypt, prior to the stress period, increases nutrients and soluble carbohydrate concentrations in the cells and decreases the cryoscopic point of the leaves, facilitating acclimatation. Floriani (2009) demonstrated a strong positive correlation ($r^2 = 0.86$) between concentrations of total soluble carbohydrates in the leaves and cold resistance in *E. dunnii* seedlings, with LT50 (lethal temperature, at which at least 50% of the plants die) decreasing from −2.2 °C for soluble carbohydrate concentrations of 16 mg g^{-1} down to −6.3 °C for concentrations of 85 mg g^{-1}. The author suggests that this quantitative trait should be considered in the selection of cold-tolerant species in breeding programs. Leborgne et al. (1995) made a comparison of soluble sugar content in various tissues of *E. gunnii* showing different levels to cold resistance revealed that the most resistant cell contained the highest soluble sugar content. Almeida et al. (1994) also related the increase in levels of cold resistance with sugar concentration in *E. globulus* and hybrid seedlings.

11. Conclusions

Eucalypt plantations fulfill multiple functions in landscapes in different Brazilian ecosystems, and in all of them, some level of environmental stress is found, being physical (water, temperature, nutrients) or biological (pests, diseases and competing vegetation) constraints, or both. Moreover, climate changes can cause the decline in forest productivity due to the augmentation of such stresses.

The Brazilian experience has shown that despite repeated short-rotation cropping, continuous gains in productivity of eucalypts are possible. The increase rate has been steady for over 40 years, indicating the large-scale productivity gain through improved genotype and silviculture.

Even so, there are a number of risks associated with intensive, short-rotation, high yielding eucalypt plantations. Those risks must be carefully assessed and managed. The search, test and selection of appropriate genotypes and site management practices, improving resource-use-efficiency of eucalypt plantations are imperative to sustain productivity and maintain environmental services of these forests for generations to come.

Eucalypt plantations as an economic activity have to compete with alternative land uses. The continued success of plantations in the future will depend on the capacity of forest managers to

obtain high productivity of the desired wood quality in an environmentally sound manner. To achieve this goal, future collaboration between scientists and foresters working on silviculture and genetics should lead to new insights on mechanisms connecting environmental stress and growth, leading to improved integration of sites, genotypes, and silvicultural practices.

Acknowledgements

References

ABRAF – Brazilian Association of Forest Plantation Producers, 2012. ABRAF Statistical Year Book – Base Year 2011. Brasília 150.

Adams, M.B., Pennell, D., Campbell, R.G., 1989. Fine root distribution in a young loblolly pine (*Pinus taeda* L.) stand: effects of preplant phosphorus fertilization. Plant Soil 113, 275–278.

Alfenas, A.C., Zauza, E.A., Mafia, R.G., Assis, T.F., 2009. Clonagem e doenças do eucalipto, second ed. Editora UFV, Viçosa.

Almeida, M.H., Chaves, M.M., Silva, J.C., 1994. Cold acclimation in eucalypt hybrids. Tree Physiol. 14, 921–932.

Almeida, J.C.R., Laclau, J.P., Gonçalves, J.L.M., Ranger, J., Saint-André, L., 2010. A positive growth response to NaCl applications in *Eucalyptus* plantations established on K-deficient soils. For. Ecol. Manage. 259, 786–1795.

Alvares, C.A., 2011. Mapping and Edaphoclimatic Modeling of Productivity of *Eucalyptus* Plantations at south of São Paulo State. Ph.D. Thesis, University of Sao Paulo, Piracicaba, Brazil, 279 pp.

Alvares, C.A., Gonçalves, J.L.M., Vieira, S.R., Silva, C.R., Franciscatte, W., 2011a. Spatial variability of physical and chemical attributes of some forest soils in southeastern of Brazil. Sci. Agric. 68, 697–705.

Alvares, C.A., Stape, J.L., Gonçalves, J.L.M., 2011b. Mapping of the Brazil *Eucalyptus* potential productivity. In: IUFRO Working Group 2.08.03 – Improvement and Culture of *Eucalyptus*. 2011: Porto Seguro, Bahia State, Brazil. Proceedings... Piracicaba: Vitor's Design, 2011, vol. 1, pp. 156–159.

Andrade, E.N., 1909. A cultura dos *Eucalyptus*. Typographia Brazil de Rothschild & Comp.

Andrade, E.N., 1923. O problema florestal no Brasil. O Estado de São Paulo.

Andrade, E.N., 1928. O eucalypto e suas aplicações. Typographia Brazil de Rothschild Comp.

Andrade, E.N., 1936. Instruções para a cultura do eucalypto. Cia. Paulista de Estradas de Ferro.

Andrade, E.N., 1961. O eucalipto, second ed. CPEF, Jundiaí.

Assis, T.F., Mafia, R.G., 2007. Hibridação e clonagem. In: Borém, A. (Ed.), Biotecnologia Florestal. Editora UFV, Viçosa, pp. 93–121.

Azevedo, J.A., 1874. *Eucalyptus globulus*: sua descoberta e introdução. Rev. Agric. Imp. Inst. Flumin. Agric. 5, 11–47.

Barbosa, L.R., Santos, F., Wilcken, C.F., Soliman, E.P., 2010. Registro de *Thaumastocoris peregrines* (Hemiptera: Thaumastocoridae) no Estado do Paraná. Pesqui. Flor. Bras. 30, 75–77.

Barros, N.F., Neves, J.C.L., Novais, O.F., 2004. Mineral fertilizer recommendations for eucalypt plantations. In: Gonçalves, J.L.M., Benedetti, V. (Eds.), Forest Nutrition and Fertilization. IPEF, Piracicaba, pp. 269–305.

Bastos, A.M., 1961. O eucalipto no Brasil. In: Conferência Mundial do Eucalipto, 2, São Paulo, 1961. Proceedings... São Paulo: FAO, pp. 214–224.

Behling, M., Piketti, M.-G., Fonseca Morello, T., Bouillet, J.-P., Neto, F.M., Laclau, J.-P., 2011. Potentiel de production des plantations d'eucalyptus sur le pôle sidérurgique de Carajas, en Amazonie: apports du modèle 3-PG. Bois For. Trop. 309, 7–49.

Bernardo, A.L., Reis, M.G.F., Reis, G.G., Harrison, R.B., Firme, D.J., 1998. Effect of spacing on growth and biomass distribution in *Eucalyptus camaldulensis*, *E. pellita* and *E. urophylla* plantations in southeastern Brazil. For. Ecol. Manage. 104, 1–13.

Binkley, D., Stape, J.L., Ryan, M.G., 2004. Thinking about efficiency of resource use in forests. For. Ecol. Manage. 193, 5–16.

Bouillet, J.-P., Nzila, J.-P., Laclau, J.-P., Ranger, J., 2000. Effects of site management on *Eucalyptus* plantations on the equatorial zone, on the coastal plains of the Congo. In: Nambiar, E.K.S., Cossalter, C., Tiarks, A., Ranger, J. (Eds.), Site Management and Productivity in Tropical Plantation Forests: Workshop Proceedings 7–11 December 1999, Kerala, India. CIFOR, Bogor, pp. 11–20.

Bouillet, J.-P., Laclau, J.-P., Arnaud, M., Thongo, A., 2002. Changes with age in the spatial distribution of roots of a *Eucalyptus* clone in the Congo. Impact on water and nutrient uptake ability. For. Ecol. Manage. 171, 43–57.

BRACELPA – Brazilian Pulp and Paper Association, 2004. Brazilian Panorama on the Pulp and Paper Industry. São Paulo, Brazil.

Brawner, J.T., Bush, D.J., Clegg, P.A., Macdonell, P.F., Warburton, P.M., 2010. Genetic parameters of red mahogany breeding populations grown in the tropics. Aust. For. 73, 177–183.

Brishir, J., Roberds, J.H., 1999. One numbers of clones needed for managing risks in clonal forestry. For. Genet. 6, 149–155.

Bubola, J.G., Sa, L.A.N., Almeida, G.R., Zaché, B., Soliman, E.P., Dias, T.K.R., Lima, A.C.V., Wilcken, C.F., 2010. Método de criação laboratorial do parasitóide exótico *Cleruchoides noackae* (Hymenoptera: Mymaridae) para controle biológico de *Thaumastocoris peregrinus* (Hemiptera: Thaumastocoridae). In: Congresso Brasileiro De Entomologia, 23, 2010, Natal, Brazil. Proceedings... Natal: Sociedade Brasileira de Entomologia: Emparn, 2010. CD-ROM.

Campinhos, E., 1999. Sustainable plantations of high-yield *Eucalyptus* trees for production of fiber: the Aracruz case. New For. 17, 129–143.

Christina, M., Laclau, J.-P., Gonçalves, J.L.M., Jourdan, C., Nouvellon, Y., Bouillet, J.-P., 2011. Almost symmetrical vertical growth rates above and below ground in one of the world's most productive forests. Ecosphere 3, 124–130.

Christoffoleti, P.J., 2008. Manejo integrado de plantas daninhas em povoamentos florestais homogêneos. In: Encontro Brasileiro de Silvicultura, 1. Curitiba, Parana State, Brazil. Proceedings... Piracicaba: PTSM/IPEF/ESALQ/FUPEF, 2008, pp. 149–156.

Comerford, N.B., Cropper, W.P., Hua, L., Smethurst, P.J., Van Rees, K., Jokela, E.J., Adégbidi, H., Barros, N.F., 2006. Modeling soil supply and plant nutrient demand. Can. J. Soil Sci. 86, 665–673.

Costa, V.A., Berti Filho, E., Wilcken, C.F., Stape, J.L., LaSalle, J., 2008. *Eucalyptus gall wasp*, *Leptoybe invasa* (Hymenoptera: Eulophidae) in Brazil: new forest pest reaches the New World. Rev. Agric. 83, 136–139.

Coterill, P.P., 1997. Nucleus breeding: is it ok for *Pinus* and *Eucalyptus*? In: IUFRO Conference on Silviculture and Improvement of *Eucalyptus*. Salvador, Bahia State, Brazil. Proceedings... Colombo, EMBRAPA-CNPF, pp. 277–284.

Cromer, R.N., Smethurst, P., Turnbull, C., Misra, R., LaSala, A., Herbert, A., Dimsey, L., 1995. Early growth of *Eucalyptus* in Tasmania in relation to nutrition. In: Potts, B.M., Borralho, N.M.G., Reid, J.B., Cromer, R.N., Tibbits, W.N., Raymond, C.A. (Eds.), Eucalypt Plantations: Improving Fibre Yield and Quality. CRC for Temperate Hardwood Forestry, Hobart, pp. 331–335.

Daane, K.M., Sime, K.R., Dahlstein, D.L., Andrews, J.W., Zuparrko, R., 2005. The biology of *Psyllaephagus bliteus* Riek (Himenoptera: Encyrtidae), a parasitoid of the red gum lerp psyllid (Hemiptera: Psylloidea). Biol. Control 228–235.

Demolinari, R.A., Soares, C.P.B., Leite, H.G., de Souza, A.L., 2007. Crescimento de plantios clonais de eucalipto não desbastados na região de Monte Dourado (PA). Rev. Árvore 31, 503–512.

Du Toit, B., Esprey, L.J., Job, R.A., Fuller, G.F., Dovey, S.D., 2000. Effects of site management in *Eucalyptus grandis* plantations in South Africa. In: Nambiar, E.K.S., Cossalter, C., Tiarks, A., Ranger, J. (Eds.), Site Management and Productivity in Tropical Plantation Forests: Workshop Proceedings 21–30 December 1999, Kerala, India. CIFOR, Bogor, pp. 11–20.

EMBRAPA – Brazilian Agricultural Research Corporation, 1988. Centro Nacional de Pesquisa de Florestas (Curitiba, PR). Zoneamento ecológico para plantios florestais no estado de Santa Catarina, Curitiba, pp. 113.

EMBRAPA, 2006. Brazilian System of Soil Classification. Brasília: Embrapa Produção de Informação, second ed. Embrapa Solos, Rio de Janeiro, Brazil.

Epron, D., Laclau, J.-P., Almeida, J.C.R., Gonçalves, J.L.M., Ponton, S., Sette, C.R., Delgado-Rojas, J.S., Bouillet, J.-P., Nouvellon, Y., 2012. Do changes in carbon allocation account for the growth response to potassium and sodium applications in tropical *Eucalyptus* plantations? Tree Physiol. 32, 667–679.

Farr, T.G., Kobrick, M., 2000. Shuttle radar topography mission produces a wealth of data. Am. Geophys. Union Eos 81, 583–585.

Ferreira, M., 1989. A situação florestal brasileira e o papel da silvicultura intensiva. IPEF, Documentos Florestais 2, 1–9.

Ferreira, M., 1992. Melhoramento e a silvicultura intensiva clonal. IPEF 45, 22–30.

Florence, R.G., 1996. Ecology and Silviculture of Eucalypt Forests. CSIRO, Australia, 413p.

Florence, R.G., 2007. Ecology and Silviculture of Eucalypt Forests. CSIRO Australia, pp. 79–106.

Floriani, M.M.P., 2009. Relação da tolerância ao frio de *Eucalyptus* spp. com a concentração foliar de carboidratos solúveis totais e prolina. Dissertation. University of State of Santa Catarina, Lages, Brazil, 54 pp.

Fonseca, S.M., Resende, M.D.V., Alfenas, A.C., Guimarães, L.M.S., Assis, T.F., Grattaplaglia, D., 2010. Manual prático de melhoramento genético do eucalipto. Editora UFV, Viçosa.

Ford, E.D., Deans, J.D., 1977. Growth of sikta spruce plantation spatial distribution and seasonal fluctuations of lengths, weights and carbohydrates concentrations of fine roots. Plant Soil 47, 463–485.

Gava, J.L., 2002. Cultivo mínimo em solos de textura arenosa e média: áreas planas e suave onduladas. In: Gonçalves, J.L.M., Stape, J.L. (Eds.), Conservação e cultivo de solos para plantações florestais. IPEF, Piracicaba, pp. 221–244.

Gava, J.L., Gonçalves, J.L.M., 2008. Soil attributes and wood quality for pulp production in plantations of *Eucalyptus grandis* clone. Sci. Agric. 65, 306–613.

Golfari, L., 1974. Esquema de zoneamento ecológico florestal para o Brasil. IBDF, Rio de Janeiro.

Gonçalves, J.L.M., 1994. Características do sistema radicular de absorção do *Eucalyptus grandis* sob diferentes condições edáficas. Tese de Livre Docência. University of Sao Paulo, Piracicaba, Brazil, 85 pp.

Gonçalves, J.L.M., 2011. Fertilização de plantação de eucalipto. In: Encontro Brasileiro de Silvicultura, 2. Campinas, São Paulo State, Brazil. Proceedings... Piracicaba: PTSM/IPEF/ESALQ/FUPEF, 2011, pp. 85–113.

Gonçalves, J.L.M., Barros, N.F., 1999. Improvement of site productivity for short-rotation plantations in Brazil. Bosque 20, 89–106.

Gonçalves, J.L.M., Mello, S.L.M. 2004. The root system of trees. In: Gonçalves, J.L.M., Benedetti, V. (Eds.), Forest Nutrition and Fertilization, first ed. IPEF, Piracicaba, pp. 223–267.

Gonçalves, J.L.M., Valeri, S.V., 2001. Eucalipto e pinus. In: Ferreira, M.E., Cruz, M.C.P., Raij, B., Abreu, C.A. (Eds.), Micronutrientes: elementos tóxicos na agricultura. CNPq/FAPESP/PATAFOS, Jaboticabal, pp. 393–423.

Gonçalves, J.L.M., Barros, N.F., Nambiar, E.K.S., Novais, R.F., 1997. Soil and stand management for short-rotation plantations. In: Nambiar, E.K.S., Brown, A.G. (Eds.), Management of Soil, Nutrients and Water in Tropical Plantations Forests. ACIAR Monograph 43, Camberra, pp. 379–417.

Gonçalves, J.L.M., Serrano, M.I.P.S., Mendes, K.C.F.S., Gava, J.L., 2000. Effects of site management in a *Eucalyptus grandis* plantation in the humid tropics: São Paulo, Brazil. In: Nambiar, E.K.S., Cossalter, C., Tiarks, A., Ranger, J. (Eds.), Site Management and Productivity in Tropical Plantation Forests: Workshop Proceedings 7–11 December 1999, Kerala, India. CIFOR, Bogor, pp. 3–9.

Gonçalves, J.L.M., Stape, J.L., Wichert, M.C.P., Gava, J.L., 2002. Manejo de resíduos vegetais e preparo de solo. In: Gonçalves, J.L.M., Stape, J.L. (Eds.), Conservação e cultivo de solos para plantações florestais. IPEF, Piracicaba, pp. 131–204.

Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Smethurst, P., Gava, J.L., 2004. Silvicultural effects on the productivity and wood quality of eucalypt plantations. For. Ecol. Manage. 193, 45–61.

Gonçalves, J.L.M., Stape, J.L., Laclau, J.L., Bouillet, J.P., Ranger, J., 2008. Assessing the effects of early silvicultural management on long-term site productivity of fast-growing eucalypt plantations: the Brazilian experience. South. 70, 105–118.

Gonçalves, J.L.M., Pulito, A.P., Arthur Júnior, J.C., Silva, L.D., 2011. Diretrizes e desafios técnico-científicos da silvicultura brasileira. In: Encontro Brasileiro de Silvicultura, 2. Campinas, São Paulo State, Brazil. Proceedings... Piracicaba: PTSM/IPEF/ESALQ/FUPEF, 2011, pp. xxiii–xxvi.

Gonçalves, J.L.M., Alvares, C.A., Gonçalves, T.D., Moreira, R.M., Mendes, J.C.T., Gava, J.L., 2012. Mapeamento de solos e da produtividade de plantações de *Eucalyptus grandis* em Itatinga, SP, com uso de sistema de informação geográfica. Sci. For. 94, 187–201.

Grove, T.S., Thomson, B.D., Malajczuk, N., 1996. Nutrition physiology of eucalypts: uptake, distribution and utilization. In: Attiwill, P.M., Adams, M.A. (Eds.), Nutrition of Eucalypts. CSIRO, Australia, pp. 77–108.

Guimarães, L.M.S., Titon, L., Lau, D., Ross, L.N., Oliveira, L.S.S., Rosado, C.C.G., Christo, G.G.O., Alfenas, A.C., 2010. *Eucalyptus pellita* as a source of resistance to rust, ceratocystis wilt and leaf blight. Crop Breed. Appl. Biotechnol. 10, 124–131.

Hardiyanto, E.B., Tridasa, A.M., 2000. Early performance of *Eucalyptus urophylla* × *E. grandis* hybrids on several sites in Indonesia. In: 'Proceedings of QFRI/CRC-SPF Symposium Hybrid Breeding and Genetics of Forest Trees'. Proceedings... Noosa, Queensland, pp. 273–279.

Harwood, C.E., Alloysius, D., Pomroy, P., Robson, K.W., Haines, M.W., 1997. Early growth and survival of *Eucalyptus pellita* provenances in a range of tropical environments, compared with *E. grandis*, *E. urophylla* and *Acacia mangium*. New For. 3, 203–219.

Hendricks, J.J., Nadelhoffer, K.J., Aber, J.D., 1993. The role of fine roots in energy and nutrient cycling. Trends Ecol. Evol. 8, 174–178.

Herbert, M.A., Schonau, A.P.G., 1989. Fertilising commercial forest species in Southern Africa: research progress and problems (part 1). S. Afr. For. J. 151, 58–70.

Hesheng, L., Jimqging, Q., Guoyang, X., Decong, H., Shirong, Z., Wenge, L., 2003. Review of cold-tolerant *Eucalyptus* improvement in Fujian Province. In: Turnbull, J.W. (Ed.), *Eucalyptus* in Asia: Proceeding of a International Conference Held in Zhanjiang, Guangdong, People's Republic of China. ACIAR, Camberra, pp. 117–122.

Higa, A.R., Silva, L.D., 2008. Situação atual e perspectivas do melhoramento genético de *Pinus* e eucaliptos no Brasil. Encontro Brasileiro de Silvicultura, 1. Curitiba, Parana State, Brazil. Proceedings... Piracicaba: PTSM/IPEF/ESALQ/FUPEF, 2008, pp. 105–115.

Higa, R.C.V., Sturion, J.A., 1991. Avaliação da brotação de treze espécies de *Eucalyptus* na região de Uberaba, MG. Bol. Pesqui. Flor. 22, 79–86.

Higa, R.C.V., Higa, A.R., Trevisan, R., Souza, M.V.R., 1997. Comportamento de 20 espécies de *Eucalyptus* em área de ocorrência de geadas na região sul do Brasil. In: Conference on Silviculture and Improvement of Eucalyptus, 1997: Salvador, Bahia State, Brazil. Proceedings... Colombo, EMBRAPA-CNPF, pp. 106–110.

IBGE – Brazilian Institute of Geography and Statistics, 2001. Mapa de Solos do Brasil. Escala: 1.5.000.000. Diretoria de Geociências. EMBRAPA Solos. Brasília.

IBGE, 2011. Sistema IBGE de Recuperação Automática – SIDRA. <http://www.sidra.ibge.gov.br/bda/silvi>.

I.F. – Instituto Florestal, 2002. Inventário florestal das áreas reflorestadas no Estado de São Paulo. SMA/IF/Imprensa Oficial, São Paulo.

Jacobs, M.R., 1955. Growth Habits of the *Eucalyptus*. Forest and Timber Bureau, Commonwealth of Australia.

Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled SRTM for the Globe Version 4. Available from the CGIAR-CSI SRTM 90m Database. <http://srtm.csi.cgiar.org>.

Joslin, J.D., Wolfe, M.H., Hanson, P.J., 2001. Factors controlling the timing of root elongation intensity in a mature upland oak stand. Plant Soil 228, 201–212.

Jourdan, C., Silva, E.V., Gonçalves, J.L.M., Ranger, J., Moreira, R.M., Laclau, J.-P., 2008. Annual fine root production and turnover in Brazilian *Eucalyptus* plantations under contrasting nitrogen fertilization regimes. For. Ecol. Manage. 256, 396–404.

Köppen, W., 1936. Das geographische system der climate. In: Köppen, W., Geiger, R. (Eds.), Handbuch der Klimatologie. Berlin, pp. 1–44.

Krejci, L.C., 1986. Desenvolvimento do sistema radicular de eucaliptos sob diferentes condições de solo. Salvador, Copener.

Laclau, J.-P., Deleporte, P., Ranger, J., Bouillet, J.-P., Kazotti, G., 2003. Nutrient dynamics throughout the rotation of *Eucalyptus* clonal stands in Congo. Ann. Bot. 91, 879–892.

Laclau, J.-P., Toutain, F., Thongo-M'Bou, A., Arnaud, M., Joffre, R., Ranger, J., 2004. The function of the superficial root mat in the biogechemical cycles of nutrient in Congolese *Eucalyptus* plantations. Ann. Bot. 93, 249–261.

Laclau, J.-P., Ranger, J., Deleporte, P., Nouvellon, Y., Saint-André, L., Marlet, S., Bouillet, J.-P., 2005. Nutrient cycling in a clonal stand of *Eucalyptus* and an adjacent savanna ecosystem in Congo 3. Input–output budgets and consequences for the sustainability of the plantations. For. Ecol. Manage. 210, 375–391.

Laclau, J.-P., Bouillet, J.-P., Gonçalves, J.L.M., Silva, E.V., Jourdan, C., Cunha, M.C.S., Moreira, M.R., Saint-André, L., Maquère, V., Nouvellon, Y., Ranger, J., 2008. Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil. 1. Growth dynamics and above-ground net primary production. For. Ecol. Manage. 255, 3905–3917.

Laclau, J.-P., Almeida, J.C.R., Gonçalves, J.L.M., Saint-André, L., Ventura, M., Ranger, J., Moreira, R.M., Nouvellon, Y., 2009. Influence of nitrogen and potassium fertilization on leaf life span and allocation of above-ground growth in *Eucalyptus* plantations. Tree Physiol. 29, 111–124.

Laclau, J.-P., Levillain, J., Deleporte, P., Nzila, J.D.D., Bouillet, J.-P., Saint André, L., Versini, A., Mareschal, L., Nouvellon, Y., Thongo-M'Bou, A., Ranger, J., 2010a. Organic residue mass at planting is an excellent predictor of tree growth in *Eucalyptus* plantations established on a sandy tropical soil. For. Ecol. Manage. 260, 2148–2159.

Laclau, J.-P., Ranger, J., Gonçalves, J.L.M., Maquere, V., Krusche, A.V., M'Bou, A.T., Nouvellon, Y., Saint-André, L., Bouillet, J.-P., Piccolo, C.M., Deleporte, P., 2010b. Biogeochemical cycles of nutrients in tropical *Eucalyptus* plantations: main features shown by intensive monitoring in Congo and Brazil. For. Ecol. Manage. 259, 1771–1785.

Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. For. Ecol. Manage. 95, 209–228.

Leborgne, N., Teulieres, C., Travert, S., Rols, M.P., Teissie, J., Boudet, A.M., 1995. Introduction of specific carbohydrates into *Eucalyptus gunnii* cells increases their freezing tolerance. Eur. J. Biochem. 229, 710–717.

Leite, F.P., Barros, N.F., Novais, R.F., Sans, L.M.A., Fabres, A.S., 1997. Crescimento de *E. grandis* em diferentes densidades populacionais. Rev. Árvore 2, 313–321.

Leite, F.P., Barros, N.F., Novais, R.F., Sans, L.M.A., Fabres, A.S., 1999. Relações hídricas em povoamento de eucalipto com diferentes densidades populacionais. Rev. Brasil. Cienc. Solo 23, 9–16.

Leksono, B., Kurinobu, S., Ide, Y., 2006. Optimum age for selection based on a time trend of genetic parameters related to diameter growth in seedling seed orchards of *Eucalyptus pellita* in Indonesia. J. For. Res. 11, 359–364.

Leles, P.S.S., Reis, G.G., Reis, M.G.F., Morais, E.J., 2001. Crescimento, produção e alocação de matéria seca de *Eucalyptus camaldulensis* e *E. pellita* sob diferentes espaçamentos na região de cerrado, MG. Sci. For. 59, 77–87.

Lemos, C.C.Z., 2012. Aprimoramentos, teste e uso do modelo 3-PG em plantios clonais de *Eucalyptus* no nordeste do estado de São Paulo. Ph.D. Thesis, University of Sao Paulo, Piracicaba, Brazil, 171 pp.

Lima, W.P., Jarvis, P., Rhizopoulou, S., 2003. Stomatal responses of *Eucalyptus* species to elevated CO_2 concentration and drought stress. Sci. Agric. 60, 231–238.

Lima, W.P., Laprovitera, R., Ferraz, S.F.B., Rodrigues, C.B., Silva, M.M., 2012. Forest plantations and water consumption: a strategy for hydrosolidarity. Int. J. For. Res. 2012, 8 (Article ID 908465).

Lorencetti, G.A.T., Menezes, M.J.S., Jung, P.H., Gonçalves, T.E., Barbosa, L.R., Potrich, M., Mazaro, S.M., Silva, E.R.L., 2011. Análise do potencial de isolados de *Beauveria bassiana vuill* (Ascomycetes: Clavicipitaceae) para o controle de *Thaumastocoris peregrinus* carpintero e dellapé (Hemiptera: Thaumastocoridae). In: Congresso de Ciência e Tecnologia da UTFPR, 1. 2011. Proceedings... Dois Vizinhos: UTFPR, pp. 94–97.

Lyr, H.L., Hoffmann, G., 1967. Growth rates and growth periodicity of tree roots. Int. Rev. For. Res. 2, 181–236.

Magnani, F., Grace, J., Borghetti, M., 2002. Adjustment of tree structure in response to the environment under hydraulic constraints. Funct. Ecol. 16, 385–393.

Maquère, V., Laclau, J.-P., Gonçalves, J.L.M., Krushe, A.V., Piccolo, M.C., Gine, M.F., Ranger, J., 2005. Influence of fertilizer inputs on soil solution chemistry in eucalypt plantations established on Brazilian sandy soils. In: Proceedings of the Workshop on Management of Tropical Sandy Soils for Sustainable Agriculture: A Holistic Approach for Sustainable Development of Problem Soils in the Tropics, Khon Kaen, Thailand. International Union of Soil Science, Khon Kaen, pp. 466–471.

Marsden, C., Nouvellon, Y., Laclau, J.-P., Corbeels, M., McMurtrie, R.E., Stape, J.-L., Epron, D., le Maire, G., 2012. Modifying the G'DAY process-based model to simulate the spatial variability of *Eucalyptus* plantation growth on deep tropical soils. For. Ecol. Manage, in press, this issue.

Mello, S.L.M., Gonçalves, J.L.M., Oliveira, L.E.G., 1998. Características do sistema radicular em povoamentos de eucaliptos propagados por sementes e estacas. Sci. For. 54, 17–28.

Mello, S.L.M., Gonçalves, J.L.M., Gava, J.L., 2007. Pre- and post-harvest fine root growth in *Eucalyptus grandis* stands installed in sandy and loamy soils. For. Ecol. Manage. 246, 186–195.

Moraes, E.J., Barros, N.F., Novais, R.F., Brandi, R.M., 1990. Crescimento e eficiência nutricional de espécies de eucalipto em duas regiões bioclimáticas de Minas Gerais. ver. Bras. Ci. Solo, 353–362.

Moratori, N.O., 2008. A história do IPEF na silvicultura brasileira. IPEF, Piracicaba.

Mujiu, L., Arnold, R., Bohai, L., Minsheng, Y., 2003. Selection of of cold-tolerant *Eucalyptus* for Hunan Province. In: Turnbull, J.W. (Ed.), *Eucalyptus* in Asia: Proceeding of a International Conference Held in Zhanjiang, Guangdong, People's Republic of China 2003. ACIAR, Camberra, pp. 107–116.

Mulligan, D.R., Sands, R., 1988. Dry matter, phosphorus and nitrogen partioning in three *Eucalyptus* species grown under a nutrient deficit. New Phytol. 109, 21–28.

Nambiar, E.K.S., Nethercott, K.H., 1987. Nutrient and water availability to and growth of young radiata pine plantations intercropped with lupins. New For. 1, 117–134.

O'Connell, A.M., Grove, T.S., Mendham, D., Rance, S.J., 2000. Effects of site management in eucalypt plantations in Southwestern Australia. In: Nambiar, E.K.S., Cossalter, C., Tiarks, A., Ranger, J. (Eds.), Site Management and Productivity in Tropical Plantation Forests: Workshop Proceedings 61–71 December 1999, Kerala, India. CIFOR, Bogor, pp. 11–20.

O'Grady, A.P., Worledge, D., Battaglia, M., 2005. Temporal and spatial changes in fine root distributions in a young *Eucalyptus globulus* stand in southern Tasmania. For. Ecol. Manage. 214, 373–383.

Oliveira, J.G., 1988. Programa de melhoramento de *Eucalyptus* spp. na Rigesa. In: Simpósio Bilateral Brasil-Finlandia Sobre Atualidades Florestais, 1988: Curitiba, Parana State, Brazil. Proceedings... Curitiba: Universidade Federal do Paraná, 1988, pp. 155–161.

Ormsby, T., Napoleon, E., Burke, R., Groessl, C., Bowden, L., 2010. Getting to Know ArcGIS Desktop: Updated for ArcGIS 10, second ed. ESRI Press, Redlands.

Pereira, J.C.D., Sturion, J.A., Higa, AR., Higa, R.C.V., Shimizu, J.Y., 2000. Características da madeira de algumas espécies de eucalipto plantadas no Brasil. Embrapa Florestas, Colombo, 113p (Documento 38).

Pitelli, R.A., Marchi, S.R., 1991. Interferência das plantas invasoras nas áreas de reflorestamento. In: Seminário técnico sobre plantas daninhas e o uso de herbicidas em reflorestamento, 3, 1991, Belo Horizonte, Minas Gerais State, Brazil. Proceedings... Belo Horizonte: 1991, pp. 1–11.

Pryor, L.D., 1971. Aspectos da cultura do eucalipto no Brasil. IPEF 2, 53–59.

Reis, B.G., 1948. O eucalipto no Rio Grande do Sul. SIPA, Porto Alegre.

Reis, M.G.F., Kimmins, J.P., Rezende, G.C., Barros, N.F., 1985. Acúmulo de biomassa em uma seqüência de idade de *Eucalyptus grandis* plantado no cerrado em duas áreas com diferentes produtividades. Rev. Árvore 9, 149–162.

Resende, M.D.V., Assis, T.F., 2008. Seleção recorrente recíproca entre populações sintéticas multi-espécies (SRR-PSME) de eucalipto. Pesqui. Flor. Brasil. 57, 57–60.

Resende, M.D.V., Higa, A.R., 1990. Estratégias de melhoramento para eucaliptos visando a seleção de híbridos. Bol. Pesqui. Flor. 20, 1–20.

Resende, G.D.S.P., Resende, M.D.V., 2000. Dominance effects in *Eucalyptus grandis*, *Eucalyptus urophylla* and hybrids. In: Dungey, H.S., Dieters, M.J., Nikles, D.J. (Eds.), Hybrid Breeding and Genetics of Forest Trees. Proceedings of QFRI/CRC-SPF Symposium, Noosa, Queensland, Austrália. Departament of Primary Industries, Brisbane, pp. 93–100.

Ryan, M.G., Binkley, D., Fownes, J.H., 1997. Age-related decline in forest productivity: pattern and process. Adv. Ecol. Res. 27, 213–262.

Salgado, T.P., Alves, P.L.C.A., Kuva, M.A., Takahashi, E.N., Dias, T.C.S., Lemes, L.N., 2011. Sintomas de intoxicação Inicial de *Eucalyptus* proporcionados por subdoses de glyphosate aplicadas no caule ou nas folhas. Planta Daninha 29, 913–922.

Sankaran, K.V., Chacko, K.C., Pandalai, R.C., Kallarackal, J., Somen, C.K., Sharma, J.K., Balagopalan, M., Balasundaruan, M., Kumaraswamy, S., Sankar, S., Gilbes, R.J., Grove, T.S., Mendham, D., O'Connel, A.M., 2000. Effects of site management on eucalypts plantations in the monsoonal tropics – Kerala, India. In: Nambiar, E.K.S., Cossalter, C., Tiarks, A., Ranger, J. (Eds.), Site Management and Productivity in Tropical Plantation Forests: Workshop Proceedings 51–60 December 1999, Kerala, India. CIFOR, Bogor, pp. 11–20.

Santana, R.C., Barros, N.F., Comerford, N.B., 1999. Aboveground biomass, nutrient content, and nutrient use efficiency of eucalypt plantations growing in different sites in Brazil. In: Richardson, J., Lowe, A., Hakkila, P., Smith, C.T. (Eds.), Conventional Systems for Bioenergy: Papers Presented at the IEA Bioenergy Task 18 Workshop in Charleston, South Carolina, New Zealand, J. For. Sci., pp. 225–237.

Santos, G.A., Assis, T.F., Stahl, J., 2008. Silvicultura e melhoramento de *Eucalyptus*, em áreas de ocorrência de geadas severas. III Seminário sobre Silvicultura em Florestas Plantadas.

Sasaki, C.M., Gonçalves, J.L.M., Silva, A.P., 2007. Ideal subsoiling moisture content of Latosols used in forest plantations. For. Ecol. Manage. 243, 75–82.

Scolforo, J.R.S., Carvalho, L.M.T., Oliveira, A.D., 2008. Inventário florestal de Minas Gerais: monitoramento dos reflorestamentos e tendências da produção em volume, peso de matéria seca e carbono, 2005–2007. UFLA, Lavras.

Silva, M.A., 1870. Silvicultura brasileira: trabalhos da floresta nacional da Tijuca. Rev. Agric. Imp. Inst. Flumin. Agric. 1, 29–33.

Silva, H.D., 2008. Espécies de *Eucalyptus* tolerantes à geada. In: Encontro Brasileiro de Silvicultura, 1. Curitiba, Parana State, Brazil. Proceedings... Piracicaba: PTSM/IPEF/ESALQ/FUPEF, 2008.

Silva, C.R., Gonçalves, J.L.M., Folegatti, B.S., Stape, J.L., Gava, J.L., 1997. Weed proliferation in eucalypt stands established under minimum and intensive site preparation. In: IUFRO Conference on Silviculture and Improvement of *Eucalypts*. Salvador, Bahia State, Brazil. Proceedings... Colombo, EMBRAPA-CNPF, pp. 234–241.

Silva, W., Silva, A.A., Sediyama, T., Freitas, R.S., 2000. Absorção de nutrientes por mudas de duas espécies de eucalipto em resposta a diferentes teores de água no solo e competição com plantas de *Brachiaria brizantha*. Cienc. Agrotec. 24, 147–159.

Silva, C.R., Camargo, F.R.A., Jacob, W.S., Iijima, J., 2002. Preparo de solo em áreas acidentadas do Vale do Paraíba do Sul – SP. In: Gonçalves, J.L.M., Stape, J.L. (Eds.), Conservação e cultivo de solos para plantações florestais. IPEF, Piracicaba, pp. 245–258.

Silva, A.M., Alvares, C.A., Watanabe, C., 2011. Natural potential for erosion for Brazilian territory. In: Godone, D., Stanchi, S. (Eds.), Soil Erosion Studies, vol. 1. InTech – Open Access Publisher, Rijeka, pp. 1–22.

Soil Survey Staff, 1993. Soil Survey Manual. Soil Conservation Service. US Department of Agriculture Handbook, p. 18.

Soliman, E.P., Dal Pogetto, M.H.F., Zaché, B., Dias, T.K.R., Pereira, J.M., Lazo, M.L., Barbosa, L.R., Wilcken, C.F., 2010. Cálculo da CL50 e TL50 de *Beauveria bassiana* para controle do Percevejo-bronzeado *Thaumastocoris peregrinus* (Hemiptera: Thaumastocoridae). In: Congresso Brasileiro De Entomologia, 23, 2010, Natal. Proceedings... Natal: Sociedade Brasileira de Entomologia: Emparn, 2010. 1 CD-ROM.

Souza, A.J., 2002. Preparo de solos coesos para cultura do eucalipto no extremo sul da Bahia. In: Gonçalves, J.L.M., Stape, J.L. (Eds.), Conservação e cultivo de solos para plantações florestais. IPEF, Piracicaba, pp. 297–311.

Souza, C.R., Rossi, L.M.B., de Azevedo, C.P., de Lima, R.M.B., 2004. Behaviour of *Acacia mangium* and clones of *Eucalyptus grandis* × *E. urophylla* in experimental plantations in Central Amazônia. Sci. Flor. 65, 95–101.

Stahl, J., 2009. Resposta inicial de *Eucalyptus* spp. à adubação fosfatada e potássica no planalto Sul Catarinense. Dissertation. University of State of Santa Catarina, Lages, Brazil, 69 pp.

Stape, J.L., Gonçalves, J.L.M., Gonçalves, A.N., 2001. Relationships between nursery practices and field performance for *Eucalyptus* plantations in Brazil. New Forests 22, 19–41.

Stape, J.L., Andrade, S., Gomes, A.N., Krejci, L.C., Ribeiro, J.A., 2002. Definição de métodos de preparo de solo para silvicultura em solos coesos do litoral norte da Bahia. In: Gonçalves, J.L.M., Stape, J.L. (Eds.), Conservação e cultivo de solos para plantações florestais. IPEF, Piracicaba, pp. 259–296.

Stape, J.L., Binkley, D., Ryan, M.G., 2004. *Eucalyptus* production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. For. Ecol. Manage. 193, 17–31.

Stape, J.L., Binkley, D., Ryan, M.G., Fonseca, S.R.L., Takahashi, E.N., Silva, C.R., Hakamada, S.R., Ferreira, J.M., Lima, A.M., Gava, J.L., Leite, F.P., Silva, G., Andrade, H., Alves, J.M., 2010. The Brazil *Eucalyptus* Potential Productivity Project: influence of water, nutrients and stand uniformity on wood production. For. Ecol. Manage. 259, 1674–1684.

Tarouco, C.P., Agostinetto, D., Panozzo, L.E., Santos, L.S., Vignolo, K.G., Ramos, L.O.O., 2009. Períodos de interferência de plantas daninhas na fase inicial de crescimento do eucalipto. Pesq. Agropec. Bras. 44, 1131–1137.

Teskey, R.O., Hinckley, T.M., 1981. Influence of temperature and water potential on root growth of white oak. Physiol. Plant. 52, 362–369.

Thongo-M'Bou, A., Jourdan, C., Deleporte, P., Nouvellon, Y., Saint-André, L., Bouillet, J.-P., Mialoundama, F., Mabiala, A., Epron, D., 2008. Root elongation in tropical *Eucalyptus* plantations: effect of soil water content. Ann. For. Sci. 65, 609–615.

Thornthwaite, C.W., Mather, J.R., 1955. The Water Balance. Publications in Climatology. Drexel Institute of Technology, Laboratory of Climatology, Centerton, NJ, p. 86.

Toledo, R.E.B., Victoria Filho, R., Pitelli, R.A., Alves, P.L.C.A., Lopes, M.A.F., 2000. Efeito de períodos de controle de plantas daninhas sobre o desenvolvimento inicial de plantas de eucalipto. Planta Daninha 18, 395–404.

Toledo, R.E.B., Victoria Filho, R., Alves, P.L.C.A., Pitelli, R.A., Lopes, M.A.F., 2003. Faixas de controle de plantas daninhas e seus reflexos no crescimento de plantas de eucalipto. Sci. For. 64, 78–92.

Tomazello, M., 1976. Estudos sobre o cancro causado por Diaporthe cubensis: etiologia e resistência em *Eucalyptus*. M.Sc. Dissertation. University of Sao Paulo, Piracicaba, Brazil, 106 pp.

Versini, A., Nouvellon, Y., Laclau, J.-P., Kinana, A., Ranger, J., Zeller, B., Mareschal, L., Epron, D., 2012. The manipulation of organic residues affects tree growth and heterotrophic CO_2 efflux in a tropical *Eucalyptus* plantation. For. Ecol. Manage. http://dx.doi.org/10.1016/j.foreco.2012.07.045.

Vigneron, P., Bouvet, J., 2000. Eucalypt hybrid breeding in Congo. In: Dungey, H.S., Dieters, M.J., Nikles, D.G. (Eds.), Hybrid Breeding and Genetics of Forest Trees. Proceedings of QFRI/CRC-SPF Symposium, 9–14th April 2000 Noosa, Queensland, Australia. Department of Primary Industries, Brisbane, pp. 14–26.

Wilcken, C.F., 2011. Breeding *Eucalyptus* for insect resistance. In: IUFRO Working Group 2.08.03 – Improvement and Culture of *Eucalyptus*. 2011: Porto Seguro, Bahia State, Brazil. Proceedings... Piracicaba: Vitor's Design, 2011. v. 1.

Wilcken, C.F., Sanchez-Bezerra, N., Oliveira, R.J.R., Orlato, C., Ferreira Filho, P.J., 2008. Manejo Integrado de Pragas em povoamentos florestais. In: Encontro Brasileiro de Silvicultura, 1. Curitiba, Parana State, Brazil. Proceedings... Piracicaba: PTSM/IPEF/ESALQ/FUPEF, 2008, pp. 129–134.

Wilcken, C.F., Barbosa, L.R., Sa, L.A.N., Soliman, E.P., Lima, A.C.V., Dal Pogetto, M.H.F.A., Dias, T.C.R., 2011. Manejo de pragas exóticas em florestas de eucalipto. In: Encontro Brasileiro de Silvicultura, 2. Campinas, São Paulo State, Brazil. Proceedings... Piracicaba: PTSM/IPEF/ESALQ/FUPEF, 2011, pp. 129–134.

Xu, D.P., Dell, B., 2002. Nutrient management of eucalypt plantations in South China. In: International Symposium on Eucalypt Plantations. Presentation Papers & Abstracts, September 2002, Guangdong, P.R. China, 1–6. RITF, Guangdong, pp. 139–159.

Xu, D.P., Yang, Z.J., Dell, B., Gong, M., 2000. Effects of site management in Eucalyptus urophylla plantations in Guangdong province, China. In: Nambiar, E.K.S., Cossalter, C., Tiarks, A., Ranger, J. (Eds.), Site Management and Productivity in Tropical Plantation Forests: Workshop Proceedings 31–40 December 1999, Kerala, India. CIFOR, Bogor, pp. 11–20.

Zen, S., 1987. Influência da matocompetição em plantas de Eucalyptus grandis. IPEF Série Téc. 12, 25–35.

Zen, S., Yonezawa, J.T., Feldeberg, J.E., 1995. Implantação de florestas no sistema de cultivo mínimo. In: Seminário Sobre Cultivo Mínimo do Solo em Florestas, 1, Curitiba-Brasil, 1995. Proceedings. Curitiba-Brasil, CNPFloresta/IPEF/UNESP/SIF/FUPEF, pp. 65–72.

Zobel, B., Campinhos, E., Ikemori, Y.K., 1982. Selection and breeding for wood uniformity. In: TAPPI Research and Development Division Conference, pp. 159–168.