



UNIVERSIDADE FEDERAL DE GOIÁS  
ESCOLA DE AGRONOMIA  
PROGRAMA DE PÓS-GRADUAÇÃO EM GENÉTICA E  
MELHORAMENTO DE PLANTAS

**SELEÇÃO DE CLONES DE *Eucalyptus* spp.  
PARA A PRODUÇÃO BIOENERGÉTICA EM  
REGIÕES DE DÉFICIT HÍDRICO**

**RODRIGO DE SOUSA OLIVEIRA**

Orientador:  
**Prof. Dr. Evandro Novaes**



UNIVERSIDADE FEDERAL DE GOIÁS  
ESCOLA DE AGRONOMIA

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**SELEÇÃO DE CLONES DE *Eucalyptus* spp. PARA A PRODUÇÃO  
BIOENERGÉTICA EM REGIÕES DE DÉFICIT HÍDRICO**

Tese apresentada ao Programa de Pós-Graduação em Genética e Melhoramento de Plantas, da Escola de Agronomia da Universidade Federal de Goiás, como requisito à obtenção do título de doutorado em Genética e Melhoramento de Plantas.

Orientador:

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## ATA DE DEFESA DE TESE

Ata Nº 76/2022 da sessão de Defesa de Tese de **Rodrigo de Sousa Oliveira**, que confere o título de Doutor em **Genética e Melhoramento de Plantas**, na área de concentração em **Genética e Melhoramento de Plantas**.

Aos dez dias do mês de maio do ano de dois mil e vinte e dois, a partir das treze horas, por meio de videoconferência, realizou-se a sessão pública de Defesa de Tese intitulada "SELEÇÃO DE CLONES DE *Eucalyptus spp.* PARA A PRODUÇÃO BIOENERGÉTICA EM REGIÕES DE DÉFICIT HÍDRICO". Os trabalhos foram instalados pelo Orientador, Professor Evandro Novaes (UFLA), com a participação dos demais membros da Banca Examinadora: Professor João Batista Duarte (EA/UFG), membro titular interno; Professor Magno Antonio Patto Ramalho (UFLA), membro titular externo; Professor Evandro Vagner Tambarussi (UNICENTRO), membro titular externo; e Doutora Izabel Christina Gava de Souza (SUZANO S.A.), membro titular externo. Durante a arguição os membros da banca **não fizeram** sugestão de alteração do título do trabalho. A Banca Examinadora reuniu-se em sessão secreta a fim de concluir o julgamento da Tese tendo sido o candidato **aprovado** pelos seus membros. Proclamados os resultados pelo Professor Evandro Novaes, Presidente da Banca Examinadora, foram encerrados os trabalhos e, para constar, lavrou-se a presente ata que é assinada pelos Membros da Banca Examinadora, aos dez dias do mês de maio do ano de dois mil e vinte e dois.

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“Pouco conhecimento faz com que as pessoas se sintam orgulhosas. Muito conhecimento, com que se sintam humildes.”

Leonardo da Vinci



À minha esposa Jéssica por todo o amor, apoio, compreensão e incentivo para percorrer esta árdua caminhada. Aos meus pais e meu irmão, por terem acreditado em mim desde o início e pelo seu apoio incondicional. Aos meus avós que ajudaram a formar muito do meu caráter, e por todo apoio. Aos meus ex-alunos e orientados que contribuíram imensamente com minha formação. A todos os professores que me ensinaram os caminhos da educação e da ciência. Aos verdadeiros amigos que fiz até aqui.

*Dedico*

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## RESUMO

OLIVEIRA, R. S. **Seleção de clones de *Eucalyptus* spp. para a produção bioenergética em regiões de déficit hídrico**. 2022. Tese (Doutorado em Melhoramento Genético de Plantas) – Escola de Agronomia, Universidade Federal de Goiás<sup>1</sup>

A eucaliptocultura tem papel importante na economia nacional e na manutenção de áreas nativas, uma vez que a madeira gerada nessa atividade abastece a maior parte das indústrias nacionais de base florestal. Recentemente, os plantios florestais se expandiram atingindo áreas presentes no bioma Cerrado e em transição com o bioma Amazônico, com clima e solos bem diferentes das regiões onde a silvicultura brasileira se desenvolveu ao longo dos anos. Estas novas fronteiras florestais apresentam novos desafios aos programas de melhoramento genético que tem que desenvolver genótipos adaptados a essas novas condições e atender às diversas necessidades, desde a produção de celulose e papel, até o fornecimento de biomassa para as caldeiras das indústrias. Esta tese está composta por três artigos. No primeiro capítulo realizou-se uma revisão de literatura com o objetivo de compreender o processo científico e evolutivo do desenvolvimento dos primeiros clones de eucalipto no Brasil e elucidar as condições atuais da silvicultura nas novas fronteiras florestais e como elas irão direcionar a necessidade do desenvolvimento de novos genótipos adaptados a essa nova realidade. No segundo capítulo avaliou-se o desempenho de 109 genótipos de eucalipto por meio de testes clonais instalados em Catalão-GO, Corumbá-de-Goiás-GO e Luziânia-GO, onde se mediram os caracteres de crescimento e produtividade de madeira em todas as árvores aos dois, quatro e seis anos de idade. Obtiveram-se as estimativas dos componentes de variância via REML (Restricted maximum likelihood) e dos valores genotípicos via BLUP (Best Linear Unbiased Prediction) para essas características. Dessa forma, foi possível avaliar a magnitude dos efeitos genéticos, ambientais e da interação G x E. Os melhores clones aos dois e aos quatro anos de idade são, em média, 65% equivalentes aos melhores clones aos seis anos de idade, quando a produtividade média foi de 255,8 m<sup>3</sup> ha<sup>-1</sup>. Todos os seis clones mais produtivos (CCL29, CCL35, CLR454, CCL27, CCL07, AEC144) apresentam *E. urophylla* em sua constituição. No terceiro e último artigo foi avaliado o potencial energético de um conjunto de 20 clones multiespécies de eucalipto plantados sob estresse hídrico sazonal e os resultados indicam genótipos de *Eucalyptus* adaptados ao estresse hídrico sazonal com alta produtividade e potencial energético, como o clone CCL36 (*E. urophylla* x *E. grandis*) com produção energética de 982.587 MJ ha<sup>-1</sup> ano<sup>-1</sup>.

**Palavras chave:** Biomassa; Silvicultura; Interação Genótipos x Ambientes

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<sup>1</sup> Orientador: Prof. Dr. Evandro Novaes. Departamento de Biologia – UFLA

## ABSTRACT

OLIVEIRA, R. S. **Selection of *Eucalyptus* spp. clones for bioenergetic production in water deficit regions.** 2022. Thesis (Doctorate in Genetic Improvement of Plants) – School of Agronomy, Federal University of Goiás<sup>1</sup>

Eucalyptus cultivation plays an important role in the national economy and in the maintenance of native areas since the wood generated in this activity supplies most of the national forest-based industries. Recently, forest plantations have expanded, reaching areas present in the Cerrado biome and in transition with the Amazon biome, with very different climate and soils from the regions where Brazilian forestry has developed over the years. These new forest frontiers present new challenges to genetic improvement programs, which have to develop genotypes adapted to new conditions to meet different needs, from pulp and paper production to the supply of biomass to industrial boilers. This thesis is composed of three articles. In the first chapter, a literature review was carried out to understand the scientific and evolutionary process of the development of the first eucalyptus clones in Brazil and to elucidate the current conditions of silviculture in the new forest frontiers and how they will direct the need for the development of new genotypes adapted to this new reality. In the second chapter, the performance of 109 eucalyptus genotypes was evaluated through clonal tests installed in Catalão-GO, Corumbá-de-Goiás-GO and Luziânia-GO, where the growth and wood productivity traits of all trees at two, four and six years. Estimates of variance components were obtained via REML (Restricted maximum likelihood) and genotypic values via BLUP (Best Linear Unbiased Prediction) for these traits. In this way, it was possible to evaluate the magnitude of the genetic, environmental, and G x E interaction effects. The best clones at two and four years are, on average, 65% equivalent to the best clones at six years, when the average productivity was 255.8 m<sup>3</sup> ha<sup>-1</sup>. All six most productive clones (CCL29, CCL35, CLR454, CCL27, CCL07, AEC144) have *E. urophylla* in their constitution. In the third and last article, the energy potential of a set of 20 multispecies eucalyptus clones planted under seasonal water stress was evaluated and the results indicate Eucalyptus genotypes adapted to seasonal water stress with high productivity and energy potential, such as clone CCL36 (*E. urophylla* x *E. grandis*) with (982.58 MJ ha<sup>-1</sup> yr<sup>-1</sup>).

**Key words:** Biomass; Silviculture; Interaction genotypes x environmentals.

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<sup>1</sup> Orientador: Prof. Dr. Evandro Novaes. Departamento de Biologia – UFLA

## 1. INTRODUÇÃO

O setor florestal brasileiro se destaca no cenário mundial devido à diversidade de suas florestas nativas e ao excelente desempenho de suas florestas plantadas. A alta produtividade dos plantios comerciais se deve às ações de melhoramento florestal e a melhoria das práticas silviculturais intensificadas a partir da década de 1970, principalmente para as espécies dos gêneros *Corymbia* e *Eucalyptus* (Alfenas et al., 2009).

Com mais de setecentas espécies, os eucaliptos estão entre as mais importantes essências florestais, devido aos diferentes ambientes aos quais são adaptados, e a sua ampla diversidade genética (Eldridge et al., 1993; Flores et al., 2016). O gênero *Eucalyptus* chegou ao Brasil como alternativa ao uso de espécies nativas para carvão e dormentes, que abasteciam a Companhia Paulista de Estradas de Ferro (Castro et al., 2016), e rapidamente teve sucesso devido ao seu rápido crescimento e boa adaptação (Andrade, 1961).

Os programas de melhoramento de *Eucalyptus* tiveram início na década de 1960 e no início dos anos 1980, produziam-se sementes melhoradas (Ferreira & Santos, 1997). A evolução das técnicas de multiplicação vegetativa, possibilitou a propagação dos híbridos e com isso a exploração da heterose e da variabilidade genética interespecífica, aumentando os recursos genéticos utilizados nos programas de melhoramento, bem como a produtividade dos plantios de *Eucalyptus* (Assis et al., 2015). Avanços tecnológicos e silviculturais também contribuíram para que o Brasil se tornasse uma referência no setor.

O melhoramento genético é um processo cíclico que utiliza técnicas de seleção e recombinação de indivíduos com características superiores, ou seja, de interesse econômico, aumentando a frequência dos alelos que as controlam (Pires et al., 2011). Também pode ser entendido como a ciência, arte e gerenciamento de recursos para aperfeiçoamento das plantas visando o benefício da sociedade (Bernardo, 2002). Assim, o melhoramento genético florestal visa o aumento da produtividade das florestas plantadas, melhoria da qualidade da madeira de acordo com a finalidade do produto, adaptação à diversas condições edafoclimáticas, resistência às pragas e doenças, e manutenção da variabilidade e dos ganhos em longo prazo (Pires et al., 2011).

O Brasil é responsável por cerca de 22% da área plantada com *Eucalyptus* em todo o mundo (Payn et al., 2015). O eucalipto produzido no Brasil possui a maior média de produtividade no mundo, com  $36,3 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{ano}^{-1}$  (IBÁ, 2021). Essa média já foi maior, e o seu decréscimo é, provavelmente, decorrente do avanço dos plantios de *Eucalyptus* spp. para áreas menos produtivas, onde estão situadas as novas fronteiras florestais.

A expansão das florestas de eucalipto para regiões com climas mais secos requer melhoramento com seleção de materiais genéticos superiores e adaptáveis à seca, uma vez que o estresse hídrico é uma das mais severas limitações à produtividade dos plantios de eucalipto e traz implicações na qualidade da madeira para bioenergia (Oliveira et al., 2021).

Estudos relacionados à estimação de parâmetros genéticos são sempre importantes para subsidiar a escolha dos melhores métodos para a seleção de genótipos superiores (Resende, 2007; Castro et al., 2016). A exploração da interação de genótipos com ambientes (GxA) também se faz necessária, para selecionar e recomendar os melhores clones para determinada região (Santos et al., 2015), principalmente nas áreas consideradas como a nova fronteira florestal brasileira.

No processo de melhoramento, o conhecimento da correlação entre caracteres fornece informações úteis para a seleção de genótipos superiores (Resende & Duarte, 2007), principalmente em características de difícil mensuração, como por exemplo as propriedades energéticas da madeira. As correlações também são fundamentais para se verificar a relação entre o desempenho dos clones em uma fase mais jovem e na sua idade de corte, a fim de verificar a possibilidade de seleção precoce (Massaro et al., 2010).

Atualmente, os programas de melhoramento genético florestal devem buscar definir as espécies e procedências adaptadas às novas áreas de plantio e selecionar árvores que possuam combinações e médias altas das características desejadas, mantendo uma população base adequada com variabilidade e médias altas para garantir ganhos futuros nas gerações seguintes (Zobel & Talbert, 2003). As estratégias de melhoramento florestal baseiam-se na seleção de genitores e combinação destes via cruzamentos controlados direcionados dentro dos programas de seleção (Fonseca et al., 2010; Assis et al., 2015). A implantação de testes de progênie e testes clonais são fundamentais para se estimar os valores genéticos e genotípicos e compõem etapas básicas do processo de melhoramento florestal.



Apesar de muito pesquisado, o gênero *Eucalyptus* ainda carece de vários estudos, sobretudo em regiões características dessa nova fronteira da eucaliptocultura nacional. Nessas regiões, existe uma carência de estudos genéticos com florestas plantadas, especialmente em *Eucalyptus* (Reis et al., 2017). Atualmente, o Estado de Goiás, apresenta um setor florestal pouco desenvolvido. Porém, como se encontra inserido no centro do Bioma Cerrado, que é uma das regiões de expansão recente da eucaliptocultura, a avaliação de clones em Goiás pode subsidiar a recomendação de cultivares em outras regiões do país.

O Estado de Goiás possui características edafoclimáticas semelhantes aos ambientes de plantio da nova fronteira florestal brasileira, com solos geralmente ácidos ou arenosos, altas temperaturas e déficit hídrico sazonal. Nesse contexto, estudos de melhoramento genético são fundamentais para identificar materiais adaptados as condições edafoclimáticas onde ocorram o déficit hídrico, típico da nova fronteira florestal, viabilizando a continuidade do desenvolvimento da eucaliptocultura nessa região. O aumento da eficiência produtiva é fundamental para a redução de custos e para evitar a expansão da silvicultura em áreas com remanescentes naturais. Segundo o relatório IBA (2021), os custos dos produtos florestais brasileiros vêm aumentando a cada ano, diminuindo a competitividade destes no mercado internacional.

A seleção de clones no Bioma Cerrado poderá servir de base para a escolha de genótipos em outras regiões do País, especialmente naquelas suscetíveis ao déficit hídrico, onde a eucaliptocultura tem avançado. Diante disso, este trabalho objetiva identificar, dentre um grupo de clones comerciais utilizados no Brasil, genótipos adaptados às condições edafoclimáticas de três locais no estado de Goiás, bem como verificar a viabilidade da seleção precoce e avaliar as propriedades energéticas dos clones potenciais para essa região.

## **CHAPTER 1**

### **HISTORY OF GENETIC BREEDING OF *Eucalyptus* IN BRAZIL, AND CHALLENGES FOR THE NEW FOREST FRONTIER <sup>1</sup>**

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<sup>1</sup> Chapter prepared according to the rules of the scientific journal *Forest Science*.

## **2. HISTORY OF GENETIC BREEDING OF *Eucalyptus* IN BRAZIL AND CHALLENGES FOR THE NEW FOREST FRONTIER**

### **Abstract**

Plant breeding is fundamental for the sustainability of any agriculture enterprise, reducing production costs and land area use. The objective of this review was to evaluate the evolution of *Eucalyptus* breeding in Brazil since introduction of the genus in the country. *Eucalyptus* has an important role for the national economy and maintenance of native areas since its wood supplies most of the national forest-based industries. Over the years, several methods of recurrent selection have been adopted to select hybrids that concentrate favorable characteristics for multiple uses. However, recent expansion of the eucalyptus plantations to new areas are requiring breeding programs to select new clones adapted to this new reality. Thus, new characteristics such as drought tolerance need to be incorporated into existing genetic materials with there is a need for new studies and improvement strategies that favor these adaptations. These studies are particularly important for Brazil to continue to lead the world ranking of forest productivity and keep the competitiveness of its wood-based products in international markets.

**Index terms:** Eucalyptus Forest; Interspecific hybrids; Clonal forestry.

## 2.1 INTRODUCTION

*Eucalyptus* L'Hér is a forestry genus is one of the most planted in the world, with a total area of about 59 million ha (Payn et al., 2015; Borralho et al., 2018). In Brazil, *Eucalyptus* is planted in 7.46 million hectares, which corresponds to 78,2% of its planted forests (IBÁ, 2021). This preference for eucalyptus is due to its short rotation (Gonçalves et al., 2008), high productivity (Binkley et al., 2017; Oliveira et al., 2020) and wood properties suitable for several end-uses (Mason et al., 2016).

*Eucalyptus* stands out mainly for being an important source of wood and fibers for multiple industrial purposes, including the production of panels, pulp, paper, and bioenergy (Grattapaglia et al., 2012; Flores et al., 2016). Plantations of eucalyptus forests is also favored by its ability to adapt to different edaphoclimatic conditions (Gonçalves et al., 2013; Binkley et al., 2017), in addition to its diversity of useful species, immense genetic variability (Campoe et al., 2020; Oliveira et al., 2020), and easy of cloning (Myburg et al., 2014; Protásio et al., 2018).

Forest productivity and growth depend on edaphoclimatic conditions, and the suitability of the species used (Roy et al., 2001; Resende et al., 2017). Plantations of eucalyptus species in tropical and subtropical regions of Brazil are among the most productive forests in the world, reaching an average of  $36.8 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  (Stape et al., 2010, Flores et al., 2016; IBÁ, 2021). This average productivity is the result of continuous investments in research programs focused on genetic improvement (Castro et al., 2016) and on silvicultural practices (Gonçalves et al., 2013; Castro et al., 2016).

The high productivity of Brazilian eucalyptus forests reflects the selection of superior clones adapted to different climatic conditions (Oliveira et al., 2020; Binkley et al., 2017;

Campoe et al., 2016; Freitas, 2018; Scolforo et al., 2019) and improvement in silvicultural techniques, such as soil preparation and fertilization, spacing between rows (André et al., 2021; Hakamada et al., 2020; Melo et al., 2016; Stape et al., 2010), integrated control and management of weeds, pests and diseases (Gonçalves et al., 2013; Londero et al., 2012), in addition to the production of high quality seedlings (Stape et al., 2001).

There is a need for continuous gain in *Eucalyptus* productivity to meet the growing demand for forest biomass to replace the use of fossil fuel-based energy (Gustavsson et al., 2015), such as in the steel industry (Moya and Tenorio, 2013), and to provide raw material for the pulp, paper, and panel industries (IBÁ, 2021). In addition, demands for forest-based products should increase with environmental awareness concerning the pressure on already threatened natural forests (Sulaiman et al., 2017). Because of higher demands for sustainable forest products, in Brazil, *Eucalyptus* and *Corymbia* plantations are expanding into regions less favorable to their development, due to a more intense and lasting water deficit associated with seasonal drought and high temperatures (Binkley et al., 2017; Elli et al., 2019; Gonçalves et al., 2017). Drought is the main cause of losses in eucalyptus productivity in Brazil (Elli et al., 2019; Freitas, 2018). This problem is projected to worsen given the future trends of increasing average temperatures for Brazil (Bender and Sentelhas, 2018), which can further increase the potential evapotranspiration (Jalota et al., 2018; Payn et al., 2015).

Climatic abnormalities in recent years are putting pressure on many eucalyptus plantations, due to the higher annual average temperature, more intense rainfall, and higher frequency of severe water stress (Gonçalves et al., 2017). According to Gonçalves et al. (2017) these extreme weather events are more common in Aw and Cwa climates, according to Köppen's classification (Alvares et al. 2013). Rainfall unevenly distributed between seasons, with rains concentrated in the summer, aggravates water stress suffered by *Eucalyptus* spp. trees resulting in outbreaks of pests and diseases, which are becoming increasingly common (Gonçalves et al. 2013; Gonçalves et al., 2017).

New forest plantations are expanding to regions subjected to stresses, such as drought and frosts, resulting in lower productive potential (Assis, 2014). In Brazil, *Eucalyptus* plantations have expanded to Mato Grosso do Sul, Tocantins and Maranhão by 286.6%, 231.7% and 67.7% in the last 10 years, respectively (IBÁ, 2021). In southern states of the country, *Eucalyptus* plantation has also increased by 100%, on average in the last decade (IBÁ, 2021).

Given the uncertainties of future economics scenarios on a regional scale (Gonçalves et al., 2017) and the climatic conditions of the Brazilian regions where eucalyptus has been established in recent years, one of the biggest current challenges will be the selection and adaptation of more productive *Eucalyptus* genotypes.

## **2.2 INTRODUCTION OF *Eucalyptus* IN BRAZIL**

Eucalypts are represented by more than 700 species of the *Corymbia* and *Eucalyptus* genera (Myrtaceae), in addition to their varieties and hybrids (Boland et al., 2006; Bayly, 2016; Flores et al., 2016). Native to Oceania, eucalyptus have a wide distribution under different edaphoclimatic conditions, occurring from sea level to the highest regions of that continent (Eldridge et al., 1993; Boland et al., 2006).

In a natural environment, eucalypts are present both in dense forests, predominantly in the upper part of the canopy, with heights reaching 30 to 50 m, and in less dense forest formations, with smaller heights between 10 and 25 m (Boland et al., 2006). In these regions, annual rainfall averages range from 250 mm to 3,500 mm, covering regions with occurrences of frost to places with temperatures close to 40 °C (Golfari et al., 1978; Boland et al., 2006; Flores et al., 2016).

After its discovery by the Europeans at the end of the 18th century, eucalyptus started to be widely used in forest plantations, with intense worldwide acceptance (Eldridge et al., 1993). In Brazil, the first specimens were planted in the Rio de Janeiro Botanical Gardens,

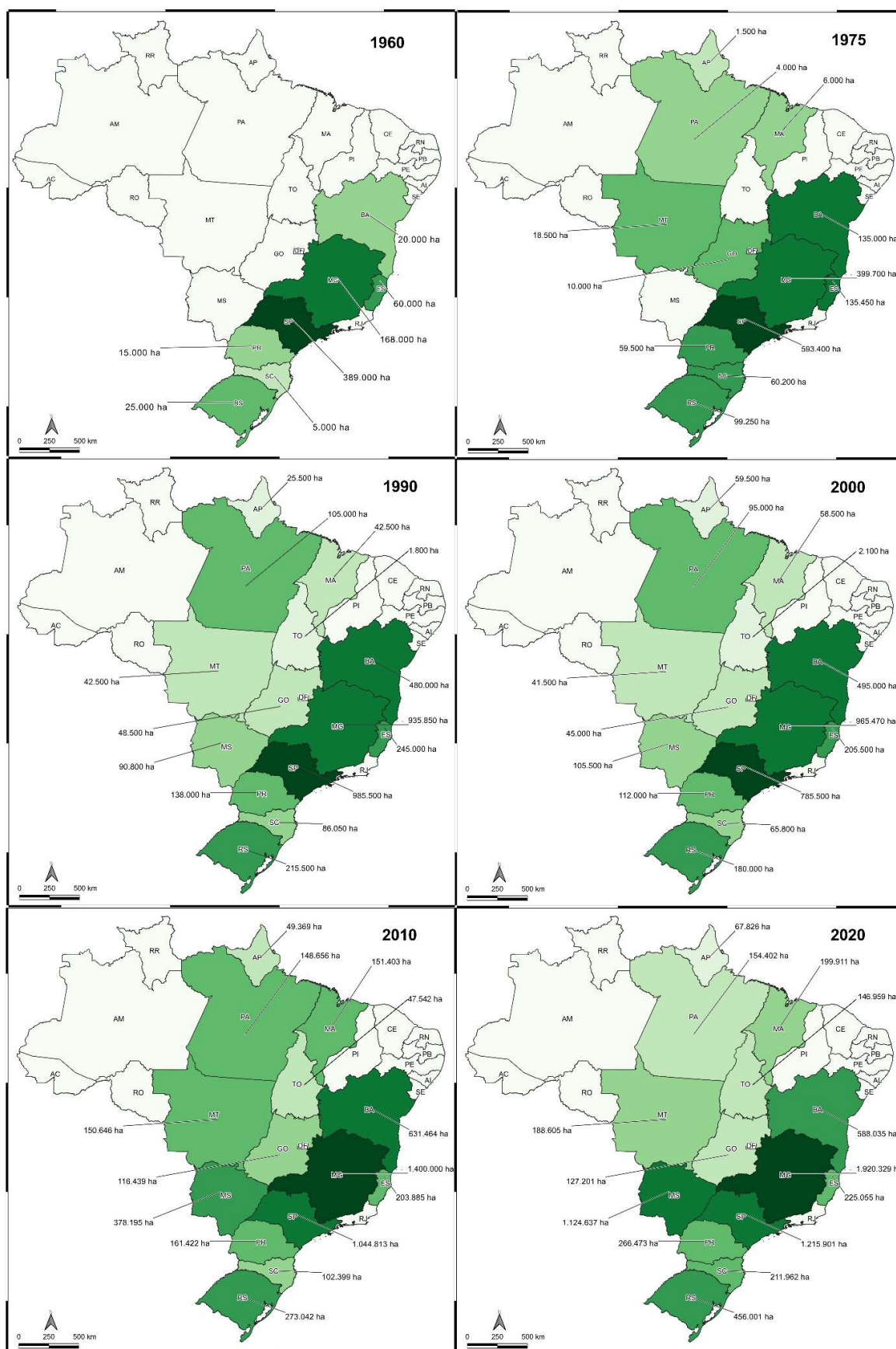
in 1825, and in rural areas of Rio Grande do Sul, in 1868 (Ferreira and Santos, 1997; Marchiori, 2014; Castro et al., 2016). The commercial exploitation of *Eucalyptus* in the country began to be considered by Edmundo Navarro de Andrade, in 1904. He worked at São Paulo State Railroad Company and was looking for new forest species that could be planted to meet the demands of wood needed to build the railroad and to provide the energy used in the train steam engine (Ferreira and Santos, 1997). At that time, his company was still extracting wood from natural ecosystems, which was unsustainable.

The first scientific studies on eucalyptus silviculture in Brazil were coordinated by Navarro de Andrade and analyzed the aspects of seedling production, soil preparation, planting spacing, pruning, thinning, harvesting, plant health, productivity and wood uses (Andrade, 1961). Initially, Navarro de Andrade evaluated the adaptation of different eucalyptus species in São Paulo State (Castro et al., 2016).

Among the evaluated species in these studies were *C. citriodora*, *E. botryoides*, *E. camaldulensis*, *E. corinocalyx*, *E. diversicolor*, *E. globulus*, *E. grandis*, *E. longifolia*, *E. maculata*, *E. obliqua*, *E. robusta*, *E. saligna*, *E. tereticornis*, *E. triantha* and *E. urophylla* (Andrade, 1961). These species were tested with several native tree species and presented higher productivity. As a result of these tests, in 1909, commercial cultivation of eucalyptus started in Brazil (Andrade, 1961).

### **2.3 START OF GENETIC BREEDING OF *Eucalyptus* IN BRAZIL**

With the increase of 6.2 million hectares of eucalyptus between 1967 and 1986 (Figure 1), in response to the incentives for reforestation in Brazil, especially law nº 5,106, of 1966 (Ferreira and Santos, 1997), forest breeding became more intense from the 1970s. During this period, the selection process was initially aimed at increasing wood productivity and, only in the 1990s, it started to consider wood quality in the selection of eucalyptus genotypes to produce cellulose, charcoal, and panels (Ferreira and Santos, 1997).



**Figure 1.** Expansion of eucalyptus culture in Brazil after the law of incentives for the reforestation sector. Darker shades of green indicate the States with the highest proportion of planted area with *Eucalyptus*. Modified from Ferreira and Santos (1997); ABRAF (2012); Gonçalves et al. (2013); IBÁ (2021).



In this period, cloning by cutting in greenhouses was adopted for several eucalyptus species (Campinhos and Ikemori, 1983). Eucalyptus cloning was discovered in the 1950s by Australian and French researchers and perfected in Brazil in 1960-1970s (Eldridge et al., 1993; Alfenas et al., 2009).

In 1970, one of the species and provenance tests resulted in an increase in productivity from  $18.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  to an average of  $30.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ , when evaluating *E. grandis* from Coff's Harbour, Australia (Ferreira and Santos, 1997). The intensification of these tests, with new provenances of 55 different species of eucalyptus, evaluated in different sites, gave rise to suitability zoning of these species in Brazil (Golfari et al., 1978; Ferreira and Santos, 1997).

In the 1970s, the emergence of canker caused by *Chrysoporthe cubensis*, in seminal eucalyptus plantations in Aracruz-ES, a humid tropical coastal region, was fundamental for the development of genetic breeding of eucalyptus in Brazil (Campinhos and Silva, 1990). In regions with high incidence of canker, it was observed that *E. urophylla* trees had higher resistance than the most planted species, *E. saligna* and *E. grandis* (Castro et al., 2016).

In addition, it was also observed that natural hybrids between *E. urophylla* and *E. grandis* or *E. saligna* also produced trees with high resistance (Tomazello, 1976). As the forest companies started to plant the *E. grandis* x *E. urophylla* hybrids, it became evident that these hybrids had advantages that extended beyond resistance to canker. These hybrids combined the higher rusticity of *E. urophylla*, which is more tolerant to drought and, also, resistant to rust caused by *Austropuccinia psidii* (syn. *Puccinia psidii*), with the high productivity of *E. grandis*. As a result, the hybrid *E. urophylla* x *E. grandis* became the basis for most planted forests in Brazil from the 1980s onwards (Ferreira and Santos, 1997).

Interspecific hybridization, when possible, as with close related species of the *Corymbia* and *Eucalyptus* genera, dramatically expands the toolbox of forest breeders,

providing genetic combinations that does not exist naturally (Grattapaglia and Kirst, 2008). As a result, hybrids greatly expand the possibilities of recombination among the enormous genetic variability present in the *Eucalyptus* (Assis, 1996).

The interspecific hybridization is a quick way to obtain genetic gains, combining growth characteristics, wood quality, resistance to biotic and abiotic factors, in addition to promoting heterosis (Paludzyszyn Filho and Santos, 2011). Initial production of interspecific hybrids depends on difficult artificial pollination techniques that generate seeds with very heterogeneous performance (Assis et al., 2015). These difficulties were circumvented by asexual propagation methods (Campinhos and Ikemori, 1983; Assis et al., 1987) that revolutionized the Brazilian forest sector (Alfenas et al., 2009).

Controlled pollination and formation of new hybrids were carried out with progenies obtained by intense intrapopulation selection in seed production areas (Assis, 1996; Ferreira and Santos, 1997). The species used in the crosses are chosen based on their complementary characteristics and on their genetic proximity, to reduce the genetic incompatibility (Ferreira and Santos, 1997). Due to heterosis, hybrids are generally more resistant to pests and have a higher growth rate (Assis and Mafia, 2007).

When the fiscal incentives for the forestry area ended, in the beginning of 1980s, companies had no alternative but to increase the production efficiency. As a result, they expanded their breeding initiatives and plantation of clonal forests (Ferreira and Santos, 1997). With clonal forestry, the breeding focus changed and basic studies at the species and provenance level were no longer a priority.

## **2.4 DEVELOPMENT OF *Eucalyptus* spp CLONAL FORESTRY**

Several cloning techniques have already been used in *Eucalyptus*, such as grafting, macrocutting, microcutting and minicutting (Alfenas et al., 2009). The first method employed in commercial scale was the macrocutting, which uses cuttings obtained from stomps of

mature trees in the field. This method has the disadvantage of low rates of adventitious rooting due to the ontogenic aging of the trees where macrocuttings are collected. As a result, in the 1990s, minicutting was developed and has become the most used technique for clonal silviculture of *Eucalyptus* (Assis, 1996; Assis, 1997). While macrocuttings are obtained from the stumps of older (< 5-6 years old) trees, minicuttings are collected in juvenile seedlings, often obtained from micropropagation. In addition to higher rooting rate, the minicuttings technique is more cost-effective and less labor-intensive compared to other techniques, such as micropropagation and grafting.

According to Assis (1996), minicutting consists of the cloning through stem apices removed from the little mother trees selectionated. Due to this technique, there was a great technological evolution in the infrastructure to produce cloned seedlings. These improvements involved the implementation of clonal mini gardens and the development of containers and greenhouses suitable for the rooting and acclimatization of seedlings. Micro-sprinklers and fertigation systems were also implemented for this intensive *Eucalyptus* propagation by minicuttings (Alfenas et al., 2009).

The first commercial cloned forest appeared in 1979, in Aracruz-ES (Ikemori, 1990). In recent decades, there has been a large increase in clonal forests. Between 1986 and 1994, genetic progress provided by vegetative propagation generated gains of over 2.5% per year (Gonçalves et al., 2001). In recent years, areas planted with eucalyptus clonal forests continue to expand, but with less intensity, due to increased production costs and the lack of genotypes adapted to new planting areas (Castro et al., 2016).

Together with advances in breeding, the improvement of silvicultural practices, such as soil preparation, fertilization and planting spacing, favored an increase in productivity, which went from 18.0 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>, in the 1970's, to the current 37.0 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> (IBÁ, 2021). These technological advances in forestry, associated with genetic breeding, have turned Brazil

a reference in the sector, accounting for about 22% of the area planted with *Eucalyptus* worldwide (FAO, 2014).

## **2.5 CURRENT SCENARIO OF *Eucalyptus* spp. FORESTS IN BRAZIL**

Brazil has 9,55 million hectares of planted forests, 78,2% of which with *Eucalyptus* spp. (IBÁ, 2021). Brazilian eucalyptus forests stand out for their high average productivity, with country-wide average of  $36.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (IBÁ, 2021). However, in some areas, productivity is above  $50 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (Stape et al., 2010). This high productivity is associated with favorable climate, as well as advances in management techniques and genetic breeding, beginning in the 1960s (Ferreira and Santos, 1997; Castro et al, 2016).

In 2020, about 35% of commercial plantations were destined to the production of pulp and paper, and another 18% were directed to the steel, charcoal, and biomass sector, while the remaining 47% were to produce wood panels, floors laminates, solid wood and other products. The planted forests accounted for about 1.0% of the country's gross domestic product (GDP) in 2020, generating about US\$ 11.15 billion, 536,000 direct jobs and 2.3 million indirect (IBÁ, 2021).

To meet demands for wood-based products, the growth of commercial tree plantations in Brazil has been boosted in recent years (Payn et al., 2015), from 1.42 million hectares in 1995 to the current 9.55 million hectares (Ferreira and Santos, 1997; IBÁ, 2021), but with a decrease in the proportion of *Eucalyptus* forests planted on land belonging to the industries (Gonçalves et al., 2013). In 2010, they represented approximately 73%, and in 2020 they represent around 65%, with 20% of plantations on leased land and 15% under a forestry promotion regime (IBÁ, 2021).

*Eucalyptus* plantations are concentrated in the Southeastern region of Brazil, with the states of Minas Gerais and São Paulo being the largest national producers, with 27% and 17% of the planted area, respectively (IBÁ, 2021). Another state worth mentioning is Mato Grosso

do Sul, in the Midwest region, which in ten years went from a state with no expression in the forestry sector to the third state in terms of planted area, having 16% of the total area. Bahia is the fourth state, with 8% of the plantations (IBÁ, 2021). The states of Rio Grande do Sul, Paraná, Maranhão and Tocantins also stand out for the increase in planted area in the last decade, with increases in planted area between 200% and 300% in this period (IBÁ, 2021).

The expansion of forests to these states is justified by the current high land prices in the consolidated markets of the South and Southeast. Thus, the eucalyptus plantations have been advancing to other regions, as observed in the last three years in the states of Mato Grosso do Sul, Maranhão, Piauí and Tocantins (IBÁ, 2021). These regions are being called the 'new forest frontiers' (Gonçalves et al., 2013).

Currently, the most planted species in the country are *E. grandis*, *E. urophylla*, *E. saligna*, *E. viminalis*, *E. dunnii* and *E. benthamii*, which gave rise to several pure and hybrid clones through breeding programs (Silva et al., 2012; Santarosa et al., 2014). World-wide, the most planted species are *E. grandis*, *E. urophylla*, *E. globulus*, *E. camaldulensis* and *E. tereticornis* (Eldridge et al., 1993; Flores et al., 2016). Among these species, *E. grandis* and *E. urophylla* stand out, constituting the most plantated species in Brazil (about 75%), mainly in the form of the hybrid *E. grandis* x *E. urophylla* (Assis et al., 2015).

## **2.6 CHALLENGES IN THE 'NEW FOREST FRONTIERS' IN BRAZIL**

The first eucalyptus plantations in Brazil were established in temperate zones in the Southeastern and Southern states of the country (Ferreira and Santos 1997). The contribution of breeding programs to eucalypt productivity in Brazil, especially in the pulp and paper business, is unquestionable and the use of monoclonal stands (MC) on a commercial scale in this country began in the 1980s (Rezende et al., 2019). Historically, the employment of clonal plantations has provided at least a 25% gain in wood volume per hectare compared to seedling

plantations established in the same locations, under the same management systems (Rezende et al., 2014).

In recent decades, eucalyptus forests have expanded to more tropical regions of the Northeast and Central-West regions of Brazil (Gonçalves et al., 2013), where Am and Aw climates predominate (Alvares et al., 2013). In these regions, with less expensive land, the great challenge is to obtain new genotypes adapted to the stress caused by higher temperatures and water deficit, due to rainfall being unevenly distributed between seasons (Gonçalves et al. 2013). Due to increased water stress, especially in tropical regions, outbreaks of pests and diseases are becoming more common in forest plantations (Gonçalves et al. 2017).

Developing highly productive eucalyptus genotypes remains a challenge in the new forest frontiers, where growth rates are still much lower than in Southeastern Brazil (Behling et al., 2011). The hybrid *E. grandis* x *E. urophylla* is not fully adapted to very warm and humid climates, as in Northern Brazil (Amazon region), especially due to leaf diseases (Hardiyanto and Tridasa, 2000).

There are some risks associated with clonal silviculture in new planting areas, in the Northern, Northeastern and Central Western regions of Brazil. Clonal forests tend to have narrower genetic basis which poses a threat when plantations face biotic and abiotic stresses (Gonçalves et al., 2013). Due to the absence of genotypes adapted to these new areas, most commercial clonal forests do not follow the recommendation of using a diversity of clones to minimize risks of susceptibility to future stresses (Brishir and Roberts, 1999).

There is a need to invest in breeding programs to generate new clones specially adapted to these new frontier regions. In different environments, different clones respond differently to allo and self-competition, but most of them perform better in allo-competition (Rezende et al., 2019). It is recommended that, on average, a new clone should be introduced each year in any region. However, this requires ongoing breeding programs as the

development and recommendation of a new clone for commercial plantations takes approximately 12 to 16 years (Gonçalves et al., 2013).

Despite the challenges in the development of new clones, the great variety of species and hybrids of eucalyptus, associated with the accumulated knowledge about silviculture and improvement of *Eucalyptus* spp., result in reasonably good adaptation of plantations in several tropical and subtropical regions of Brazil (Gonçalves et al., 2013).

In tropical conditions, with periods of moderate to long seasonal drought, it is advantageous to plant hybrid genotypes, propagated by cloning. Multiclonal plantations with interspecific hybrids have been fundamental for the adaptation of eucalyptus in regions with water and nutritional stress and may present good plasticity but are not free from genotype-environment incompatibility (Gonçalves et al., 2011).

Rezende et al. (2019) showed that the use of clonal composites (CC), defined by them as “mixtures of improved, phenotypically similar, genotypically distinct clones”, for the establishment of commercial stands, instead of the traditional monoclonal (MC) approach, is a possible alternative to reduce breeders’ uncertainty regarding future conditions and to mitigate the genetic vulnerability of plantations to biotic and abiotic stresses. It is important to emphasize that the clonal composites are dynamic in time. When a genotype does not present, for any reason, at a given moment, a good performance, they can be easily identified by DNA fingerprinting and removed from the composite (Rezende et al., 2019).

Thus, the specific assignment of a genotype to a location must be well tested, based on field trials (Gonçalves et al., 2013). Selection procedures will be optimal, if the experimental phase is adequate, which depends on the use of efficient experimental designs, together with adequate plot sizes, numbers of repetitions and sufficient evaluation sites to maximize selective accuracy and improve clonal deployment (Resende, 2007). Clonal composites can have higher productivity than monoclonal plantations, but with similar growth uniformity and lower genetic vulnerability (Rezende et al., 2019).

The use of clones in forest-based enterprises is the result of large investments in research and pilot plantations in regions with different soil and climate characteristics (Higa and Silva, 2008). When it is necessary to analyze the interaction of genotypes x environments (GxE), the number of locations must be adequate, and can be determined based on the genetic correlation of genotypes in different environments (Resende, 2007). Low correlations of genotypes in different sites indicate low uniformity in the performance of genotypes in these places.

In areas with low water stress, it is recommended to plant *E. grandis*, *E. urophylla* and their hybrid *E. urophylla* x *E. grandis* (Flores et al., 2016). *E. grandis* is the most productive species but is sensitive to water stress. However, it can be planted in regions with an Aw climate with deeper, clayey soils.

In conditions of moderate water stress, drought-tolerant genotypes are recommended, such as the hybrids *E. urophylla* x *E. grandis*, *E. grandis* x *E. camaldulensis*, *E. urophylla* x *E. camaldulensis*, and some provenances of the pure species *E. urophylla*, *E. camaldulensis* and *E. tereticornis*. These species can yield in regions with seasonal rainfall as much as the productivity observed in regions with low water stress, in Southeast Brazil.

When there is high water stress, typical of tropical conditions, as in the Aw climate with hot and dry winter, the best performing genotypes are hybrids of *E. grandis* x *E. camaldulensis*, *E. urophylla* x *E. camaldulensis*, *E. tereticornis* x *E. brassiana* and *E. urophylla* x *E. tereticornis*, in addition to the pure species *E. camaldulensis*, *E. tereticornis* and *E. brassiana*.

The hybrid *E. urophylla* x *E. grandis* is the genetic material most planted in Brazil, due to its wide edaphoclimatic adaptation (Assis et al., 2015). This hybrid combines the high growth rate of *E. grandis* with the high rusticity and adaptability of *E. urophylla* to different tropical regions (Gonçalves et al. al., 2013; Flores et al., 2016).



*E. urophylla* and *E. camaldulensis* have some characteristics in common, being good sources of rust resistance, but *E. camaldulensis* has greater drought tolerance and higher wood density than *E. urophylla* but has a lower adaptability. (Flores et al., 2016). On the other hand, *E. camaldulensis* is susceptible to many insects and, in general, *E. urophylla* has a higher wood productivity.

*Eucalyptus* plantations are very sensitive to weed competition in early stages of growth (Gonçalves et al., 2013), which can result in a reduction of up to 70% in productivity (Toledo et al., 2000; Tarouco et al., 2009) and mortality of young trees (Gonçalves and Barros, 1999). In areas of new forest frontiers, due to the seasonality of the drought, which can last from six to seven months, it is very important to plant during the rainy season (4-6 months). However, this is also period when there is a higher infestation of weeds.

Thus, it is necessary to select fast-growing genotypes in addition to performing integrated weed control practices. Once established, trees may be able to absorb water in deeper soil layers than most annual herbaceous species, outcompeting them. Fast-growing genotypes, promoting greater shading caused by canopy closure, prevent weed growth. Pure species or hybrids with *E. camaldulensis* and *E. tereticornis* present a rapid initial development, in areas with seasonal water deficit.

The use of eucalyptus genotypes already established in the regions of the new forest frontier without prior knowledge of their resistance, associated with the stress caused by water deficiency with successive rotations in the same area, has favored the incidence of pests and diseases, caused by endemic, or accidentally introduced pathogens. In the new forest frontiers, the following diseases stand out: eucalypt canker (*C. cubensis*), eucalypts rust (*A. psidii*), leaf blights and defoliation (*Cylindrocladium* spp., *Rhizoctonia* spp. and *Xanthomonas axonopodis*), bacterial wilt (*Ralstonia solanacearum*), ceratocystis wilt (*Ceratocystis fimbriata*), eucalypts die-back (*Erwinia eucalypti*), and Quambalaria stem girdling and leaf spot (*Quambalaria eucalypti*).

The expansion of eucalyptus in Brazil was accompanied by infestation and outbreaks of some species of native insects, which have become key pests for the activity, requiring investments in prevention and control (Gonçalves et al., 2013). The most important pests that have occurred since the beginning of commercial eucalyptus plantations in the country are leaf-cutting ants, termites, caterpillars and defoliating beetles, most of which are efficiently monitored and controlled with the use of insecticides (Wilcken et al., 2008).

In the last decade, there has been establishment of Australian pest species in many Brazilian states such as the psyllid redgum lerp (*Glycaspis brimblecombei*), bronze stink bug (*Thaumastocoris peregrinus*) and eucalyptus gall wasp (*Leptocybe invasa*) (Costa et al., 2008; Barbosa et al. al., 2010). Despite the control measures, these pests have been spreading, compromising the planting of several species of eucalyptus, mainly in the new forest frontier, where there is a defined drought, which favors the proliferation cycle of these pests.

Control strategies for these exotic pests are based on Integrated Pest Management, with classical biological control, by importing and releasing natural enemies, with the use of pesticides and the evaluation of progenies and resistant species/genotypes, or with the induction of resistance by transgenics. Selection of resistant plants is another important method used for control. However, specific selection methods for pest resistance are very incipient, even though there are strong evidence that there is genetic variation for resistance to insects. It is known, for example, that eucalyptus species belonging to the subgenus *Symphyomyrtus*, section *Exsertaria* (*E. camaldulensis*, *E. terenticornis*, *E. brassiana*) are particularly susceptible to the psyllid redgum lerp, while species from the other sections tend to be more resistant, except for *E. urophylla*.

In Brazil, eucalyptus plantations with *E. camaldulensis*, indicated for areas of the new forest frontier, present tree mortality ranging from 30% to 95%, after three years of infestations with plague insects. High infestations were also observed in *E. urophylla* plantations, and *E. grandis* x *E. urophylla* hybrids, particularly in the last two years. Hybrid

clones tested by forestry companies showed a gradient of response to pest attack, with some genotypes being highly resistant. However, the pest has a high adaptability to newly developed genotypes (Wilcken, 2011).

*E. camaldulensis* and its hybrid clones show high susceptibility to gall wasp, affecting tree development until the second year, reducing tree growth. The best option to control this pest is the development of resistant clones, given the difficulty of using chemical and biological methods for control (Costa et al., 2008).

In summary, as the *Eucalyptus* plantations expand into other regions of Brazil, new challenges arise, given the lack of adapted genotypes for these new conditions. In addition, the drought stress imposed by the seasonal rainfall in these new frontiers is a major challenge to the *Eucalyptus* cropping. Challenge have also been arising from new diseases and plagues that have been recently introduced in Brazil or that have become adapted to the genus. To meet these challenges, it is important that public and private investments are directed towards forestry research and breeding. The global leadership of Brazil in *Eucalyptus* productivity, technology and market share depends on the continuous development of clones adapted to these new planting regions.

## 2.7 CONCLUSIONS

Since its introduction until the present day, eucalyptus has gone through numerous selection and adaptation processes in Brazil. Over the 50 years since the first breeding programs started, numerous advances have been made, resulting in an 165% increase in forest productivity and in the selection of clones resistant to many diseases and tolerant to abiotic stresses. In addition to genetic improvement, advances in planting techniques and seedling production contributed to this astonishing increase in forest productivity.

Given its importance and variety of uses, *Eucalyptus* breeding programs have sought to diversify the constitution of hybrids, as well as to unit several characteristics of interest in

individual clones. The current focus of forest breeding programs is the adaptation and development of specific genetic materials for the new planting areas, located in inland regions of the Cerrado biome, with well-drained soils and seasonal rainfall. Another objective is the combination of characteristics that favor the production of biomass for energy use, mainly in large agro-industrial districts in these new planting frontiers.

The development of transgenic trees and genomic selection are already a reality and the tendency is for these to be improved and increasingly integrated into breeding programs, facilitating the process of adapting genotypes to the new forest frontiers in Brazil.

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## CHAPTER 2

### EARLY SELECTION AND GENOTYPE-BY-ENVIRONMENT INTERACTIONS OF *Eucalyptus* CLONES IN BRAZILIAN SAVANNA <sup>1</sup>

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### 3. EARLY SELECTION AND GENOTYPE-BY-ENVIRONMENT INTERACTIONS OF *Eucalyptus* CLONES IN BRAZILIAN SAVANNA

#### ABSTRACT

*Eucalyptus* cultivation in Brazil plays an important role in the national economy and has recently expanded to new regions where the Cerrado biome predominates. *Eucalyptus* still needs to be better studied in these new planting regions, especially regarding the adaptation and productivity of clones originally developed for other regions of the country. Given this need, our objective was to evaluate the performance of 109 eucalyptus clones throughout the production cycle in different locations in the State of Goiás to select clones adapted in the region. For that, three clonal tests were planted in Catalão, Corumbá-de-Goiás and Luziânia. The experimental design was a randomized complete block with single tree plots and 29 replicates. The diameter at breast height and the total height of all trees were measured at two, four and six years of age, allowing estimation of continuous wood productivity. A random effect model was used to estimate the Best Linear Unbiased Prediction (BLUP) of wood yield of each clone in each site and year. Through the genetic parameters obtained by Restricted maximum likelihood (REML) it was possible to evaluate the magnitude of the genetic, environmental and GxE interaction effects. Spearman correlation at harvest age (six years) was lower with wood productivity at two-years ( $r = 0.61$ ) than at four ( $r = 0.68$ ). This level of correlation indicate the possibility of early selection with some degree of selection errors. In general, the survival rate of trees decreases with age, reaching 91.3% at six years. Biomass productivity in Luziânia and Catalão was higher than in Corumbá-de-Goiás, due to the best growth conditions. Considering the three sites, the best clones at two- and four-years are, on average, 65% equivalent to the best clones at harvesting age, when the average productivity was  $255.8 \text{ m}^3 \text{ ha}^{-1}$ . All six most productive clones (CCL29, CCL35, CLR454, CCL27, CCL07, AEC144) have *E. urophylla* in their pedigree.

**Keywords:** Clonal tests; Forest Breeding; Silviculture.

### 3.1 INTRODUCTION

Wood-based products have great worldwide demand, which stimulates predatory logging of trees in natural ecosystems (Oliveira and Franca, 2020). One alternative to reduce illegal deforestation in native areas (Sulaiman et al., 2017) is the use of wood from commercial plantation of forest species. In addition to providing a renewable source of wood, protecting remaining native areas, planted forests fix atmospheric carbon and contribute to the hydrological cycle (Payn et al., 2015). Therefore, plantation of forests is important for countries to comply with international climate agreements (Christoff, 2016; Almer and Winkler, 2017).

Planted forests are responsible for meeting over 50% of the world demand for wood products (Binkley et al., 2017). From 1990 to 2015, there was a 50% increase in the area dedicated to planted forests (Payn et al., 2015). Currently, planted forests represent about 7% of all forests in the world (Whiteman, 2014), and 2% of Brazilian forests (IBGE, 2018), with 9.55 million hectares (IBÁ, 2021).

The contribution of breeding programs to eucalypt productivity in Brazil, especially in the pulp and paper business, is unquestionable (Castro et al., 2016; Rezende et al., 2019). The national productivity average of *Eucalyptus* spp. plantings has increased four-fold over the past 50 years (Binkley et al. 2017). In 2020, the average yield of the eucalyptus forests in Brazil was of  $36.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  under short rotations of 5-7 years (IBÁ, 2021).

Recent studies have shown the potential of *Eucalyptus* to achieve productivities of more than  $60.0 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (Stape et al., 2010; Binkley et al., 2017; Scolforo et al., 2019; Oliveira et al., 2020; André et al., 2021). With this high productivity, *Eucalyptus* plantations are the main suppliers for the Brazilian demands of wood in several industrial sectors, such as pulp and paper, wood panels, charcoal, sawn timber, biomass with energy source, among others (Flores et al. 2016; Eufrade Júnior et al., 2017; Sette Júnior et al., 2020; IBÁ 2021). This success is mostly due to the identification of adapted species and provenances, and to interspecific hybridization programs (e.g. *E. grandis* × *E. urophylla*) with further selection of the best individuals for clonal forests (Ferreira and Santos, 1997; Rezende et al., 2014; Assis et al., 2015; Castro et al., 2016). In addition to genetic gains, the increase in forest

productivity depends also on environmental conditions and on the correct adoption of silvicultural practices, such as site preparation, fertilization, spacing, control of weeds, pests, and diseases (Castro et al., 2016; Gonçalves et al., 2017; Binkley et al., 2020).

To determine which clones are best adapted to different environments, it is necessary to assess their performance in different planting regions (Cruz et al., 2012) and over time (Oda et al., 1989). Forest productivity is largely affected by environmental factors. The problem, from a breeding and selection perspective, is that genotypes respond differently to environmental factors. These differential responses results in the so-called genotype x environment (GxE) interaction (Santos et al., 2016; Teodoro et al., 2016). Because of GxE, breeders must evaluate the performance of new genotypes in multi-environment trails, to estimate their stability and adaptability before cultivar recommendation (Moraes et al., 2014; Engel et al., 2016; Pupin et al., 2018).

In addition to the G x E interaction, time is another crucial factor in forest breeding programs, as they involve species with long cropping cycles, making them time-consuming and expensive (Kageyama and Vencovsky, 1983; Gonçalves et al., 1998; Massaro et al. al., 2010). The species of *Eucalyptus* and *Corymbia*, despite having one of the smallest production cycles in Brazil (IBÁ, 2021), have a breeding cycle that that can last up to 20 years (Assis et al., 2015).

Thus, selection of superior genotypes is an extremely important activity and must be carried out with all possible rigor using robust experimental design and precise selection methods (Massaro et al., 2010). Despite the need for high selection accuracy, breeders should also consider selecting the best trees before the end of cultivation cycle, aiming at more gains per unit of time (Resende, 1994). Early selection for silvicultural traits has been shown to be efficient in eucalyptus clonal tests (Massaro et al., 2010; Pinto et al., 2014). However, there is need to study whether early selection can also be performed in regions with seasonal rainfall and highly susceptible to drought, where the *Eucalyptus* plantations are expanding in Brazil.

Selection of superior trees is usually carried out before the economic rotation age because trees typically have long generation intervals (Yang et al., 2013). Therefore, testing the early vs. rotation age correlation of economically important traits is essential to determine the optimal time for early selection (Wu et al., 2007).

In recent years, eucalypts clonal forests continue to expand, but with less intensity, due to increased production costs and the lack of genotypes adapted to new planting areas (Castro et al., 2016). The selection of drought tolerant *Eucalyptus* clones is necessary as the

increasing demands for wood is driving a territorial expansion of its cultivation inland, especially in the Cerrado biome with seasonal rainfall (Andrade et al., 2018).

Tropical regions with high temperatures and drought pose difficulties to the cultivation of *Eucalyptus* (Gonçalves et al., 2017). Thus, knowledge about parameters of genetic variation, such as the genotype x environment interaction effects, are important to ensure the success of clonal *Eucalyptus* forestry, particularly in regions where they have just started to be cultivated.

Here, we aimed to estimate genetic variation, genetic and phenotypic correlations, and genotype-by-environment interactions for growth in clones of *Eucalyptus* and *Corymbia*, at different ages to verify the possibility of early selection of clones in the Cerrado biome region.

## **3.2 MATERIAL AND METHODS**

### **3.2.1 Characterization of the study area**

A network of clonal tests was established during the rainy season in Catalão-GO, Corumbá-de-Goiás-GO and Luziânia-GO, in December of 2012 (Figure 1). All three experiments were within the Cerrado biome. Thus, the regions have typical conditions of Cerrado, including soil with acidic pH, low bases, and high aluminum saturation (Table 1).

The region's climate is tropical with well-defined dry and rainy seasons, being classified as Aw according to the Köppen-Geiger classification (Alvares et al. 2013). The average annual temperature is around 22 °C, with average annual rainfall ranging from 1,321.0 mm to 1,673.0 mm, with approximately 90% of this rain concentrated from October to April (Table 1).

### **3.2.2 Experimental design and plantation**

The treatments consisted of 109 distinct clones, derived from 12 pure species and their interspecific hybrids (Table 2). Of these clones, 94 were evaluated in Catalão and 93 in each of the other two experiments, with 85 clones common to all three experiments (Figure 2). The experiments were planted in a randomized complete block design, with 29 replicates in single tree plots, using a 3.0 m x 3.0 m spacing between trees (9.0 m<sup>2</sup> tree<sup>-1</sup>). The Clone AEC144 (*E.*

*urophylla*), was used as control as it is the most planted clone in the country and in the Goiás state (Reis et al. 2017).

Silvicultural practices were conducted as recommended for *Eucalyptus* cropping. Briefly, surface liming (1,500 – 2,500 Kg ha<sup>-1</sup>) was performed two months before planting, with the incorporation of limestone at a depth of 80 cm within the planting line. During soil preparation, with a 90 cm deep furrower, gypsum was also applied (1,500 Kg ha<sup>-1</sup>). The fertilization was applied within the planting lines at a rate of 300 kg ha<sup>-1</sup> (NPK 10-30-10) with 0.5 kg ha<sup>-1</sup> of boron. At 3, 12, and 24 months after planting, topdressing was applied at a rate of 180 kg ha<sup>-1</sup> (NPK 12-05-12) with 0.5 kg ha<sup>-1</sup> of boron. Invasive grasses and leaf-cutting ants were controlled chemically with glyphosate and fipronil, respectively, using recommended doses.

### 3.2.3 Evaluation of tree growth

Three evaluations were performed at two, four and six years after planting (harvest age). Tree total height (*Ht*) was measured, in meters, with a clinometer Haglöf ECII. The circumference at breast height (*CBH*, 1.30 m above ground level) was obtained with a tape measure for all trees. For the analyses of trunk secondary growth, the *CBH* was converted into diameter at breast height (*DBH*), in cm.

Individual wood volume with bark (*Vi*), in m<sup>3</sup> tree<sup>-1</sup>, was estimated as a function of the *DBH* and *Ht*, according to equation (Eq. [1]).

$$Vi = \frac{DBH^2 * \pi}{40000} * Ht * f$$

[1]

Where:  $\pi$  corresponds to 3.1416; and  $f = 0.46$  is a generic taper factor for different genotypes, obtained with the measurement of 80 representative trees from each site by the Smalian method.

Tree mortality was also recorded at each evaluation. The total volume per hectare (*Vt*, in m<sup>3</sup> ha<sup>-1</sup>) was estimated considering the individual volume of trees multiplied by the number of trees per hectare, corrected for the survival rate. The survival rate was taken into consideration to avoid bias caused by differences in tree mortality among clones.

### 3.2.4 Statistical analysis

Estimates of the variance components and genetic parameters of growth traits (*DBH*, *Ht* and *Vt*) for each site were obtained through a random effects model (Eq. [2]).



$$y = \mu + Xr + Zg + e$$

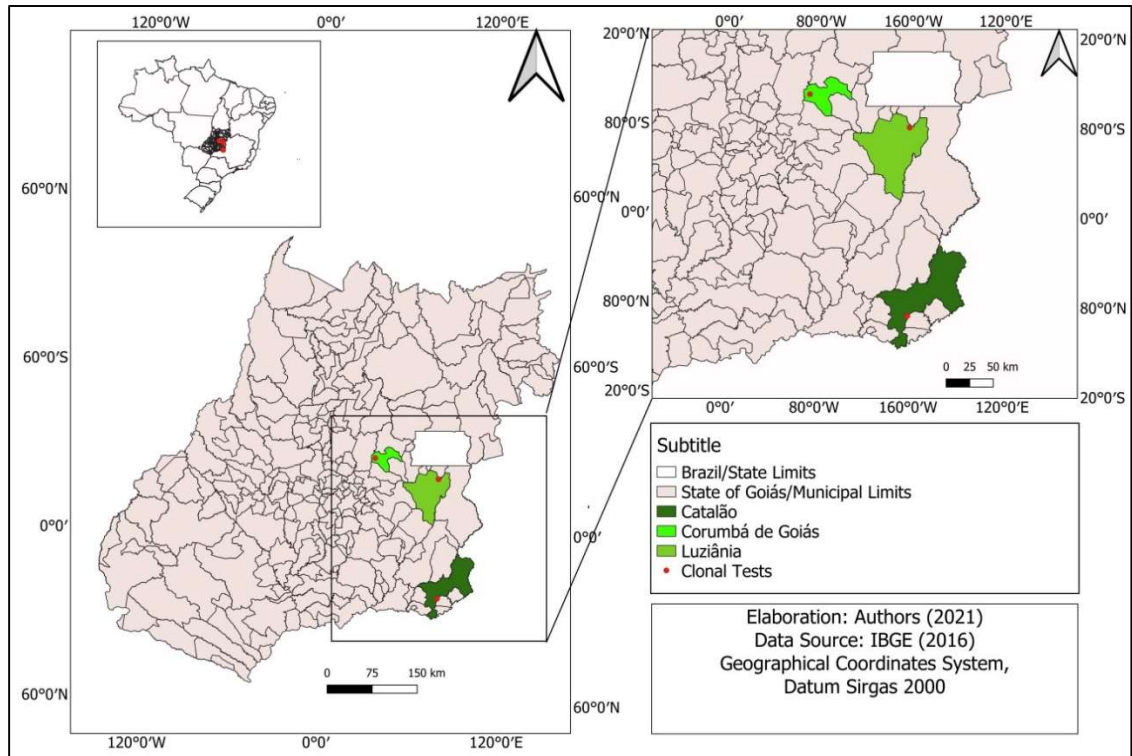
[2]

For the joint analysis of the sites, the genotypic values of each clone were also predicted using a random model (Eq. [3]), as well as the harmonic means of the relative performance of genetic values (MHPRVG) to also consider the stability of each clone (Resende, 2007).

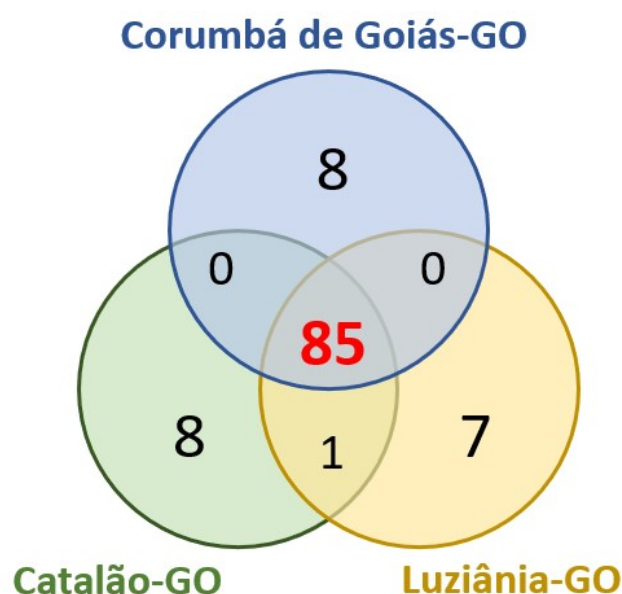
$$y = \mu + Xr + Zg + Wge + e$$

[3]

On Eq. 2 and Eq. 3 we have the following parameters:  $\mu$  is the constant (fixed effect);  $y$  is the vector of individual observations;  $r$  is the vector of repetition or block effects (random);  $g$  is the vector of genotypic effects (random);  $ge$  is the genotype x environment interaction effects (random) and  $e$  is the vector of errors (random);  $X$ ,  $Z$  and  $W$  represent the incidence matrices for the effects.



**Figure 1.** Localization of the three clonal tests for *Eucalyptus* and *Corymbia* in the municipalities of Catalão-GO, Corumbá-de-Goiás-GO and Luziânia-GO.



**Figure 2.** Distribution of the 109 clones in all three sites, 94 were evaluated in Catalão-GO and 93 in Corumbá-de-Goiás-GO and Luziânia-GO, with 85 clones common to all three experiments.

**Table 1.** Geographic coordinates and environmental conditions of the sites where the clonal tests of *Corymbia* and *Eucalyptus* were installed in the Goiás state.

Characteristics	Sites <sup>1</sup>		
	CAT	COR	LUZ
Latitude (South)	18°10'05,04"	15°55'44,71"	16°15'56,83"
Longitude (West)	47°51'22,15"	48°50'20,69"	47°49'57,26"
Altitude (m. a. l. s.)	843.0	1072.0	978.0
Relief	Slightly Ondulated	Plain	Ondulated
Mean temperature (°C)	22.20	22.70	20.70
Maximum mean temperature (°C)	27.90	27.70	27.50
Minimum mean temperature (°C)	16.60	17.60	14.50
Average annual rainfall (mm)	1,484.10	1,772.20	1,515.50
soil	Red-Yellow latosol	Yellow latosol	Yellow latosol
<b>Leyer 0 - 20 cm</b>			
Clay content (%)	48.40	39.00	44.00
Sand content (%)	39.20	43.00	35.10
Silt content (%)	12.40	18.00	20.90
Soil pH (CaCl <sub>2</sub> )	4.50	4.60	4.40
Cation exchange capacity (CEC)	5.30	4.60	4.40
Base saturation: V(%)	10.0	35.00	13.00
Aluminum content (H + Al(%))	90.0	64.00	88.00

<sup>1</sup> *Cat* as reference to Catalão-GO; *Cor* as reference to Corumbá-de-Goiás; *Luz* as reference to Luziânia-GO.

The genotypic ( $\sigma_g^2$ ), residual ( $\sigma_e^2$ ), and individual phenotypic variances ( $\sigma_f^2$ ) for the single site model (Eq. 2) were estimated by Restricted Maximum Likelihood (REML) by equations 4, 5 and 6. The genotypic ( $\sigma_g^2$ ), genotype x environment interaction ( $\sigma_{ge}^2$ ), residual ( $\sigma_e^2$ ), and individual phenotypic variances ( $\sigma_f^2$ ) for the joint model (Eq. 3) were estimated by REML by equations 7, 8, 9 and 10:

$$\hat{\sigma}_g^2 = [\hat{g}'\hat{g} + \hat{\sigma}_e^2 \text{tr}(C^{22})/q]$$

[4]

$$\hat{\sigma}_e^2 = [y'y - \hat{r}'X'y - \hat{g}'Z'y]/[N - r(x)]$$

[5]

$$\hat{\sigma}_f^2 = \hat{\sigma}_g^2 + \hat{\sigma}_e^2$$

[6]

$$\hat{\sigma}_g^2 = [\hat{g}'g + \hat{\sigma}_e^2 \text{tr}(C^{22})]/q$$

[7]

$$\hat{\sigma}_{ge}^2 = [\hat{g}\hat{e}'\hat{g}\hat{e} + \hat{\sigma}_g^2 \text{tr}(C^{33})/s]$$

[8]

$$\hat{\sigma}_e^2 = [y'y - \hat{b}'X'y - \hat{g}'Z'y - \hat{g}\hat{e}'W'y]/[N - r(x)]$$

[9]

$$\hat{\sigma}_f^2 = \hat{\sigma}_g^2 + \hat{\sigma}_{ge}^2 + \hat{\sigma}_e^2$$

[10]

Where:  $C^{22}$  and  $C^{33}$  is the inverse of the matrix of coefficients of random model equations;  $\text{tr}$  is the trace of a matrix;  $r(x)$  is the rank matrix of  $X$ ;  $N$ ,  $q$  and  $s$  are the total number of observations, clones, and genotype x environment combinations, respectively.

For each site, the individual broad sense heritability for each single-tree plot ( $h_g^2$ ) or the total genotypic effects, and the average clone heritability ( $h_m^2$ ) were estimated by the expressions 11 and 12. For the joint analyses of all sites, the individual broad sense heritability for each single-tree plot ( $h_g^2$ ) and average clone heritability ( $h_m^2$ ) were estimated by the expressions 13 and 14.

$$\hat{h}_g^2 = \frac{\hat{\sigma}_g^2}{\hat{\sigma}_g^2 + \hat{\sigma}_e^2}$$

[11]

$$\hat{h}_m^2 = \frac{\hat{\sigma}_g^2}{\hat{\sigma}_g^2 + \frac{\hat{\sigma}_e^2}{b}}$$

[12]

$$\hat{h}_g^2 = \frac{\hat{\sigma}_g^2}{\hat{\sigma}_g^2 + \hat{\sigma}_{ge}^2 + \hat{\sigma}_e^2}$$

[13]

$$\hat{h}_m^2 = \frac{\hat{\sigma}_g^2}{\hat{\sigma}_g^2 + \frac{\hat{\sigma}_{ge}^2}{n} + \frac{\hat{\sigma}_e^2}{b}}$$

[14]

Where: **n** is the number of environments; and **b** is the number of blocks.

The accuracy of clone selection ( $\hat{r}_{aa'}$ ), were estimated by the equation 15.

$$\hat{r}_{aa'} = \sqrt{\hat{h}_m^2}$$

[15]

The coefficient that determines the genotype  $\times$  environment interaction effects ( $\hat{C}_{ge}^2$ ) and the genotypic correlation between the clones in various environments ( $\hat{r}_{gloc}$ ) were determined by expressions 16 and 17:

$$\hat{C}_{ge}^2 = \frac{\hat{\sigma}_{ge}^2}{\hat{\sigma}_g^2 + \hat{\sigma}_{ge}^2 + \hat{\sigma}_e^2}$$

[16]

$$\hat{r}_{gloc} = \frac{\hat{\sigma}_g^2}{\hat{\sigma}_g^2 + \hat{\sigma}_{ge}^2}$$

[17]

The coefficients of genotypic variance ( $CV_{gi}\%$ ), of residual variance ( $CV_e\%$ ), and the relative variance ( $CV_r$ ) were determined by expressions (18, 19 and 20):

$$\widehat{CV}_{gi}\% = \frac{\sqrt{\hat{\sigma}_g^2}}{m} * 100$$

[18]

$$\widehat{CV}_e\% = \frac{\sqrt{\hat{\sigma}_e^2}}{m} * 100$$

[19]

$$\widehat{CV}_r = \frac{\widehat{CV}_{gi}}{\widehat{CV}_e}$$

[20]

Where: **m** is the average of the evaluated trait.

The significances of the effects of clones, sites and G x E interaction were evaluated using the likelihood ratio test (LRT), as performed by Oliveira et al. (2020). The effects of the G x E interaction, when significant, were decomposed into simple and complex parts using the method suggested by Cruz and Castoldi (1991).

**Table 2.** Description of species of *Corymbia* spp. and *Eucalyptus* spp. used in the three clonal tests planted in the of Goiás state.

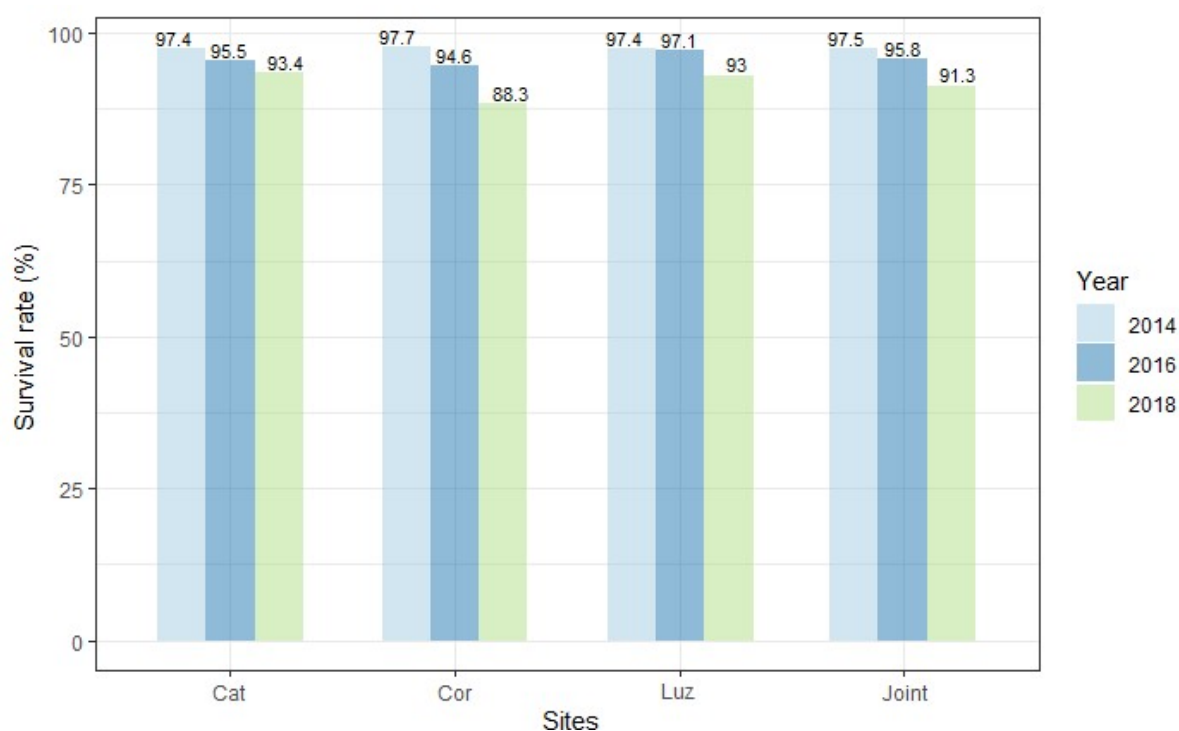
Constitution of genetic material	Clone (commercial name)	Qtd
<i>C. citriodora</i>	Citriodora	1
<i>C. torelliana</i> x <i>C. citriodora</i>	Toreliodora	1
<i>E. camaldulensis</i>	CCL60, CCL 62	2
<i>E. cloeziana</i>	Cloeziانا	1
<i>E. grandis</i>	CCL06, CCL33, CCL58, CCL24	4
<i>E. grandis</i> x ( <i>E. urophylla</i> x <i>E. tereticornis</i> )	CCL56	1
<i>E. grandis</i> x <i>E. urophylla</i>	CCL11, CCL16, CCL17, CCL19, CCL25, CCL27, CCL28, CCL29, CCL31, CCL32	10
<i>E. platyphylla</i>	CCL22, CCL23	2
<i>E. saligna</i>	CLR292	1
<i>E. saligna</i> x <i>E.tereticornis</i>	CCL55	1
<i>E. urophylla</i>	CCL02, CCL05, CCL15, CCL26, CCL30, CCL45, CCL51, CLR400, CLR401, CLR402, CLR403, CLR404, CLR405, CLR406, CLR407, CLR408, CLR409, CLR410, CLR411, CLR412, CLR413, CLR414, CLR415, CLR416, CLR417, CLR418, CLR421, CLR422, CLR423, CLR424, CLR425, CLR426, CLR427, CLR428, CLR429, CLR431, CLR432, CLR433, CLR434, CLR435, CLR438, CLR440, CLR441, CLR444, CLR454, CLR455, CLR458, GG100	48
<i>E. urophylla</i> x <i>E. brassiana</i>	CCL54	1
<i>E. urophylla</i> x <i>E. camaldulensis</i>	CCL04, CCL34, CCL39, CCL62	4
<i>E. urophylla</i> x <i>E. grandis</i>	CCL01, CCL03, CCL06, CCL13, CCL14, CCL18, CCL20, CCL21, CCL35, CCL36, CCL37, CCL38, CCL40, CCL41, CCL50, CCL59, CCL63	14
<i>E. urophylla</i> x <i>E. tereticornis</i>	CCL52, CCL53, CCL57	3
<i>E. pellita</i> x <i>E. grandis</i>	CCL43	1
<i>E. resinifera</i> x <i>E.grandis</i>	CCL46, CCL47	2
<i>E. tereticornis</i> x <i>E.pellita</i>	CCL48	1
Spontaneous hybrid of <i>E. camaldulensis</i>	CCL09	1
Spontaneous hybrid of <i>E. urophylla</i>	CCL07, CCL10, CCL12, CCL49, AEC042, AEC144	6
Unidentified species	CCL08	1

### 3.3. RESULTS

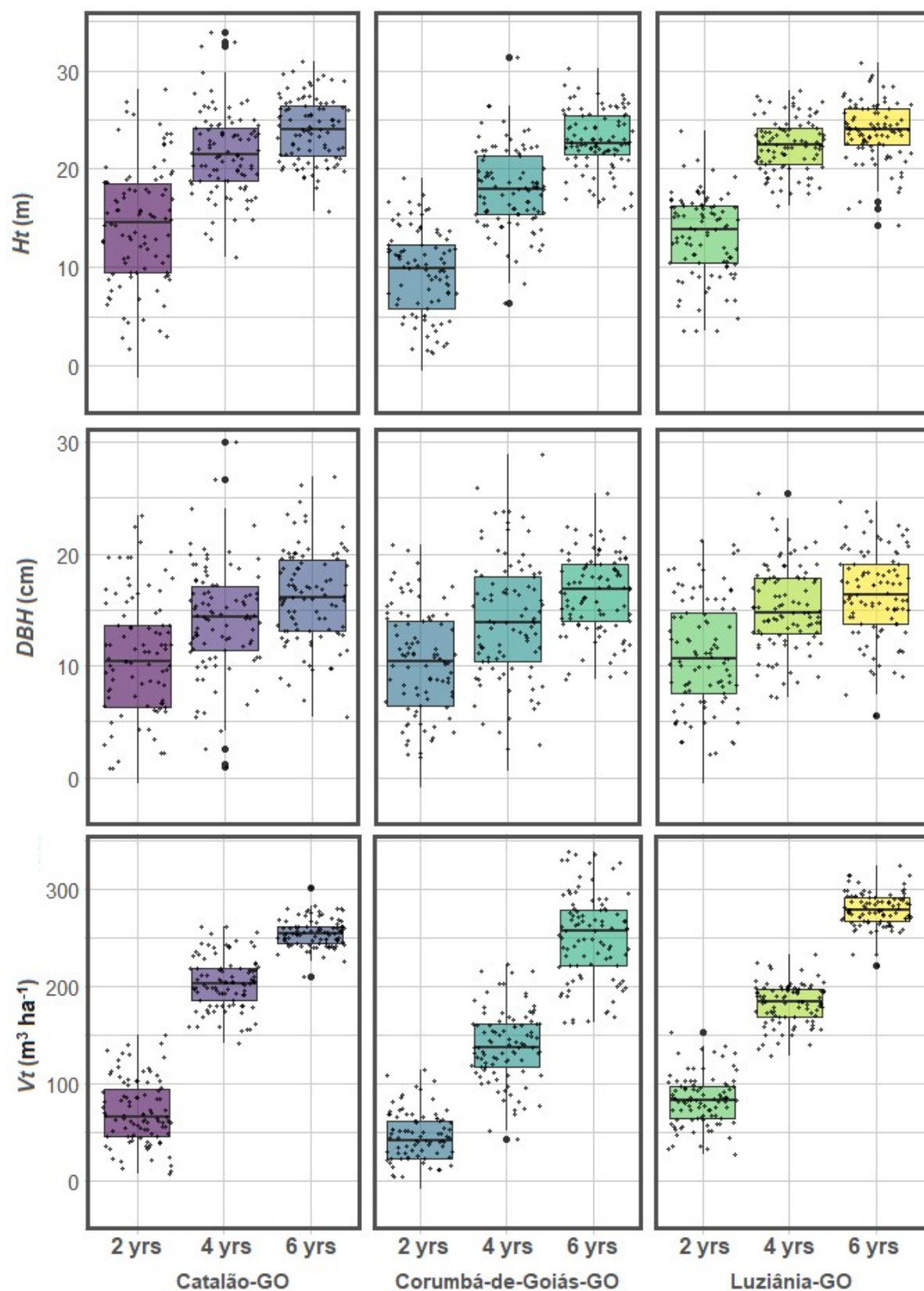
#### 3.3.1. Tree mortality, yield, and genetic parameters

Tree mortality was low at two years after planting, but as trees grew (>4 years) the survival rate decreased in the experiments (Figure 3). In the first two years after planting, the survival rate was above 97.0 % for all sites. At four years, the survival rate was around 95.0 % and further dropped to 93.0% at six years of age in Catalão and Luziânia. In Corumbá de Goiás, the mortality rate was higher, reaching 88.3% at six years after planting.

Across all three environments, average *DBH* were 10.59 cm, 14.28 and 16.44 cm, at two, four- and six-years age, respectively (Figure 4). At two years, the best growth performance in *DBH* was observed in Luziânia, with 11.1 cm (Figure 4). At four years, the greatest growth in *DBH* was detected in Catalão, with 14.43 cm, and at harvesting age, the best performance was observed in Corumbá-de-Goiás, with average of 17.02 cm (Figure 4).



**Figure 3.** Survival rate (%) of trees in the experiments, at two, four and six years after planting. Cat refers to Catalão-GO, Cor to Corumbá-de-Goiás, Luz to Luziânia-GO, and Joint to all three sites evaluated together.



**Figure 4.** Evolution of growth (DBH and Ht) and yield (Vt) traits in the experiments, at 2, 4 and 6 years after planting. *Cat* to Catalão-GO; *Cor* to Corumbá-de-Goiás; *Luz* to Luziânia-GO, and *Joint* to all three sites evaluated together. DBH is the diameter at breast height; Ht is the total height of the tree; Vt is the total volume of wood with bark per hectare.



The average total height were 12.31 m, 20.11 m and 23.35 m, at two, four and six years of age, respectively (Figure 4). The highest average heights at two and four years after planting, were observed in Catalão, with 14.25 m and 21.88 m, respectively. At six years, the highest average total height was observed in Luziânia, with 23.87 m (Figure 4).

At two, four and six years of age, wood productivity averaged 67.10, 180.04 and 278.04 m<sup>3</sup> ha<sup>-1</sup>, respectively (Figure 4). The highest average yield at two years of age was observed in Luziânia, with 86.08 m<sup>3</sup> ha<sup>-1</sup>. At four years, Catalão was the most productive region, with 202.80 m<sup>3</sup> ha<sup>-1</sup>. Another inversion occurred at six years, with Corumbá-de-Goiás having the highest yield of 285.17 m<sup>3</sup> ha<sup>-1</sup> (Figure 4).

For Catalão and Luziânia, the residual variance ( $\sigma_e^2$ ) was lower than the genotypic variance ( $\sigma_g^2$ ) for *DBH* and *Vt*, and higher for *Ht*. In Corumbá-de-Goiás, the residual variance was higher than the genotypic variance for all three evaluated traits, in the three ages (Table 3). The estimated variance components were significantly different from zero, indicating that genotypes (clones) differed for all traits evaluated.

Significative differences between sites were shown for growth traits (*DBH* and *Ht*) and yield (*Vt*) across all ages ( $P \leq 0.001$ ). For these traits, the average values of the genetic parameters were approximately at the same order of magnitude among the three sites and ages.

The broad sense heritabilities ( $h_g^2$ ) varied according to the trait, age and evaluated site, but, generally, presented higher values for all traits in Catalão and Luziânia than in Corumbá-de-Goiás, where the residual variance was higher (Table 3). Thus, the  $h_g^2$  for *DBH* ranged from 0.29 to 0.60 in the three different sites across evaluations (Table 3). For *Ht*, the  $h_g^2$  ranged from 0.13 to 0.57 among the three ages and environments (Table 3). Under these same conditions, for wood productivity (*Vt*), the broad sense heritabilities ranged from 0.30 to 0.60 (Table 3).

The estimates of the heritability of the clone mean ( $h_m^2$ ) were high for all evaluated traits at different ages, in all sites, ranging from 0.81 to 0.98 (Table 3). The accuracy estimate ( $\hat{r}_{aa}$ ) refers to the correlation between the true and the estimated genotypic values of the analyzed clones (Resende, 2007). The estimated accuracy values ( $\hat{r}_{aa'}$ ) of all the evaluated traits were, consistently, above 0.90 in Corumbá-de-Goiás, and above 0.98 in Catalão and Luziânia, for all traits and ages (Table 3).

**Table 3.** Estimates of genetic parameters (individual REML) for *DBH* (cm), *Ht* (m) and *Vt* ( $\text{m}^3 \text{ha}^{-1}$ ) at 2, 4 and 6 years of the clones, evaluated in each site.

Genetic Parameters	Catalão - GO								
	2 years			4 years			6 years		
	<i>DBH</i>	<i>Ht</i>	<i>Vt</i>	<i>DBH</i>	<i>Ht</i>	<i>Vt</i>	<i>DBH</i>	<i>Ht</i>	<i>Vt</i>
$\sigma_g^2$	1.98	1.09	450.91	5.43	4.95	5,520.77	7.63	7.98	11,424.47
$\sigma_e^2$	1.50	1.22	313.69	4.84	6.04	4,593.20	7.38	8.11	9,964.91
$\sigma_f^2$	3.48	2.31	764.60	10.27	10.99	10,113.97	15.02	16.09	21,389.38
$h_g^2$	0.5686 +/- 0.04	0.4732 +/- 0.04	0.5897 +/- 0.04	0.5282 +/- 0.04	0.4502 +/- 0.04	0.5459 +/- 0.04	0.5083 +/- 0.04	0.4962 +/- 0.04	0.5341 +/- 0.04
$h_m^2$	0.97	0.96	0.98	0.97	0.96	0.97	0.97	0.97	0.97
$\hat{r}_{aa'}$	0.99	0.98	0.99	0.98	0.98	0.99	0.98	0.98	0.99
$CV_{gi}\%$	12.91	7.34	30.20	16.14	10.16	38.11	17.19	12.00	41.33
$CV_e\%$	11.25	7.75	25.19	15.25	11.23	34.76	16.91	12.09	38.60
$CV_r$	1.15	0.95	1.20	1.06	0.90	1.10	1.02	0.99	1.07
<b>Means</b>	<b>10.90</b>	<b>14.25</b>	<b>71.98</b>	<b>14.43</b>	<b>21.88</b>	<b>202.80</b>	<b>16.07</b>	<b>23.55</b>	<b>275.85</b>
	Corumbá-de-Goiás - GO								
$\sigma_g^2$	1.40	0.64	160.17	2.52	1.10	1,516.78	6.80	2.20	7,373.00
$\sigma_e^2$	1.41	2.80	203.30	5.93	7.66	3,451.92	7.39	7.87	7,460.19
$\sigma_f^2$	2.81	3.44	363.47	8.45	8.76	4,968.71	14.19	10.08	14,833.19
$h_g^2$	0.4969 +/- 0.04	0.1863 +/- 0.02	0.4407 +/- 0.04	0.3000 +/- 0.03	0.1260 +/- 0.02	0.3053 +/- 0.03	0.4793 +/- 0.04	0.2186 +/- 0.03	0.4971 +/- 0.04
$h_m^2$	0.97	0.87	0.96	0.93	0.81	0.93	0.96	0.89	0.97
$\hat{r}_{aa'}$	0.98	0.93	0.98	0.96	0.90	0.96	0.98	0.94	0.98
$CV_{gi}\%$	11.99	9.02	29.44	11.22	5.96	26.51	15.32	6.57	33.96
$CV_e\%$	12.07	18.84	33.17	17.19	15.69	39.99	15.97	12.42	34.16
$CV_r$	0.99	0.48	0.89	0.65	0.38	0.66	0.96	0.53	0.99
<b>Means</b>	<b>9.86</b>	<b>8.88</b>	<b>43.92</b>	<b>14.16</b>	<b>17.64</b>	<b>154.86</b>	<b>17.02</b>	<b>22.59</b>	<b>285.17</b>
	Luziânia - GO								
$\sigma_g^2$	1.97	1.10	632.40	4.04	3.00	3,539.49	7.21	4.01	9,698.98
$\sigma_e^2$	1.42	0.83	455.34	3.43	4.35	3,086.35	4.78	5.41	6,561.41
$\sigma_f^2$	3.39	1.93	1087.74	7.47	7.35	6,625.84	11.99	9.42	16,260.39
$h_g^2$	0.5809 +/- 0.04	0.5710 +/- 0.04	0.5814 +/- 0.04	0.5413 +/- 0.04	0.4080 +/- 0.03	0.5342 +/- 0.04	0.6013 +/- 0.04	0.4254 +/- 0.04	0.5965 +/- 0.04
$h_m^2$	0.98	0.97	0.98	0.97	0.95	0.97	0.98	0.96	0.98
$\hat{r}_{aa'}$	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.98	0.99
$CV_{gi}\%$	12.64	7.59	29.88	14.06	8.33	33.12	16.40	8.38	37.66
$CV_e\%$	10.74	6.58	25.36	12.95	10.03	30.93	13.35	9.74	30.98
$CV_r$	1.18	1.15	1.18	1.09	0.83	1.07	1.23	0.86	1.22
<b>Means</b>	<b>11.10</b>	<b>13.82</b>	<b>86.08</b>	<b>14.30</b>	<b>20.79</b>	<b>184.23</b>	<b>16.37</b>	<b>23.87</b>	<b>279.17</b>

$\sigma_g^2$ : Genetic variance;  $\sigma_e^2$ : Environmental or residual variance;  $\sigma_f^2$ : Phenotypic variance;  $h_g^2$ : heritability;  $h_m^2$ : mean heritability per clone;  $\hat{r}_{aa'}$ : the accuracy estimate;  $CV_{gi}\%$ : Genotype Variation Coefficient;  $CV_e\%$ : Coefficient of environmental variation;  $CV_r$ : Relative Variation

Coefficient; *Ht*: total height (m); *DBH*: diameter at breast height (cm); *Vt*: volume of wood produced per hectare (m<sup>3</sup> ha<sup>-1</sup>).

Coefficients of genetic variance ( $CV_{gi}\%$ ) followed a similar pattern for the different traits, across the different sites and ages.  $CV_{gi}\%$  ranged from 11.22% to 17.19% for *DBH*; 5.96% to 12.00% for *Ht*, and from 26.51% to 41.33% for wood productivity per hectare (*Vt*) (Table 3). The values of environmental variance coefficients ( $CV_e\%$ ) varied from 10.74% to 17.19% for *DBH*; 6.58% to 18.84% for *Ht*, and from 25.19% to 39.99% for *Vt* (Table 3).

The values obtained for the relative coefficient of variance ( $CV_r$ ) were consistently lower for the *Ht* of trees in all situations (sites  $\times$  ages), as  $CV_e\%$  values are higher for this compared to the other traits.  $CV_r$  values were less than 1.0 for all traits evaluated in Corumbá de Goiás, while on the other sites these values were greater than 1.0 for *DBH* and *Vt*.

For the joint analysis of the three experiments, we observed that phenotypic variance ( $\sigma_f^2$ ) was more influenced by the genotypic ( $\sigma_g^2$ ) and environmental ( $\sigma_e^2$ ) variances than by the variance of the genotype  $\times$  environment (G  $\times$  E) interaction ( $\sigma_{ge}^2$ ) (Table 4). The coefficient of determination of the G  $\times$  E interaction ( $C_{ge}^2$ ) showed low variation among years and traits, except for total height (*Ht*) and volume (*Vt*) in the first assessment, where the values were higher than the others (Table 4).

The broad sense heritabilities ( $h_g^2$ ), for the joint analysis, varied from 0.36 to 0.41 according to age and the evaluated trait (Table 4). These values are lower compared to the estimate of  $h_g^2$  for each site separately (Table 3). For *Ht*, the joint  $h_g^2$  ranged from 0.04 to 0.26 and for *Vt* the from 0.30 to 0.38 (Table 4).

The estimates of heritability of the clones means ( $h_m^2$ ) for the joint analysis increased with age for all traits, reaching values around 0.80 at six years of age (Table 4). The estimated values for accuracy ( $\hat{r}_{aar}$ ) for the joint analysis of all evaluated characteristics were high, at different ages. The genotypic correlation between environments ( $\hat{r}_{gloc}$ ) showed increasing values over the years for *Ht* and stability for the other traits. The  $\hat{r}_{gloc}$  values were close to 0.70 for all evaluated traits at six years of age.

The coefficients of genetic ( $CV_{gi}\%$ ) and environmental variances ( $CV_e\%$ ) for the joint analysis follow the same trend of the individual sites. With higher values for *Vt*, and lower values for *Ht*. The values for the relative coefficient variance ( $CV_r$ ) were less than 1.0 for all traits evaluated, with the lowest values for total height (*Ht*).

**Table 4.** Joint estimates of genetic parameters (individual REML) for *DBH* (cm), *Ht* (m) and *Vt* (m<sup>3</sup> ha<sup>-1</sup>) at 2, 4 and 6 years of the clones.

Genetic Parameter	2 years			4 years			6 years		
s	<i>DBH</i>	<i>Ht</i>	<i>Vt</i>	<i>DBH</i>	<i>Ht</i>	<i>Vt</i>	<i>DBH</i>	<i>Ht</i>	<i>Vt</i>
$\sigma_g^2$	1.32	0.15	246.59	3.06	1.90	2415.51	5.16	3.16	6510.25
$\sigma_{ge}^2$	0.47	2.07	258.72	0.78	1.56	1064.36	1.86	1.50	2756.70
$\sigma_e^2$	1.45	1.64	328.64	4.72	6.38	3749.73	6.53	7.28	8101.47
$\sigma_f^2$	3.24	3.86	833.95	8.55	9.85	7229.59	13.55	11.94	17368.42
$h_g^2$	0.4082 +/- 0.02	0.0390 +/- 0.01	0.2957 +/- 0.02	0.3576 +/- 0.02	0.1934 +/- 0.01	0.3341 +/- 0.02	0.3806 +/- 0.02	0.2645 +/- 0.02	0.3748 +/- 0.02
$h_m^2$	0.87	0.15	0.70	0.90	0.74	0.84	0.87	0.83	0.85
$\hat{r}_{aar}$	0.93	0.39	0.84	0.95	0.86	0.92	0.93	0.91	0.92
$C_{ge}^2$	0.14	0.54	0.31	0.09	0.16	0.15	0.14	0.13	0.16
$\hat{r}_{gloc}$	0.74	0.07	0.49	0.80	0.55	0.69	0.74	0.68	0.70
$CV_{gi}\%$	10.86	3.15	23.96	12.25	6.86	28.39	13.81	7.61	31.55
$CV_e\%$	11.38	10.40	27.66	15.22	12.56	35.38	15.55	11.55	35.19
$CV_r$	0.95	0.30	0.87	0.80	0.55	0.80	0.89	0.66	0.90
<b>Means</b>	<b>10.59</b>	<b>12.31</b>	<b>65.55</b>	<b>14.28</b>	<b>20.11</b>	<b>173.09</b>	<b>16.44</b>	<b>23.35</b>	<b>255.77</b>

$\sigma_g^2$ : Genetic variance;  $\sigma_e^2$ : Environmental or residual variance;  $\sigma_f^2$ : Phenotypic variance;  $h_g^2$ : heritability;  $h_m^2$ : mean heritability per clone;  $\hat{r}_{aar}$ : the accuracy estimate;  $C_{ge}^2$ : coefficient of determination of the interaction GxE;  $\hat{r}_{gloc}$ : genotype correlation of clones performance between environments;  $CV_{gi}\%$ : Genotype Variation Coefficient;  $CV_e\%$ : Coefficient of environmental variation;  $CV_r$ : Relative Variation Coefficient; *Ht*: total height (m); *DBH*: diameter at breast height (cm); *Vt*: volume of wood produced per hectare (m<sup>3</sup> ha<sup>-1</sup>).

### 3.3.2 Correlations

Estimates of genotypic and phenotypic correlations among traits at different ages and sites generally showed high positive values, ranging from 0.68 and 0.96 (Table 5).

As for the phenotypic correlations of the same trait among the different ages, high positive values were also obtained, mainly for the wood volume, which had magnitudes varying between 0.50 and 0.87 (Table 6). The genotypic correlations for *Vt* among the different ages ranged from 0.67 to 0.93 (Table 6).

The genotypic correlations between consecutive ages, 2-4 years, or 4-6 years, are higher compared to ages of 2-6. The high phenotypic correlations among *DBH*, *Ht* and the wood yield produced at two, four- and six-years age are represented in figure 4, in the form of regression equations, with high coefficients of determination ( $R^2 > 0.68$ ).

**Table 5.** Genotypic (below the diagonal) and phenotypic (above the diagonal) correlations estimated between different age-matched traits at 2, 4, and 6 years.

<b>Catalão-GO</b>									
	<b>2 years</b>			<b>4 years</b>			<b>6 years</b>		
	<i>Ht</i>	<i>DBH</i>	<i>Vt</i>	<i>Ht</i>	<i>DBH</i>	<i>Vt</i>	<i>Ht</i>	<i>DBH</i>	<i>Vt</i>
<i>Ht</i>	1.0	0.90	0.75	1.0	0.89	0.77	1.0	0.91	0.77
<i>DBH</i>	0.94	1.0	0.91	0.94	1.0	0.90	0.96	1.0	0.90
<i>Vt</i>	0.82	0.95	1.0	0.87	0.95	1.0	0.86	0.94	1.0
<b>Corumbá-de-Goiás-GO</b>									
<i>Ht</i>	1.0	0.68	0.80	1.0	0.84	0.76	1.0	0.89	0.74
<i>DBH</i>	0.75	1.0	0.83	0.91	1.0	0.88	0.93	1.0	0.91
<i>Vt</i>	0.85	0.89	1.0	0.82	0.92	1.0	0.82	0.95	1.0
<b>Luziânia-GO</b>									
<i>Ht</i>	1.0	0.90	0.91	1.0	0.86	0.90	1.0	0.89	0.90
<i>DBH</i>	0.94	1.0	0.74	0.90	1.0	0.75	0.93	1.0	0.72
<i>Vt</i>	0.95	0.80	1.0	0.95	0.83	1.0	0.94	0.77	1.0
<b>Joint</b>									
<i>Ht</i>	1.0	0.74	0.79	1.0	0.83	0.77	1.0	0.89	0.75
<i>DBH</i>	0.80	1.0	0.85	0.88	1.0	0.88	0.94	1.0	0.91
<i>Vt</i>	0.85	0.91	1.0	0.85	0.93	1.0	0.82	0.94	1.0

*Ht*: total height (m); *DBH*: diameter at breast height (cm); *Vt*: volume of wood produced per hectare (m<sup>3</sup> ha<sup>-1</sup>).

**Table 6.** Genotypic (below the diagonal) and phenotypic (above the diagonal) correlations estimated for the same trait at different ages.

<b>Catalão-GO</b>									
	<i>Ht</i>			<i>DBH</i>			<i>Vt</i>		
	2 yrs	4 yrs	6 yrs	2 yrs	4 yrs	6 yrs	2 yrs	4 yrs	6 yrs
2 yrs	1.0	0.71	0.63	1.0	0.81	0.71	1.0	0.83	0.76
4 yrs	0.80	1.0	0.70	0.89	1.0	0.76	0.91	1.0	0.79
6 yrs	0.72	0.85	1.0	0.82	0.84	1.0	0.82	0.87	1.0
<b>Corumbá-de-Goiás-GO</b>									
2 yrs	1.0	0.36	0.26	1.0	0.45	0.39	1.0	0.51	0.54
4 yrs	0.65	1.0	0.32	0.68	1.0	0.37	0.72	1.0	0.50
6 yrs	0.55	0.70	1.0	0.65	0.65	1.0	0.78	0.67	1.0
<b>Luziânia-GO</b>									
2 yrs	1.0	0.82	0.57	1.0	0.89	0.67	1.0	0.87	0.77
4 yrs	0.91	1.0	0.53	0.90	1.0	0.68	0.93	1.0	0.76
6 yrs	0.72	0.75	1.0	0.72	0.68	1.0	0.84	0.88	1.0
<b>Joint</b>									
2 yrs	1.0	0.67	0.45	1.0	0.71	0.57	1.0	0.72	0.61
4 yrs	0.85	1.0	0.52	0.90	1.0	0.58	0.93	1.0	0.68
6 yrs	0.63	0.88	1.0	0.72	0.68	1.0	0.84	0.88	1.0

*Ht*: total height (m); *DBH*: diameter at breast height (cm); *Vt*: volume of wood produced per hectare (m<sup>3</sup> ha<sup>-1</sup>).

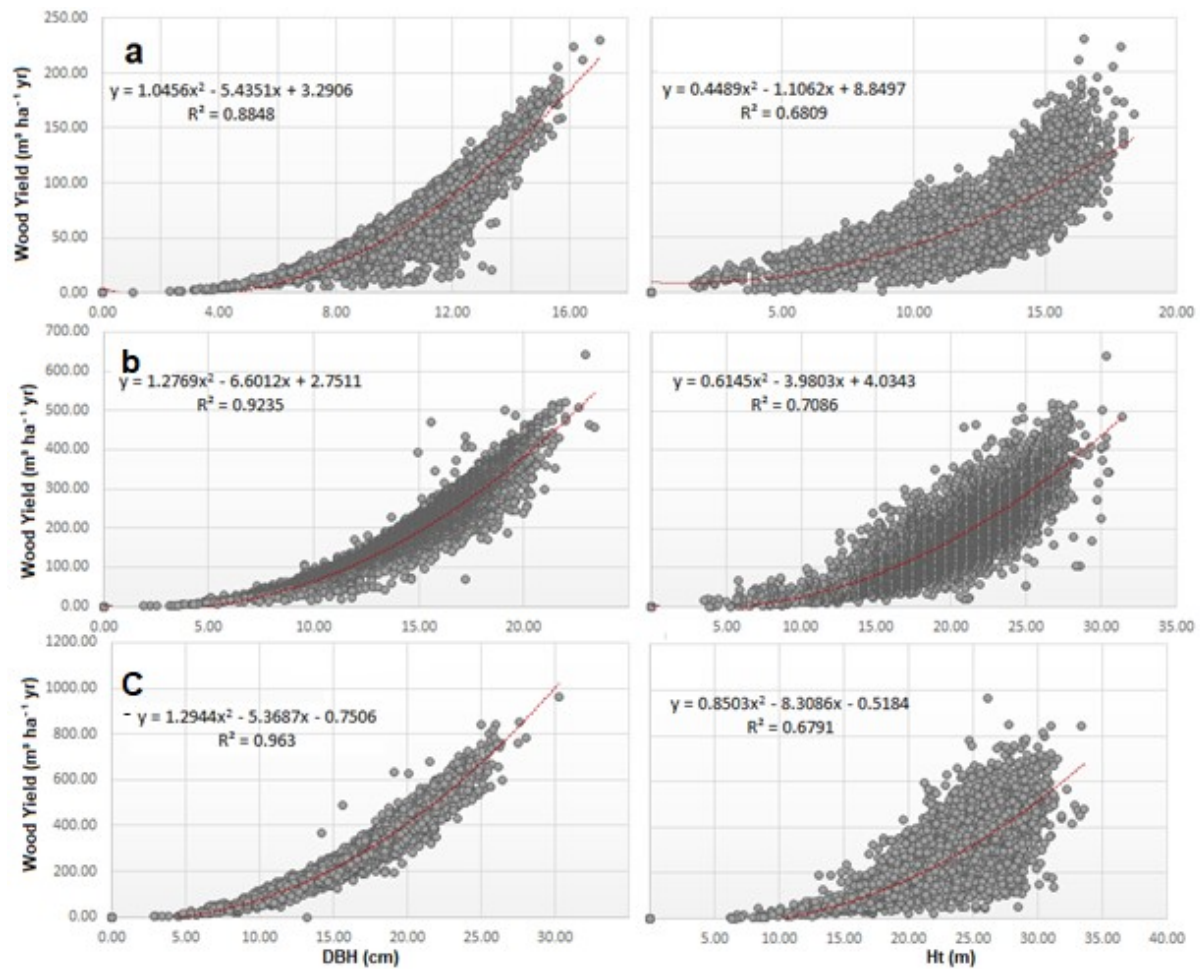
### 3.3.3 Clonal selection

The ranking of the ten best clones, selected at ages two, four and six years for each site and in the three sites jointly, was used for selection (Tables 7, 8, 9 and 10). Clones were selected based on their genotypic values.

The predicted genetic gain with selection of the ten best clones in Catalão, ranged from 37,62% at 2 years to 56,57% at harvest age. These gains were estimated in relation to the average of the experiment (Table 7). CCL21 (*E. urophylla* x *E. grandis*), AEC 144 (*E. urophylla*), CCL 07 (*E. urophylla*), CCL27 (*E. grandis* × *E. urophylla*), CCL36 (*E. urophylla* × *E. grandis*) and CCL28 (*E. grandis* × *E. urophylla*) clones were the most productive at harvesting age. However, it is worth noting that they have always been among the best clones since the first evaluation at age two, demonstrating the good adaptability of these genotypes in Catalão (Table 7).

In Corumbá de Goiás, the genetic gain with selection of the ten best clones was close to 43.0% at six years after planting (Table 8). Clones CLR454 (*E. urophylla*), CCL29 (*E. grandis* × *E. urophylla*), CCL35 (*E. urophylla* × *E. grandis*), CCL49 (*E. urophylla*) and CCL59 (*E. urophylla* × *E. grandis*) were the most productive at six years. Except for clone CCL29, all others were ranked among the ten most productive at two- and four-years age.

The genetic gain with the selection of the best clones in Luziânia has increased since the first evaluations, going from 39,09% at two years to 45,68% at six years (Table 9). Clones CCL30 (*E. urophylla*), CCL21 (*E. urophylla* x *E. grandis*), AEC144 (*E. urophylla*), CCL29 (*E. grandis* x *E. urophylla*) and CLR454 (*E. urophylla*) were the most productive at harvest age. As in Corumbá-de-Goiás, only CCL29 was not among the best in the first two evaluations.



**Figure 4.** The phenotypic association between *DBH* and *Ht* and the volume of wood produced at two, four- and six-years age. a: Association between wood yield ( $\text{m}^3 \text{ha}^{-1}$ ) and *DBH* (cm) and *Ht* (cm) at two years age; b: Association between wood yield ( $\text{m}^3 \text{ha}^{-1}$ ) and *DBH* (cm) and *Ht* (cm) at four years age; c. Association between wood yield ( $\text{m}^3 \text{ha}^{-1}$ ) and *DBH* (cm) and *Ht* (cm) at six years age.

In the joint analyses of all three sites, the predicted genetic gain with selection of the ten best clones also increased with time, going from 36.72% at year two to 46.92% at six. Clones CCL29 (*E. urophylla*), CCL35 (*E. urophylla*  $\times$  *E. grandis*), CLR454 (*E. urophylla*), CCL27 (*E. grandis*  $\times$  *E. urophylla*), CCL07 (*E. urophylla*) and AEC144 (*E. urophylla*) were the most productive at the harvest age (Table 10). Among these six best clones, only CCL29 was not among the best at two years after planting.

**Table 7.** Genotypic values predicted for productivity of wood volume (m<sup>3</sup> ha<sup>-1</sup>) of the ten best and five worst clones in the Catalão-GO.

Rank	2 years			4 years			6 years		
	Clone	u + g*	G(%) <sup>1</sup>	Clone	u + g*	G(%) <sup>1</sup>	Clone	u + g*	G(%) <sup>1</sup>
1	CCL07	113.18	60.29%	CCL21	341.31	75.10%	CCL21	498.45	91.80%
2	CCL21	106.74	51.16%	CCL36	328.92	68.75%	AEC144	457.61	76.08%
3	CCL27	105.56	49.50%	CCL07	325.68	67.08%	CCL07	451.94	73.90%
4	CCL28	104.85	48.50%	CCL27	319.77	64.05%	CCL27	432.18	66.30%
5	CCL49	104.35	47.78%	AEC144	317.50	62.89%	CCL36	426.13	63.97%
6	CCL47	103.60	46.72%	CCL35	303.61	55.76%	CCL28	423.06	62.79%
7	CCL14	102.77	45.55%	CCL47	299.08	53.44%	CCL56	419.79	61.53%
8	AEC144	102.69	45.43%	CCL15	294.01	50.84%	CCL29	413.21	59.00%
9	CCL36	101.66	43.97%	CCL51	291.17	49.38%	CCL30	411.91	58.50%
10	CCL50	97.17	37.62%	CCL28	289.08	48.31%	CCL35	406.90	56.57%
...	...	...	...	...	...	...	...	...	...
90	CLR410	35.97	-49.0%	CLR410	75.35	-61.3%	CLR426	97.58	-62.4%
91	CLR426	32.05	-54.6%	CLR426	74.48	-61.8%	CCL57	97.56	-62.5%
92	CCL54	30.30	-57.1%	<i>E. cloeziana</i>	73.08	-62.5%	CLR401	83.58	-67.8%
93	<i>E. cloeziana</i>	29.34	-58.4%	CCL54	55.12	-71.7%	CCL54	68.24	-73.7%
94	<i>C. citriodora</i>	20.28	-71.3%	<i>C. citriodora</i>	47.80	-75.5%	<i>C. citriodora</i>	45.93	-82.3%

\* Genotypic value, in which 'u' is the general mean and 'g' is the genotypic effect of the clones; <sup>1</sup> Genetic gain in relation to the experimental mean.

**Table 8.** Genotypic values predicted for productivity of wood volume (m<sup>3</sup> ha<sup>-1</sup>) of the ten best and five worst clones in the Corumbá-de-Goiás-GO.

Rank	2 years			4 years			6 years		
	Clone	u + g	G(%)	Clone	u + g	G(%)	Clone	u + g	G(%)
1	CCL49	126.84	169.36%	CCL59	274.93	82.76%	CLR454	484.95	90.83%
2	CCL47	116.27	146.92%	CCL47	253.62	68.60%	CCL29	475.68	87.18%
3	CCL59	114.30	142.73%	CCL51	251.36	67.10%	CCL35	466.38	83.52%
4	CCL51	113.52	141.06%	CLR454	248.39	65.12%	CCL49	429.88	69.16%
5	CCL60	105.97	125.05%	CCL35	239.56	59.25%	CCL59	395.26	55.54%
6	CCL46	94.99	101.71%	CCL21	229.42	52.51%	CCL20	389.18	53.14%
7	CCL48	76.88	63.25%	AEC042	227.62	51.31%	GG100	380.51	49.73%
8	CCL35	70.64	50.02%	CCL46	210.85	40.17%	CCL43	375.45	47.74%
9	CCL27	68.27	44.99%	CCL49	209.76	39.44%	CCL07	366.59	44.25%
10	CLR454	67.05	42.39%	CCL60	208.77	38.78%	CCL45	365.15	43.68%
...	...	...	...	...	...	...	...	...	...
89	Toreliodora	24.02	-49.0%	CLR401	81.66	-45.7%	CCL52	105.23	-58.6%
90	CCL53	22.79	-51.6%	CCL31	79.16	-47.4%	CCL53	104.12	-59.0%
91	<i>E. cloeziana</i>	21.91	-53.5%	CLR441	70.91	-52.9%	CCL57	101.35	-60.1%
92	CCL57	14.49	-69.2%	Toreliodora	51.67	-65.7%	Toreliodora	90.87	-64.2%
93	<i>C. citriodora</i>	9.60	-79.6%	<i>C. citriodora</i>	49.96	-66.8%	<i>C. citriodora</i>	43.47	-82.9%

\* Genotypic value, in which 'u' is the general mean and 'g' is the genotypic effect of the clones; <sup>1</sup> Genetic gain in relation to the experimental mean.



**Table 9.** Genotypic values predicted for productivity of wood volume ( $\text{m}^3 \text{ha}^{-1}$ ) of the ten best and five worst clones in the Luziânia-GO.

Rank	2 years			4 years			6 years		
	Clone	u + g	G(%)	Clone	u + g	G(%)	Clone	u + g	G(%)
1	CCL21	132.58	66.23%	CCL21	310.89	76.23%	CCL30	473.87	83.22%
2	CCL07	129.08	61.84%	CCL49	309.27	75.31%	CCL21	466.87	80.51%
3	CCL30	125.83	57.76%	AEC144	290.73	64.80%	AEC144	443.42	71.44%
4	AEC144	123.82	55.25%	CCL30	283.87	60.91%	CCL29	404.10	56.24%
5	CCL27	122.10	53.08%	CCL27	272.28	54.34%	CLR454	401.80	55.35%
6	CCL35	121.50	52.33%	CCL07	269.93	53.02%	CCL60	401.36	55.18%
7	CCL43	116.08	45.54%	CCL35	264.26	49.80%	CCL45	385.55	49.07%
8	CCL11	114.95	44.11%	CLR454	263.80	49.54%	CLR422	381.60	47.54%
9	CCL41	113.27	42.01%	CCL11	258.23	46.38%	AEC042	377.09	45.80%
10	CLR454	110.89	39.03%	CCL29	242.40	37.41%	CCL27	376.80	45.68%
...	...	...	...	...	...	...	...	...	...
89	CCL52	39.05	-51.0%	CLR410	80.72	-54.2%	CCL52	104.71	-59.5%
90	CCL57	37.15	-53.4%	<i>E. cloeziana</i>	77.68	-56.0%	CLR410	95.24	-63.2%
91	<i>E. cloeziana</i>	33.76	-57.7%	CCL57	75.59	-57.2%	CCL57	82.33	-68.2%
92	<i>C. citriodora</i>	26.96	-66.2%	<i>C. citriodora</i>	47.74	-72.9%	Toreliodora	80.94	-68.7%
93	Toreliodora	20.95	-73.7%	Toreliodora	43.80	-75.2%	<i>C. citriodora</i>	68.47	-73.5%

\* Genotypic value, in which 'u' is the general mean and 'g' is the genotypic effect of the clones; <sup>1</sup> Genetic gain in relation to the experimental mean.

**Table 10.** Genotypic values predicted for productivity of wood volume ( $\text{m}^3 \text{ha}^{-1}$ ) of the ten best and five worst clones in the joint analyses of all three sites.

Rank	2 years			4 years			6 years		
	Clone	u+g+gem	G (%)	Clone	u+g+gem	G (%)	Clone	u+g+gem	G (%)
1	CCL49	106.20	62.01%	CCL21	293.88	69.78%	CCL29	431.00	68.51%
2	CCL07	100.52	53.35%	CCL35	269.15	55.50%	CCL35	415.35	62.39%
3	CCL27	98.64	50.49%	CCL27	266.65	54.05%	CLR454	403.71	57.84%
4	CCL35	94.97	44.89%	CCL07	262.67	51.75%	CCL27	390.09	52.52%
5	AEC144	92.37	40.92%	CCL49	255.64	47.69%	CCL07	388.09	51.73%
6	CCL28	92.30	40.80%	AEC144	252.79	46.05%	AEC144	385.82	50.85%
7	CCL47	92.10	40.51%	CCL36	250.23	44.57%	CCL36	385.27	50.63%
8	GG100	90.98	38.79%	CLR454	249.11	43.92%	CCL30	382.05	49.37%
9	CCL43	90.40	37.90%	CCL04	247.43	42.95%	CCL49	379.95	48.55%
10	CCL21	89.62	36.72%	CCL47	247.33	42.89%	CCL21	375.78	46.92%
...	...	...	...	...	...	...	...	...	...
105	CCL52	33.35	-49.1%	CCL52	84.38	-51.3%	CCL53	107.97	-57.8%
106	CCL57	29.48	-55.0%	<i>E. cloeziana</i>	79.50	-54.1%	CCL52	104.44	-59.2%
107	<i>E. cloeziana</i>	28.34	-56.8%	CCL54	76.99	-55.5%	CCL54	94.27	-63.1%
108	Toreliodora	28.14	-57.1%	Toreliodora	57.79	-66.6%	CCL57	93.75	-63.3%
109	<i>C. citriodora</i>	18.95	-71.1%	<i>C. citriodora</i>	48.50	-72.0%	<i>C. citriodora</i>	52.62	-79.4%

\* Genotypic value, in which 'u' is the general mean and 'g' is the genotypic effect of the clones; <sup>1</sup> Genetic gain in relation to the experimental mean.

Some clones exhibited low wood productivity over the six years of evaluations. Among these genotypes, clones CCL52 (*E. urophylla* x *E. tereticornis*), CCL53 (*E. urophylla* x *E. tereticornis*), CCL54 (*E. urophylla* x *E. brassiana*), CCL57 (*E. urophylla* x *E. tereticornis*), CLR 401 (*E. urophylla*), CLR 410 (*E. urophylla*), CLR 426 (*E. urophylla*), Citriodora (*C. citriodora*), Toreliodora (*C. torelliana* × *C. citriodora*) have productivities lower than 108,00 m<sup>3</sup> ha<sup>-1</sup> at six years of age. This productivity is, on average, 55.0% lower than the average of the clonal tests, which is 278.04 m<sup>3</sup> ha<sup>-1</sup>.

### 3.4. DISCUSSION

#### 3.4.1 Genetic parameters and yield

Survival rates reflect the adaptability of clones under different environmental conditions. In Brazil, *Eucalyptus* plantations for wood biomass are, generally, planted at high densities (e.g. 3.0 x 2.0 m) and harvested at 5-7 years. Over time, there is an increase in competition between trees, reducing tree growth and increasing mortality if no thinning is carried out (Furlan et al., 2020; Medeiros et al., 2020).

The survival rates at six years found in this study corroborate this information, indicating that our clonal tests might have surpassed the ideal harvesting time, which for the evaluated regions has an average time of five years (Reis et al., 2017). The decrease in survival rate over the years indicates that clones, in general, are facing greater competition for essential factors, such as water, light and nutrients. In general, large forest companies seek survival rates above 95% for clonal eucalyptus forests (Stape et al., 2001).

The growth in *DBH* remained constant throughout the years, but at decreasing rates from the fourth to sixth year, indicating a slowdown in secondary growth. This is due to increased competition between trees for growth factors (water, light and nutrients). This trend was observed at all evaluated sites. The reduction in height growth rate was even more evident. This indicates that trees, in general, reached their maximum primary growth potential at four years of age.

Considering the wood yield, all sites evaluated are suitable for plantation of *Eucalyptus* spp. clones, as they present an average annual increment of wood of 46.4 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>, about 31.4% higher than the national average, which was 35.3 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> in 2019 (IBÁ, 2020). This demonstrates the high potential for commercial cultivation of *Eucalyptus* spp. in these regions. The average yield of wood at six years for the three sites was 278.3 m<sup>3</sup> ha<sup>-1</sup>.

In Catalão and Luziânia, the genotypic variance was the main component of phenotypic variation in wood volume, with 55,0% and the remaining 45,0% for environmental variance (Table 3). The proportion of environmental variance in Corumbá-de-Goiás was higher, indicating a greater effect of the environment on the expression of the phenotype in this site (Table 3).

The broad-sense heritability of single-tree plots ( $h_g^2$ ), evaluated for each experiment, showed higher values in Catalão and Luziânia for all evaluated traits, in all ages (Table 3). This reinforces that environmental variation had a greater influence in Corumbá-de-Goiás-GO, due to the more intense effect of the water deficit in this site (Gonçalves et al., 2017).

Higher heritability values result in a greater existence of genetic variability and possibility of selection (Resende and Duarte, 2007). Makouanzi et al. (2017) also found high heritability values ( $>0.55$ ) for *E. urophylla* x *E. grandis* clones, evaluated between two and six years of age in edaphoclimatic conditions like this study.

The broad-sense-heritability based on the clonal averages ( $h_m^2$ ) was greater than 0.9, indicating high accuracy for selection of the best clones. This high  $h_m^2$  is due to the high number of repetitions of our experimental design (29 blocks), which reduce the influence of environmental variation and experimental errors, further increasing the precision of the selection (Vencovsky and Barriga 1992; Resende and Barbosa, 2005). The high  $h_m^2$  provide greater precision in the classification of genotypes, resulting in higher selection gains (Resende and Duarte, 2007; Oliveira et al., 2020). In previous studies with *Eucalyptus* clones,  $h_m^2$  above 0.75 are common, especially for DBH and volume of wood (Beltrame et al., 2012; Santos et al., 2015; Resende et al., 2017; Tambarussi et al., 2017; Furlan et al., 2020).

The high estimated values for accuracy ( $\hat{r}aa$ ) for all evaluated traits in all sites (Table 4) are vital for selection purposes, and for the accurate estimation of genotypic values (Resende, 2007). These values attest the reliability of the experimental design adopted and the efficiency in the selection of better clones (Resende and Duarte, 2007). As with high  $h_g^2$ , high values of  $\hat{r}aa$  are common in experiments with eucalyptus clones, as the accuracy is derived from  $h_m^2$  (Furlan et al., 2020). Values greater than 0.85 have been reported by various authors for DBH and volume in *Eucalyptus* clones (Beltrame et al., 2012; Rosado et al., 2012; Santos et al., 2015; Tambarussi et al., 2017; Furlan et al., 2020).

The high accuracy obtained in this study can be attributed to the high number of repetitions, which reduce the phenotypic variation, especially among clonal means (Santos et al., 2021). The high number of repetitions was due to the use of a single tree plot design,

which allows the use of a greater number of repetitions even when a large number of clones is evaluated (Santos et al., 2021). In Brazil, the use of single tree plots has been widely used with the objective of increasing accuracy of selection with higher number of replicates (Santos et al. 2016; Nunes et al. 2018; Rezende et al. 2019).

The coefficient of genetic variation ( $CV_{gi}\%$ ) expresses the genetic variation between clones. The estimated values of  $CV_{gi}\%$  increased with age for all traits at the all sites (Table). The same trend was observed for the coefficient of environmental variation ( $CV_e\%$ ).

The  $CV_e\%$ , for  $V_t$ , reached values above 30.98% at six years of age. These values are considered average for wood yield in clonal tests of *Eucalyptus*, indicating good experimental precision (Garcia, 1989). Volume is a quantitative trait dependent on its component variables (DBH and height) and, thus, is highly influenced by the environment. Environmental influence increases with age as they can accumulate throughout the growth cycle. Therefore, it is common to have higher  $CV_e\%$  values as perennial plants age (Garcia, 1989).

The high values of  $CV_{gi}\%$  (33.96%) obtained for the volume, at six years of age, indicates the existence of genetic variation among clones. As such, selection of the best clones can result in productivity gains (Table 3).

The coefficient of relative variation is a important genetic parameter for tree improvement. The higher the value of  $CV_r$ , the greater the genetic control over the influence of environmental factors on the phenotype (Vencovsky, 1987). The volume of wood presented the highest  $CV_r$  value in Catalão and Luziânia, indicating higher relative influence of environmental variance in Corumbá-de-Goiás.

These high values of the relative coefficients of variation ( $CV_r$ ) reinforce the high experimental quality and reliability of the estimates in this study, for all ages evaluated in the different sites (Resende, 2007; Resende and Duarte, 2007). Thus, the selection of clones with higher wood volume would be effective (Vencovsky and Barriga, 1992). Similar values of  $CV_r$  were obtained in clonal tests of *Eucalyptus* spp. (Santos et al., 2015, Nunes et al., 2016; Furlan et al., 2020).

The coefficient of determination of the  $G \times E$  interaction ( $C_{ge}^2$ ) was significant for all traits in all ages, indicating that clones have a different response in each environment (Furlan et al., 2020). Total height and wood volume were the most influenced by GxE interaction in the first two years. This can be observed by  $C_{ge}^2$ , which measures the proportion of variance of the  $G \times E$  interaction in the phenotypic variation of the clones (Table 4).

For wood productivity, the GxE interaction had a greater effect on harvest age. However, in general, the coefficient of determination of the genotype x environment interaction ( $C_{ge}^2$ ) showed low levels of variation over the 6 years of planting (Table 4).

The genotypic correlation between environments ( $\hat{r}_{gloc}$ ) increased over the years, with higher values for *DBH* and wood volume at six years of age (Table 4). These values (0.49-0.80) indicate that the G x E interaction is predominantly simple (Vencovsky and Barriga, 1992). When this occurs, the relative ranking of genotypes tends to be the same across environments. In other words, even though genotypes may present differences of productivity in each environment, the best clones in one site are generally also the best in the other evaluated locations (Morais et al., 2010; Santos et al., 2015).

The G x E interaction at age six years was decomposed into a simple and a complex part. According to the methodology of Cruz and Castoldi (1991), 67.35% of the interaction was considered simple and 32.65% complex. The simple interaction is due to difference in variability between the genotypes at the sites and is associated with a high genetic correlation between the environments (Table 4) (Cruz and Castoldi, 1991, Ramalho et al., 2012).

Considering only the 85 genotypes planted in all three sites, the genetic correlations between pairs of sites were classified as high (Ramalho et al., 2012), being 0.70 for Cat-Cor, 0.76 for Cat-Luz and 0.65 for Cor-Luz. These correlations show moderate to low GxE interaction among these sites that represent well the Cerrado biome. As such, the joint selection can provide adequate genotypes for the three environments and genotypes with potential high adaptability in the Cerrado region.

### 3.4.2 Correlation and Early Selection

The high positive correlations among the three evaluated traits (Tables 2 and 3) facilitate the selection process. Positive correlations allow to practice selection in more than one desirable trait simultaneously in an indirect way (Massaro et al., 2010). The values of the genotypic correlations were superior to the values of the phenotypic correlations, showing a strong association between the genetic component of the trait's expression, which can be explained by the presence of pleiotropic genes or linkages in the genetic control of these traits (Massaro et al., 2010; Oliveira et al., 2020).

Therefore, the genes that control tree growth and development, such as those that influencing nutrient uptake, photosynthesis and respiration, will influence *Ht*, *DBH* and, consequently, *Vt* (Pupin et al. 2017). High correlations between

*DBH*, *Ht* and *Vt* were observed in other clonal tests of *Eucalyptus* spp. (Massaro et al., 2010; Tambarussi et al. 2017).

The genotypic correlation coefficients among evaluations at ages two, four and six, indicate favorable perspectives for the realization of early selection, in each of the clonal tests and in the joint analysis. According to Yang et al 2013, high genotypic correlations between different ages indicate the efficiency of early selection. Thus, the selection of clones at two years of age would have an efficiency of 61% for selecting the best clones for wood productivity (*Vt*) at six years of age. The selection of clones at four years age would increase efficiency to 68%, in the joint analysis of all three sites (Table 4).

The efficiency of early selection at four years of age to determine the most productive clones at harvest age (six years) ranged from 50% in Corumbá-de-Goiás, where there was greater environmental interference in phenotypic expression, to 79% in Catalão.

### 3.4.3 Clonal Selection

In all evaluated sites, the most productive clones at six years of age had *E. urophylla* in their genetic makeup, either monospecifically or as hybrid. Most of the Brazilian *Eucalyptus* spp. plantations are formed by *E. urophylla* clones, due to their high adaptive capacity (Figure 5), high productivity and stability in almost all regions of Brazil, as well as resistance to some economically important diseases, such as rust and canker (Binkley et al., 2017; Silva et al., 2018; Campoe et al., 2020).

Among the ten most productive clones in the joint analysis, five are hybrids of *E. urophylla* x *E. grandis* (CCL35, CCL36 and CCL21, CCL29 and CCL27). The other clones have only *E. urophylla* in their constitution (CLR 454, CCL07, AEC144, CCL30 and CCL40). Among these hybrid clones, only CCL29 was not among the most productive in previous evaluations (Table 10), showing a high growth capacity after four years of planting.

The high productivity of *E. grandis* makes the hybrid *E. urophylla* × *E. grandis* (Figure 7) and its reciprocal prominent in Brazilian clonal forestry (Assis et al., 2015; Castro et al., 2016), even in tropical regions where *E. grandis* does not have high adaptation (Flores et al., 2016). The hybrid of *E. urophylla* x *E. grandis* combines the high growth rate of *E. grandis*, with higher stump resprout, density, and tolerance to canker (*Crysoporthe cubensis*), to rust (*Austropuccinia psidii*) and to water deficit of *E. urophylla* (Resende et al., 2014; Gonçalves et al., 2013).

Although *E. grandis* does not have high natural adaptation to the Aw climate, (Figure 6) some provenances can tolerate some level of water stress conditions (Resquin et al., 2019;

Christina et al., 2017), even than with a lower rate of biomass accumulation due to high phenotypic plasticity for *E. grandis* (Bradshaw, 1965). This phenotypic plasticity, together with its wide genetic variability (Silva et al., 2019), contributed to the better performance of some *E. grandis* x *E. urophylla* as in CCL29 and CCL27 hybrids. The alternation of ranking between the most productive clones in the growth cycle, at different ages, can also be explained by the phenotypic plasticity, as reported by Araújo et al. (2019).

Currently, the species *E. grandis*, *E. urophylla* and their hybrids represent almost all clones planted in forests in Brazil (Resende et al., 2014; Gonçalves et al. 2013). Other *Eucalyptus* species such as *E. camaldulensis*, *E. tereticornis*, *E. pellita*, *E. saligna* and *E. brassiana* also stand out (Silva et al., 2012; Santarosa et al., 2014), giving infinite possibilities to breeders as they can target selection of pure and hybrid clones. Each species may carry interesting alleles for special characteristics such as density, resistance to water deficit and resistance to diseases, especially in regions of expansion of *Eucalyptus* plantations (Cunha et al., 2020; Rocha et al., 2020).

In Catalão, in addition to the hybrids between *E. grandis* and *E. urophylla*, another clone stood out, among the most productive. This clone (CCL56), a triple hybrid of *E. grandis* x (*E. urophylla* x *E. tereticornis*) (Figure 7), had a much higher productivity ( $\sim 294 \text{ m}^3 \text{ ha}^{-1}$ ) than the other clones that have *E. tereticornis* in their constitution (CCL52, CCL53 and CCL57).

Despite having medium aptitude to the planting regions (Figure 6), most *E. tereticornis* clones did not present good productivity, at six years, with wood yield below  $\sim 108 \text{ m}^3 \text{ ha}^{-1}$  (Table 7). *E. tereticornis* presents moderate productivity together with resistance to pests, diseases, water deficit and high wood density (Gonçalves et al., 2013). Therefore, the high productivity of CCL 56 is probably associated with heterosis in this triple hybrid and the presence of *E. grandis* in its constitution.

In Corumbá-de-Goiás, CCL43 stood out among the most productive clones, with a wood yield of  $375.45 \text{ m}^3 \text{ ha}^{-1}$  at six years age. This clone, a hybrid of *E. pellita* x *E. grandis*, had a high productivity in other sites (348,35 in Catalão and 306,56 in Luziânia at six years age). The species *E. pellita* having high aptitude for the entire region (Figure 6). *E. pellita* is one of the most promising species for eucalyptus breeding programs in humid tropics (Brawner et al., 2010), because it is resistant to many tropical pests and diseases (Guimarães et al., 2010) and, also, it can be used for hybridization with *E. urophylla* (Gonçalves et al., 2013).

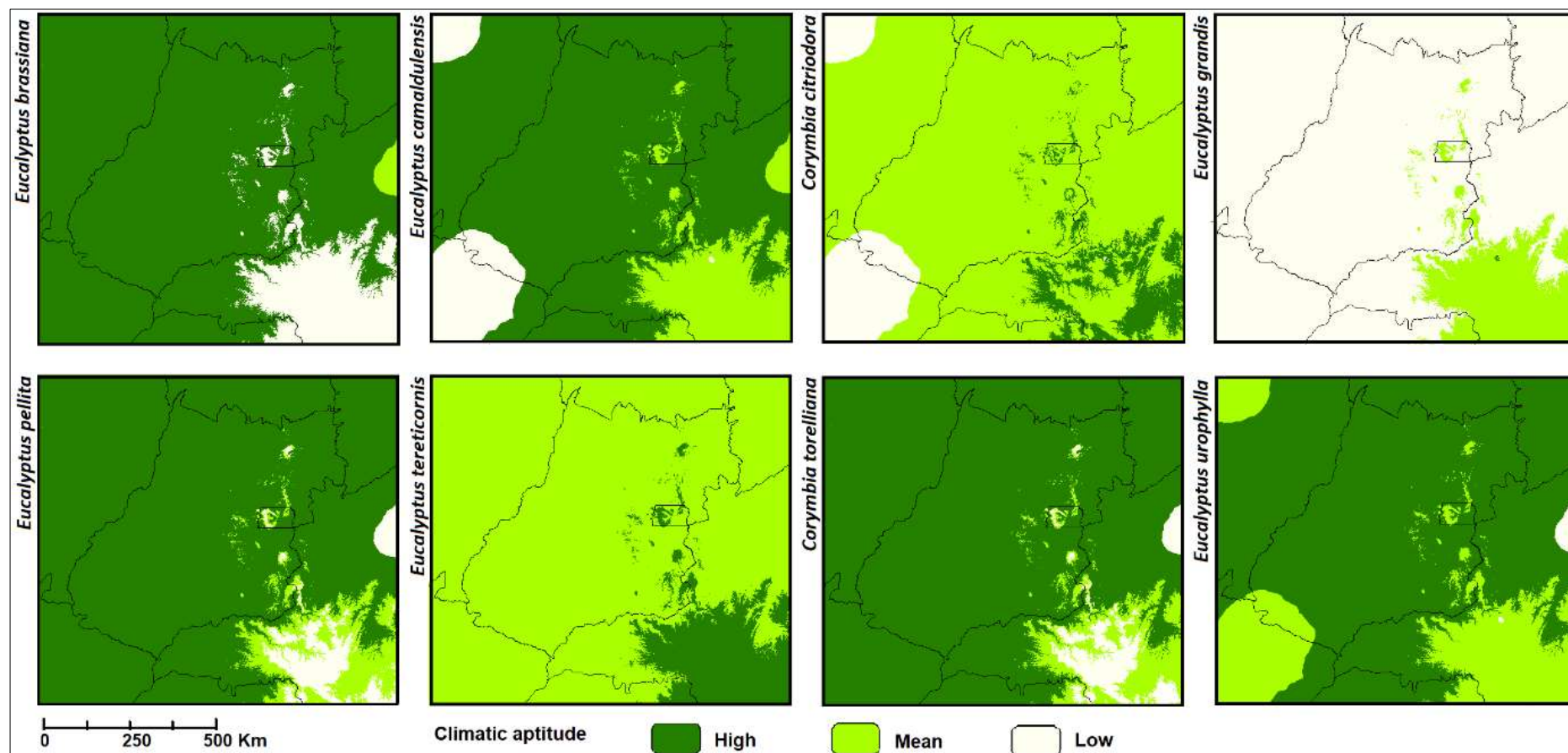
CCL60 clone (*E. camaldulensis*) is among the most productive at six years of age in Luziânia and in Corumbá-de-Goiás at 4 years age (Figure 7). The species *E. camaldulensis* has high climatic aptitude in the sites where clonal tests were installed (Figure 6) as it is tolerant to drought (Gonçalves et al., 2013; Rocha et al., 2020). In Corumbá-de-Goiás there was a problem of severe water deficit in the first two years age, while in Luziânia, the water deficit was between the fifth- and sixth-year age (INMET, 2022). This abiotic stress favored the better performance of the CCL60 clone in the beginning of the grow cycle (Oliveira et al., 2020).

Despite its high suitability for Cerrado regions with Aw-type climate, *E. camaldulensis* is very susceptible to various pest insects, such as red gum psyllid (*Glycaspis brimblecombei*), blue gum wasp (*Leptocybe invasa*) and bronze bug (*Thaumascotocoris peregrinus*) (Gonçalves et al., 2013). Due to the attack of these insects, especially *G. brimblecombei*, this clone probably was not among the most productive in Catalão. Thus, the choice of *E. camaldulensis* clones for planting in regions of the Cerrado biome must be carefully examined, as insects damages can cause tree mortality. A previous study has recorded 30% to 95% of mortality in a *E. camaldulensis* forest after three years of infestation (Gonçalves et al., 2013).

Considering the genetic diversity of *E. urophylla* introduced in Brazil (Santos et al., 2019), some genotypes did not show good productivity in the present study. Examples include pure *E. urophylla* clones (CLR 401, CLR 410 and CLR 426) or interspecific hybrids (CCL52, CCL53, CCL54 and CCL57) (Tables 7-10).

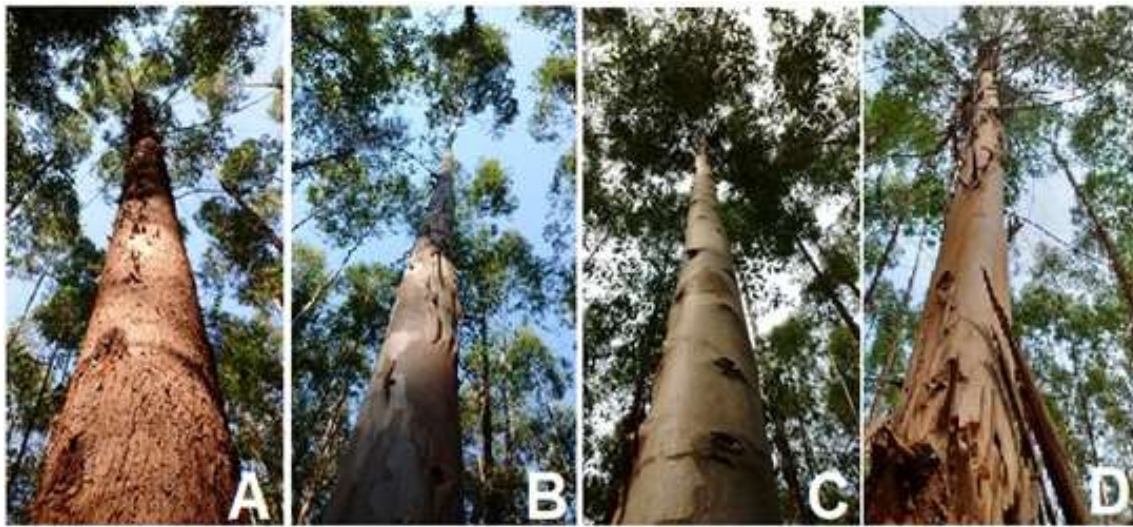
Part of these hybrids are *E. urophylla* x *E. tereticornis* (Table 7), while CCL54 is *E. urophylla* x *brassiana*. Part of the low performance of these hybrids can be attributed to the species *E. brassiana* and *E. tereticornis*, which have high and medium aptitude to the evaluation regions, respectively (Figure 6), mainly due to tolerance to water deficit (Assis and Máfia, 2007; Gonçalves et al., 2013). Usually species adapted to water deficit, have lower productivity and higher density (Rocha et al., 2020), being recommended for energy purposes, in regions of expansion of the forest frontier in Brazil (Gonçalves et al., 2017).





**Figure 6.** Adaptation of some *Eucalyptus* species to the state of Goiás. Adapted from Flores et al. (2016).

Despite showing high adaptation to regions where seasonal water deficit occurs, such as the evaluated locations (Reis et al., 2013; Flores et al., 2016), the few clones of *C. citriodora* and Toleriodora (*C. torelliana* × *C. citriodora*) (Figure 7) analyzed here all showed low productivity. This is due to the slow initial growth rates of these species observed in this study. Therefore, *Corymbia* spp. clones do not develop well when they compete for resources with *Eucalyptus* spp. clones, reaching lower wood productivity at harvest age, in water deficit regions.



**Figure 7.** Some *Eucalyptus* clones evaluated in the state of Goiás. A: CCL 21 clone (*E. urophylla* x *E. grandis*); B: CCL 56 clone (*E. grandis* x (*E. urophylla* x *E. tereticornis*)); C: Toleriodora clone (*C. torelliana* × *C. citriodora*); D: CCL 60 clone (*E. urophylla* x *E. camaldulensis*).

### 3.5 CONCLUSIONS

Thus, the selection of clones at two years of age would have an efficiency of 61% for selecting the best clones for wood productivity at six years age (harvest age). The selection of clones at four years of age would increase efficiency to 68%, in the joint analysis of all three sites. This is an important implication for tests with many *Eucalyptus* genotypes, facilitating the discard of less promising clones and, thus, allowing the anticipation of the next evaluation steps.

Biomass productivity in Luziânia and Catalão was higher than in Corumbá-de-Goiás, which underwent a prolonged period of water deficit with boron deficiency and loss of apical dominance between the first and second assessments. This contributed to

the fact that the clones with the best performance in Corumbá-de-Goiás were, for the most part, different from the best clones in the other sites evaluated, evidencing the need to observe commercial genotypes in areas subject to water deficit, to select clones adapted to these situations.

The six most productive clones (CCL29, CCL35, CLR454, CCL27, CCL07, AEC144) present *E. urophylla* in their constitution confirming the high suitability of this species for regions with a climate like the evaluated sites, typical of areas of the ‘new forest frontier’. Different clones of *E. urophylla* suitable for this region favor the increase of intraspecific diversity.

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## CHAPTER 3

### WOOD ENERGY YIELD FOR *Eucalyptus* CLONES GROWING UNDER SEASONAL DROUGHT-STRESS IN BRAZIL<sup>1</sup>

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# Wood energy yield for *Eucalyptus* clones growing under seasonal drought-stress in Brazil

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## ABSTRACT

Brazil is internationally recognized for the high yield of its *Eucalyptus* plantation forests and the use of wood as bioenergy. The expansion of *Eucalyptus* forests to water-limited regions in Brazil and around the world has required the selection of superior drought-adapted clones, since this is a limiting factor for the wood yield of *Eucalyptus* plantations. In addition to growth, the wood quality for bioenergy must be considered when selecting these *Eucalyptus* genotypes growing under seasonal drought-stress. Our study focused on evaluating the energy potential based on wood energy yield from a diverse set of 20 *Eucalyptus* multispecies clones planted under seasonal drought-stress in Brazil. In addition, correlation and path analyses were used to indicate which wood quality and yield traits influenced energy yield the most. The experiment area is characterized as tropical with dry winter climate type (Aw), with precipitation irregularly distributed throughout the year, with 5 months of water deficit. The mean annual increment (MAI) was calculated, trees were cut and wood samples were obtained six years after installing the experiment to determine the wood basic density, higher heating value, energy density, dry matter, and energy yield. Our results indicate that there are *Eucalyptus* genotypes adapted to seasonal drought-stress and present a high yield. The CCL36 (*E. urophylla* x *E. grandis*) clone has the greatest energy potential as it has the largest wood energy yield (982,587 MJ ha<sup>-1</sup> year<sup>-1</sup>), and is also the most productive with 94.99 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> of wood. The wood energy yield of the *Eucalyptus* clones is strongly related to the mean annual increment and the increment in dry matter. However, wood traits such as basic density and heating value had little influence on wood energy yield. Thus, it is concluded that there are clones with high productive potential which can increase the biomass supply for energy in tropical regions with dry winter climate types, such as areas of recent forest expansion.

## 1. Introduction

The global demand for energy continues to increase and the use of fossil fuels can cause negative environmental impacts [1]. Several countries are currently investing in the search for renewable energy sources to comply with the Paris Climate Agreement [2,3]. In this context, wood biomass originating from forest plantations is an important source of renewable energy [4,5].

A large proportion of the forest plantations used for energy purposes

in Brazil and in many other tropical countries are made up of *Eucalyptus* spp [4–6]. The vast majority of *Eucalyptus* planting stock is of inter-specific hybrids, particularly hybrid clones [7]. This preference for *Eucalyptus* is due to its short rotation [4], high yield [8], high wood quality for energy and many other uses [9], and its ability to adapt to different edaphoclimatic conditions, in addition to easy cloning [10].

The major industrial-scale interest has led to a steady rise in the extent of *Eucalyptus* plantations, especially in new forest frontiers, such as north and central-western regions of Brazil [6]. These new frontiers

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are predominantly characterized by dystrophic soils and very distinct seasonal rainfall compared with traditional regions [11]. The climatic condition specifically for the central-western region is marked by seasonal drought stress of about 5 months by year [11].

The expansion of *Eucalyptus* plantations to new regions with drier climate conditions has therefore demanded superior drought-tolerant genotypes to compose commercial plantations [12,13]. In a wider perspective, this demand is also related to the growing concern with respect to climate change and the risk for more intense and frequent droughts all over the world [14] which is expected to affect forestry even in regions which are currently productive.

The expansion of *Eucalyptus* forests to regions with drier climates requires breeding with selection of superior and adapting genetic materials to drought, since drought stress is one of the most severe limitations on *Eucalyptus* plantation yield and poses implications on the wood quality for bioenergy.

The genetic breeding of *Eucalyptus* has focused on tree growth for a long time. However, wood quality has also been evaluated recently, especially in breeding programs for cellulose pulp and paper industries [15,16]. Growth and wood properties are considered major economic traits affecting the forest plantation yield [7]. Developing genotypes with wood quality for energy purposes has also recently been sought [17–19].

Based on the wood and yield characteristics, it is possible to estimate the wood energy yield which represents the amount of energy available per unit of area and time, expressed in  $\text{MJ ha}^{-1} \text{ year}^{-1}$ . This is the important trait used for selection of genotypes (e.g. clones) for energy purposes. However, there is not enough information on the energy yield of most *Eucalyptus* clones publicly available, especially for new forest frontiers in Brazil and other countries which are characterized by seasonal drought-stress.

Thus, a clonal test was conducted in seasonal drought-stress conditions with several *Eucalyptus* clones in this study to assess the wood energy yield. The area of the experiment is characterized as tropical with dry winter climate type (Aw), with precipitation irregularly distributed throughout the year and 5 months of water deficit. High-water stress is more typical in the Aw climate type [11,13]. Water stress in Aw is medium to high due to rainfall being unequally distributed among the seasons [12,13]. The aim was to evaluate the energy potential based on wood energy yield from a diverse set of 20 *Eucalyptus* multispecies clones. In addition, correlation and path analyses were used to indicate which wood quality and yield traits influenced energy yield the most.

We hypothesized that there are drought-adapted genotypes of

*Eucalyptus* and these will maintain high productivity and wood energy yield. We also hypothesized that the wood energy yield of the *Eucalyptus* clones is strongly related to the mean annual increment of wood volume and increment in dry matter.

## 2. Material and methods

### 2.1. Characterization of the experimental area and selection of *Eucalyptus* clones

A multispecies clonal test of *Eucalyptus* was installed in an area of 2.45 ha in the municipality of Catalão, in Goiás State in the central-western region of Brazil. This area is located at  $18^{\circ}10'05.04''$  South and  $47^{\circ}51'22.15''$  West at an average altitude of 850 m.

The experimental area presents seasonally dry tropical forest as the predominant phytophysognomy. The climate of the region is classified by Köppen as Aw - tropical with dry winter and rainy summer, with mean annual rainfall of 1485 mm and average annual temperature of  $22.2^{\circ}\text{C}$  [11,13]. The dry winter occurs from May to September (five dry months per year), with precipitation ranging from 07 mm (July) to 47 mm (September) (Fig. 1). The soil is characterized as Red-yellow latosol with a clayey texture [20].

The soil preparation started with spreading dolomitic limestone ( $\text{CaMg}(\text{CO}_3)_2$ ) in the entire area and plowing the soil for incorporation. The planting line was furrowed at 90 cm depth. The fertilization was applied in the planting furrow with a dosage of  $300 \text{ kg ha}^{-1}$  of compound fertilizer NPK 10-30-10 with  $0.5 \text{ kg ha}^{-1}$  of boron. Topdressing fertilization was carried out with  $180 \text{ kg ha}^{-1}$  of NPK 12-05-12 with  $0.5 \text{ kg ha}^{-1}$  of boron at 3, 12 and 24 months after planting. The chemical control of invasive grasses was carried out with glyphosate in the total area before planting, and between planting rows as necessary. Control of leaf-cutting ants was performed with fipronil baits. The mortality rate in the trial was only 4.41%, indicating adequate management of the forest and a resistance of the clones to de water deficit.

A total of 94 clones of pure *Eucalyptus* species and interspecific hybrids, were planted in a randomized complete block design with 29 repetitions (blocks) in single tree plots with  $3 \text{ m} \times 3 \text{ m}$  spacing, totaling 2726 trees. However, only 20 clones were analyzed in this study (see Table 1). The selection included the 10 most productive clones, and the remaining clones were selected considering their current market importance and their species constitution to sample a diversity of species.

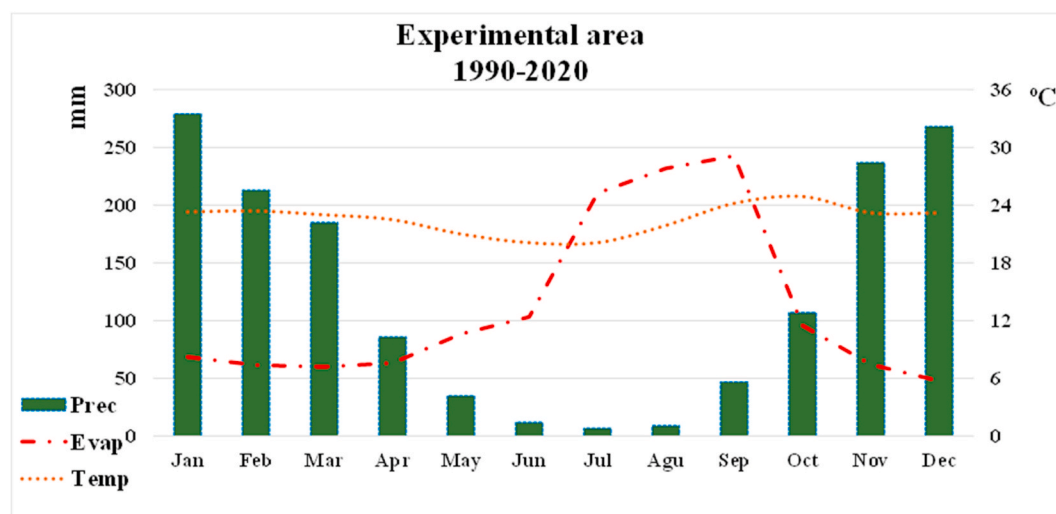


Fig. 1. Monthly average climate data from the experimental area. Source: INMET (<https://tempo.inmet.gov.br/>); Prec: rainfall (mm); Evap: evapotranspiration (mm); Temp: temperature ( $^{\circ}\text{C}$ ).

**Table 1**

Average of diameter at breast height (DBH), and total height (Ht) per *Eucalyptus* clone growing under seasonal drought-stress in Brazil.

Clone	Species and hybrids	DBH (cm)	Ht (m)
AEC144	<i>E. urophylla</i>	17.91	29.13
AEC1528	<i>E. urophylla</i> x <i>E. grandis</i>	16.09	26.78
CCL07	<i>E. urophylla</i>	17.55	28.15
CCL21	<i>E. urophylla</i> x <i>E. grandis</i>	20.79	28.95
CCL27	<i>E. grandis</i> x <i>E. urophylla</i>	18.63	29.35
CCL35	<i>E. urophylla</i> x <i>E. grandis</i>	17.68	27.53
CCL36	<i>E. urophylla</i> x <i>E. grandis</i>	19.76	29.40
CCL37	<i>E. urophylla</i> x <i>E. grandis</i>	17.03	28.23
CCL43	<i>E. pellita</i> x <i>E. grandis</i>	15.85	27.53
CCL47	<i>E. resinifera</i> x <i>E. grandis</i>	17.22	27.88
CCL56	<i>E. grandis</i> x ( <i>E. urophylla</i> x <i>E. tereticornis</i> )	18.96	28.70
CCL61	<i>E. urophylla</i> x <i>E. camaldulensis</i>	15.01	22.38
Cloeiziana	<i>E. cloeziana</i>	9.69	17.35
CLR409	<i>E. urophylla</i>	14.59	27.33
CLR417	<i>E. urophylla</i>	12.24	23.03
CLR422	<i>E. urophylla</i>	14.61	25.03
CLR427	<i>E. urophylla</i>	16.51	27.78
CLR438	<i>E. urophylla</i>	15.93	27.95
CLR454	<i>E. urophylla</i>	15.98	26.60
Toreliodora	<i>C. torelliana</i> x <i>C. citriodora</i>	9.50	16.90
<b>Means</b>		<b>16.08</b>	<b>26.23</b>
Coefficient of Variation. (%)		<b>15.06</b>	<b>21.91</b>

## 2.2. Measurement of *Eucalyptus* trees

All trees of the 20 selected clones had their total height (Ht) and diameter at breast height (DBH; measured at approximately 1.3 m) measured at six years after planting, thereby enabling to estimate the mean annual increment of wood volume without bark (MAI) (Equation

(1)).

Next, four trees from each clone (20 clones) were felled, totaling 80 trees sampled. These trees were from four systematically chosen blocks. The wood volume of these trees was also strictly measured by the Smalian method through which a taper factor was individually obtained for each clone (*ff*). With that, the MAI without bark was estimated for each clone.

$$MAI = \frac{\pi^2 DBH^2 * H * ff * N * S}{40000 * Y} \quad (1)$$

In which:

MAI: mean annual increment of wood volume (m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>).

DBH: diameter at breast height (cm).

H: total height of tree (m).

ff: taper factor.

N: number of trees by hectare (1111 trees ha<sup>-1</sup>; 3 m × 3 m spacing).

S: survival rate (%)

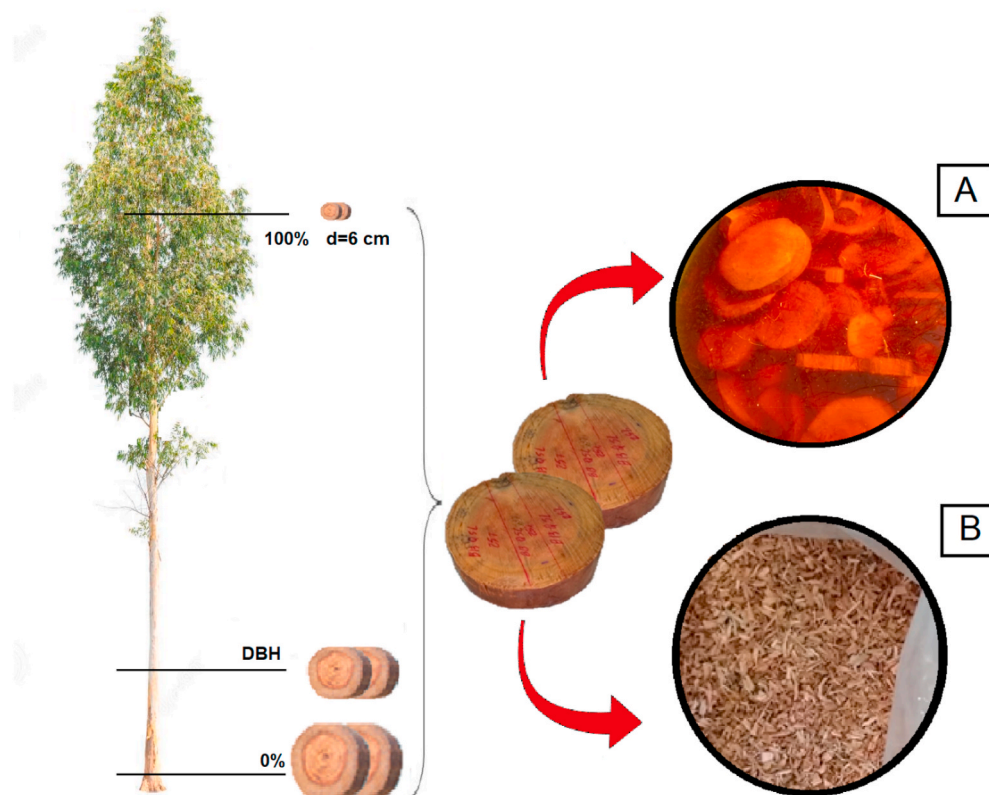
Y: age (years).

## 2.3. Wood samples preparation

First, 2.5 cm thick wood discs were obtained in duplicates from three different longitudinal positions of the trunk of the felled trees (4 trees by clone) to determine the basic density (BD) and higher heating value (HHV), totaling 480 samples. Wood discs were cut at 0%, DBH and 100% of commercial height (6 cm in diameter) (Fig. 2). Half of these wood discs were used to determine the BD and the other half for HHV.

## 2.4. Bark percentage

Next, two perpendicular straight lines were made on the wooden discs passing through the pith to determine the bark percentage. Thus, the diameter of wood discs was measured with and without bark. The



**Fig. 2.** Scheme for sampling wood discs at three longitudinal positions in the tree trunk (0%, DBH and 100%). A: samples under water to determine the wood basic density using the hydrostatic balance method; B: Crushed wood to determine the HHV using an adiabatic calorimetric pump.

bark percentage was obtained by the difference between the diameters, as performed by Silva et al. [21].

## 2.5. Wood basic density

The wood basic density without bark (BD) in  $\text{kg m}^{-3}$  was determined by the hydrostatic balance method according to NBR 11941 [22]. The entire wood discs of the three different longitudinal positions of the trees were used. The wood discs had their bark removed and were submerged in water until complete saturation for measuring their mass (Fig. 2A). Then, the wood discs were dried in an oven at  $103 \pm 2^\circ\text{C}$  until constant dry mass was reached and recorded.

Thus, the volume-weighted wood basic density from the trees was calculated with the following equation (Equation (2)), adapted from Trugilho et al. [23].

$$BD_w = \frac{BD_{w(0\%-DBH)} * V_{(0\%-DBH)} + BD_{w(DBH-100\%)} * V_{(DBH-100\%)}}{V_{(0\%-DBH)} + V_{(DBH-100\%)}} \quad (2)$$

In which:

$BD_w$ : average wood basic density of the tree ( $\text{kg m}^{-3}$ ).

$BD_{w(0\%-DBH)}$ : average basic density between base (0%) and DBH positions ( $\text{kg m}^{-3}$ ).

$BD_{w(DBH-100\%)}$ : average basic density between DBH and 100% positions ( $\text{kg m}^{-3}$ ).

$V_{(0\%-DBH)}$ : wood volume between base (0%) and DBH positions ( $\text{m}^3$ ).

$V_{(DBH-100\%)}$ : wood volume between DBH and 100% positions ( $\text{m}^3$ ).

## 2.6. Heating value and energy density

The wood discs without bark were crushed (Fig. 2B) and ground to determine the higher heating value (HHV) in  $\text{MJ kg}^{-1}$  using an IKA WORKS C-200 adiabatic calorimetric pump, following ASTM D5865-13 [24]. The lower heating value (LHV) was calculated using the hydrogen content (H) of 6% as a reference (Equation (3)). H refers to the hydrogen content released in water vapor that is lost in the combustion process [24]. Energy density (ED) was also obtained from the LHV and BD, in  $\text{MJ m}^{-3}$  (Equation (4)):

$$LHV = HHV - \left[ 600 \cdot \left( \frac{9H}{100} \right) \right] \quad (3)$$

In which:

LHV: lower heating value ( $\text{MJ kg}^{-1}$ ).

HHV: higher heating value ( $\text{MJ kg}^{-1}$ ).

H: hydrogen content of 6% as a reference.

$$ED = LHV \times BD \quad (4)$$

In which:

ED: energy density ( $\text{MJ m}^{-3}$ ).

LHV: lower heating value ( $\text{MJ kg}^{-1}$ ).

BD: basic density ( $\text{kg m}^{-3}$ ).

## 2.7. Dry matter and wood energy yield

The increment in dry matter (DM), which is the wood biomass per unit of area and time, was calculated in  $\text{Mg ha}^{-1} \text{ year}^{-1}$  (Equation (5)). Only wood was considered for use as energy. Leaves, branches, and bark are usually left in the forest for nutrient cycling. Wood energy yield (EY) was estimated and represents the amount of wood energy available per unit of area and time, expressed in  $\text{MJ ha}^{-1} \text{ year}^{-1}$  (Equation (6)).

$$DM = \frac{MAI \times BD}{1000} \quad (5)$$

In which:

DM: dry matter ( $\text{Mg ha}^{-1} \text{ year}^{-1}$ ).

MAI: mean annual increment of wood volume ( $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ).

BD: wood basic density ( $\text{kg m}^{-3}$ )

$$EY = DM \times LHV \quad (6)$$

In which:

EY: wood energy yield ( $\text{MJ ha}^{-1} \text{ year}^{-1}$ ).

DM: dry matter ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ).

LHV: lower heating value ( $\text{MJ kg}^{-1}$ ).

## 2.8. Statistical analysis

Data outliers, normality and distribution were evaluated for each parameter. The effect of clones in each evaluated trait was analyzed separately using a model of Analysis of variance (ANOVA), with a 5% p-value threshold (Equation (7)):

$$x_{ijk} = \mu + \alpha_j + \beta_k + e_{ijk} \quad (7)$$

In which:  $x$  is the data vector;  $\mu$  is the mean of the traits;  $j$  is the vector of genotypic effects;  $k$  is the vector of the repetition effects, and  $e$  the vector of errors or residuals; all of these effects were assumed to be random.  $\alpha$  and  $\beta$  represent the incidence matrices for these effects.

The Scott-Knott test was performed to compare the clonal averages at 5% significance. In addition, Pearson's correlation and Path analyses were performed to assess the relationship among energetic wood properties and yield traits of *Eucalyptus* clones.

The path analyses can decompose the associations into direct and indirect effects of each trait in the main, as well as dependent variables. In our case, the main variable was the energy yield, which was dependent on all the other variables: mean annual increment without bark (MAI); wood basic density (BD); higher heating value (HHV); lower heating value (LHV); increment of dry matter (DM); and energy density (ED).

The R software program [25] was used to perform the statistical analysis using the *ggplot2* [26] and *ggcorrplot* [27] packages to generate correlation plots, and *ScottKnott* [28] to compare the averages of the clones. The *lavaan* [29] package was used for performing the path analysis.

## 3. Results and discussion

The analysis of variances (ANOVA) showed that the effect of clones was significant at a level of 5% probability for all the evaluated traits (Table 2). This significant variation is due to genetic differences among

**Table 2**

Analysis of variance (ANOVA) for the evaluated traits in the 20 selected *Eucalyptus* clones growing under seasonal drought-stress in Brazil.

Evaluated traits	Source of variation	Df	SS	F Ratio	p-value
MAI	Blocks	3	1699	2.5360	0.0657 <sup>ns</sup>
	Clones	19	40,072.0	9,4431	$1.8 \times 10^{-11}$ *
BD	Blocks	3	870.3	0.7193	0.5446 <sup>ns</sup>
	Clones	19	23,951.8	3,1256	0.0004 *
Bark (%)	Blocks	3	146.35	0.9123	0.6426 <sup>ns</sup>
	Clones	19	3645.82	1,5600	0.0002 *
HHV	Blocks	3	0.0085	2,2897	0.0880 <sup>ns</sup>
	Clones	19	3.3480	142,51	$2.0 \times 10^{-16}$ *
ED	Blocks	3	285,172	0,7051	0.5529 <sup>ns</sup>
	Clones	19	$1.02 \times 10^7$	3,9894	$2.6 \times 10^{-5}$ *
DM	Blocks	3	3.0000	0.5711	0.6363 <sup>ns</sup>
	Clones	19	9169,5	272.58	$2.0 \times 10^{-16}$ *
EY	Blocks	3	$1.14 \times 10^9$	0.5590	0.6443 <sup>ns</sup>
	Clones	19	$3.52 \times 10^{12}$	273.21	$2.0 \times 10^{-16}$ *

Df: Degrees of freedom; SS: Sum of Squares; F Ratio: F Test Value; <sup>ns</sup> and \*: not significant and significant at 5% probability, respectively. MAI: mean annual increment without bark in  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ; BD: wood basic density in  $\text{kg m}^{-3}$ ; Bark (%): Bark percentage; HHV: higher heating value in  $\text{MJ kg}^{-1}$ ; DM: increment of dry matter in  $\text{Mg ha}^{-1} \text{ year}^{-1}$ ; ED: energy density in  $\text{MJ m}^{-3}$ ; EY: wood energy yield in  $\text{MJ ha}^{-1} \text{ year}^{-1}$ .



clones. The 20 clones were grouped according to the averages for all evaluated growth and wood traits with Scott-Knott tests at 5% probability (Table 3).

### 3.1. Wood yield estimates

*Eucalyptus* wood yield is an important factor, as the greater the quantity of wood produced, the greater the biomass production which is a raw material for energy purposes [6].

The wood yield (MAI) was statistically higher for CCL36, CCL21, CCL27, CCL56 and AEC144 clones with values above  $75 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  at six years of age. The lowest MAI values were observed for Cloeziana and Toreliodora clones, below  $13.5 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ . The different yield observed among clones in our study can be attributed to genetic differences, including the variation among species that constitute the clones (Table 1).

As we hypothesized, there are drought-tolerant genotypes of *Eucalyptus* in our experiment. The region of the experimental area is characterized by the Aw climate subtype (tropical humid with dry winter), which has lower water availability [12,13]. High-water stress is more typical in the Aw climate type [10,13]. Water stress in Aw is medium to high due to rainfall being unequally distributed among the seasons [13].

The mean annual precipitation in the Aw climate type can vary between 700 and 2000  $\text{mm y}^{-1}$ , irregularly distributed throughout the year with 4–5 months of water deficit, along with high mean annual temperatures between 24 and 26 °C [11,13], which confers high evapotranspiration to these regions (Fig. 1).

Water stress is one of the commonly reported factors in the literature as being responsible for the reduction in the productivity of *Eucalyptus* forest plantations [12], with a decrease in the growth rate and biomass accumulation [30,31]. Despite this, some *Eucalyptus* species, and hybrids and clones are able to develop adaptation mechanisms to drought situations [32,33] or even have greater water use capacity when available [34], presenting great growth recovery ability.

In the contexts of expanding *Eucalyptus* forests to regions with drier climates in Brazil and other countries and considering the risk for more intense and frequent droughts all over the world caused by climate changes, tree resilience to water stress is crucial for the sustainability of forest plantations.

**Table 3**

Average for the traits evaluated in the 20 *Eucalyptus* clones growing under seasonal drought-stress in Brazil and submitted to grouping by the Scott-Knott test at 5% probability.

Clones	MAI	Bark (%)	BD	HHV	LHV	DM	ED	EY
AEC144	75.68 a	4.59 c	535.24 b	19.52 e	18.24 e	40.51 a	9762.8 b	738,847.0 a
AEC1528	59.32 b	5.19 b	508.09 b	19.71 c	18.41 c	30.14 b	9353.9 b	554,875.5 b
CCL07	66.91 b	4.23 c	507.61 b	19.71 c	18.41 c	33.96 b	9345.1 b	625,280.6 b
CCL21	90.78 a	4.32 c	544.97 a	19.74 c	18.43 c	49.47 a	10,043.8 a	911,775.9 a
CCL27	80.06 a	5.05 b	528.99 b	19.48 f	18.19 f	42.35 a	9622.3 b	770,363.6 a
CCL35	71.54 b	4.40 c	527.75 b	19.33 g	18.05 g	37.76 b	9525.9 b	681,482.0 b
CCL36	94.99 a	5.61 b	562.18 a	19.71 c	18.40 c	53.40 a	10,344.1 a	982,587.2 a
CCL37	65.63 b	5.60 b	548.08 a	19.39 g	18.11 g	35.97 b	9925.7 b	651,425.6 b
CCL43	58.74 b	5.09 b	546.16 a	19.33 g	18.05 g	32.08 b	9858.2 b	579,070.0 b
CCL47	66.43 b	5.80 a	549.20 a	19.89 b	18.57 b	36.48 b	10,198.6 a	677,495.9 b
CCL56	77.75 a	5.12 b	562.95 a	19.99 a	18.67 a	43.77 a	10,510.3 a	817,174.0 a
CCL61	33.59 c	6.43 a	538.56 b	19.96 a	18.63 a	18.09 c	10,033.4 a	337,021.0 c
Cloeziana	13.15 d	6.98 a	561.06 a	19.76 c	18.46 c	7.38 d	10,357.2 a	136,196.7 d
CLR409	46.79 c	5.14 b	534.61 b	19.63 d	18.34 d	25.01 c	9804.7 b	458,764.1 c
CLR417	28.27 c	4.75 c	536.83 b	19.35 g	18.07 g	15.18 c	9700.5 b	274,233.6 d
CLR422	46.95 c	5.54 b	533.94 b	19.27 h	18.00 h	25.07 c	9610.9 b	451,233.6 c
CLR427	63.19 b	3.95 c	525.09 b	19.61 d	18.31 d	33.18 b	9614.4 b	607,533.8 b
CLR438	61.15 b	4.74 c	525.72 b	19.55 e	18.26 e	32.15 b	9599.6 b	587,018.4 b
CLR454	54.69 b	3.98 c	515.16 b	19.73 c	18.42 c	28.17 b	9489.2 b	518,966.9 b
Toreliodora	11.03 d	7.91 a	570.04 a	19.63 d	18.33 d	6.29 d	10,448.8 a	115,250.6 d
Mean	58.33	5.22	538.11	19.61	18.32	31.32	9857.5	573,829.8
CV (%)	39.37	25.94	3.30	1.07	1.82	39.65	3.68	39.82

MAI: mean annual increment without bark in  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ; Bark (%): Bark percentage; BD: wood basic density in  $\text{kg m}^{-3}$ ; HHV: higher heating value in  $\text{MJ kg}^{-1}$ ; LHV: lower heating value in  $\text{MJ kg}^{-1}$ ; DM: increment of dry matter in  $\text{Mg ha}^{-1} \text{ year}^{-1}$ ; ED: energy density in  $\text{MJ m}^{-3}$ ; EY: wood energy yield in  $\text{MJ ha}^{-1} \text{ year}^{-1}$ . CV (%) Coefficient of Variation in percentage.

All five most productive clones contain *E. urophylla* in their genetic composition. *E. urophylla* is highly adapted to the climatic conditions of the experimental area with seasonal drought-stress [35]. Within this group of more productive clones, three are interspecific hybrids of *E. urophylla* × *E. grandis* or its reciprocal, *E. grandis* × *E. urophylla* (Table 1). There is also a triple hybrid, *E. grandis* × (*E. urophylla* × *E. tereticornis*), and a spontaneous hybrid of *E. urophylla* (Table 1). Interspecific hybrids between the two species have great potential for heterosis exploitation and genetic gain for growth in forestry plantations [7].

The high adaptive capacity of *E. urophylla* in almost all regions of Brazil associated with the high yield of *E. grandis* [35,36] makes the *E. urophylla* × *E. grandis* hybrid clone important in Brazilian clonal forestry [17], as well as in Africa in regions where the Aw climate predominates [37]. Thus, most Brazilian plantations are constituted by several hybrid clones of *E. urophylla* × *E. grandis* and pure *E. urophylla* [17,35].

The CCL56 clone was created by a cross between *E. grandis* and a *E. urophylla* × *E. tereticornis* hybrid, thus the heterosis between genotypes may explain its great performance. *E. urophylla* × *E. tereticornis* hybrid clones present rapid growth, high yield and wood resistance [38].

The use of the AEC144 clone in the experiment is of great value because it is the most planted clone in various parts in Brazil, including in the edaphoclimatic conditions of the Cerrado biome [39] where the experiment was installed. Thus, its use validates the discovery of more productive clones such as CCL36, CCL21, CCL27 and CCL56 for the region, as reported by Oliveira et al. [39].

The low yield of Cloeziana (*E. cloeziana*) and Toreliodora (*C. torelliana* × *C. citriodora*) indicate a low adaptation of these clones. Despite the low yield found in this study, *E. cloeziana* is suitable for planting in regions with Aw climate [35]. This fact can be explained by the wide genetic variability observed in *E. cloeziana* due to its natural distribution in different edaphoclimatic conditions resulting in provenances with different capacities to adaptation [35,36,39]. Thus, this provenance for the evaluated clone did not adapt well to the edaphoclimatic conditions of the experimental area, but there may be other genotypes of this species which are more promising for these conditions [40].

The yield of *C. citriodora* can vary between 9 and  $51 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ,

depending on the provenance [39]. On the other hand, *C. torelliana* x *C. citriodora* hybrids can produce  $40 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  in regions where they were selected [39]. The *C. citriodora* and *C. torelliana* species can be recommended for the Cerrado biome, as they are tolerant to prolonged periods of drought [35,36].

However, the sampled *C. torelliana* x *C. citriodora* clone showed low yield in this study, possibly because it was not specifically selected in the Cerrado biome. Another justification for the low yield is the slow initial growth of *Corymbia* spp [39]. As a result, *Corymbia* trees do not develop well when in competition for resources with *Eucalyptus* spp., such as in this clonal trial. Just as the single tree plot experiments overestimate the yield of the best performing clones, they also underestimate the yield of clones with lower growth rate [41,42].

Our results are promising because the national average for mean annual increment in *Eucalyptus* forests is  $36 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  [43]. However, it is important to note that single-tree plot designs tend to overestimate the growth of the most productive trees compared to monoclonal plantations [41,42]. This is because the most productive clones in single-tree plots are always competing with inferior clones (allocompetition) compared to the auto competition of monoclonal plantations [42]. Even though the values are overestimated, the results can be used to compare among them. Other studies with *Eucalyptus* clones in different regions of Brazil also obtained high yields ranging from  $53$  to  $79.0 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  [44,45].

Clones with higher MAI tend to generate more biomass and are therefore recommended for commercial plantations. However, it is also important to evaluate the wood quality traits such as basic density and higher heating value (see below) to determine the yield of the final product (i.e. wood energy) in each clone.

### 3.2. Bark content

The bark content of the evaluated clones ranged between 3.95 and 7.91% (Table 3). In another study, the bark content of *Eucalyptus* trunks ranged from 2 to 10%, depending on the species, age of the tree, their metabolism and edaphoclimatic characteristics [46].

A high proportion of bark is prejudicial for energy purposes due to its high ash content. Ashes do not participate in the wood combustion [47], as it is mainly constituted of minerals which have a high concentration in the bark [48,49], thus resulting in waste in the boiler and requiring more frequent cleaning [47]. The negative and significant correlation ( $r = -0.44$ ) between the bark content and wood energy yield (EY) found in this study reinforces this information (Fig. 3).

In addition, severe depositions when ash is formed on the heat exchange surfaces of steam generators can generate slag which leads to malfunction and reduced efficiency of heat transfer. In the long run, ash can also cause corrosion in the metal elements of the burners, as it is abrasive [50]. Thus, lower bark content is better for wood-based energy production.

In our results, the CLR454 and CLR427 clones stand out as having lower than 4% of bark in their trunk (Table 3). In addition to these clones, the most productive genotypes and other clones consisting of *E. urophylla* had the lowest bark rate (%) (Table 3). Wu et al. [51] found high genetic variability for the percentage of bark in *E. urophylla* clones which presented an average of 14.7% of bark, ranging between 1.1% and 28.1%. Unproductive clones (CCL61, Cloeziana and Toreliodora) had the highest bark rate (%) (Table 3). This is due to the negative and significant correlation ( $r = -0.48$ ) between the bark content (%) and the MAI (Fig. 3).

### 3.3. Wood basic density

Wood basic density is one of the most important variables for choosing clones for applying wood as a solid biofuel [18] and it is widely used as an indicator of wood quality and in breeding programs [19]. The Toreliodora, CCL56, CCL36 and Cloeziana clones have the highest basic

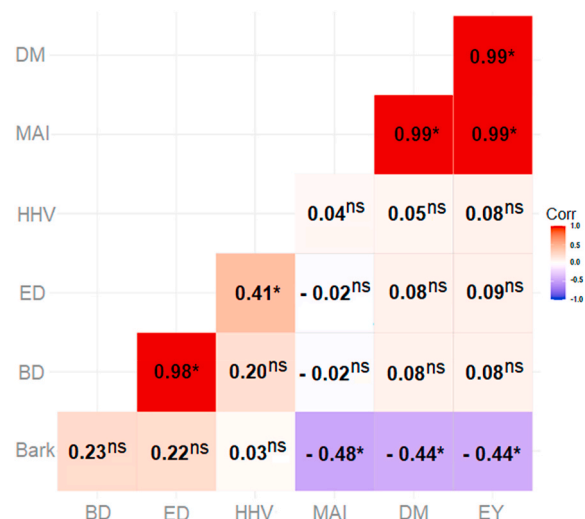


Fig. 3. Correlations between the wood yield and energy traits evaluated in 20 *Eucalyptus* and *Corymbia* clones growing under seasonal drought-stress in Brazil. MAI: mean annual increment without bark in  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ; BD: wood basic density in  $\text{kg m}^{-3}$ ; HHV: higher heating value in  $\text{MJ kg}^{-1}$ ; DM: increment of dry matter in  $\text{Mg ha}^{-1} \text{ year}^{-1}$ ; ED: energy density in  $\text{MJ m}^{-3}$ ; EY: wood energy yield in  $\text{MJ ha}^{-1} \text{ year}^{-1}$ . <sup>ns</sup> and \*: not significant and significant at 5% probability, respectively.

densities with values above  $560.0 \text{ kg m}^{-3}$ . On the other hand, CCL07 and AEC1528 clones presented the lowest basic density values with approximately  $508.0 \text{ kg m}^{-3}$  (Table 3).

The *C. citriodora*, *C. torelliana* and *E. cloeziana* species generally have high wood basic density [35,52], which explains the high value observed in the *C. torelliana* x *C. citriodora*, and the Cloeziana clones. These species normally present a lower growth rate (as verified in our study). The negative relationship between growth rate and wood basic density is corroborated in the literature [53]: the lower the tree trunk volume growth, the greater the wood basic density [19,53].

A high variability in wood density was observed among *E. urophylla* x *E. grandis* hybrids, as they included the clone with highest (CCL36) and lowest averages (CCL07 and AEC1528) for this trait. This is corroborated by Wu et al. [51] and Castro et al. [54] who found high genetic variability for wood density in *E. urophylla* and *E. grandis* clones, respectively. High wood density is reported for species of *E. tereticornis* [55], and this characteristic was transmitted to the CCL56 clone.

Basic density is a wood attribute with high genetic heritability [56]. In the work of Nabais et al. [57], it was found that eight of the 25 species studied indicated that the wood density is genetically determined. Therefore, genetic differences in wood density can be identified among clones, hybrids or *Eucalyptus* species. In addition to genetic variation, wood basic density can also change according to the growth rate of trees, edaphoclimatic conditions, age, etc. [16].

### 3.4. Dry matter

The dry matter (DM) increment is a product of MAI with wood basic density and varied between  $6.29$  and  $53.40 \text{ Mg ha}^{-1} \text{ year}^{-1}$  (Table 3). The higher values observed in our study are due to the higher values observed for MAI and wood basic density, which reflect an excellent site quality and the genetic potential of the clones for wood use as bioenergy.

The clones with the highest increment in dry matter were interspecific hybrids of *E. urophylla* x *E. grandis*, CCL36 and CCL21, with a DM greater than  $49.0 \text{ Mg ha}^{-1} \text{ year}^{-1}$  (Table 3). Cloeziana and Toreliodora clones had the lowest DM with  $7.38$  and  $6.29 \text{ Mg ha}^{-1} \text{ year}^{-1}$ , respectively (Table 3). As expected, the wood dry matter values were largely influenced by MAI with a strong and positive correlation ( $r = 0.99$ ) (Fig. 3). Thus, more productive clones showed a greater increase in dry

matter. On the other hand, the wood basic density was not correlated with dry matter (Fig. 2). For example, *Cloeziaria* and *Toreliodora* clones which have the highest densities had the lowest DM values due to their low yield.

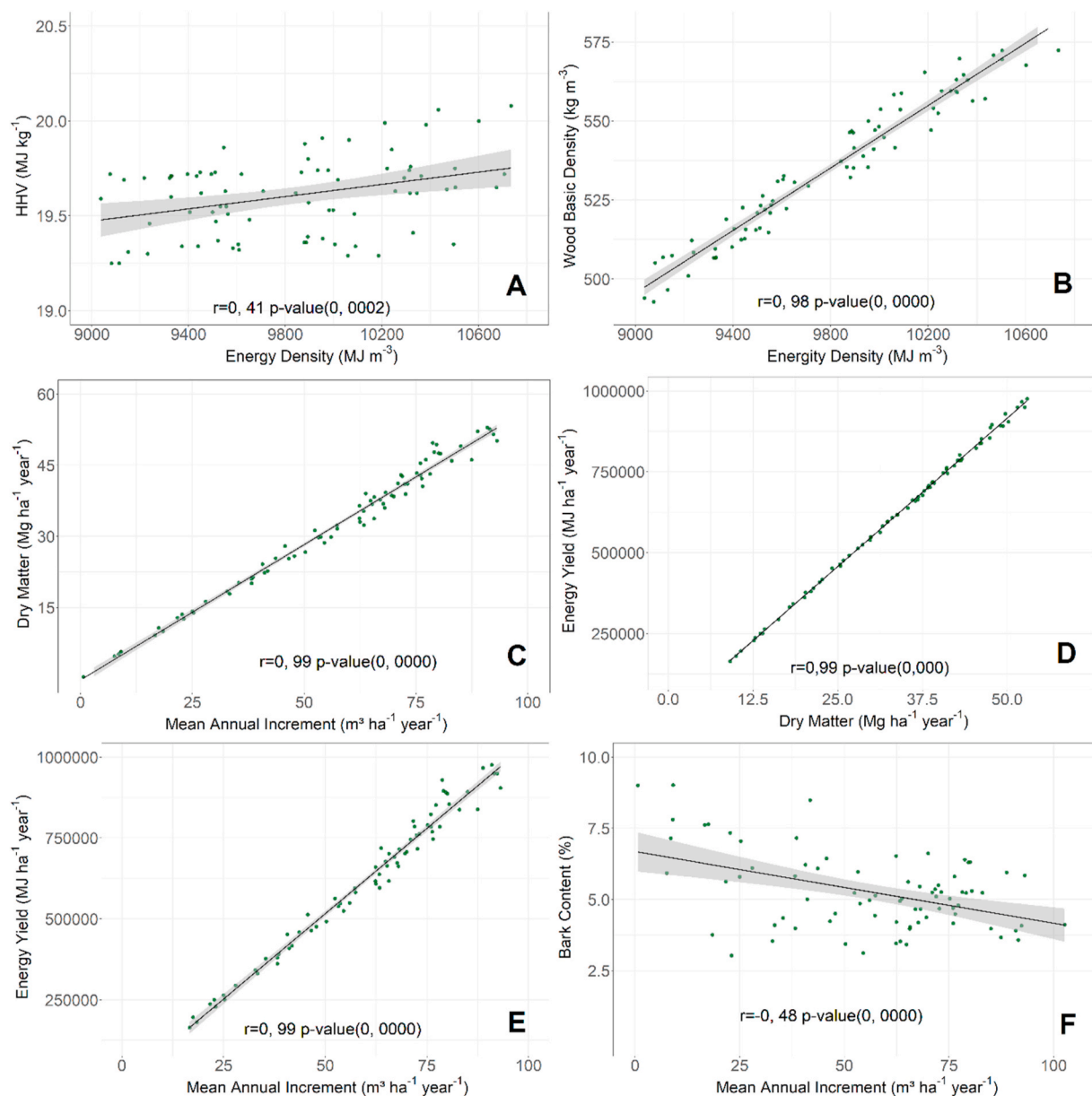
### 3.5. Wood energy yield

The higher (HHV) and lower (LHV) heating values presented averages of 19.61 and 18.32 MJ kg<sup>-1</sup>, respectively (Table 3). Similar heating values were found by Ignácio et al. [58] and Cunha et al. [6] with *Eucalyptus* species. Due to the chemical composition of wood, the HHV can vary between species and individuals [7]. For example, CCL56 and CCL61 clones have the highest HHV values with averages above 19.96 MJ kg<sup>-1</sup>, while the CLR422 clone has the lowest average, 19.27 MJ kg<sup>-1</sup>. Clones from the same species have a wide variation of heating value [6,58], reinforcing the influence of provenances and individuals on the magnitude of these values.

Regarding the amount of energy generated per cubic meter of wood (energy density), it can be observed that the most promising clones are CCL56, *Toreliodora*, *Cloeziaria*, CCL36, CCL47, CCL21 and CCL61 with averages above 10,030.0 MJ m<sup>-3</sup>. On the other hand, CCL07 and AEC1528 clones have the lowest values of energy density with less than 9350.00 MJ m<sup>-3</sup>. Energy density is a product of the LHV and the wood basic density, which explains the positive correlations between these parameters (Fig. 3).

Wood energy yield (EY) is obtained by the product between dry matter increment (DM) and lower heating value (LHV). This can be considered the important parameter for selecting clones for energy purposes, as it indicates the wood energy yield per unit of area and time. The AEC144, CCL27, CCL56, CCL21, and CCL36 clones showed the best averages for this trait, ranging from 738,847 to 982,587 MJ ha<sup>-1</sup> year<sup>-1</sup>, respectively.

On the other hand, *Cloeziaria* and *Toreliodora* clones have the lowest averages for this variable with 155,830 and 133,724 MJ ha<sup>-1</sup> year<sup>-1</sup>,



**Fig. 4.** Graphical representation of the main correlations observed in this experiment. A) BD x ED B) HHV x ED; C) DM x MAI; D) EY x MAI; E) EY x DM; F) Bark x MAI. MAI: mean annual increment without bark in m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>; BD: wood basic density in kg m<sup>-3</sup>; HHV: higher heating value in MJ kg<sup>-1</sup>; DM: increment of dry matter in Mg ha<sup>-1</sup> year<sup>-1</sup>; ED: energy density in MJ m<sup>-3</sup>; EY: wood energy yield in MJ ha<sup>-1</sup> year<sup>-1</sup>.



respectively. These lower energy efficiencies are due to their low yield.

### 3.6. Correlation and path analysis between evaluated traits

Some wood and yield traits were significantly correlated (Figs. 3 and 4), as observed by Silva et al. [19]. The energy density (ED) has a statistically positive correlation (Fig. 3) with the HHV ( $r = 0.41$ ) and with BD ( $r = 0.98$ ). This was expected as HHV and BD are used in the energy density calculation. Note that wood basic density has the greatest correlation (Figs. 3 and 4) and direct effect on energy density, as observed in the path analysis (Fig. 5).

The relationship between mean annual increment without bark (MAI) and increment of dry matter (DM) was also strong and positive ( $r = 0.99$ ). Therefore, as expected given the relationship in equation (4), the higher the wood yield, the greater the biomass productivity (Fig. 4C). Path analyses show that MAI has a direct effect on DM, while DB does not have a significant effect (Fig. 5).

One interesting result was observed for the energy density. Contrary to our expectation, ED was not correlated with wood energy yield (Fig. 3). This is confirmed by the results of the path analysis, which does not show a direct effect of ED on EY (Fig. 5). This is counter intuitive, as wood with higher ED should result in higher EY per hectare. This result shows the power of path analysis (Fig. 5) and indicate that this lack of correlation is because ED is influenced by BD and HHV, which are not significantly associated with MAI (Fig. 3). In addition, the wood property traits such as BD, HHV and ED are less variable compared to the wood yield (MAI). Coefficient of variation for the wood property traits range from 1.07 to 3.68%, while MAI and DM have  $CV \cong 39\%$  (Table 3). Thus, most of the variation in wood energy yield is directly affected by the larger variation in wood yield (MAI) (Fig. 5).

As previously mentioned, the wood energy yield (EY) is a product of

dry matter increment and calorific value. However, only the relationship with DM was significant, indicating that the HHV and LHV has little influence on the amount of energy available, since its amplitude was very reduced among the clones (Table 3). Thus, the positive correlation between EY and DM is almost perfect ( $r = 0.99$ ), indicating that as the DM increases, there will be a proportional increase in EY (Fig. 4).

## 4. Conclusions

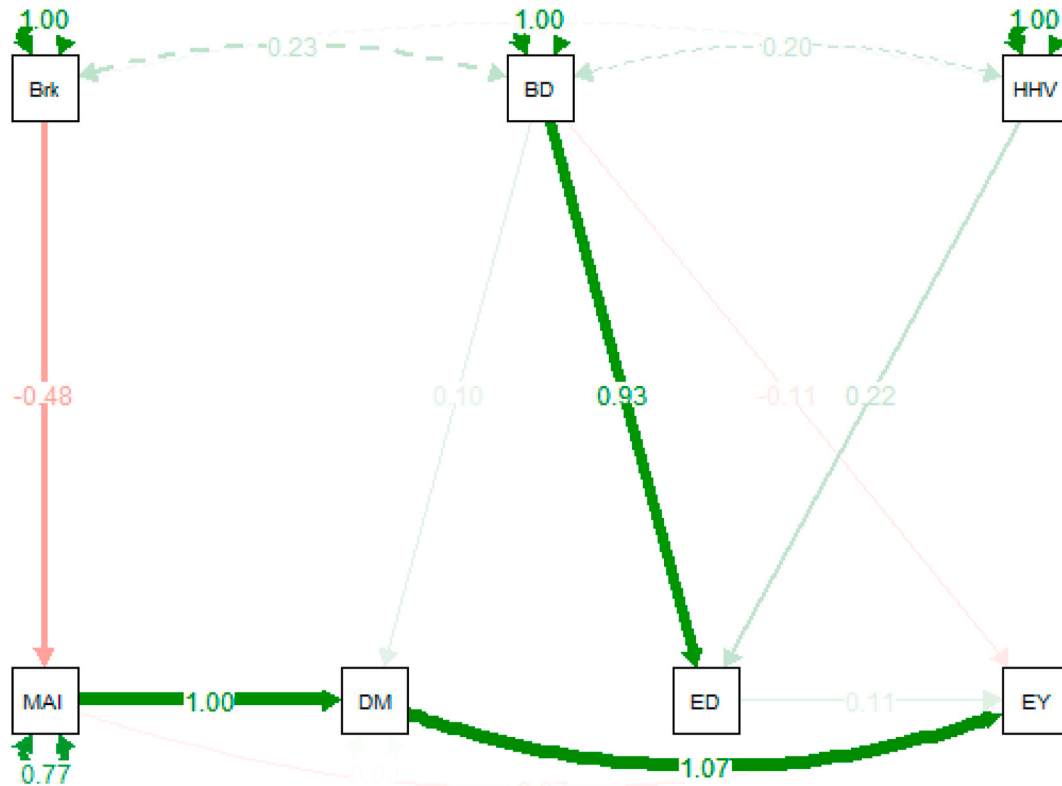
The prior selection of *Eucalyptus* genotypes with high wood energy yield and adapted to drought represents the basis for expanding commercial plantations for energy purposes in regions with seasonal drought-stress.

Our results indicate that there are *Eucalyptus* genotypes adapted to seasonal drought-stress and with high wood yield. The CCL36 (*E. urophylla* x *E. grandis*) clone has the greatest energy potential as it has the largest wood energy yield ( $982,587.0 \text{ MJ ha}^{-1} \text{ year}^{-1}$ ) and is the most productive with  $94.99 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  of wood. Other promising clones are CCL21 (*E. urophylla* x *E. grandis*) and CCL56 (*E. grandis* x (*E. urophylla* x *E. tereticornis*)) with wood energy yields greater than  $815,000.0 \text{ MJ ha}^{-1} \text{ year}^{-1}$ , demonstrating that there are alternative clones to AEC144 (*E. urophylla*), which is the most planted for bioenergy use in the Aw climate type regions in Brazil.

The best clones for energy purposes have *E. urophylla* in their genetic background, confirming their capacity for good growth and adaptation in tropical regions under seasonal drought-stress.

The wood energy yield of *Eucalyptus* clones is strongly related to the mean annual increment and the increment in dry matter. However, wood traits such as basic density and heating value had little influence on wood energy yield.

This study can be used as an indication for selecting *Eucalyptus* clones



**Fig. 5.** Path analysis between wood and yield traits. MAI: mean annual increment without bark in  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ; BD: wood basic density in  $\text{kg m}^{-3}$ ; HHV: higher heating value in  $\text{MJ kg}^{-1}$ ; DM: increment of dry matter in  $\text{Mg ha}^{-1} \text{ year}^{-1}$ ; ED: energy density in  $\text{MJ m}^{-3}$ ; EY: wood energy yield in  $\text{MJ ha}^{-1} \text{ year}^{-1}$ . Between traits: (a) Green arrows show direct and positive effect; (b). Red arrows show direct and negative effect; (c) Dotted arrows show indirect effect. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for regions with similar climatic conditions under seasonal drought-stress.

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## 5. CONCLUSÕES

O melhoramento genético do eucalipto ao longo destes 50 anos resultou em um aumento de 165% na produtividade florestal e na seleção de clones resistentes a muitas doenças e tolerantes a estresses abióticos. Além do melhoramento genético, os avanços nas técnicas de plantio e na produção de mudas contribuíram para esse surpreendente aumento da produtividade florestal.

O tempo é o fator crucial para o melhoramento florestal e a possibilidade da seleção de clones antes da idade de rotação é crucial para o desenvolvimento de novos clones. Assim, testou-se a eficiência da seleção precoce, obtendo-se uma correlação de 61% dos melhores clones aos dois anos e a idade de colheita para produtividade de madeira. Aos quatro anos de idade essa eficiência sobe para 68%, evidenciando a possibilidade de seleção precoce. Porém, esses números deixam claro que haverá sim erros quando a seleção é feita de forma precoce.

Foram obtidas altas produtividades em todos os ambientes avaliados (Catalão-GO, Corumbá-de-Goiás-GO e Luziânia-GO). Isso contribuiu para identificar novos clones com bom desempenho nessas localidades, evidenciando a necessidade de observar genótipos comerciais em áreas sujeitas a déficit hídrico, selecionar clones adaptados a essas situações.

Os clones mais produtivos e com melhor desempenho energético apresentam *E. urophylla* em sua constituição confirmando a alta adaptação desta espécie para regiões com clima Aw, típicos de áreas da nova fronteira florestal sujeitas a estresse hídrico sazonal. Diferentes clones de *E. urophylla* adequados favorecem o aumento da diversidade intraespecífica e as possibilidades de recomendação para diferentes usos da madeira, além da energia avaliada nesse trabalho.

A seleção de clones de eucalipto com alta produtividade energética da madeira em regiões susceptíveis à seca representa a base para a expansão de plantações comerciais para fins energéticos em regiões com estresse hídrico sazonal.

O rendimento energético da madeira de clones de eucalipto está fortemente relacionado ao incremento médio anual e ao incremento de matéria seca. Características da madeira como densidade básica e poder calorífico tiveram pouca influência no rendimento energético da madeira nesse estudo.

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## APÊNDICES

### ANEXO A

**Tabela A** – Médias de fatores de forma para os diferentes clones e métodos de cubagem para o volume comercial.

<b>Clones</b>	<b>Huber</b>	<b>Heyer</b>	<b>Newton</b>	<b>Smalian</b>	<b>Médias</b>
CCL27	0,4992 a	0,4899 a	0,5674 a	0,4931 a	0,5124
CCL07	0,5699 a	0,5874 a	0,6481 a	0,5896 a	0,5988
AEC 144	0,4891 a	0,5281 a	0,5400 a	0,5279 a	0,5213
AEC 1528	0,5575 a	0,5297 a	0,6217 a	0,5549 a	0,5660
CLR 409	0,5276 a	0,5173 a	0,5941 a	0,5223 a	0,5403
CLR 417	0,5129 a	0,5437 a	0,5671 a	0,5423 a	0,5415
CLR 422	0,5371 a	0,5019 a	0,5611a	0,4983 a	0,5246
CLR 427	0,5544 a	0,5454 a	0,5908 a	0,5469 a	0,5594
CLR 438	0,5552 a	0,5321 a	0,6249 a	0,5412 a	0,5633
CLR 454	0,4886 a	0,5155 a	0,5625 a	0,5205 a	0,5218
CCL35	0,5181 a	0,5448 a	0,5944 a	0,5457 a	0,5507
CCL36	0,4995 a	0,5126 a	0,5784 a	0,5232 a	0,5285
CCL37	0,5364 a	0,5228 a	0,5782 a	0,5239 a	0,5403
CCL43	0,5206 a	0,5217 a	0,5580 a	0,5347 a	0,5339
CLOEZIANA	0,6573 a	0,6219 a	0,7145 a	0,6475 a	0,6603
CCL47	0,5351 a	0,5522 a	0,6060 a	0,5652 a	0,5646
CCL21	0,4247 a	0,4532 a	0,5179 a	0,4560 a	0,4630
CCL56	0,4725 a	0,4839 a	0,5457 a	0,4843 a	0,4966
TORELIODORA	0,5345 a	0,5484 a	0,6485 a	0,5740 a	0,5764
CCL61	0,4552 a	0,4723 a	0,5282 a	0,4732 a	0,4822
<b>Média</b>	<b>0,5223</b>	<b>0,5263</b>	<b>0,5874</b>	<b>0,5332</b>	<b>0,5423</b>
<b>CV (%)</b>	<b>9,27%</b>	<b>7,23%</b>	<b>8,01%</b>	<b>8,07%</b>	<b>7,85%</b>

Médias seguidas pelas mesmas letras não diferem estatisticamente pelo Teste de Skott-Knott ao nível de 5% de probabilidade.

**Tabela B** – Médias de fatores de forma para os diferentes clones e métodos de cubagem para o volume total.

<b>Clones</b>	<b>Huber</b>	<b>Heyer</b>	<b>Newton</b>	<b>Smalian</b>	<b>Médias</b>
CCL07	0,4154 a	0,4466 a	0,4494 b	0,4494 b	0,4402
AEC 144	0,4147 a	0,4406 b	0,4422 b	0,4422 b	0,4349
AEC 1528	0,4530 a	0,4679 a	0,4678 a	0,4678 a	0,4641
CCL27	0,4734 a	0,4748 a	0,4970 a	0,4970 a	0,4855
CLR 409	0,4429 a	0,4611 a	0,4655 a	0,4655 a	0,4588
CLR 417	0,4738 a	0,4664 a	0,4652 a	0,4652 a	0,4677
CLR 422	0,4758 a	0,4850 a	0,4814 a	0,4814 a	0,4809
CLR 427	0,4712 a	0,4752 a	0,4765 a	0,4765 a	0,4749
CLR 438	0,4577 a	0,4822 a	0,4904 a	0,4904 a	0,4802
CLR 454	0,4259 a	0,4555 a	0,4598 a	0,4598 a	0,4502
CCL35	0,4874 a	0,4888 a	0,4896 a	0,4896 a	0,4888
CCL36	0,4350 a	0,4602 a	0,4695 a	0,4695 a	0,4585
CCL37	0,4430 a	0,4624 a	0,4633 a	0,4633 a	0,4580
CCL43	0,4171 a	0,4688 a	0,4807 a	0,4807 a	0,4618
CLOEZIANA	0,3455 b	0,4202 b	0,4303 b	0,4303 b	0,4066
CCL47	0,3937 b	0,4476 a	0,4590 a	0,4590 a	0,4398
CCL21	0,3426 b	0,4125 b	0,4150 b	0,4150 b	0,3963
CC56	0,4016 b	0,4384 b	0,4387 b	0,4387 b	0,4294
TORELIODORA	0,3595 b	0,4270 b	0,4456 b	0,4456 b	0,4194
CCL61	0,3211 b	0,3887 b	0,3894 b	0,3894 b	0,3721
<b>Média</b>	<b>0,4225</b>	<b>0,4535</b>	<b>0,4588</b>	<b>0,4588</b>	<b>0,4484</b>
<b>CV (%)</b>	<b>11,62%</b>	<b>5,76%</b>	<b>5,81%</b>	<b>5,81%</b>	<b>7,25%</b>

Médias seguidas pelas mesmas letras não diferem estatisticamente pelo Teste de Skott-Knott ao nível de 5% de probabilidade.



## ANEXO B

**Tabela C** – Médias de produtividade de madeira (m<sup>3</sup>.ha<sup>-1</sup>) dos diferentes clones testados em Catalão-GO aos dois (2014), quatro (2016) e seis (2018) anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CCL21	106.74	341.31	498.45
AEC144	102.69	317.50	457.61
CCL07	113.18	325.68	451.94
CCL27	105.56	319.77	432.18
CCL36	101.66	328.92	426.13
CCL28	104.85	289.08	423.06
CCL56	76.31	249.78	419.79
CCL29	89.09	267.07	413.21
CCL30	93.82	288.69	411.91
CCL35	92.78	303.61	406.90
CCL04	85.09	287.25	405.06
CCL37	79.37	248.24	387.39
CCL51	95.00	291.17	385.61
CCL49	104.35	247.90	384.04
CCL11	87.19	259.81	363.99
CCL47	103.60	299.09	358.60
GG100	96.16	285.13	358.22
CCL63	96.35	272.24	357.97
AEC042	91.12	244.77	357.65
CCL41	89.43	252.14	355.33
CCL14	102.77	275.93	353.49
CCL43	95.26	268.35	348.17
CCL15	96.67	294.01	345.61
CLR438	83.15	244.79	338.89
CCL20	69.41	216.68	335.28
CCL32	72.49	247.96	330.40
CLR454	79.17	235.16	324.39
CLR427	76.64	230.81	318.68
CCL05	84.75	244.54	318.47
CCL45	82.61	227.05	310.35
CCL40	71.94	211.79	302.59
CLR458	67.90	199.97	301.87
CCL17	85.06	232.37	301.23
CCL50	97.17	271.23	300.63
CCL19	69.96	214.45	300.36
CCL46	75.26	216.96	298.94
CCL02	73.74	203.32	296.11
CCL38	71.91	204.34	294.76

**Continuação da Tabela C** – Médias de produtividade de madeira ( $\text{m}^3.\text{ha}^{-1}$ ) dos diferentes clones testados em Catalão-GO aos dois, quatro e seis anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CCL10	71.13	215.26	291.90
CLR409	85.80	248.13	287.60
CLR422	75.02	192.10	286.20
CCL01	64.14	186.90	272.44
CCL61	86.76	212.16	272.34
CCL26	74.46	199.86	270.06
CCL03	77.71	208.13	267.62
CCL48	72.89	198.89	259.26
CLR423	65.89	184.02	255.80
CCL58	72.67	201.14	253.33
CLR408	81.96	201.59	251.18
CCL60	82.15	220.83	249.92
CLR424	80.99	195.35	248.06
CLR405	83.33	204.42	245.87
CCL18	60.22	183.33	243.81
CCL06	64.44	184.89	240.17
CCL13	73.48	186.62	237.67
CCL24	59.67	182.17	236.38
CLR404	58.55	166.47	225.88
CCL59	86.48	201.49	225.64
CLR416	71.17	177.38	225.39
CLR433	49.89	163.20	221.27
CCL62	69.20	171.17	212.55
Toreliodora	39.44	77.90	211.80
CLR428	55.50	175.28	203.14
CLR455	55.37	146.50	201.81
CLR413	62.63	149.39	201.19
CLR418	62.03	156.57	198.53
CLR412	62.15	153.35	196.31
CCL55	62.99	169.52	192.45
CLR411	61.16	170.07	192.17
CCL39	62.26	145.97	180.70
CLR435	51.06	138.69	172.74
CLR421	50.31	128.20	171.02
CLR407	58.46	149.17	169.33
CCL34	53.92	129.87	166.60
CCL22	49.69	130.75	160.74
CLR417	45.21	107.42	159.00
CLR406	50.17	113.12	154.45
CLR429	42.33	110.28	150.91

**Continuação da Tabela C** – Médias de produtividade de madeira (m<sup>3</sup>.ha<sup>-1</sup>) dos diferentes clones testados em Catalão-GO aos dois, quatro e seis anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CCL31	59.77	114.57	150.88
CLR415	54.36	134.51	150.47
CLR440	52.49	131.12	144.12
CLR414	56.92	122.51	142.85
CLR425	52.14	113.78	142.62
CLR431	50.80	112.00	138.30
CCL23	44.53	108.88	119.09
CCL52	36.59	82.49	103.40
CLOEZIANA	29.35	73.08	102.23
CCL53	39.58	94.82	102.22
CLR410	35.97	75.35	101.70
CLR426	32.05	74.48	97.58
CCL57	36.79	88.42	97.56
CLR401	42.44	97.56	83.58
CCL54	30.30	55.12	68.24
CITRIODORA	20.28	47.80	45.93
<b>Médias</b>	<b>70.61</b>	<b>194.92</b>	<b>259.89</b>

**Tabela D** – Médias de produtividade de madeira ( $\text{m}^3.\text{ha}^{-1}$ ) dos diferentes clones testados em Luziânia-GO aos dois (2014), quatro (2016) e seis (2018) anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CCL30	125.83	283.87	473.87
CCL21	132.58	310.89	466.87
AEC144	123.82	290.73	443.42
CCL29	101.17	242.40	404.10
CLR454	110.89	263.80	401.80
CCL60	74.44	224.72	401.36
CCL45	104.31	233.29	385.55
CLR422	97.28	229.09	381.60
AEC042	110.78	241.69	377.09
CCL27	122.10	272.28	376.80
CCL11	114.95	258.23	376.54
CCL35	121.50	264.26	372.76
CCL36	107.31	240.20	370.44
CCL41	113.27	228.59	363.45
CCL06	83.95	198.82	357.82
CCL38	102.32	233.14	356.77
CCL07	129.08	269.93	345.73
CCL08	84.18	201.84	344.30
CCL16	97.21	215.46	342.29
GG100	109.98	231.67	330.97
CCL56	97.84	216.37	329.82
CCL49	87.40	309.27	325.92
CCL51	53.01	190.72	322.58
CCL61	109.16	228.45	320.75
CCL28	107.76	221.15	316.40
CLR404	77.83	175.81	312.10
CCL25	86.85	195.26	310.43
CCL13	98.92	198.91	310.39
CCL10	81.21	196.89	309.95
CCL43	116.08	235.34	306.56
CCL14	107.44	209.04	301.94
CCL46	53.14	167.48	299.50
CLR409	102.56	218.69	297.64
CCL32	78.85	192.88	295.86
CCL20	85.01	189.86	294.67
CCL63	91.46	200.58	293.80
CCL03	84.22	191.29	291.14
CCL59	52.07	171.89	289.56
CCL48	48.17	176.99	289.09
CCL26	77.69	179.72	288.53

**Continuação da Tabela D** – Médias de produtividade de madeira (m<sup>3</sup>.ha<sup>-1</sup>) dos diferentes clones testados em Luziânia-GO aos dois, quatro e seis anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CCL47	56.44	189.28	284.61
CCL15	95.27	201.36	281.70
CLR438	86.57	197.48	281.65
CCL37	84.72	187.03	277.46
CLR427	82.99	184.15	277.22
CLR424	106.30	180.93	275.74
CLR426	71.01	161.63	275.70
CCL01	76.97	169.78	269.04
CLR458	72.18	159.14	261.71
CCL50	43.64	156.95	258.48
CCL40	79.51	175.62	258.00
CCL62	101.86	201.31	257.34
CLR433	67.83	160.76	254.81
CCL19	74.27	176.78	252.22
CLR428	81.71	171.74	251.95
CCL02	86.21	178.96	249.56
CCL58	74.58	171.14	246.02
CLR423	72.32	166.76	244.61
CLR455	75.26	141.60	239.29
CCL12	87.91	178.12	233.90
CCL06	74.56	166.07	229.79
CCL33	99.63	191.29	227.55
CLR405	82.04	161.60	211.43
CLR418	65.90	133.64	207.08
CLR408	76.38	156.24	202.66
CCL18	68.93	147.76	202.43
CCL39	95.61	159.11	197.11
CLR431	71.27	147.55	195.71
CLR421	71.56	139.03	186.93
CLR414	60.91	124.41	176.58
CLR415	63.36	139.55	174.86
CLR413	73.51	141.13	168.33
CCL34	62.52	120.72	166.34
CLR440	56.62	124.86	164.49
CLR412	67.02	124.42	164.47
CLR417	61.47	134.04	162.71
CLR425	58.24	110.12	159.49
CCL09	65.49	120.52	158.20
CCL31	71.85	115.76	146.82
CLR406	58.16	123.06	141.87

<b>Continuação da Tabela D – Médias de produtividade de madeira (m³.ha⁻¹) dos diferentes clones testados em Luziânia-GO aos dois, quatro e seis anos de idade.</b>			
<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CCL55	60.07	117.42	139.72
CCL22	56.22	100.98	134.12
CLR401	63.26	126.58	126.36
CCL53	45.18	88.63	117.57
CLOEZIANA	33.76	77.68	117.15
CCL23	50.99	89.16	112.80
CLR435	45.10	96.50	110.41
CCL54	47.32	86.33	107.78
CCL52	39.05	82.06	104.71
CLR410	45.29	80.72	95.24
CCL57	37.15	75.59	82.33
Toreliodora	20.95	43.80	80.94
CITRIODORA	26.96	47.74	68.47
<b>Médias</b>	<b>79.76</b>	<b>176.41</b>	<b>258.64</b>

**Tabela E** – Médias de produtividade de madeira ( $\text{m}^3.\text{ha}^{-1}$ ) dos diferentes clones testados em Corumbá-de-Goiás-GO aos dois (2014), quatro (2016) e seis (2018) anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CLR454	67.05	248.39	484.95
CCL29	57.87	196.74	475.68
CCL35	70.64	239.56	466.38
CCL49	126.84	209.76	429.88
CCL59	114.30	274.93	395.26
CCL20	61.31	140.76	389.18
GG100	66.79	196.35	380.51
CCL43	59.85	200.26	375.45
CCL07	59.30	192.40	366.59
CCL45	56.72	192.70	365.15
AEC042	58.50	227.62	362.09
CCL27	68.27	207.90	361.30
CCL51	113.52	251.36	361.05
CCL36	52.00	181.58	359.25
CLR409	60.46	203.06	356.31
CCL37	47.74	183.67	354.56
CCL47	116.27	253.62	346.89
CCL41	61.53	183.94	329.99
CCL28	64.27	186.20	319.88
CCL50	53.61	182.73	319.05
CCL46	94.99	210.85	314.52
CCL62	63.56	199.00	312.59
CCL11	53.10	166.61	311.06
CCL02	46.91	172.13	303.31
CLR438	45.02	171.82	295.79
CLR404	44.34	169.36	290.64
CCL14	54.36	161.83	288.57
CCL61	58.37	170.75	287.80
CCL26	33.78	175.05	283.75
CLR403	47.61	176.72	278.25
CCL60	105.97	208.77	275.65
CLR455	48.03	167.31	275.57
CCL38	48.93	159.02	273.26
CCL03	34.14	143.69	272.72
CLR433	34.36	158.43	272.34
CCL10	46.04	161.41	272.27
CCL40	35.15	149.57	270.29
CLR422	36.61	141.16	269.67
CCL39	52.91	183.65	267.57
CCL13	47.50	136.78	265.70

**Continuação da Tabela E** – Médias de produtividade de madeira ( $\text{m}^3.\text{ha}^{-1}$ ) dos diferentes clones testados em Corumbá-de-Goiás-GO aos dois, quatro e seis anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CCL32	33.72	116.88	264.95
CLR444	37.08	135.25	263.86
CCL48	76.88	171.97	263.66
CLR418	42.37	146.35	261.86
CCL30	48.30	143.99	260.37
CCL15	46.52	155.39	257.23
AEC144	50.60	150.15	256.44
CLR427	40.04	143.71	255.24
CLR405	55.50	149.36	254.39
CCL06	36.05	147.94	252.90
CLR408	45.12	146.94	249.67
CCL18	41.59	138.16	245.64
CLR426	40.19	133.58	245.58
CLR432	37.15	140.00	242.75
CLR424	43.27	140.73	238.25
CLR431	39.59	141.81	235.14
CLR428	45.81	128.52	230.26
CCL19	33.12	129.90	229.45
CLR423	51.79	136.95	226.97
CLR413	48.39	147.02	225.11
CCL34	34.09	133.66	223.90
CLR458	39.92	130.08	222.67
CCL31	36.67	79.16	221.73
CLR414	38.88	141.60	219.26
CLR440	36.78	134.08	217.66
CLR421	32.22	121.22	217.35
CCL55	31.20	97.32	214.14
CCL01	32.34	109.47	209.42
CLR400	38.14	145.80	204.57
CLR412	38.02	108.06	197.97
CLR402	36.67	116.19	195.34
CLR425	41.63	130.13	190.28
CLR417	41.16	123.99	188.72
CCL22	37.19	86.87	187.70
CCL63	37.75	114.35	187.57
CLR410	35.56	113.95	182.64
CLR435	34.92	121.25	176.09
CLR292	25.15	100.97	168.34
CCL21	29.54	229.42	162.02



**Continuação da Tabela E** – Médias de produtividade de madeira (m<sup>3</sup>.ha<sup>-1</sup>) dos diferentes clones testados em Corumbá-de-Goiás-GO aos dois, quatro e seis anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CLR406	32.17	104.45	158.54
CLR401	24.47	81.66	139.47
CLR434	25.47	99.18	137.62
CCL56	27.36	105.00	131.14
CCL23	31.49	120.10	124.43
CCL58	29.12	132.48	123.14
CLOEZIANA	21.91	87.75	120.90
CLR441	27.29	70.91	118.83
CCL54	25.37	89.54	106.79
CCL52	24.42	88.60	105.23
CCL53	22.79	99.63	104.12
CCL57	14.49	89.72	101.35
Toreliodora	24.02	51.67	90.87
CITRIODORA	9.60	49.96	43.47
<b>Médias</b>	<b>47.09</b>	<b>150.43</b>	<b>254.13</b>

**Tabela F** – Médias de produtividade de madeira ( $\text{m}^3.\text{ha}^{-1}$ ) dos diferentes clones testados para o conjunto de locais (Catalão-GO, Luziânia-GO e Corumbá-de-Goiás-GO), aos dois (2014), quatro (2016) e seis (2018) anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CCL29	82.71	235.40	431.00
CCL35	94.97	269.15	415.35
CLR454	85.71	249.11	403.71
CCL27	98.64	266.65	390.09
CCL07	100.52	262.67	388.09
AEC144	92.37	252.79	385.82
CCL36	86.99	250.23	385.27
CCL30	89.32	238.85	382.05
CCL49	106.20	255.64	379.95
CCL21	89.62	293.88	375.78
CCL04	75.27	247.43	373.56
AEC042	86.80	238.03	365.61
GG100	90.98	237.72	356.57
CCL51	87.18	244.42	356.42
CCL45	81.21	217.68	353.68
CCL28	92.30	232.14	353.11
CCL11	85.08	228.21	350.53
CCL41	88.08	221.56	349.59
CCL43	90.40	234.65	343.39
CCL37	70.61	206.31	339.80
CCL20	71.91	182.43	339.71
CCL06	68.72	192.23	338.25
CCL47	92.10	247.33	330.03
CCL08	68.87	194.63	327.41
CCL16	77.45	205.47	325.80
CCL14	88.19	215.60	314.67
CLR409	82.94	223.29	313.85
CLR422	69.64	187.45	312.49
CCL60	87.52	218.10	308.98
CCL38	74.39	198.83	308.27
CLR438	71.58	204.70	305.44
CCL46	74.46	198.43	304.32
CCL05	75.04	213.43	304.14
CCL59	84.29	216.10	303.49
CCL25	70.63	189.39	300.25
CCL32	61.69	185.91	297.07
CCL15	79.49	216.92	294.84
CCL61	84.77	203.79	293.63
CCL56	67.17	190.38	293.58

**Continuação da Tabela F** – Médias de produtividade de madeira (m<sup>3</sup>.ha<sup>-1</sup>) dos diferentes clones testados para o conjunto de locais (Catalão-GO, Luziânia-GO e Corumbá-de-Goiás-GO), aos dois, quatro e seis anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CCL50	64.81	203.64	292.72
CCL10	66.13	191.19	291.37
CCL17	75.25	203.73	290.31
CLR427	66.56	186.22	283.71
CCL02	68.95	184.80	282.99
CCL26	61.97	184.87	280.78
CCL63	75.19	195.72	279.78
CCL03	65.36	181.04	277.16
CCL40	62.20	178.99	276.96
CLR404	60.24	170.55	276.21
CLR403	65.84	193.87	275.02
CCL13	73.30	174.10	271.25
CCL48	65.98	182.62	270.67
CLR444	58.90	160.86	263.49
CLR458	60.00	163.06	262.08
CCL62	78.21	190.49	260.83
CCL19	59.12	173.71	260.68
CLR424	76.85	172.34	254.01
CCL01	57.82	155.38	250.30
CLR433	50.69	160.80	249.47
CLR432	58.95	164.64	246.56
CLR423	63.34	162.58	242.46
CCL06	58.35	166.30	240.95
CCL12	71.32	175.75	238.90
CLR455	59.55	151.80	238.89
CCL24	58.52	163.77	238.33
CLR405	73.62	171.79	237.23
CLR408	67.82	168.26	234.50
CCL33	79.05	186.23	233.81
CCL18	56.91	156.42	230.63
CLR416	66.10	159.96	229.52
CLR428	61.01	158.51	228.45
CLR418	56.77	145.52	222.49
CLR400	59.61	169.26	215.96
CCL39	70.26	162.91	215.13
CLR402	58.63	145.68	208.55
CCL58	58.79	168.25	207.50
CLR426	47.75	123.23	206.29
CLR411	59.50	154.14	202.88

**Continuação da Tabela F** – Médias de produtividade de madeira ( $\text{m}^3.\text{ha}^{-1}$ ) dos diferentes clones testados para o conjunto de locais (Catalão-GO, Luziânia-GO e Corumbá-de-Goiás-GO), aos dois, quatro e seis anos de idade.

<b>Clones</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
CLR413	61.51	145.84	198.21
CLR421	51.36	129.48	191.77
CLR431	53.88	133.79	189.71
CLR292	51.05	133.57	186.91
CLR412	55.73	128.61	186.25
CCL34	50.18	128.08	185.61
CLR407	57.72	137.50	184.57
CCL55	51.42	128.09	182.10
CLR414	52.24	129.51	179.56
CCL09	56.56	129.89	178.21
CLR440	48.63	130.02	175.42
CCL31	56.10	103.17	173.14
CLR417	49.28	121.82	170.15
CLR429	47.10	106.54	169.81
CLR415	51.49	128.64	167.37
CLR425	50.67	118.01	164.13
CLR434	51.26	132.14	162.29
CCL22	47.70	106.20	160.85
CLR435	43.69	118.82	153.08
CLR406	46.83	113.54	151.62
CLR441	52.45	109.64	147.22
Toreliodora	28.14	57.79	127.87
CLR410	38.94	90.00	126.53
CCL23	42.34	106.05	118.77
CLR401	43.39	101.93	116.47
CLOEZIANA	28.34	79.50	113.43
CCL53	35.85	94.36	107.97
CCL52	33.35	84.38	104.44
CCL54	34.33	76.99	94.27
CCL57	29.48	84.58	93.75
CITRIODORA	18.95	48.50	52.62
<b>Médias</b>	<b>65.55</b>	<b>173.09</b>	<b>255.77</b>