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WILLYAM DE LIMA VIEIRA

PROPRIEDADES FÍSICAS E MECÂNICAS, CARACTERÍSTICAS ANATÔMICAS E CONSTITUINTES QUÍMICOS DA MADEIRA DE *Corymbia citriodora* (HOOK.) K. D. HILL & L. A. S. JOHNSON EM TRÊS TIPOS DE SOLO

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Orientador: Prof. Dr. Eduardo Luiz Longui

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À minha amada esposa,

Luciana,

dedico

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“Good Science, is fun Science”.

Dr. Gustavo Maia Souza

RESUMO

A espécie *Corymbia citriodora*, anteriormente classificada como *Eucalyptus citriodora*, de origem da Austrália, é cultivada em todo o mundo. No Brasil, seus plantios foram iniciados com vistas à adaptação fisiológica, crescimento e utilização da madeira para produção de carvão vegetal. No decorrer do tempo, os plantios foram ampliados no intuito de produção de madeira para serraria, energia e exploração de folhas para extração de óleo essencial. Nosso objetivo foi esclarecer como as diferenças físicas, químicas e de retenção de água entre os três tipos de solo: Neosolo Quartzarênico (RQ), Latossolo Vermelho (LV) e Nitossolo Vermelho (NV) podem ocasionar alterações no crescimento das árvores, nas propriedades físicas, mecânicas, características anatômicas, nos constituintes químicos, poder calorífico e índices de qualidade para papel e celulose na madeira de *Corymbia citriodora*. Foram selecionadas árvores com 33 anos, da Estação Experimental de Luiz Antônio, do Instituto Florestal, no município de Luiz Antônio, com base nas maiores alturas e diâmetros das árvores de 18 progênies para cada tipo de solo, totalizando 54 árvores. De acordo com os nossos resultados os três tipos de solo apresentaram diferenças na granulometria, composição química e capacidade de retenção de água. O NV foi o solo com maior fertilidade e disponibilidade de água. Os valores de diâmetro, volume de árvore e porcentagem de cerne foram mais altos nos solos LV e NV que apresentaram maior disponibilidade de água e argila. Somente a densidade básica apresentou diferença, com menor valor para NV. Houve um aumento gradativo nas características anatômicas no sentido medula-casca, com exceção para diâmetro do lume, e frequência de vasos e raios. Entre os solos, o NV apresentou os maiores valores para as características de fibra, diâmetro do vaso e altura do raio. A composição química não apresentou um padrão entre os tipos de solos, o teor de extrativos totais foi maior no solo NV, o teor de lignina foi maior no LV e teor de holocelulose foi maior no RQ. A Os maiores valores do poder calorífero e índice de seguiram o mesmo padrão da densidade em RQ e LV. Nos índices indicativos de qualidade para produção de celulose e papel, a madeira de C. citriodora apresenta valores muito altos para todos os índices, desta forma para produção de papel acarretaria uma folha de alta densidade e rigidez, o que não é adequado para o uso geral de papel para escrita. Concluímos que os diferentes tipos de solos influenciaram na qualidade e produtividade da madeira de *C. citriodora.*

Palavras-chave: Densidade da madeira. Índice de uniformidade. Qualidade da madeira. Retenção de água. Textura do solo.

ABSTRACT

The species *Corymbia citriodora*, previously classified as *Eucalyptus citriodora*, of Australian origin is cultivated worldwide. In Brazil, its planting was started with a view to physiological adaptation, growth and use of wood for charcoal production. Over time, the plantations were expanded in order to produce lumber, energy and exploitation of leaves to extract essential oil. Our objective was to clarify how physical, chemical and water retention differences between the three types of soil: Quartzarenic Neosol (RQ), Red Latosol (LV) and Red Nitosol (NV) can cause changes in the growth of the trees, in the physical properties , mechanical, anatomical characteristics, in chemical constituents, calorific value and quality indexes for paper and pulp in *Corymbia citriodora* wood. Thirty-three-year-old trees were selected from the Luiz Antônio Experimental Station, from the Forestry Institute, in the municipality of Luiz Antônio, based on the highest and diameters of 18 progenies for each type of soil, totaling 54 trees. According to our results, the three types of soil showed differences in granulometry, chemical composition and water retention capacity. NV was the soil with the highest fertility and water availability. The values of diameter, tree volume and heartwood percentage were higher in the LV and NV soils that showed greater availability of water and clay. Only the basic density showed a difference, with a lower value for NV. There was a gradual increase in anatomical characteristics in the pith-bark direction, except for the fiber lumen diameter, and the frequency of vessels and rays. Among the soils, the NV presented the highest values for fiber characteristics, vessel diameter and radius height. The chemical composition did not show a pattern between the types of soils, the content of total extracts was higher in the NV soil, the lignin content was higher in the LV and the holocellulose content was higher in the RQ. A The highest values of calorific value and index followed the same pattern of density in RQ and LV. In the indicative quality indexes for pulp and paper production, *C. citriodora* wood has very high values for all indexes, so for paper production it would result in a sheet of high density and rigidity, which is not suitable for use. general writing paper. We conclude that the different types of soils influenced the quality and productivity of *C. citriodora* wood.

Keywords: Wood density. Uniformity index. Wood quality. Water holding capacity. Soil texture.

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INTRODUÇÃO GERAL

Independente do sistema de plantio, para que a madeira seja usada de forma otimizada é necessário atestar a sua qualidade, que é definida como o grau de excelência em relação à aplicação destinada, não existindo, portanto, uma medida exata. Contudo, é possível estabelecer alguns parâmetros que indiquem a qualidade da madeira e o seu uso mais apropriado (SAVIDGE, 2003).

Por meio de testes de progênies e procedências é possível avaliar a capacidade de adaptação de determinadas espécies em um novo ambiente. Essa adaptação depende da variabilidade genética existente entre e dentro das procedências, da origem das sementes, e de informações dos locais de plantio, como suas características geográficas, climáticas e atributos do solo (MCKAY et al. 2005). Como exemplos de estudos de adaptação de espécies, podemos citar os desenvolvidos com os gêneros *Eucalyptus* e *Corymbia*, cujas espécies são plantadas há décadas no Brasil, o gênero *Eucalyptus* utilizado especialmente para a produção de papel e celulose, e o gênero *Corymbia* utilizado para produção de energia e madeira em serrarias.

No Brasil os plantios de eucalipto ocupam uma área de 5,7 milhões de hectares e nos últimos anos apresentaram um aumento médio anual de 2,4% , sob uma ampla distribuição geográfica, e as maiores áreas de plantios estão localizadas nos estados de Minas Gerais (24%), São Paulo (17%) e Mato Grosso do Sul (15%) (IBÁ, 2017). As áreas de plantio de espécies de crescimento rápido no país encontram-se, na sua maioria, em solos da classe Latossolos. Estes solos geralmente são profundos e com textura variável, possuem de média a boa capacidade de armazenamento de água, porém são pobres do ponto de vista nutricional, com carência de fósforo e cátions, especialmente (GONÇALVES et al., 1997).

De maneira geral, a produtividade dos plantios de *Eucalyptus* e a qualidade da madeira estão relacionadas as propriedades físicas do solo (PEREIRA et al., 2019), ao grau de acidez (HONG; GANA; CHEN, 2019), à disponibilidade de água (BORDRON et al., 2019; PLOYET et al., 2019), e a disponibilidade de nutrientes (CASTRO et al., 2020).

Em diversos estudos em escala regional no Brasil, a presença de um gradiente estrutural do solo, em termos da textura (mais argilosos a arenosos), como também da disponibilidade de nutrientes e hídrica foram observadas diferenças nas interações fenotípicas inter e intra específicas em diferentes genótipos de *Eucalyptus* (RYAN et al., 2010; GONÇALVES et al., 2013; ATTIA et al., 2019). Desta forma, é importante compreender a seleção e análise de características funcionais de árvores, tais como, propriedades físicas e mecânicas, constituintes químicos, e propriedade energéticas da madeira, interessantes na produção de madeira que são afetadas por diferentes condições ambientais no contexto das práticas florestais (ARNAUD et al., 2019).

Neste sentido, conhecer as condições dos locais de plantio para ter clareza de como elas podem influenciar na produtividade e qualidade da madeira, sendo que os atributos do solo são um dos fatores chave nesse conhecimento (GONÇALVES et al., 1997; SILVEIRA et al., 2001).

A espécie *Corymbia citriodora* é de origem Australiana e cultivada em todo o mundo. No Brasil, seus plantios foram iniciados com vistas à adaptação fisiológica, crescimento e utilização da madeira para produção de carvão vegetal. No decorrer do tempo, os objetivos dos plantios foram ampliados no intuito de produção de madeira para serraria, energia e exploração de folhas para extração de óleo essencial (VITTI; BRITO, 1999).

Nosso objetivo é esclarecer como as diferenças físicas, químicas e de retenção de água de três tipos de solos: Neosolo Quartzarênico, Latossolo Vermelho e Nitossolo Vermelho podem ocasionar alterações no crescimento das árvores, nas propriedades físicas, mecânicas, características anatômicas, nos constituintes químicos, poder calorífico e índices de qualidade para papel e celulose na madeira de *Corymbia citriodora*. Hipotetizamos que as árvores que cresceram em solos mais arenosos e com menor teor de nutrientes apresentaram um crescimento mais lento, devido às restrições hídricas e nutricionais, e possuem madeira mais densa, com maior proporção de parede celular e menor diâmetro dos lúmens das células, e consequentemente, com maiores valores nas propriedades mecânicas e constituintes químicos quando comparadas com aquelas árvores que cresceram em solos mais argilosos e ricos nutricionalmente. Tais diferenças devem ocasionar variações que interfiram na qualidade da madeira e seus usos potenciais como madeira serrada, material para bioenergia e matéria prima para papel e celulose.

REVISÃO DA LITERATURA

Corymbia citriodora

Corymbia recentemente foi classificado como um gênero separado de *Eucalyptus*, *Corymbia* incluindo 113 espécies, a maioria em zonas endêmicas, tropicais, áridas e semi-áridas do norte da Austrália (BUTLER et al., 2017). *Corymbia citriodora* é uma espécie arbórea de médio a grande porte, cujas árvores ocasionalmente as árvores podem atingir 50 m de altura e 1,2 m de DAP (diâmetro a altura do peito). Na Austrália a espécie é tolerante a uma variedade de solos, porém é comumente encontrada em solos pobres e pedregosos, podzóis e podsols residuais de origem laterítica, e prefere subsolos bem drenados, mas um tanto pedregosos (ORWA et al., 2009).

No Brasil a espécie *C. citriodora* é utilizada para reflorestamento na região central do país, norte do Paraná, São Paulo, Minas Gerais e no litoral da Região Nordeste. A ampla distribuição da espécie é explicada devido à sua boa adaptação a regiões com diferentes condições edafoclimáticas, bom incremento volumétrico de madeira e capacidade de brotação após o corte (REIS et al., 2013). Em São Paulo, a espécie apresenta susceptibilidade às geadas, boa resistência à deficiência hídrica, e em solos pobres pode haver alta incidência de bifurcações ligadas a deficiências nutricionais, principalmente boro (SOUZA et al., 2020).

A importância econômica de *C. citriodora* no Brasil está mais ligada a produção de madeira para energia e serraria, além da extração de óleos essenciais das folhas (REIS et al., 2013). Os óleos são encontrados em glândulas nas folhas e possuem um grande interesse econômico, uma vez que compõem o preparo de óleos medicinais, industriais e produtos para perfumaria (VITTI; BRITO, 2003). A madeira de *C. citriodora* tornou-se mais difundida e apreciada para aplicações na indústria e movelaria devido às suas qualidades, mas também à escassez de madeira certificada (VILAS BÔAS; MAX; MELO, 2009). O interesse no uso da madeira de *C. citriodora* é explicado pela durabilidade e por ser pouco suscetível à quebra (CUNHA et al. 2019). Porém, a espécie ainda não possui prioridade de cultivo no setor de grandes empresas florestais no Brasil (VIEIRA et al., 2004), sendo cultivada por pequenos e médios proprietários rurais para diversos usos. Segundo Cunha et al. (2019) sugerem que o menor uso e estudos de *C. citriodora* comparando com espécies de *Eucalyptus*, que geralmente são cultivadas em ciclos curtos para celulose, carvão, construção civil, etc., é devido à *C. citriodora* não possuir extensas plantações e ter um ciclo longo de produção.

De acordo com Zenid et al. (2009) a madeira de *C. citriodora* apresenta boa resistência física, elevada densidade básica, alta durabilidade e elevado grau de rendimento na serraria, além de apresentar boas características de aplainamento, lixamento, furação e acabamento (FERREIRA, 2003), sua madeira é muito utilizada para construções, estruturas, caixotaria, postes, dormentes, mourões, lenha, e também é utilizada para produção industrial de chapas de madeira aglomerada (IWAKIRI et al., 2000) e como carvão vegetal com grande destaque na economia brasileira, com maior demanda no setor siderúrgico. De acordo com Geromel et al. (2011), *C. citriodora* com 5 anos de idade pode atingir 231,36 ton/ha de madeira e o que corresponde a cerca de 71,58 ton/ha de carvão.

Como visto, *C. citriodora* possui uma madeira de boa qualidade para diversos usos. Entretanto, requer uso de técnicas apropriadas de desdobro e secagem para minimizar os efeitos das tensões de crescimento, que são decorrente do próprio processo de crescimento da madeira, no qual as novas células produzidas pelo câmbio encontram uma certa resistência de expansão oferecida pelas células já diferenciadas, gerando assim forças de tração entre as células. Esse processo ao longo do tempo produz as tensões de crescimento, distribuídas ao longo de todo o tronco, mas que são liberadas quando as árvores são cortadas e produzem rachaduras e distorções nas peças de madeira (HILLIS; BROWN, 1978), que são relativamente comuns em espécies de *Eucalyptus* e *Corymbia*.

A madeira desses gêneros é considerada de difícil secagem, e particularmente deve ser realizada em estufa por meio de programas suaves, com baixas temperaturas e altas umidades relativas (RESENDE et al., 2015).

Antes da secagem em estufa, é recomendável a secagem ao ar (FERREIRA, 2003). De outra forma, Fonseca et al. (2010) reportam que a madeira de *C. citriodora* possui ausência de trincas ou rachaduras no tronco, fuste cilíndrico, inexistência de desvio da grã ou espiralamento, baixas taxas de retração tangencial e radial, ramos finos com inserção perpendicular ao fuste e em menor número possível, características que qualificam a madeira dessa espécie.

Incremento volumétrico de árvores, propriedades físico-mecânicas e anatomia da madeira

O setor florestal brasileiro apresenta a maior produtividade, medida em volume de madeira por unidade de área ao ano e a menor rotatividade dos plantios no mundo. Além disso, em 2016 o Brasil alcançou a liderança em produtividade florestal, com uma média de 35,7 m^3/ha ao ano para plantios de eucalipto (IBÁ, 2017). Além da produtividade, avaliar as propriedades físicas, mecânicas e anatômicas da madeira garante melhorias na qualidade dos produtos do setor industrial florestal. A formação da madeira está diretamente relacionada às características edafoclimáticas (DOWNES; DREW, 2008).

O Incremento médio anual (IMA) é um dos indicadores de crescimento da floresta, além de ser um fator fundamental que afeta a escolha das espécies. Esta variável é resultado da razão do volume total pela idade da floresta. Neste sentido, é uma informação imprescindível para a escolha de espécies e das melhores condições de crescimento para os produtores. Stape et al. (2010) demonstraram que o incremento médio anual de árvores de *Eucalyptus* crescidas em sítios sem fertilização e sem irrigação foi 28% menor (33 m^3 ha^{-1} ano^{-1}) comparado com a produtividade em sítios com fertilização tradicional e sem irrigação (46 m^3 ha^{-1} ano^{-1}). Entretanto, a fertilização não mostrou interação significativa com a irrigação. A resposta da irrigação em todos os sítios apresentou um aumento de 30% para IMA quando comparado ao efeito da fertilização.

Avaliação de respostas a fertilização de eucaliptos com sete anos em três regiões do estado de São Paulo, Brasil, foi observado que as regiões sem período de seca e com maior conteúdo de argila obteve um incremento de madeira anual maior que 54 m^3 ha^{-1} ano^{-1} quando comparado com regiões de maior conteúdo de areia (38 m^3 ha^{-1} ano^{-1})(SILVA et al. (2016).

A qualidade da madeira é dada pela interação de suas características anatômicas e químicas que influenciam diretamente nas propriedades físicas e mecânicas e na variação destas ao longo do tronco, o que irá conferir a qualidade de determinada madeira para fins específicos (WIEDENHOEFT, 2010).

Dentre as propriedades físicas que analisamos nesse estudo estão a densidade e a retração volumétrica. A densidade de um material é definida como a razão entre sua massa e seu volume (GLASS; ZELINKA, 2010). A densidade varia entre espécies diferentes, indivíduos da mesma espécie ou, ainda, na mesma árvore, nas direções radial e axial (CASTRO et al. 1993, WOODCOCK; SHIER 2002). Essas variações podem ser explicadas pelas diferenças nas dimensões e frequências das células e características da parede, além da presença e teor de extrativos (KOLLMANN; CÔTÉ, 1968; PANSHIN; DE ZEEUW, 1980, RAO et al., 1997; HOADLEY, 2000).

Outra propriedade física importante é a retração volumétrica. A madeira pode aumentar ou reduzir o volume em razão do ganho ou perda de água até o ponto de saturação das fibras. As variações dimensionais (retração ou expansão) vão depender de fatores como a densidade da madeira e teor de umidade. A retração apresenta diferentes valores nas três direções principais (longitudinal, tangencial e radial). A diferença entre a retratibilidade tangencial e radial pode ser explicada pela influência restritiva dos raios na direção radial e também pelo arranjo helicoidal diferente das microfibrilas nas paredes tangenciais e radiais (KOLLMAN; CÔTÉ, 1968).

Além do conhecimento das propriedades fisícas, a determinação das propriedades mecânicas da madeira auxilia no conhecimento de sua estrutura e na sua utilização (MOTTA, 2011). As propriedades mecânicas são a expressão do comportamento de um material, quando submetido a uma força. Sempre que a madeira se quebra ou se deforma, isso ocorreu pela ação de alguma força e, portanto, expressa alguma propriedade mecânica (WANGAARD, 1950). O conhecimento das características mecânicas da madeira pode explicar seu comportamento após o corte da árvore e garantir correta destinação, assegurando assim segurança e qualidade ao produto final.

Dentre as propriedades mecânicas que estudamos estão a compressão paralela à grã, o módulo de elasticidade e o módulo de ruptura. O processo de compressão é a máxima carga sustentada, no sentido em que a força é aplicada paralela à grã da amostra, apresentando uma proporção de comprimento com dimensão menor do que 11 (KRETSCHMANN, 2010).

A elasticidade é a propriedade dos corpos de armazenar, sob a forma de energia potencial interna, o trabalho mecânico de deformação provocado por uma força externa, devolvendo esta energia total ou parcialmente quando desaparece a causa da deformação (GREEN et al., 1999). A elasticidade implica em deformações que são produzidas por cargas nesse processo e que são completamente recuperadas assim que a carga é removida, e quando esta carga ultrapassa um nível determinado (limite de proporcionalidade) ocorrem deformações plásticas e rupturas na madeira (KRETSCHMANN, 2010).

O módulo de elasticidade é o quociente entre a tensão aplicada a um corpo e a deformação que ela provoca, podendo ser utilizado para explicar a correlação entre a rigidez e a flexibilidade da madeira, desde que se comparem peças com dimensões iguais (GREEN et al., 1999). O módulo de ruptura à flexão reflete a carga máxima que uma amostra pode resistir até que ocorram deformações plásticas (GREEN et al., 1999, KRETSCHMANN, 2010).

As células da madeira são formadas a partir do câmbio, que em linhas gerais produz fibras, elementos de vaso e células de parênquima axial a partir das células iniciais axiais e células de parênquima radial a partir das células iniciais radiais (EVERT, 2013). Segundo Gonçalves (2006), o conhecimento da estrutura anatômica da madeira, é um elemento fundamental para qualquer emprego industrial, levando em conta que seu comportamento mecânico, secagem, adesão e trabalhabilidade estão intimamente associados à sua estrutura celular. Sabe-se que os fatores geográficos e ambientais (temperatura, precipitação, disponibilidade hídrica) e os fatores genéticos são determinantes na formação do lenho, e as propriedades físicas e mecânicas são influenciadas pelas características anatômicas (HOADLEY, 2000).

Características potenciais da madeira como matéria prima para bioenergia

A biomassa lenhosa representa um recurso renovável com múltiplas aplicações industriais. Ela serve como matéria-prima para a indústria de celulose e papel, mas também pode ser plantada especificamente para atender às necessidades de matéria-prima para a indústria de energia ou biocombustíveis (HINCHEE et al. 2009).

Com base em dados da Agência Internacional de Energia, Vale e Gentil (2007) relatam que cerca de 11% do consumo mundial de energia primária é proveniente da biomassa e que esse percentual pode ser maior nos países em desenvolvimento, particularmente no caso de informações oficiais imprecisas. A maior parte dessa energia é gerada diretamente pela madeira, ou seus resíduos, derivados de processos industriais que utilizam a madeira como matéria-prima. Em geral, a contribuição de resíduos de diferentes tipos para o balanço energético brasileiro ainda é relativamente pequena, e o potencial disponível de resíduos agroflorestais ainda não é totalmente conhecido (VALE; GENTIL 2007).

Entre os maiores produtores de derivados florestais em 2005, o Brasil contribuiu com 8% da produção mundial de madeira para energia, atrás apenas da Índia (17%) e da China (11%). Em 2006, o Brasil tinha a segunda maior área reflorestada por eucaliptos do mundo, atrás apenas da Índia. Em resumo, o Brasil atendeu, até o momento, às demandas excepcionais das indústrias de base florestal, e o país desenvolveu tecnologias para melhoramento genético e manejo florestal que colocam o Brasil entre os produtores de produtos florestais com o menor custo e maior produtividade. Além disso, as extensas terras do país e as boas condições de solo e clima contribuem para plantação de árvores e crescimento rápido da floresta. Além disso, possui uma força de trabalho com conhecimento tecnológico das atividades florestais (SILVA et al., 2007).

Segundo Nahuz (2007), o consumo industrial de madeira de *Pinus* e *Eucalyptus* destina-se principalmente a suprir a indústria de celulose e carvão vegetal com matéria-prima, especialmente para a indústria siderúrgica. De acordo com Hinchee et al. (2009) certas espécies de *Eucalyptus* e seus híbridos são ideiais para produção de energia, pois têm excelente produção de biomassa, relativamente alto teor de lignina e um ciclo de rotação curto. Espécies de *Eucalyptus* variam com relação à taxa de crescimento e enraizamento, resistência à seca ou geada, resistência a doenças e pragas de insetos, densidade da madeira e teor de lignina e hemiceluloses (GONÇALVES et al., 2013). A escolha de espécies depende, portanto, das condições ambientais da área a ser plantada. As plantações de eucalipto em larga escala foram introduzidas no estado de São Paulo no início do século passado. As principais espécies que foram plantadas são *Eucalyptus grandis*, *Corymbia citriodora*, *E. camaldulensis*, *E. saligna* e *E. urophylla*.

Na cadeia de florestas plantadas, 75% a 90% dos resíduos são gerados em todo o processo de produção (SCHNEIDER et al., 2012). Dependendo do volume, esses resíduos podem ser processados em pellets (6-16 mm de diâmetro e 25-30 mm de comprimento) ou briquetes (50-100 mm de diâmetro e 250-400 mm de comprimento). Além de apresentar maior valor de aquecimento do que a lenha, os pellets e os briquetes apresentam maior heterogeidade de tamanho e forma, maior facilidade de armazenamento e maior segurança contra incêndio. Essas vantagens sobre a madeira bruta aumentaram o crescimento do fornecimento de pellets e briquetes no mercado interno, bem como a exportação para países europeus e asiáticos que aumentaram o consumo, principalmente para aquecimento doméstico e uso em pequenas e médias empresas (DIAS; ARROJA, 2012).

Poder calorífico superior é a quantidade de calor liberada pela combustão completa da massa unitária (ou volume) do combustível (BRAND, 2010). O poder calorífico de um material é expresso pelo conteúdo energético que é liberado quando o material é queimado no ar. Assim, o calor gerado durante a combustão de diferentes espécies florestais ou resíduos de madeira pode variar dependendo de suas propriedades físicas, químicas e anatômicas (ALMEIDA; BRITO; PERRE, 2010). A combustão de biomassa é a principal tecnologia de bioenergia, responsável por 90% da contribuição global da bioenergia (FORESTRY COMMISSION, 2011).

Para o uso racional e adequado de resíduos florestais, é necessário estudar suas propriedades energéticas (PROTÁSIO et al., 2011). Neste caso, o poder calorífico superior é um excelente parâmetro para avaliar o potencial energético dos combustíveis de biomassa (BRAND, 2010). Poder calorífico inferior de um material combustível é definido como a quantidade de calor liberado pela combustão de uma quantidade específica (inicialmente a 25 °C) e retornando a temperatura dos produtos de combustão para 150 °C, a qual assume que o calor de vaporização da água nos produtos de reação não é recuperado (GREET, 2010).

Tais dados destacam a necessidade de encontrar materiais que atendam a demanda por madeira e a demanda por seus resíduos como bioenergia. Quirino et al. (2005) compilaram informações do poder calorífico e densidade de 240 madeiras, dando a escala de diversidade de produção de biomassa a partir de resíduos de madeira. No entanto, é essencial que o potencial para a biomassa também seja determinado a partir de condições de plantio nas quais as idades e o espaçamento das árvores sejam conhecidos, de modo que informações precisas sejam fornecidas aos produtores.

Em linhas gerais, um processo de combustão gera vapor de água e certas técnicas podem ser usadas para recuperar a quantidade de calor contida neste vapor de água, condensando-o. No poder calorífico superior, a água de combustão é totalmente condensada e o calor contido no vapor de água é recuperado, enquanto, no poder calorífico inferior, os produtos da combustão contêm o vapor de água e o calor no vapor de água não é recuperado (TELMO; LOUSADA, 2011).

Os constituintes químicos da madeira influenciam a qualidade para bioenergia. A madeira é composta principalmente de celulose, hemiceluloses e lignina, responsáveis pela formação da parede celular e, consequentemente, influenciando nas propriedades do material. De forma simplificada, pode-se dizer que a celulose forma a estrutura da parede que é complementada pelas hemiceluloses, e ambas são envolvidas pela lignina. Além destes constituintes, há outras substâncias, como os extrativos, que atuam como componentes complementares, apresentando grande variabilidade tanto no teor, quanto na constituição. O conhecimento da natureza química da madeira possibilita o entendimento de seu comportamento como matéria prima nas mais diversas aplicações (LEPAGE 1986; MORI et al., 2003; MORAIS; NASCIMENTO; MELO, 2005; SILVA et al., 2005; ROWELL, 2013).

Qualidade da madeira para produção de papel e polpa celulósica

A indústria de papel e celulose possui grande importância na economia brasileira, de acordo com dados da Indústria Brasileira de Árvores – Ibá (2017), em 2016o o Brasil subiu para segundo no ranking de produção de polpa celulósica, e oitavo maior produtor mundial de papel.

Esses resultados podem ser explicados pela alta eficiência e competitividade do Brasil na produção de celulose, em grande parte devida às condições de solo e clima e pelo histórico de investimento em pesquisa e desenvolvimento florestal, realizado pelas empresas do setor e por órgãos de pesquisas. Decorrente desses aspectos, a produção nacional de celulose tem apresentado alto crescimento desde o início dos anos 1990 (HORA, 2017). De acordo com Risi (2015), o Brasil apresentou em 2015 quase 15 milhões de toneladas/ano para a capacidade instalada de celulose e mercado.

Quase todo o preparo de polpa e papel é feito a partir da madeira de diferentes espécies (FOEKEL, 2009), mas principalmente de espécies de *Pinus* e *Eucalyptus*. Apesar de todo o desenvolvimento tecnológico ao longo dos anos e dos equipamentos empregados na produção de papel, sempre há que se considerar que há variações na madeira e também naquelas impostas pelos seres humanos na produção (FOEKEL, 2009). Sendo assim, sempre há espaço para o estudo de novas espécies, das espécies já empregadas em condições diferentes de crescimento e desenvolvimento, para o melhoramento genético, para o desenvolvimento de novos processos ou equipamentos, etc.

Dessa forma, é essencial o estudo de espécies de *Eucalyptus* e *Corymbia* em diferentes condições a fim de se encontrar novos materiais para a produção de papel e celulose. Nesse contexto destacamos o plantio de *Corymbia citriodora* plantado de forma experimental em unidades do Instituto Florestal (GURGEL-GARRIDO et al., 1997).

Diversas características, desde as condições de solo e clima, tipo e condução do plantio, crescimento e desenvolvimento das árvores, características da madeira como a densidade e suas variações celulares, devem ser estudadas para atestar a qualidade de madeiras a serem empregadas na produção de papel e celulose. Foekel (2009) apresenta algumas caraterísticas essenciais para produção de celulose e papel, como o volume das árvores, densidade da madeira, porcentagem de constituintes químicos como extrativos, lignina e holocelulose, as características e proporções das células que compõem a madeira.

Outros dados essenciais são obtidos a partir do conhecimento sobre a qualidade da madeira, em particular, a densidade, que é definida como a razão entre massa e volume expressa pelo sistema internacional (SI) em unidades de quilogramas por metro cúbico (kg.m^{-3}) (GLASS; ZELINKA, 2010). A densidade é usada para estimar propriedades mecânicas (HOADLEY, 2000), mas também é um importante parâmetro para estimar a qualidade da madeira como matéria prima para a indústria de papel e celulose. Contudo como, em geral, maior densidade é encontrada em regiões de madeira adulta comparada com madeira jovem, sendo que de acordo com Foekel (2009), essa última possui características mais apropriadas para a produção de papel.

Características das fibras como o índice de Runkel (RUNKEL, 1952), obtido a partir das dimensões do lume das fibras e da espessura de suas paredes, constitui-se em parâmetros mais próximos para determiner a qualidade do papel. Adicionalmente, Horn (1978) reporta que o índice de Runkel é como se fosse uma extensão microscópica da densidade da madeira, justamente por usar as características das fibras citadas acima.

Assim, o estudo das variações anatômicas é essencial para o entendimento e escolha de espécies para papel e celulose. Pois as diferenças nas características das células parenquimáticas, os vasos e especialmente as fibras influenciam diretamente a qualidade da matéria prima para tal fim. Diferentes índices de qualidade podem ser calculados com base em características das fibras.

CAPÍTULO 1 - SOIL TYPE INFLUENCE ON MEAN ANNUAL INCREMENT, WOOD ANATOMY AND PHYSICAL AND MECHANICAL PROPERTIES OF 33-YEAR-OLD *Corymbia citriodora* (HOOK.), K. D. HILL & L. A. S. JOHNSON[1]

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ABSTRACT

The soil conditions of different soil types can influence the productivity and wood quality of fast growing species. In the present study, we investigated the wood of 33-year-old *Corymbia citriodora* in three soil types: Quartzarenic Neosol, Red Latosol and Red Nitosol. Our objective is to clarify how physical, chemical and water holding capacity differences among these three types of soils can cause changes in tree growth, physical and mechanical properties, and anatomical features in *C. citriodora* wood. Our results showed that more clayey soils with higher water availability present in Red Latosol and Red Nitosol increased the mean annual increment and heartwood percentage. In opposite way in more sandy soils such as Quartzarenic Neosol there was an increase in density and decrease in the size and diameter of fibers and vessels, increase in fiber cell wall thickness and frequency of vessels and rays. Wood shrinkage and mechanical properties did not differ between soils. We observed a gradual increase in the anatomical, physical and mechanical characteristics in the pith-bark direction. The uniformity index showed that Quartzarenic Neosol and Red Latosol soils produced more homogeneous woods. We concluded that soil texture and water availability influenced the tree growth, anatomical properties and density of wood.

Keywords: Clay, Sandy, Fiber, Vessel, Growth wood, Uniformity index

1.1 Introduction

Knowledge of plantation sites characteristics, such as temperature, precipitation, as well as texture, chemical and soil water holding capacity is essential to clear how these characteristics can influence the productivity and wood quality. In Brazil, most *Eucalyptus/Corymbia* plantations occur in Latosols (Gonçalves et al., 1997; Silveira et al., 2001). In general, *Eucalyptus/Corymbia* plantation productivity and wood quality are related to soil physical properties (Pereira et al., 2019), degree of soil acidity (Hong et al., 2019), water availability (Bordron et al., 2019; Ployet et al., 2019), and availability of mineral nutrients (Castro et al., 2020).

In the present study, we investigated growth, physical and mechanical properties, anatomical features of 33-year-old *Corymbia citriodora* (Hook.), K. D. Hill, & L. A. S. Johnson (formerly *Eucalyptus citriodora* Hook.) in three soil types: Quartzarenic Neosol, Red Latosol and Red Nitosol. We emphasize that soil classification is obtained from evaluation of morphological, physical, chemical and mineralogical data of soil profile. Environmental aspects of the profile site such as climate, vegetation, relief, source material, water conditions, external soil characteristics and soil-landscape relationships are also used (Santos et al., 2018).

In general, Neosols occur in approximately 15% of the Brazilian territory. These soils are pedogenetically poorly evolved soils with absence of subsurface diagnostic horizons, they are young soils and have a predominance of characteristics inherited from original material. Latosols are the most representative soils in Brazil, with about 39% total area of the country, are highly pedogenetically developed soils, highly weathered and no deep clay increment.

Nitosols has low occurrence in Brazil, approximately 1.5%, but occupy large areas in the state of São Paulo, are clayey soils, lacking a textural gradient and well structured (Embrapa, 2019a).

Eucalyptus/Corymbia species have been planted for decades in Brazil, especially as raw material for paper and pulp, but also used as material for energy and lumber. *Eucalyptus/Corymbia* plantations occupy 5.7 million hectares of planted tree area in Brazil, and the largest planted areas are located in the states of Minas Gerais (24%), São Paulo (17%) and Mato Grosso do Sul (15%) (Ibá, 2017).

Corymbia includes 113 species, mostly in endemic, tropical, arid and semi-arid areas of northern Australia (Butler et al., 2017). In Brazil, *C. citriodora* plantations were started with a view to physiological adaptation, growth and wood utilization for charcoal production. Over time, objectives of plantations were expanded in order to produce sawmill wood, energy and exploration of leaves to essential oil extraction (Vitti and Brito, 1999).

Our objective is to clarify how physical, chemical and water holding capacity differences among three types of soils: Quartzarenic Neosol, Red Latosol and Red Nitosol can cause changes in tree increment, physical and mechanical properties, and anatomical features in *C. citriodora* wood. We hypothesized that trees that grew in sandy and less nutrient soils presented a slower growth, due to water and nutritional restrictions and have denser wood, with larger cell wall proportion and smaller cell lumen diameter, and consequently with higher values in physical and mechanical properties when compared to those trees that grew in more clay and nutritionally rich soils. Such differences should cause variations that interfere with wood quality and its potential uses.

1.2 Materials and methods

1.2.1. Provenances of the seeds, planting area and sampling

In 1982, *Corymbia citriodora* seeds of open-pollinated plants were collected in commercial plantations in Pederneiras State Forest, located in Pederneiras City, São Paulo State, Brazil (22°27′S, 48°44′W, elevation 500 m), climate is CWa. In 1983, progeny test was established with 56 progenies at the Luiz Antonio Experimental Station (LAES), in Luiz Antônio City, São Paulo (21º40’S, 47º49’W, elevation 550 m) (Gurgel-Garrido et al., 1997). Climate is Aw in the Köppen-Geiger classification (Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura – CEPAGRI, 2019). The average annual rainfall is 1,365 mm and average annual temperature is 21.7º C, with the warmest months occurring in January, February and March, and the coldest months in May, June and July. Luiz Antônio's climate diagram is presented in Fig 1.

The planting was established at a spacing of 3 x 2 m, with one external border rows of the same species, without fertilization. The planting was installed with the same design in three different soil types according to Brazilian system of soil classification - SiBCS (Embrapa, 2019b): site 1 has soil classified as Quartzarenic Neosol (symbol is RQ), site 2 as Red Latosol (LV), and site 3 as Red Nitosol (NV). The correspondence between classes of SiBCS compared with WRB/FAO and Soil Taxonomy, categorical order and suborder level of their most recent editions (Embrapa, 2019b).

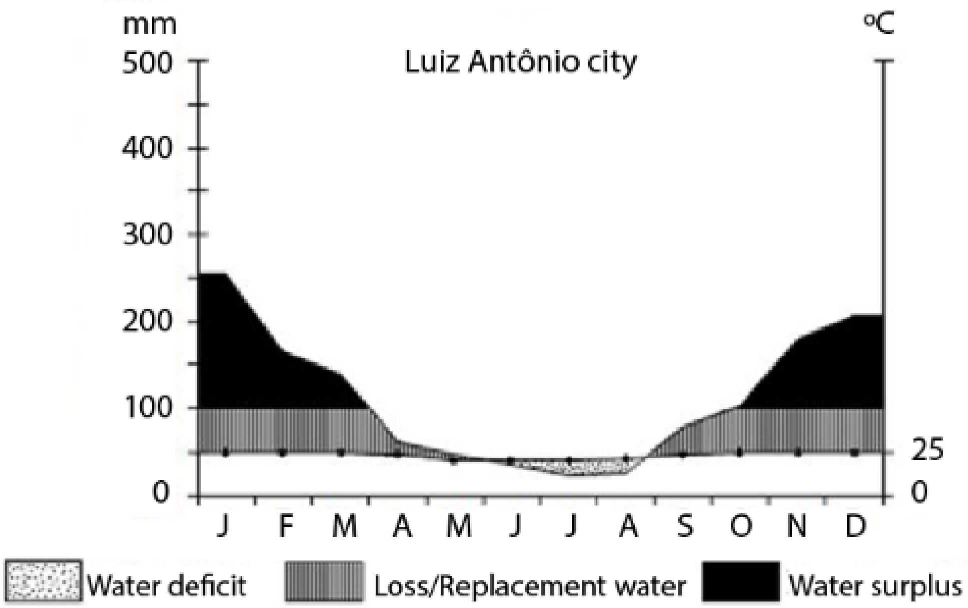

Fig 1. Climate diagram according to Walter (1986) from Luiz Antônio, SP, planting area and tree collection. Averages obtained from January/2005 to September/2015. Source CIAGRO - Integrated Center for Agrometeorological Information (http://www.ciiagro.sp.gov.br/).

In 2008, LAES team determined height, DBH (diameter at breast height - 1.30 m from the ground), stem shape, using a grading system, with values ranging from one (worst grade, crooked trunks) to five (best grade, straighter trunks).. In 2015, LAES team conducted new growth, shape and survival analyzes, but competition among the trees was added. The 2008 and 2015 information served as basis for us to select 18 trees (one of each progeny), the tallest and largest in diameter, for each type of soil, totaling 54 trees.

In 2016, we felled selected trees, and from each tree, a disc (for heartwood and sapwood percentages and uniformity index) at the base of trunk, and a , 1 meter long log (for physical, mechanical and anatomical investigations) was cut at the region immediately below the breast height. From logs, a central plank (5 cm thick), and from these planks, we cut three specimens (at three distinct radial positions) with cross section of 50 x 50 mm². The three radial positions established were: the nearest part of trunk center, designated as pith, a middle position, and a position close to the bark, designated as bark. Specimens for anatomical features was taken to the laboratory and for physical and mechanical properties were conditioned to equilibrium in a climate-controlled room under 65% of relative humidity and 21ºC (approximately 12% to 14% EMC). After acclimatization, specimens were prepared according to the ASTM D 143 secondary method (ASTM, 2007).

1.2.2. Soil sampling and analysis

We performed physical and soil water retention analysis according to Embrapa (1997). For each soil type we collect samples at depths between 0-20 cm three points within plantation and then we mixed samples to prepare a composite sample. For texture analysis we determined the percentages of sand, clay and silt. We also determined soil water retention content, and soil bulk density with volumetric cylinder.

Air-dried soil samples were analyzed for phosphorus (P); aluminum (Al); H+Al; aluminum saturation (m%); the basic cations including potassium (K), calcium (Ca), and magnesium (Mg); sum of the bases Ca, Mg and K (SB); pH; base saturation (V%); micronutrients boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn); cation exchange capacity (CEC); total organic carbon (O.M.). Soil analysis was carried out as per the procedures described by Raij et al. (2001).

1.2.3. Mean annual increment

From 54 trees we measured DBH (diameter at breast height) with caliper, and height with a hypsometer Vertex IV (Table 1).

Table 1

Dendrometric data of 33-year-old *Corymbia citriodora* trees. DBH = diameter at breast height.

	Quartzarenic Neosol		Red Latosol		Red Nitosol	
Tree	Height (m)	DBH (cm)	Height (m)	DBH (cm)	Height (m)	DBH (cm)
1	20.5	14.0	23.0	14.0	27.5	20.5
2	27.0	20.0	32.9	32.0	20.6	14.5
3	18.2	11.0	21.7	16.0	33.0	27.0
4	22.8	16.0	30.5	27.0	20.0	21.5
5	23.5	14.5	18.6	14.0	22.5	13.0
6	21.4	13.0	18.0	19.5	23.0	26.5
7	23.0	18.0	20.2	13.0	23.7	16.0
8	19.2	10.5	26.5	24.0	29.4	25.0
9	21.5	23.0	27.3	24.0	17.4	15.0
10	21.0	15.0	24.0	19.0	25.5	16.0
11	20.4	16.0	25.4	17.5	24.4	16.0
12	20.3	16.0	29.0	22.0	18.7	12.5
13	25.0	18.5	25.0	22.5	24.6	18.0
14	14.8	9.0	32,5	23.0	22.1	17.5
15	31.6	18.5	26.2	15.5	21.0	14.0
16	26.0	22.0	23.0	16.0	16.4	12.0
17	23.3	16.0	23.7	18.5	25.0	16.0
18	20.0	14.0	16.1	12.0	26.2	24.5

For conversion of cylindrical volume to real volume (m^3) we used the average form factors per species, since tree volumes were calculated based on the formula proposed by Scolforo (1993).

1.2.4. Density (ρ12)

Wood density at 12% moisture content was determined according to Glass and Zelinka (2010). The mass and volume at 12% moisture content (MC) were evaluated. Specimens of size 2 cm x 2 cm x 3 cm were conditioned at constant temperature (21°C) and 65% MC, respectively and, in these conditions, the mass was determined using an analytical balance and the volume was estimated by means of measurements of their diameters with an external digital micrometer.

1.2.5. Volumetric shrinkage

The volumetric shrinkage was obtained from the same samples as those used for the basic density (ABNT, 1997). The samples were saturated in water, their dimensions measured with a caliper (accuracy = 0.001mm) taking three measurements per direction, then oven-dried at 105 ± 3°C, followed by determination of the dry volume of each sample. Volumetric shrinkage (as a percentage) is the difference between initial saturated and oven-dried volume divided by initial volume.

1.2.6. Uniformity index

The wood density at equilibrium moisture content (EMC; 12%) was calculated for each disc. In the cross-section of the discs, wood samples were demarcated in radial strips with a parallel circular saw (1.7 mm thick) and conditioned in a climate room (20°C, 60% relative humidity, 24 h) (Amaral and Tomazello Filho, 1998). The samples were scanned in a collimated X-ray source (25 kV) using a QTRS-01X tree ring analyser (Quintek Measurement Systems Inc., Knoxville, TN, USA), at a resolution of 80μm (QMS, 1999). Then, with the results we calculated the uniformity index.

The uniformity index (Echols, 1973) numerically quantifies the dispersion around the average density of punctual density values of the wood along the region under evaluation of the sample. Using the histogram of punctual densities, taking the class that contain the average - reference class - and its contiguous (upper and lower) with weight 1, to the other classes are assigned incremental weights (2, 3, 4, etc), which increase as they move away from the referential. The uniformity index is obtained by the sum of multiplications of the frequencies of each class by their respective weights. By this methodology, one ideally uniform wood would have only three frequency classes (referential and its two contiguous) and a uniformity index of 100. The higher the index, the lower would be wood uniformity. In this study, for all trees in each soil type, frequency classes with amplitude of 50 kg.m^{-3} were used (Cherelli et al., 2018).

1.2.7. Mechanical properties

Mechanical characterization was carried out with the following tests: compression strength parallel to grain ($\sigma c \parallel$), modulus of rupture (MOR), and modulus of elasticity (MOE) in static bending (three-point test). These tests were performed in a computer-controlled 300kN electromechanical testing machine (INSTRON/EMIC, Paraná, Brazil). Deformations in bending were evaluated using a mechanical extensometer (accuracy = 0.01mm).

All variables of the mechanical tests were adopted according to NBR7190 (ABNT, 1997). Compression tests were performed on 20mm x 20mm x 60mm specimens and bending tests on 20mm x 20mm x 460mm specimens and a span length of 420mm. Both tests used a loading speed of 10MPa/min. Initial results of strength and elastic properties (modulus of elasticity) were corrected to the Equilibrium Moisture Content - EMC (12%) using a conversion coefficient of 3% (of variation per 1% of variation in the MC) for strength properties and 2% for elastic properties.

In the Brazilian standard NBR 7190, (ABNT, 1997), the characteristic value of compression strength parallel to the grain is used to classify the wood in the system of strength classes (Table 2), guiding the choice of the most suitable species for structural projects.

Table 2

Strength classes and characteristic values for hardwoods at 12 % MC, according to the NBR 7190 (ABNT, 1997).

Hardwoods					
Classes	$\sigma_{c\parallel,k}$ (MPa)	$\sigma_{s,k}$ (MPa)	$E_{c\parallel,m}$ (MPa)	D_b (g.cm^{-3})	D_{12} (g.cm^{-3})
C20	20	4	9500	0.500	0.650
C30	30	5	14500	0.650	0.800
C40	40	6	19500	0.750	0.950
C60	60	8	24500	0.800	1.000

$\sigma_{c\parallel,k}$ = Compression parallel to the grain. $\sigma_{s,k}$ = volumetric shrinkage. $E_{c\parallel,m}$ = modulus of elasticity. D_b = basic density. D_{12} = apparent density.

1.2.8. Anatomical analysis

Corymbia citriodora wood is characterized by presenting color differences between heartwood (reddish) and sapwood. We polished with sand papers the base surface of each disc and measured percentages of heartwood and sapwood with ruler (Table 10).

We cut small pieces of wood from each sample for maceration using Franklin’s method (Berlyn and Miksche 1976). Wood fragments were stained with aqueous safranin and mounted temporarily in a solution of water and glycerin (1:1). Samples of 2 cm^3 were softened in boiling water and glycerin (4:1) for 1 hour. From these samples, transverse and longitudinal sections 20μm in thickness were obtained with a sliding microtome. Sections were bleached with sodium hypochlorite (60%), washed thoroughly in water, and stained with 1% safranin (Johansen, 1940). Measurements followed the recommendations of the IAWA Committee (IAWA, 1989). Quantitative data are based on at least 25 measurements for each feature from each tree, thus fulfilling statistical requirements for the minimum number of measurements. Anatomical measurements of fiber length, fiber diameter, fiber lumen diameter, fiber wall thickness, vessel diameter, vessel frequency, ray height,ray width and ray frequency were obtained using an Olympus CX 31 microscope equipped with a camera (Olympus E330 EVOLT) and a computer image analysis software (Image-Pro 6.3).

1.2.9. Data analysis

We initially undertook descriptive statistical analysis and used Box Plot graphics to detect outliers. Thus, values 1.5 times higher than the 3rd quartile and values 1.5 times lower than the 1st quartile were excluded from the analysis.

Normality tests were performed to check the distribution of data, and when a normal distribution was not observed, data were square root-transformed. Then, a parametric analysis of variance (one-way analysis of variance ANOVA) was performed. When a significant difference was observed, Tukey's test was used to identify pairs of significantly different means. We analyzed the radial variation within the same tree and also three radial positions together comparing the results in three soil types.

1.3 Results and Discussion

1.3.1. Soils

We found differences in soil texture according to granulometry analyzes in the three soil types. The RQ has 52% coarse sand, 41% fine sand, 4% clay and 3% silt. The LV has 40% coarse sand, 41% fine sand, 16% clay and 3% silt. The NV presented the lowest amount of coarse sand (6%), fine sand (13%) and the largest amount of clay (52%) and silt (29%) (Table 3).

Table 3

Physical attributes of three soil types (0-20 cm layer) of 33-year-old *Corymbia citriodora* plantings.

Soils	Sand			Clay	Silt	Soil texture
	Coarse	Fine	Total ($g.kg^{-1}$)			
RQ	516	415	930	43	27	Sandy
LV	399	413	812	158	30	Medium
NV	65	130	195	519	286	Clayey

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV).

For chemical attributes we observed differences in pH, organic matter, macronutrient and micronutrient, base saturation. We noticed a lower pH in LV and a higher the organic matter content in NV. The soils LV and RQ have high value of Al^{3+}, and phosphorus, potassium, calcium and magnesium have low values. Sulfur has average reference values for three soil types. On the other hand, micronutrients present difference between LV, with high values and NV with low values for copper. In both soils, iron presents high values, and manganese and zinc low values. NV has high values for all macronutrients and micronutrients. According to the reference values the base saturation (V%) is very low for LV and low for RQ and NV soils (Table 4). RQ has higher soil density, while NV has lower density (Table 5).

Table 4

Soil pH, organic matter and mineral nutrients of 33-year-old *Corymbia citriodora* in three soil types (0-20 cm layer).

	pH	O.M	P	Al^{3+}	H+Al	K	Ca	Mg	S	SB	CEC	m%	V%	B	Cu	Fe	Mn	Zn
Soils	$CaCl_2$	$g.dm^{-3}$	$mg.dm^{-3}$		$mmol_c.dm^{-3}$									$mg.dm^{-3}$				
RQ	4.1	7	3	6	29	0.4	2	1	7	3	32	64	9	0.15	0.2	88	0.5	0,1
LV	3.8	10	4	10	56	0.4	2	1	6	3	59	75	5	0.20	1.4	68	0.9	0,1
NV	4.6	24	96	1	92	6.1	62	13	7	81	173	1	47	0.26	14.6	49	94.8	4,4

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV). total organic carbon (O.M.); phosphorus (P); aluminum (Al); H+Al; potassium (K), calcium (Ca), magnesium (Mg); sulfur (S); sum of the bases Ca, Mg and K (SB); cation exchange capacity (CEC); aluminium saturation (m%); base saturation (V%); boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn).

The areas are characterized by sandy (RQ), medium (LV) and clayey (NV) soils, with no physical impediment to water infiltration into the soil and different water holding capacity (Table 6). Clay soils have higher water holding capacity (Table 6) compared to medium and sandy soils. This is due to higher clay contents, the well-developed block structure and higher percentage of micropores in NV, additionally Rossi et al. (2005) show that clay minerals typology also influences this soil water holding capacity. According to Brady and Weil (2010), clay soils have higher water holding capacity at a given potential than those of sandy soils.

The mean values of soil water holding capacity in field capacity after natural drainage range from 0.09 dm3.dm-3 in RQ to 0.33 dm3.dm-3 in LV. This higher water retention in the evaluated matric potentials always occurs in NV (Table 5), although it does not reflect differences in the available water data (0.04MPa), since available H_2O = FC-PWP. Rossi et al. (2005) report that total soil water reserve (water retained under matric potentials below the permanent wilting point) can be used by native forest vegetation and correlated with variations in vegetation. On the other hand, available soil water also depends on plant properties such as root depth, since the analyzes here were fixed on 20cm surface layer.

NV is a soil that has variable fertility condition according to its origin, however our experimental site in the state of São Paulo has a high fertility Nitosol (Morais et al., 2010; Rossi, 2017). The soils RQ and LV had low saturation values per base (9 and 5 V%, respectively), classified as dystrophic soils following the Brazilian Soil Classification System (Embrapa, 2018) and NV (47 V%), almost presenting a eutrophic soil classification (higher than 50%).

Table 5

Soil water holding capacity and soil density of 33-year-old *Corymbia citriodora* in three soil types (0-20 cm layer).

	Retained water (dm^3.dm^{-3})								
	Tension (MPa)								Soil density
Soils	Saturated	0.003	0.006	0.01	0.03^{FC}	0.1	0.5	1.5^{PWP}	(kg.dm^{-3})
RQ	0.43c	0.33c	0.22c	0.13c	0.09c	0.07c	0.06c	0.05c	1.85a
LV	0.53b	0.39b	0.29b	0.19b	0.14b	0.12b	0.10b	0.10b	1.70b
NV	0.63	0.47a	0.44a	0.38a	0.33a	0.31a	0.29a	0.29a	1.51c

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV). FC = field capacity, PWP = permanent wilting point.

1.3.2. Tree growth

Tree height did not vary between soil types. The RQ trees presented the smallest diameters at breast height and consequently the lowest volume per tree (Table 6) and (Figure 2). In our study, as the plantations are in the same area and therefore under same rainfall regime, soil water retention are crucial for their availability to trees. RQ presented lowest water retention, which contributes to explain lower volumetric growth of trees compared to those in LV and NV soils, which have higher water retention capacity. Although RQ and LV may be considered nutrient poor soils, LV has slightly higher cation exchange capacity but very low base saturation.

Variations in soil types are determining factors in forest productivity (Fisher and Binkley, 2000). In our study we found differences in grain size, chemical composition and water holding capacity among three soil types. In general, NV values were higher compared to RQ and LV. One explanation may be the soil source material, NV has a basaltic origin, while RQ has a sandstone origin, whereas LV also has a probable origin in sandstone, but may contain basalt contributions. Another determining factor is water availability, a key resource for tree productivity in *Eucalyptus* plantations (Stape et al., 2010).

Table 6

Dendrometric data of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol	Red Latosol	Red Nitosol
Height (m)	14(22.19a)31	9(24,64a)32	16(23.38a)33
DBH (cm)	9(15.83b)23	12(19.41a)32	12(18.08a)27
Tree volume (m^3)	0.217b	0.356a	0.307a

Minimum, (mean) and maximum values for DBH, height and tree volume are presented. In the same row, distinct letters differ statistically ($P < 0.05$) by Tukey’s test.

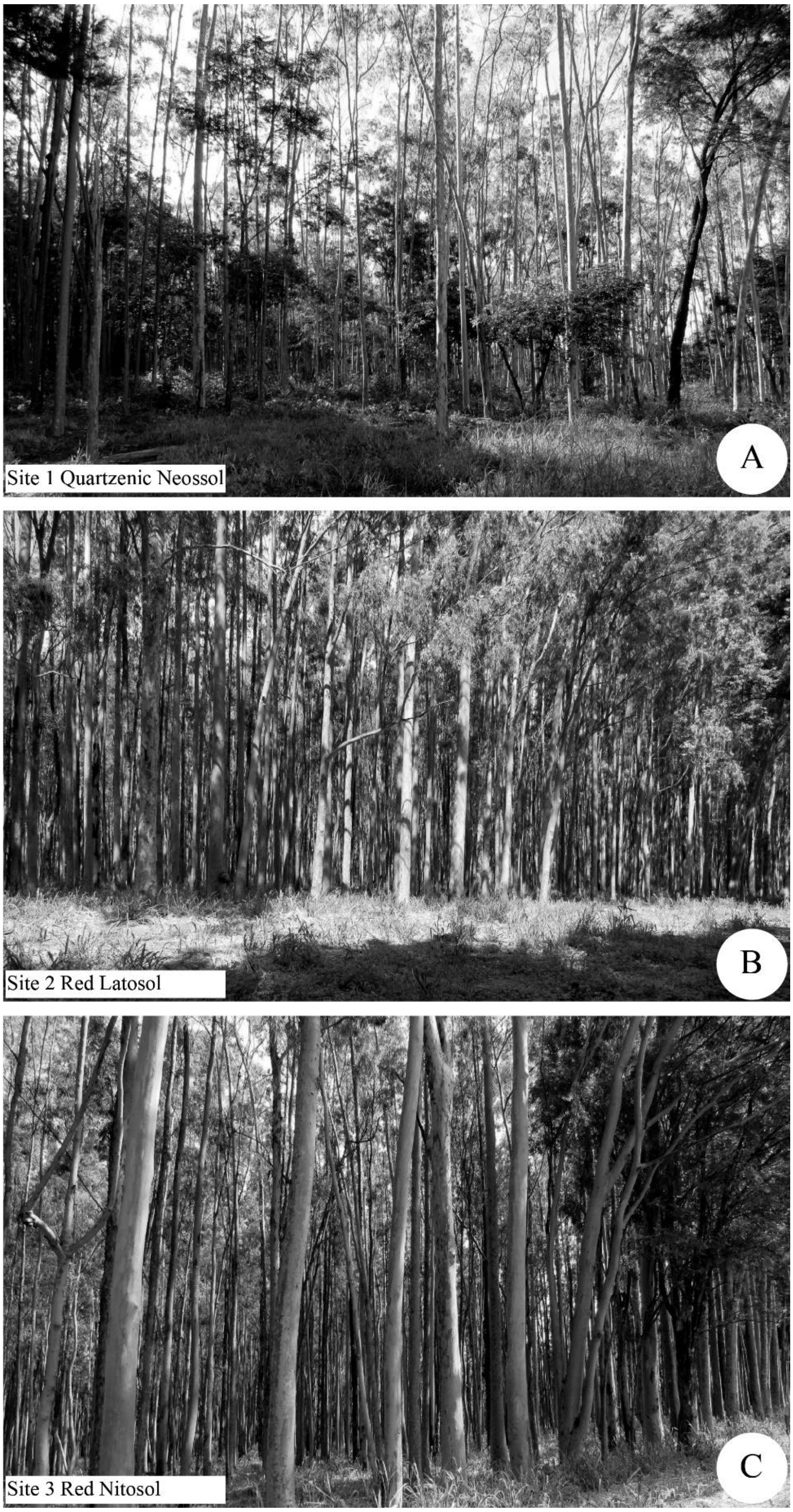

Fig. 2. Overview of *Corymbia citriodora* plantations in the three soil types. A. Quartzarenic Neosol. B. Red Latosol. C. Red Nitosol.

According to Forrester et al. (2010) and White et al. (2014), homogeneous *Eucalyptus* plantations have high water use efficiency, and this reflects their ability to produce more wood. According to Amazonas et al. (2018) low water amount in soil can decrease water potential in xylem and force plants to close stomata to avoid water loss, which in turn leads to a decrease in photosynthetic rate and consequently a decrease in growth and biomass.

Gava and Gonçalves (2008) studied the influence on *Eucalyptus grandis* wood in three soil types: Red Latosol, Yellow Red Latosol and Quartzarenic Latosol. The authors reported that soil physical attributes, especially clay content, directly related to water amount available was the one that most affected wood productivity and quality. Similar results occur in our study with *C. citriodora*, lower mean annual increment in Quartzarenic Latosol and higher in Red Latosol.

Other authors have reported the influence of macro and micronutrients on tree growth in different species. Harris et al. (1978) found that nitrogen and phosphorus deficiency restrict trunk and branch diameter but have low influence on trunk height growth in *Pinus radiata*. In our study, according to soil fertility (layer 0-20 cm) for *Eucalyptus* plantations (Castro et al., 2010), RQ and LV soils have low organic matter and phosphorus values, while in NV, values are medium and high, respectively.

Fromm (2010) studying wood formation of *Populus tremula* and *P. tremuloides* trees in relation to amount of sodium and potassium, reported that when these species grow with low amounts of K^+ ou Ca^{2+}, there is a decrease in wood increment. The RQ and LV soils have low potassium and calcium contents and NV values are medium and high, respectively. Biagiotti et al. (2017) studied the effect of potassium fertilization on *C. citriodora* during the first two years of plant life and concluded that until nine months fertilization promoted higher growth in height and at 12 months fertilization promoted greater growth in diameter and biomass. At 24 months, there was no response to potassium fertilization, suggesting a higher nutrient requirement in initial growth phase. According to Cunha et al. (2019), the cycling of nutrients N, P, K Ca, and Mg in long rotation *C. citriodora* planting is important in maintaining forest productivity.

Smith et al. (2009) compared the effects of Ca^{2+} fertilization on calcium concentration in *Picea rubens* wood at two sites with different initial levels of Ca^{2+} in the soil. The authors found higher amounts of calcium in the wood in higher soil concentrations, evidencing interrelated processes between soil and tree chemistry, confirming that calcium cycle plays a key role in the health and productivity of *P. rubens* forests in the northeastern of USA. Silva et al. (2008) studying water efficiency use in tree species with calcium and phosphorus fertilization in abandoned pastures in Brazilian Amazon, reported a significant effect on photosynthesis rate. In contrast to isolated phosphorus, fertilized trees growing in plots fertilized with phosphorus and calcium increased photosynthesis, indicating that calcium is an important limiting nutrient in secondary pasture succession. Effect of boron amount on soils with different textures (clay and sand) in *C. citriodora*, showed increased in volume per hectare in clayey soil and water availability (Pinheiro et al., 2019).

Although it is known that macro and micronutrient contents influence tree growth, in our study, despite values classified as low in some nutrients, as discussed above, trees in LV did not differ in tree height, DBH and volume from NV trees. This suggests that amounts of macro or micronutrients did not directly influence tree growth.

1.3.3. Physical and Mechanical properties

We observed a gradual increase of density 12% from the pith to the bark in LV and NV soils, whereas in RQ soil, pith showed lower density and there was no significant difference between intermediate and bark positions. Among soil types, we observed lower density in NV, and no significant differences between LV and RQ. In pith to bark variation for three soil types, volumetric shrinkage was higher in bark position, pith and intermediate positions showed no significant differences. Among the soils, we did not find significant differences to volumetric shrinkage (Table 7).

We found a gradual increase of the compression parallel to the grain in LV and NV soils, while in RQ soil we observed lower values in pith, with no difference between intermediate and bark positions. From MOE. we observed a gradual increase in LV and RQ soils, while in NV soil we noticed the higher MOE in bark. From MOR, we observed lower values in bark position only in RQ soil, in which there is a gradual increase towards to the bark. We did not find significant differences between three types of soils for mechanical properties (Table 7).

According to the average values of the physical and mechanical properties, the wood of *C. citriodora* was grouped in resistance class 40 following the strength classes of standard NBR 7190 (Sales, 2004; Sales and Calil, 2005) (Table 2).

Table 7

Radial variation of physical and mechanical properties in wood of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol				Red Latosol				Red Nitosol			
	Pith	Inter	Bark	Mean	Pith	Inter	Bark	Mean	Pith	Inter	Bark	Mean
ρ12	0.85b	0.93a	0.95a	0.91A	0.82c	0.93b	1.01a	0.92A	0.80c	0.85b	0.95a	0.87B
VS	15.03b	14.48b	16.40a	15.32A	14.42b	15.51b	17.24a	15.72A	13.67b	14.67b	16.32a	14.88A
fc0	51.11b	62.09a	65.48a	59.40A	49.54c	63.23b	72.75a	61.82A	48.35c	60.90b	69.52a	59.42A
MOE	11138c	13763b	17449a	14123A	10985c	15872b	19453a	15507A	12141b	13623b	18596a	14818A
MOR	82c	112b	134a	109A	79b	124a	139a	114A	98b	103ab	127a	110A

density at 12% moisture content ρ12 = (g.cm^{-3}); VS = volumetric shrinkage (%); fc0 = compression parallel to the grain (MPa); MOE = modulus of elasticity (MPa); MOR = modulus of rupture (MPa). The difference between the radial positions is represented by lowercase letters, while the comparison between the provenances is represented by uppercase letters. In the same row, distinct letters differ statistically (P < 0.05) by Tukey’s test.

When we analyze the radial variations of physical and mechanical properties we find differences in all soil types. Vale et al. (1995) report that for better yield and quality in the final product it is desirable that wood has as homogeneous density as possible. In this approach, RQ tree woods were slightly more homogeneous in density and overall, as they varied less than LV and NV tree woods. One explanation would be the smaller tree diameter in RQ.

However, among soil types, we only observed differences in wood density. Gava and Gonçalves (2008), in a study with wood density of *Eucalyptus grandis* in three soil types (Red Latosol, Yellow Latosol and Quartzaren Neosol) did not find differences. In the present study, we found lower wood density in NV, which has higher amount of clay compared to RQ and LV. Similar result was observed by Rigatto et al. (2004) with *Pinus* species, who observed lower wood density from trees in clayey soils compared to other soils of different particle size compositions.

In addition to soil texture, chemical composition can influence wood features. Ramanantoandro et al. (2016) studied the influence of soil types on trees from Madagascar forest with differences in relief. The authors report that wood density is higher in poor ferralitic soils than in lowlands with iron-rich soils. They explained that along the slope, soil is chemically poor, dominated by young, clayey soils that have poor structural stability and are easily eroded.

In contrast, lowland soils are more fertile due to soil nutrient accumulation due to erosion. Thus, Ramanantoandro et al. (2016) suggest that tree growth is slower on poor soil, allowing wood to become denser. In our study, although the relief has no interference, since *C. citriodora* plantations are in flat locations, we found a similar result, the nutrient poor soils were RQ and LV, which despite having iron content higher than NV, the highest wood densities occurred in RQ and LV trees when compared to wood from NV trees. Other authors have also found similar results with high density wood related to low soil fertility, e.g., Chave et al. (2006) who compiled data from more than 2400 neotropical tree species. Hättenschwiler et al. (1996) and Kostiainen et al. (2004) in studies with conifers also reported a decrease in wood density with soil fertilization.

Sette et al. (2014a) describe that effect of mineral fertilizers on *Eucalyptus* wood properties are controversial, indicating an increase and decrease in wood density. Sette et al. (2014b) and Castro et al. (2017) who studied the effect of potassium and sodium application on wood density of young *Eucalyptus grandis* trees found lower density with lower fertilization. Barbosa et al. (2014) reported higher wood density in *Eucalyptus* spp. with lower NPK contents. While Sansigolo and Ramos (2011), in a study with *Eucalyptus grandis* found different result with lower wood density in soil with higher fertility. These results show that there is a tendency of higher wood density in less nutritional condition, although each situation should be analyzed in a more general context. This is one of gains to be emphasized in our study, since plantations are in the same area, and obviously knowing that they may have microenvironments, in general, we are analyzing trees under same temperature and precipitation conditions.

Arnaud et al. (2019) and Ployet et al. (2019) have evaluated the effect of soil fertilization and water availability on wood density in *Eucalyptus grandis* submitted to treatments with and without potassium fertilization and with rain inclusion and exclusion. The authors observed that the presence of potassium and rainfall exclusion increased basic density when compared to the presence of potassium and rainfall. Our results showed very low K values and lower water availability in RQ and LV soils, and higher basic density values compared to NV soil that has higher fertility and higher water availability. This suggests that water availability was a major factor for differences in basic density.

Studies relating soil attributes to wood density are more common, but some also related to other properties. Lima and Garcia (2011), with *E. grandis* at 21 years-old, observed radial variations in properties, increase in bark direction, corroborating our results with *C. citriodora*. Lima and Garcia (2011) also evaluated the effect of thinning and NPK fertilization at planting time and also at five years of planting on *E. grandis* wood at 21 years-old. The authors observed a positive relationship between fertilization and compression parallel to the grain and modulus of elasticity, but found no significant relationship with shear strength and modulus of rupture. Haselein et al. (2002) observed an increase in modulus of elasticity and modulus of rupture with increasing soil fertilization in *Eucalyptus saligna* wood. As previously mentioned, only wood density presented variations between soil types, the other properties were not influenced. This result may be interesting, since if values of other properties are satisfactory for a given producer, our study gives an indication that wood properties, generally, do not change if they use seeds of this trees and will plant in different soil types. High wood density and strength values are also suitable for use as lumber. According to Saranpää (2003), wood as a structural material generally has high density and strength, results that we find in *C. citriodora*.

In the present study, soil collections occurred when trees were adults, older than 30 years. Therefore, the relationships and inferences discussed here reflect a current soil condition. We know that some studies indicate that *Eucalyptus* culture alters soil conditions. For instance, Leite et al. (2010) studied edaphic characteristics in *Eucalyptus* forested area, near pasture area, pasture area, *Eucalyptus* area near native forest area, and native forest area. The authors reported that in areas cultivated with *Eucalyptus*, there was a reduction in exchangeable Ca^{2+}, Mg^{2+} e K^{+} levels; pH reduction; and increases in Al^{3+} and H + Al contents. In addition to increases in phosphorus nutrient content in areas cultivated with *Eucalyptus*. Thus, it is possible that some changes have occurred over time, but we do not have soil attributes before planting to compare with the current situation.

The uniformity index was higher in NV and did not differ between RQ and LV (Table 8). In our study, NV soil wood presented higher uniformity index. Cherelli et al. (2018) evaluating uniformity index in *C. citriodora*, *E. tereticornis* and *E. grandis*, aged 28, 35 and 18 years, respectively, observed that *C. citriodora* (UI = 187) did not differ from *E. tereticornis* (UI = 194), but was lower than *E. grandis* (UI = 267). The authors suggest that higher density of sapwood with mature wood characteristics may interfere with uniformity index.

Table 8

Uniformity index in wood of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol	Red Latosol	Red Nitosol
Uniformity index	167.545b	177.066b	214.350a

In the same row, distinct letters differ statistically (P < 0.05) by Tukey’s test.

1.3.4. Anatomical features

We observed higher heartwood percentage and consequently lower sapwood percentage in LV and NV soils, respectively (Table 9).

Table 9

Heartwood and sapwood percentage in wood of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol	Red Latosol	Red Nitosol
heartwood (%)	57b	70a	71a
sapwood (%)	43a	30b	29b

In the same row, distinct letters differ statistically (P < 0.05) by Tukey’s test.

Another important data in wood qualification is the quantification of heartwood and sapwood percentages (Oliveira, 1997). According to Pereira et al. (2013) for timber used in construction or furniture production, it is interesting that it has a higher heartwood percentage than sapwood, since most of sapwood is lost in wood cutting. For this analysis, wood from RQ trees has lower quality, as they have lower heartwood percentage compared to wood from trees of other two soil types. However, according to Vieira (2003) in Rio Grande do Sul, *Eucalyptus* sapwood is used as external walls in rustic buildings. Although sapwood have low value-added products due to their faster degradation.

The increase in tree diameter in LV and NV soils was accompanied by increase of heartwood percentage, which were higher than RQ soil with low water availability and sandy texture. This result was observed in six-year-old *E. grandis* × *E. urophylla* clones that presented lower heartwood percentage in soils with low water availability (Barbosa et al., 2019). In 19-year-old *C. citriodora* in deep sandy loam soil, an increase in sapwood above 48% was observed, increasing gradually to the commercial height limit when compared to six other *Eucalyptus* species (Oliveira et al., 1999). In our study, wood from RQ soil presented 43% of sapwwod, values close to found by (Oliveira et al., 1999). Heartwood percentage in 20-year-old *C. citriodora* trees in India ranged from 74% to 84% at the trunk base (0.6 m) and 68% to 79% at the trunk top (6.6 m) in Our results with 33-year-old trees showed that heartwood percentage in LV (70%) and LV (71%) soils is close to values found by the authors, regardless of height (Shashikala and Rao, 2009).

We found a gradual increase in pith to the bark direction for fiber length in three soil types. Fibers with larger diameter occur in bark. Fiber lumen diameter gradually decreased toward to the bark in the three soil types. Fiber wall thickness increased gradually from pith to the bark in the three soil types. Longer, with larger diameter, and larger lumen diameter fibers occurred in LV and smaller diameter fibers in LV. Thicker wall fibers occurred in RQ. Vessel diameter increased and vessel frequency decreased from pith to the bark in the three soil types. Larger vessels occurred in NV and narrower in LV, with higher frequency in RQ and lower in NV. Lower rays occurred in pith position in the three soil types. Ray width gradually increased toward to the bark in the three soil types. Among soil types, lower ray occurred in LV, and no difference between RQ and NV. Width ray was larger in RQ and smaller in NV. Ray frequency decreased toward to the bark in all three soil types. Higher frequency was observed in RQ, while LV and NV did not differ (Table 10).

Table 10

Radial variation of anatomical features in wood of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol				Red Latosol				Red Nitosol			
	Pith	Inter	Bark	Mean	Pith	Inter	Bark	Mean	Pith	Inter	Bark	Mean
FL	947c	989b	1037a	991B	901c	1014b	1071a	995B	905c	1065b	1099a	1023A
FD	15.5b	15.3b	16.2a	15.7B	14.8b	14.9b	15.4a	15.0C	16.0b	16.4b	17.0a	16.5A
FLD	4.8a	3.3b	2.7c	3.6B	4.4a	3.5b	2.9c	3.6B	6.1a	4.7b	4.0c	4.9A
FWT	5.3c	5.9b	6.7a	5.7B	5.2c	5.7b	6.2a	5.7B	4.9c	5.8b	6.5a	6.0A
VD	73c	90b	106a	90B	72c	87b	103a	88C	76c	94b	113a	95A
VF	19a	14b	11c	15A	16a	12b	10c	13B	13a	10b	8c	10C
RH	156b	167a	167a	163A	155b	161a	159a	159B	153b	168a	164a	162A
RW	11c	13b	15a	14A	11c	13b	15a	13B	11c	12b	14a	12C
RF	12a	11b	10c	11A	11a	10b	9c	10B	12a	10b	9c	10B

Fiber length (FL); fiber diameter (FD); fiber lumen diameter (FLD); fiber wall thickness (FWT); VD = vessel diameter; VF = vessel frequency; RH = ray height; RW = ray width; RF = ray frequency. Difference between radial positions is represented by lowercase letters, while comparison between provenances is represented by uppercase letters. In the same row, distinct letters differ statistically ($P < 0.05$) by Tukey’s test.

If there are changes in radial direction and trees growth and wood properties between soil types, it can be expected that they can be determined by anatomical variations. In terms of radial variation, our results are in agreement with Baas et al. (2004) and Lachenbruch et al. (2011), which outline the changes from the pith to the bark: increase in fiber wall length and thickness, negative relationship between vessel diameter (increase) and vessel density (decrease) and increase ray dimensions.

In our study, in terms of comparison between soils, longer fibers, larger diameter and larger lumen diameter occurred in LV and smaller diameter fibers in LV. Thicker wall fibers occurred in RQ. Loustarinen et al. (2017) in a study with *Betula pubescens* in forest and peat-like soil (high organic matter content), found larger and fewer cells in forest soils compared to peat-like soil, where plants showed high growth rates and decrease in wall / lumen of fiber in adult wood. Oliveira et al. (2012) studied 64-month-old *Eucalyptus grandis* natural hybrid clone wood grown in different municipalities of the states of Espírito Santo and Minas Gerais with different edaphoclimatic characteristics. The authors found longer and larger diameter fibers in a region with sandy loam soil (authors' classification) compared to latosol regions. Lupi et al. (2012) investigated the effect of soil nitrogen increase on *Picea mariana* wood in boreal forest in Canada. The authors reported only an increase in tracheid wall thickness in initial wood of treated trees.

Vilotić et al. (2015) studied over two years the dimensions of *Paulownia elongata* fibers with and without addition of macronutrients (N, P, K, Ca and Mg) and micronutrients (Fe, Mn, B, Zn, Cu). The authors observed that in plants in control soil (without fertilization), fibers were longer than in plants in fertilized soil, in this case, fertilizer treatment interfered negatively in fiber length. In our study, *C. citriodora* fibers were longer in NV, soil with higher amounts of macro and micronutrients compared with the other two soil types.

In our study, larger vessels occurred in NV and narrower in LV. Longui et al (2014) in a study with *Copaifera langsdorffii* with differences in vegetation type and soil attributes found narrower vessels in trees that were on stony soils with low water retention and poorer nutrients. Oliveira et al. (2012) found vessels with larger diameters and frequency in latosol regions, compared with clayey soil in *Eucalyptus grandis*. Remembering that our results showed larger diameter vessels in NV, more clay soil. Not only the texture, but the soil chemical constitution also influences the wood. Fromm (2010) studying wood formation of *Populus tremula* and *P. tremuloides* trees in relation to amount of sodium and potassium, reported that when these species grow with low amounts of K^+ or Ca^{2+}, there is a decrease in cambial activity and vessel diameter. This may have occurred in our study, since C. citriodora wood vessels in RQ (90 µm) and LV (88 µm) trees were narrower than those found in LV wood (95 µm), where K and Ca contents were respectively: RQ and LV = 0.4 and 2 $mmol_c/dm^3$, and NV = 6.1 and 62 $mmol_c/dm^3$. However, it is noteworthy that trees in LV presented largest increments, even with narrower vessel diameter. Knowing that vessel diameter is positively related to water conduction and therefore, if water is available, more suitable conditions for photosynthetic efficiency (Hacke et al., 2005). Perhaps, result of vessel density helps us to explain this variation, or in case of the trees we analyzed, significant differences between vessel diameters are not sufficient to imply significant differences in water conduction, photosynthesis and consequently growth rate.

Lower rays occurred in LV, and no difference between RQ and NV. The rays width was larger in RQ soil and smaller in NV soil. When observing ray dimensions (multiplying the height by the width), we notice that RQ presents bulker rays than other two soil types. Longui et al (2014) in the aforementioned study with *Copaifera langsdorffii*, also found wider ray in trees that occurred in stony soils with low water retention and poorer nutrients. The authors suggested that higher ray volume, in this context could confer greater potential for starch reserv, which may be important due to the lower photosynthetic rate of *C. langsdorffii* plants due to low soil water availability. In our study there is a similar situation with *C. citriodora* trees, in RQ soil with lower water retention capacity, which may interfere with photosynthesis, remembering that in RQ we observed trees with smaller diameter and smaller increment. Oliveira et al. (2012) in a study with *Eucalyptus grandis* found bulker rays in a region with clayey soil compared with latosol regions.

We did not measure the proportion of axial parenchyma, but it may also play an interesting role in the results, since Loustarinen et al. (2017) found an increase in axial parenchyma in *Betula pubescens* wood in peat-like soil (high organic matter content) compared to forest soils. In our study we observed an inverse association between the organic matter content, decreasing from NV, LV to RQ, and ray volume was smaller in LV and higher in RQ.

1.4 Conclusions

The different physical, chemical and water properties of three soil types influenced the physical, mechanical and anatomical properties of *Corymbia citriodora* wood. Our results corroborate findings in the literature. The sandy, less fertile and low water soils such as RQ soil presented lower mean annual increments, with larger cell wall proportion and smaller cell lumen diameter. A more fertile, clayey soil condition with greater water availability influenced the formation of less homogeneous and dense woods. Although there are no differences in mechanical properties between soils, the average values obtained for these properties fall into higher resistance classes.

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References

Amaral, A.C.B., Tomazello Filho, M., 1998. Avaliação das características dos anéis de crescimento de *Pinus taeda* pela microdensitometria de raios X. Revista Ciência e Tecnologia 11/12, 17-23.

Amazonas, N.T., Forrester, D.I., Oliveira, R.S., Brancalion, P.H.S., 2018. Combining Eucalyptus wood production with the recovery of native tree diversity in mixed plantings: Implications for water use and availability. Forest Ecology and Management 418, 34–40.

Arnaud, C., Brancheriau, L., Sabatier, S., Heinz, C., Chaix, G., Tomazello-Filho, M., 2019. Interactions between the mechanical and hydraulic properties of

Eucalyptus trees under diferente environmental conditions of fertilization and water availability. BioResources 14, 7157-7168.

Associação brasileira de normas técnicas (ABNT), 1997. NBR 71/90: Projeto em estruturas de madeira. Projeto de revisão NBR 7190. Rio de Janeiro.

American society for testing and materials (ASTM) D143-94, 2007. Standard test methods for small clear specimens of timber. West Conshohocken.

Barbosa, B.M., Colodette, J.L., Cabral, C.P.T., Gomes, F.J.B., Silva, V.L., 2014. Effect of fertilization on the quality of the Eucalyptus spp. wood. Scientia Forestalis 42, 29-39.

Barbosa, T.L., Oliveira, J.T.S., Rocha, S.M.G., Câmara, A.P., Vidaurre, G.B., Rosado, A.M., Leite, F.P., 2019. Influence of site in the wood quality of Eucalyptus in plantations in Brazil. Southern Forests 81, 247–253.

Baas, P., Ewers, F.W., Davis, S.D., Wheeler, E.A., 2004. Evolution of xylem physiology, in: Poole, I., Hemsley, A. (Eds.), Evolution of Plant Physiology. Elsevier Academic Press. (Linnaean Society Symposium Series), London, pp. 273-295.

Berlyn, G.P., Miksche, J.P. 1976. Botanical microtechnique and cytochemistry, State University Press, Ames, Iowa.

Biagiotti, G., Valeri, S.V., Cruz, M.C.P., Vasconcelos, R.T., 2017. Potassium fertilization in plantation of C*orymbia citriodora* (Hook.) K.D. Hill & L.A.S. Johnson. Scientia Forestalis 45, 129-137.

Bordron, B., Robin, A., Oliveira, I.R., Guillemot, J., Laclau, J.P., Jourdan, C., Nouvellon, Y., Abreu-Junior., C.H., Trivelin, P.C.O., Gonçalves, J.L.M., Plassard, C., Bouillet, J.P., 2019. Fertilization increases the functional specialization of fine roots in deep soil layers for young Eucalyptus grandis trees. Forest Ecology and Management 431, 6–16.

Brady, N., Weil, R., 2010. Elements of the nature and properties of soils, third ed. Pearson Education, Inc.

Butler, J.B., Vaillancourt, R.E., Potts, B.M., Lee, D.J., King, G.J., Baten, A., Shepherd, M., Freeman, J.S., 2017. Comparative genomics of Eucalyptus and Corymbia reveals low rates of genome structural rearrangement. BMC Genomics 18, 397.

Castro, P.P., Curi, N., Neto, A.E.F., Resende, A.V., Guilherme, L.R.G., Menezes, M.D., Araújo, E.F., Freitas, D.A.F., Mello, C.R., Silva, S.H.G., 2010. Chemistry and minerology of soils cultivated with Eucalyptus (*Eucalyptus* sp.). Scientia Forestalis 38, 645-657.

Castro, V.R., Surdi, P.G., Sette Junior, C.R., Mario Tomazello Filho, M., Chaix, G., Laclau, J.P., 2017. Application effect of potassium, sodium and water availability in the apparent density at 12% humidity of juvenile wood of *eucalyptus grandis* trees. Ciência Florestal 27, 1017-1027.

Castro, R.V., Legoas, R.C., TommasielloFilho, M., Surdi, P.G., Zanuncio, J.C., Zanuncio, A.J.V., 2020. The effect of soil nutrients and moisture during ontogey on apparent wood density of Eucalyptus grandis. Scientic Reports 10, 1-10.

Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura – CEPAGRI, 2019. https://www.cpa.unicamp.br/ (accessed 20 May 2019).

Chave, J., Muller-landau, H.C., Baker, T.R., Easdale, T.A., Steege, H.T., Webb, C.O., 2006. Regional and phylogenetic variation of wood density across 2456 neotropical tree species. Ecological Applications 16, 2356–2367.

Cherelli, S.G., Sartori, M.M.P., Próspero, A.G., Ballarin., A.W., 2018. Heartwood and sapwood in Eucalyptus trees: non-conventional approach to wood quality. Anais da Academia Brasileira de Ciências 90, 425-438.

Cunha, G.M., Gama-Rodrigues, A.C., Gama-Rodrigues, E.F., Moreira, G.R., 2019. Nutrient Cycling in *Corymbia citriodora* in the State of Rio de Janeiro, Brazil. Floresta e Ambiente 26, 1-10.

Echols, R.M., 1973. Uniformity of wood density assessed from X-rays of increment cores. Wood Sci Technol 7: 34-44.

Empresa brasileira de pesquisa agropecuária – EMBRAPA., 1997. Manual de métodos de análises de solo, segunda edição, Ministério da Agricultura e do Abastecimento, Rio de Janeiro.

Empresa brasileira de pesquisa agropecuária – EMBRAPA., 2018. Sistema Brasileiro de Classificação de Solos, quinta edição, Embrapa, Brasília.

Empresa brasileira de pesquisa agropecuária – EMBRAPA., 2019a. Solos Brasileiros. https://www.embrapa.br/tema-solos-brasileiros/solos-do-brasil/ (accessed 20 May 2019).

Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA., 2019b. WRB/FAO and Soil Taxonomy. https://www.embrapa.br/solos/sibcs/correlacao-com-wrb-fao-e-soil-taxonomy/ (accessed 20 May 2019).

Fisher, R.F., Binkley, D., 2000. Ecology and Management of Forest Soils. John Wiley and Sons, New York.

Forrester, D.I., Theiveyanathan, S., Collopy, J.J., Marcar, N.E., 2010. Enhanced water use efficiency in a mixed Eucalyptus globulus and *Acacia mearnsii* plantation. For. Ecol. Manage 259, 761–1770.

Fromm, J., 2010. Wood formation of trees in relation to potassium and calcium nutrition. Tree Physiology 30, 1140–1147.

Gava J.L., Gonçalves, J.L.M., 2008. Soil atributes and wood quality for pulp production in plantations of *Eucalyptus grandis* clone. Sci. Agric., 65, 306-313.

Glass, S., Zelinka, S.L., 2010. Moisture relations and physical properties of wood, in: Ross, R. (Ed.), Wood handbook – wood as an engineering material. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, pp. 4-1/4-19.

Gonçalves, J.L.M., Barros, N.F., Nambiar, E.K.S., Novais, R.F., 1997. Soil and stand management for short-rotation plantations, in: Nambiar, E.K.S., Brown, A.G. (Eds), Management of soil, nutrients and water in tropical plantation forests. Australian Centre for International Agricultural Research, Camberra, Australia, pp. 379–417.

Gurgel-Garrido, L.M.A., Siqueira, A.C.M.F., Cruz, S.F., Romanelli, R.C., Ettori, L.G., Crestana, C.S.M., Sato, A.S., 1997. Programa de melhoramento genético florestal do Instituto Florestal. IF Série Registros 18, 1-53.

Hacke, U.G., Sperry, J.S., Pittermann, J., 2005. Efficiency versus safety tradeoffs for water conduction in angiosperm vessels versus gymnosperm tracheids, in: Holbrook, N.M., Zwienniecki, M.A. (Eds.), Vascular transport in plants. Elsevier Inc., Amsterdam, pp. 333–354.

Harris, J.M., McConchie, D.L., Povey, W.A., 1978. Wood properties of clonal radiata pine grown in soils with different levels of available nitrogen, phosphorus and water. New Zealand Journal of Forestry Science 8, 417-30.

Haselein, C.R., Berger, R., Goulart, M., Sthal, J., Trevisan, R., Santini, E.J., Lopes, M.C., 2002. Propriedades de flexão estática da madeira úmida e a 12% de umidade de um clone de *Eucalyptus saligna* Smith sob o efeito do espaçamento e da adubação. Ciência Florestal 12, 147-152.

Hättenschwiler, S., Schweingruber, F.H., Körner, C., 1996. Tree ring responses to elevated [CO2] and increased N deposition in Picea abies. Plant, Cell & Environment 19, 1369–1378.

Hong, S., Gan, P., Chen, A., 2019. Environmental controls on soil pH in planted forest and its response tonitrogen deposition. Environmental Research 172, 159–165.

Indústria brasileira de árvores., 2017. Relatório IBÁ 2017, São Paulo.

Iawa Committee., 1989. IAWA list of microscopic features for hardwood identification.

IAWA Bulletin, 10, 219-332.

Johansen, D., 1940. Plant microtechnique. McGraw Hill, London.

Kostiainen, K., Kaakinen, S., Saranpaä, P., Sigurdsson, B.D., Linder, S., Vapaavuori, E., 2004. Effect of elevated [CO2] on stem wood properties of mature Norway spruce grown at different soil nutrient availability. Glob. Change Biol, 10, 1526–1538.

Lachenbruch, B., Moore, J.R., Evans, R., 2011. Radial variation in wood structure and function in woody plants, and hypotheses for its occurrence, in: Meinzer, F.C., Lachenbruch, B., Dawson, T.E. (Eds), Size-and age-related changes in tree structure and function. Springer, New York, pp. 121-164.

Leite, F.P., Silva, I.R., Novais, R.F., Barros, N.F., Neves, J.C.L., 2010. Alterations of soil chemical properties by *Eucalyptus* cultivation in five regions in the Rio Doce Valle. R. Bras. Ci. Solo 34, 821-831.

Lima, I.L., Garcia, J.N., 2011. Efeito da fertilização em propriedades mecânicas da madeira de *Eucalyptus grandis.* Ciência Florestal 21, 601-608.

Longui, E.L., Costa, N.O., Cielo-Filho, R., Marcati, C.R., Romeiro, D., Rajput, K.S., Lima, I.L., Florsheim, S.M.B., 2014. Wood and leaf anatomy of Copaifera langsdorffii dwarf trees. IAWA Journal, 35, 170–185.

Loustarinen, K., Hakkarainen, K., Kaksonen, H., 2017. Connection of growth and wood density with wood anatomy in downy birch grown in two different soil types. Scandinavian Journal of Forest Research 32, 789-797.

Lupi, C., Morin, H., Deslauriers, A., Rossi, S., Houl, D., 2012. Increasing nitrogen availability and soil temperature: effects on xylem phenology and anatomy of mature black spruce. Can. J. For. Res. 42: 1277–1288.

Morais, E., Zanatto, A.C.S., Freitas, M.L.M., Moraes, M.L.T., Sebbenn, A.M., 2010. Genetic variation, genotype x soil interaction and genetic gains in a *Corymbia citriodora* Hook progeny test in Luiz Antonio, São Paulo, Brazil. Sci. For., 38, 11-18.

Oliveira, J.T.S., 1997. Caracterização da madeira de eucalipto para a construção civil. Tese (Doutorado em Engenharia Civil) – Universidade de São Paulo, São Paulo.

Oliveira, J.T.S., Hellmeister, J.C.,Simões, J.W., Tomazello-Filho, M., 1999. Characterization of seven eucalypt wood species to civil construction: 1-dendrometrics evaluations of the trees. Scientia forestalis 56, 113-124.

Oliveira, J.G.L., Oliveira, J.T.S., Abad, J.I.M., Silva, A.G., Fiedler, N.C., Vidaure, G.B., 2012. Parâmetros quantitativos da anatomia da madeira de eucalipto que cresceu em diferentes locais. Revista Árvore 36, 559-567.

Pereira, B.L.C., Oliveira, A.C., Carvalho, A.M.M.L., Carneiro, A.C.O., Vital, B.R., Santos, L.C., 2013. Correlations among the heart/sapwood ratio of Eucalyptus wood, yield and charcoal properties. Sci. For., 41, 217-225.

Pereira, N.A., Medeiros, J.C., Lacerda, J.J.J., Rosa, J.D., Dias, B.A.S., Silva, E.M., Ratke, R.F., Mendes, W.S., 2019. Soil physical attributes under *Eucalyptus stands* with non-living and living plants. Journal of Agricultural Science11, 197-207.

Pinheiro, A.L., Caiafa, K.F., Pinheiro, D.T., Soares, T.F.S.N., Leite, R.V., Barros, P.R., Teixeira, M.F.F., 2019. Soil fertilization and texture on boron accumulation and wood volume in *Corymbia citriodora* (Hook) K. D. Hill & L.A.S Johnson. Journal of Experimental Agriculture International 37, 1-8.

Ployet, R., Labate, M.T.V., Cataldi, T.R., Christina, M., Morel, M., Clemente, H.S., Denis, M., Favreau, B., Tomazello Filho, M., Laclau, J.P., Labate, C.A., Gilles Chaix, G., Grima-Pettenati, J., Mounet, F., 2019. A systems biology view of wood formation in Eucalyptus grandis trees submitted to different potassium and water regimes. New Phytologist 222, 1-17.

Quintek measurement systems., 1999. QMS Tree Ring Analyzer Model QTRS-01X. Users Guide., Knoxville, TN.

Raij, B.V., Cantarella, H., Quaggio, J.A., Furlani, A.M.C., 1996. Recomendações de adubação e calagem no Estado de São Paulo, second ed. Instituto Agronômico, Campinas.

Ramanantoandro, T., Ramanakoto, M., Rajoelison, G.L., Randriamboavonjy, J.C., Rafidimanantsoa, H.P., 2016. Influence of tree species, tree diameter and soil types on wood density and its radial variation in a mid-altitude rainforest in Madagascar. Annals of Forest Science 73, 1113–1124.

Rigatto, P.A., Dedecek, R.A., Matos, J.L.M., 2004. Influência dos atributos do solo sobre a qualidade da madeira de Pinus taeda para produção de celulose Kraft. Revista Árvore 28, 267-273.

Rossi, M., Mattos, I.F.A., Coelho, R.M., Menk, J.R.F., Rocha, F.T., Pfeifer, R.M., Demaria, I.C., 2005. Relação solos/vegetação em área natural no Parque Estadual de Porto Ferreira, São Paulo. Revista do Instituto Florestal 17, 45-61.

Rossi, M., 2017. Mapa pedológico do Estado de São Paulo: revisado e ampliado. Instituto Florestal, São Paulo.

Sales, A., 2004. Sistema de classes de resistência para dicotiledôneas: revisão da NBR 7190/97. Revista Madeira Arquitetura e Engenharia 17, 1-10.

Sales, A., Calil, C., 2005. Sistema de classes de resistência para dicotiledôneas: revisão da NBR 7190/97. Revista Madeira Arquitetura e Engenharia 17, 1-10.

Sansígolo, C.A., Ramos, E.S., 2011. Quality of wood and pulp from a clone of *Eucalyptus grandis* planted at three locations. Cerne 17, 47-60.

Santos, S.H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M. R., Almeida, J.A., Araujo-Filho, J.C., Oliveira, J.B., Cunha, T.J.F., 2018. Sistema Brasileiro de Classificação de Solos. EMBRAPA, Brasília.

Saranpää, P., 2003. Wood density and growth, in: Barnett, J.R., Jeronimidis, G. Wood Quality and its Biological Basis. Blackwell Publishing, Victoria, pp. 87-117.

Scolforo, J.R.S., 1993. Mensuração florestal 3: relações quantitativas em volume, peso e a relação hipsométrica. ESAL/FAEPE, Lavras.

Sette Jr, C.R., Deus JR, J.C., Tomazello-Filho, M., Pádua, F.A., Calil, F.N., Laclau, J.P., 2014a. Alterações na qualidade da madeira de *Eucalyptus grandis* causadas pela adubação mineral. Cerne 20, 251-258.

Sette Jr, C.R., Tomazello-Filho, M., Silva Jr, F.G., Laclau, J.P., 2014b. Alterações nas características químicas da madeira com a substituição do K por Na em plantações de eucalipto. Revista Árvore 38, 569-578.

Shashikala, S., Rao, R.V., 2009. Radial and axial variation in specific gravity and anatomical properties of platation grown *Eucalyptus citriodora* Hook. Journal of the Institute of Wood Science 19, 84-90.

Silva, C.E.M., Goncalves, J.F.C., Feldpausch, T.R., 2008. Water-use efficiency of tree species following calcium and phosphorus application on an abandoned pasture, central Amazonia, Brazil. Environ. Exp. Bot., 64, 189–195.

Silveira, R.L.V.A., Higashi, E.N., Sgarbi, F., Muniz, M.R.A., 2001. Seja o doutor do seu eucalipto. Informações agronômicas 12, 1-32.

Smith, K.T., Shortle, W.C., Conolly, J.H., Minocha, R., Jellyson, J., 2009. Calcium fertilization increases the concentration of calcium in sapwood and calcium oxalate in foliage of red spruce. Environ. Exp. Bot., 67, 277–283.

Stape, J.L., Binkley, D., Ryan, M.G., Fonseca, S., Loos, R.A., Takahashi, E.N., Silva, C.R., Silva, S.R., Hakamada, R.E., Ferreira, J.M.A., Lima, A.M.N., Gava, J.L., Leite, F.P., Andrade, H.B., Alves, J.M., Silva, G.G.C., Azevedo, M.R., 2010. The Brazil Eucalyptus potential productivity project: influence of water, nutrients and stand uniformity on wood production. For. Ecol. Manage, 259, 1684–1694.

Vale, A.T., Moura, V.P.G., Martins, I.S., Rezende, D.C.A., 1995. Densidade básica média em função da produtividade e da penetração do pino Pilodyn e da classe diamétrica e variação axial da densidade básica em *Eucalyptus grandis* W. Hill ex. Maiden. Árvore, 19, 80-91.

Vieira, H.A.F., 2003. Diagnostico da produção de madeira serrada e geração de resíduos do processamento de madeira de florestas plantadas no Rio Grande do Sul. Dissertação (Mestrado em Engenharia Cívil). Universidade Federal do Rio Grande do Sul, Porto Alegre.

Vilotić, D., Popović, J., Mitrović, S., Šijačić-Nikolić, M., Ocokoljić, M., Novović, J., Veselinović, M., 2015. Dimensions of Mechanical Fibres in *Paulownia elongata* S. Y. Hu Wood from Different Habitats. Drvna Industrija 66, 229-234.

Vitti, A.M.S., Brito, J., 1999. Evaluation of the yield and citronelal content of the essential oil of Eucalyptus citriodora provenances and land races. Scientia Forestalis 56, 145-154.

Walter, H., 1986. Vegetação e zonas climáticas. EPU, São Paulo.

White, D.A., Mcgrath, J.F., Ryan, M.G., Battaglia, M., Mendham, D.S., Kinal, J., Downes, G.M., Crombie, D.S., Hunt, M.E., 2014. Managing for water-use efficient wood production in Eucalyptus globulus plantations. For. Ecol. Manage, 331, 272–280.

CAPÍTULO 2 - SOILS TYPE INFLUENCE WOOD CHEMICAL CONSTITUENTS AND CALORIFIC VALUES OF 33-YEAR-OLD *Corymbia citriodora* (HOOK.) K. D. HILL, & L. A. S. JOHNSON*

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ABSTRACT

The objective of this study is to clarify how physical, chemical and water holding capacity differences among three types of soils can cause changes in wood density, extractive, lignin and holocellulose contents, higher heating value (HHV), lower heating value (LHV) and useful heating value (UHV) in *C. citriodora* wood. Wood density was lower in NV. We observed differences in chemical constituents of *C. citriodora* wood in three soil types. Regarding bioenergetic analysis, trees in RQ and LV soils have higher values of HHV, LHV and UHV than trees in NV soil. We concluded that the produced wood from three soils are suitable for use in bioenergy, since in Brazilian market, HHV values between 16500 and 18000 kJ.kg^{-1} are suitable values for use in bioenergy. Although in literature it is described that extractives and lignin are positively related, and holocellulose is negatively related to calorific value, in our study, wood density seems had a greater influence on calorific results than chemical constituents. It is possible that better water and nutrient availability from NV soil compared to RQ and LV may have led to higher tree growth, which resulted in lower density and therefore lower calorific values.

Keywords: extractives, holocellulose, higher heating value, lignin, lower heating value, wood density

2.1 Introduction

Woody biomass represents a renewable resource with multiple industrial applications. It serves as a raw material for the pulp and paper industry, but can also be planted specifically to meet the energy or biofuel needs (Hinchee et al. 2009).

The economic importance of *C. citriodora* in Brazil is more related to wood production for energy and sawmill, besides extraction of essential oils from leaves (Reis et al., 2013). The oils located in leaf glands are of great economic interest, since they make up the preparation of medicinal, industrial oils and perfumery products (Vitti and Brito, 2003). Recently, the use of *C. citriodora* has become more widespread and its wood has come to be appreciated for applications in industry and furniture making due to its qualities but also to scarcity of certified wood (Vilas Bôas et al., 2009). The interest in use of *C. citriodora* wood is explained by its durability and its little susceptible to cracking (Cunha et al. 2019). However, species does not yet have priority cultivation in forestry companies in Brazil (Vieira et al., 2004), being cultivated by small and medium rural owners for various uses. Cunha et al. (2019) suggest that lower use and studies of *C. citriodora* compared to *Eucalyptus* species, which are generally grown in short cycles for cellulose, coal, construction, etc., is due to *C. citriodora* not having extensive plantations and having a long production cycle.

In Australia, *C. citriodora* is tolerant of a variety of soils, but is commonly found in poor, stony soils, podzols and residual podsols of lateritic origin, and prefers well-drained but somewhat stony basements (Orwa et al., 2009). In Brazil it is used for reforestation in central region of country and northeast coast. The wide distribution of *C. citriodora* is explained due to its good adaptation to regions with different edaphoclimatic conditions, good wood volumetric incremente, and sprouting capacity after cutting (Reis et al., 2013). In São Paulo, *C. citriodora* has susceptibility to frost and a good resistance to water deficit (IPEF - Forest Research Institute, 2017).

According to IPEF (Forest Research Institute, 2017), wood is widely used for buildings, structures, sleepers, charcoal, etc. *C. citriodora* wood is also used for industrial production of chipboard (Iwakiri et al., 2000) and as coal most demanded in the steel industry. According to Geromel et al. (2011), 5-year-old *C. citriodora* produces 231.36 tons/ha of wood and consequently 71.58 tons/ha of coal.

In the present study, we investigated the wood of *Corymbia citriodora* (Hook.) K. D. Hill, & L. A. S. Johnson (formerly *Eucalyptus citriodora* Hook.) in three soil types: Quartzarenic Neosol, Red Latosol and Red Nitosol. Our objective is to clarify how physical, chemical and water holding capacity differences among three types of soils: Quartzarenic Neosol, Red Latosol and Red Nitosol can cause changes in wood density, extractive, lignin and holocellulose contents, higher heating value, lower heating value and useful heating value in *C. citriodora* wood.

2.2 Materials and methods

2.2.1. Provenances of the seeds, planting area and sampling

In 1982, *Corymbia citriodora* seeds of open-pollinated plants were collected in commercial plantations in Pederneiras State Forest, located in Pederneiras City, São Paulo State, Brazil (22°27′S, 48°44′W, elevation 500 m), climate is CWa. In 1983, progeny test was established with 56 progenies at the Luiz

Antonio Experimental Station (LAES), in Luiz Antônio City, São Paulo (21º40’S, 47º49’W, elevation 550 m) (Gurgel-Garrido et al., 1997). Climate is Aw in the Köppen-Geiger classification (Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura – CEPAGRI, 2019). The average annual rainfall is 1,365 mm and average annual temperature is 21.7º C, with the warmest months occurring in January, February and March, and the coldest months in May, June and July.

The planting was established at a spacing of 3 x 2 m, with one external border rows of the same species, without fertilization. The planting was installed with the same design in three different soil types According to Brazilian system of soil classification - SiBCS (Embrapa, 2019): site 1 has soil classified as Quartzarenic Neosol (symbol is RQ), site 2 as Red Latosol (LV), and site 3 as Red Nitosol (NV). The correspondence between classes of SiBCS compared with WRB/FAO, Soil Taxonomy, categorical order and suborder level of their most recent editions (Embrapa, 2019).

In 2008, LAES team determined height, DBH (diameter at breast height - 1.30 m from the ground), stem shape, using a grading system, with values ranging from one (worst grade, crooked trunks) to five (best grade, straighter trunks) and survival. In 2015, LAES team conducted new growth, shape and survival analyzes, but competition among the trees was added. The 2008 and 2015 information served as basis for us to select 18 trees (one of each progeny), the tallest and largest in diameter, for each type of soil, totaling 54 trees.

In 2016, we felled selected trees, and from each tree, a log, 1 meter in length was cut at the region immediately below the breast height. From logs, a central plank (5 cm thick), and from these planks, we cut three specimens in three radial positions: the nearest part of trunk center, designated as pith, a middle position, and a position close to the bark, designated as bark.

2.2.2. Soil sampling and analysis

We performed physical and soil water retention analysis according to Embrapa (1997). We collect samples at depths between 0–20 cm three points within plantation and then we mixed samples to prepare a composite sample, we repeat the same procedure for each soil type. For texture analysis we determined the percentages of sand, clay and silt. We also determined soil water retention content, and soil bulk density with volumetric cylinder.

Air-dried soil samples were analyzed for phosphorus (P); aluminum (Al); H+Al; aluminum saturation (m%); the basic cations, including potassium (K), calcium (Ca), and magnesium (Mg); sum of the bases Ca, Mg and K (SB); pH; base saturation (V%); micronutrients boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn); cation exchange capacity (CEC); total organic carbon (O.M.). Soil analysis was carried out as per the procedures described by Raij et al. (1996).

2.2.3 Density (ρ12)

Wood density at 12% moisture content was determined according to Glass and Zelinka (2010). The mass and volume at 12% moisture content (MC) were evaluated. Specimens of size 2 cm x 2 cm x 3 cm were conditioned at constant temperature (21°C) and 65% MC, respectively and, in these conditions, the mass was determined using an analytical balance and the volume was estimated by means of measurements of their diameters with an external digital micrometer.

2.2.4. Chemical assays

To determine extractives (EX) and lignin (LI) contents, TAPPI standards T204 (TAPPI, 1998/1999a) and T222 (1998/1999b) were used, respectively. The samples were fragmented into smaller pieces with a hammer and chisel and milled in a micro mill. The resulting powder was sieved through 40 and 60 mesh screens, and the material retained on the last sieve was used for analysis. The analyses were sequential such that the extractives were first removed, then lignin by acid treatment and holocellulose content was calculate. For extractive contents, solutions of toluene: alcohol (2:1 v:v) and alcohol extractions were employed, at times exceeding 12 h in a Soxhlet extractor. For lignin, extractive-free powder was prepared in several stages with 72% sulfuric acid to obtain insoluble and soluble lignin (Cary 100 UV–visible spectrophotometer). Finally, the two values of lignin were added. Insoluble lignin (IL) content was determined as IL = [(DWlig) / (DW)] * 100, where: DW = Dry sawdust weight, and DWlig = Dry weight of insoluble lignin. Soluble lignin (SL) we analyzed filtrates and the blank were read at two wavelengths (215nm and 280nm) using quartz cuvettes, soluble lignin content was determined as the SL = [4.53 * (L.215 – blank) – (L.280 – blank) / (300 * DW) * 100], where: DW = Dry sawdust weight. Ex and Li were expressed as a percentage (%) of oven-dry weight of unextracted wood. Then, the holocellulose (HO) content was determined as Ho% = [100 – Li].

2.2.5. Bioenergy values

In this step, samples from pith to the bark (wood near to the bark) were mixed. The moisture content was determined based on the methodology described by NBR 14929: 2003 (Wood - Determination of the moisture content of chips - Method for oven drying). Wood chips were placed in forced ventilation oven at 103 °C ± 2 °C until constant mass was obtained. Mass is considered constant when after successive weighing there is no change in reading (± 0.5 g) within a time interval of one hour. The moisture content was determined as MC = (WM - DM / DM) * 100 (%), where: MC = moisture content (%), WM = Sample wet mass (g) and DM = Sample dry mass (g).

We determinate Higher Heating Value (HHV) using an adiabatic calorimeter pump, following NBR 8633: 1984 (Charcoal - Determination of calorific value - test). The samples were fragmented into smaller pieces with a hammer and chisel and milled in a micro mill. The resulting powder was sieved through 40 and 60 mesh screens, and the material retained on the last sieve was used for analysis. A 1g sample was taken from each sample, homogenized and again separated into three fractions.

We determined Lower Heating Value (LHV) by equation:

$LHV = HHV – [600 * 9 * H) / 100]$,

where LHV = Lower Heating Value ($kJ.kg^{-1}$), HHV = Higher Heating Value ($kJ.kg^{-1}$), and H = Hydrogen (%).

For calculation of Useful Heating Value (UHV), we used a moisture content of 20% in dry basis (average value in which wood for burning firewood in poultry is used), which represents 16.67% moisture in wet basis, which is the value used in equation:

$UHV = LHV * (100 – U / 100) – 6 * U$ ($kJ.kg^{-1}$),

where UHV = Useful Heating Value ($kJ.kg^{-1}$), LHV = Lower Heating Value ($kJ.kg^{-1}$), U = Wet basis moisture content (%).

2.6 Data Analyses

We utilize a multivariate analysis via principal components analysis to verify the grouping of the different observed responses to different soil classes taking into account the entire set of physical, chemical e heating values features. Because the measurement units differed between features, the data were log-transformed to reduce the effect of the numeric scale (McGarigal et al. 2000).

2.3 Results

2.3.1. Soils

We found differences in soil texture according to granulometry analyzes in the three soil types. The RQ has 52% coarse sand, 41% fine sand, 4% clay and 3% silt. The LV has 40% coarse sand, 41% fine sand, 16% clay and 3% silt. The NV presented the lowest amount of coarse sand (6%), fine sand (13%) and the largest amount of clay (52%) and silt (29%) (Table 1).

Table 1

Physical attributes of three soil types (0-20 cm layer) of 33-year-old *Corymbia citriodora* plantings.

Soils	Sand			Clay	Silt	Soil texture
	Coarse	Fine	Total			
			($g.kg^{-1}$)			
RQ	516	415	930	43	27	Sandy
LV	399	413	812	158	30	Medium
NV	65	130	195	519	286	Clayey

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV).

For chemical attributes we observed differences between pH, organic matter, macronutrient and micronutrient, base saturation. We noticed the most acidic pH in LV, the organic matter is higher in NV. The soils LV and RQ have high Al^{3+}, phosphorus, potassium, calcium and magnesium have low values. Sulfur has average reference values for three soil types. On the other hand, micronutrients present difference between LV, with high values and NV with low values for copper. In both soils, iron presents high values, and manganese and zinc low values. NV has high values for all macronutrients and micronutrients. According to the reference values the base saturation (V%) is very low for LV and low for RQ and NV soils (Table 2). RQ has higher soil density, while NV has lower density and higher retained water (Table 3).

Table 2

Soil pH, organic matter and mineral nutrients of 33-year-old *Corymbia citriodora* in three soil types (0-20 cm layer).

	pH	O.M	P	Al^{3+}	H+Al	K	Ca	Mg	S	SB	CEC	m%	V%	B	Cu	Fe	Mn	Zn
Soils	$CaCl_2$	$g.dm^{-3}$	$mg.dm^{-3}$		$mmol_c.dm^{-3}$									$mg.dm^{-3}$				
RQ	4.1	7	3	6	29	0.4	2	1	7	3	32	64	9	0.15	0.2	88	0.5	0,1
LV	3.8	10	4	10	56	0.4	2	1	6	3	59	75	5	0.20	1.4	68	0.9	0,1
NV	4.6	24	96	1	92	6.1	62	13	7	81	173	1	47	0.26	14.6	49	94.8	4,4

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV). total organic carbon (O.M.); phosphorus (P); aluminum (Al); H+Al; potassium (K), calcium (Ca), magnesium (Mg); sulfur (S); sum of the bases Ca, Mg and K (SB); cation exchange capacity (CEC); aluminium saturation (m%); base saturation (V%); boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn).

Table 3

Soil water holding capacity and soil density of 33-year-old *Corymbia citriodora* in three soil types (0-20 cm layer).

	Retained water ($dm^3.dm^{-3}$)								
	Tension (MPa)								Soil density
Soils	Saturated	0.003	0.006	0.01	0.03^{FC}	0.1	0.5	1.5^{PWP}	($kg.dm^{-3}$)
RQ	0.43c	0.33c	0.22c	0.13c	0.09c	0.07c	0.06c	0.05c	1.85a
LV	0.53b	0.39b	0.29b	0.19b	0.14b	0.12b	0.10b	0.10b	1.70b
NV	0.63a	0.47a	0.44a	0.38a	0.33a	0.31a	0.29a	0.29a	1.51c

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV). FC = field capacity, PWP = permanent wilting point.

We observed differences in wood density and chemical constituents of *C. citriodora* wood in three soil types. Wood density was lower in NV. We found differences in extractives content, higher in NV and lower in RQ, and LV did not differ from NV and RQ. Lignin content was higher in LV and holocellulose was higher in RQ (Table 4).

Table 4

Wood density (ρ12%) and chemical constituents of 33-year-old *Corymbia citriodora* wood in three soil types.

	Quartzarenic Neosol	Red Latosol	Red Nitosol
ρ12% (g.cm^{-3})	0.91a	0.92a	0.87b
EC (%)	8.04b	8.97ab	9.33a
LC (%)	29.28b	30.14a	29.85b
HC (%)	62.66a	60.88b	60.81b

ρ12% = wood density; EC = extractive content; LC = lignin content; HC = holocellulose content. In the same line, distinct letters differ statistically ($P < 0.05$) by Tukey's test.

Regarding bioenergetic analysis, trees in RQ and LV soils has higher values of HHV, LHV and UHV than trees in NV soil (Table 5).

Table 5

Comparison among Higher Heating Value, Lower Heating Value and Useful Heating Value of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol	Red Latosol	Red Nitosol
HHV (kJ.kg^{-1})	20036a	19949a	19599b
LHV (kJ.kg^{-1})	18763a	18676a	18327b
UHV (kJ.kg^{-1})	16142a	16218a	15828b

HHV = Higher Heating Value; LHV = Lower Heating Value; UHV = Useful Heating Value. In the same line, distinct letters differ statistically ($P < 0.05$) by Tukey's test.

Table 6 and Figure 1 show the correlations among the variables examined and the first and the second ordination axes, responsible for 82.3% of the explanation of PCA. Axis 1 contributed 58% of the variability and the variables which were most correlated to it were: holocellulose content (r = -0.979), lignin content (r = 0.917), and extractive content (r = 0.896). Axis 2 contributed with 24.2% of the variability, and the variables with higher correlation coefficients were: useful heating value (r = 0.887) and density (r = 0.576).

Table 6

Principal component analysis of physical and chemical properties and heating values of 33-year-old *Corymbia citriodora* in three soil types.

	Principal Components	
Variables	PC 1	PC 2
Density 12%	0.544	0.576
Extractive content	0.896	-0.246
Lignin content	0.917	0.022
Holocellulose content	-0.979	0.171
Useful heating value	0.060	0.887
Percentage of explained variation	58.09%	24.22%

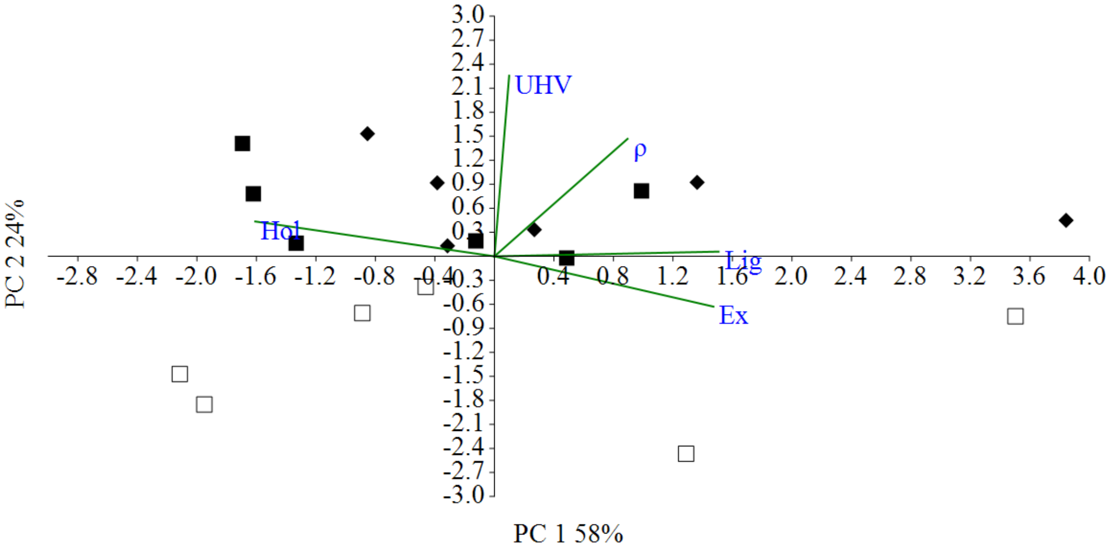

Fig. 1. Ordination generated via principal components analysis based on the entire data set obtained of physical and chemical properties and heating values. Soil classes are represented by (■) Quartzarenic Neosol, (◆Red Latosol (LV) and (□) Red Nitosol. Density 12% (ρ), Contents of extractives (Ex), Contents of lignin (Lig), Contents of holocellulose (Hol) and Useful Heating Value (UHV). The percentage of variation explained by each principal componente (PC1 and PC2) is shown.

2.4 Discussion

The three soil types significantly influenced wood density, chemical constituents and calorific value of *C. citriodora* wood. According to Dias and Arroja (2012), calorific value is directly related to wood density. In a study of coal production from timber industry waste in northern Brazil, Silva et al. (2007) reported that density is used as one of parameters for selecting species with energy potential. Considering these statements, based on density, wood from RQ and LV trees presents higher potential for energy, since the mean value (between radial positions) shows higher density when compared to wood from NV trees. The wood density results corroborate these statements, since wood from LV trees presented the lowest values of HHV, LHV and UHV. However, Quirino et al. (2005) suggest that woods with lower densities and wood waste can be transformed into briquettes or pellets to increase calorific value.

Gava and Gonçalves (2008) observed that extractives content in *Eucalyptus grandis* wood was not affected by soil attributes, while total lignin content decreased and holocellulose content increased with soil clay content increased. In the present study, we observed distinct results in *C. citriodora*, in which extractives content was increasing together with clay content in the soil, with lowest value in RQ and highest in NV. Whereas lignin content was higher in LV that has intermediate clay amount. While holocellulose content was higher in RQ, with lower clay amount. Showing that results may vary depending on the species despite studies on same soil type, emphasizing that Gava and Gonçalves (2008) also studied the chemical constituents of *Eucalyptus grandis* wood in Red Latosol, Yellow Red Latosol and Quartzarenic Neosol.

In addition to differences found in extractives content between soil types for *C. citriodora*, the age factor also has an effect on extractives content. Our results on 33-year-old *C. citriodora* presented mean ET values from 8.04% to 9.33% similar to those found for older trees. Several studies with *C. citriodora* of different ages have verified different values for extractives content. The 32-year-old *C. citriodora* presented an average extractive content of 7.29% (Severo et al., 2006), 10-year-old presented average extractive content of 5.68% (Costa et al., 1997) and 7-year-old presented average extractive content of 6.25% (Zanuncio et al., 2014). Sette Jr. et al. (2014) evaluated the effect of fertilization with K and Na on

Eucalyptus grandis from 1 to 4 years, under similar climatic conditions to this study and dystrophic Red-Yellow Latosol soil with medium texture (200 g.kg^{-1} clay). The authors found that there was no difference for extractive content between fertilization and control treatments, however there was a difference between the different ages, with 5.1% in the first year and 2.1% in the fourth year.

The lignin contents of three soil types did not present the same response pattern found for the extractives contents. Between soil classes, NV and RQ there was no difference for lignin contents, both soils have distinct characteristics for the physical, nutritional and water properties. The LV soil class showed a slight increase for NV soil (0.97%) and RQ soil (2.94%). Barbosa et al. (2019) found in 6-year-old *Eucalyptus grandis* x *Eucalyptus urophyla* clones a positive correlation between lignin contents and rainfall and a negative correlation for water deficit in different localities with different climatic conditions.

Sansígolo and Ramos (2011) in *Eucalyptus grandis* approximately 4-year-old planted in three different fertile soils, founded that extractive content showed no difference between three soil types, but there was a trend of increasing from less fertile soil to more fertile soil and lignin content also showed no difference between soil types and did not follow the same response trend regarding soil fertility.

The soil RQ presented highest holocellulose content with a difference of 3% to other soils. We suggest that higher holocellulose content in our results is related to increase in basic density. Similar results were founded by Melo et al. (2016) and Arnaud et al. (2019) in *Eucalyptus* woods planted in low fertility and hydrically available soils.

Extractives and lignin are positively related to calorific value (Telmo and Lousada, 2011), and high lignin values are associated with higher charcoal gravimetric yield (Pereira et al. 2000). While holocellulose is negatively related to calorific value, as thermal degradation of holocellulose is faster than lignin (Costa et al. 2014). In this context, woods with highest potential for energy use would be those with higher extractives and lignin content, but with lower holocellulose content (Menucelli et al., 2019).

Based on this information, wood from LV trees with higher values of lignin and LV and NV due to higher extractives values would be most suitable for energy use. While wood from RQ presents lowest potential for energy. However, when analyzing calorific results, we found that they did not follow the expected pattern for chemical constituents, since wood from LV trees presented higher extractives content, together with LV wood and lower lignin content, together with RQ wood. Thus, it seems that density had a greater influence on calorific results than chemical constituents. From principal components analysis, it was clear the separation of soils RQ and LV, with chemical onstituents (EC, LC and HC) from NV. In Table 7 we identified that UHV showed lowest value in axis 1, but had highest participation in axis 2, contributing to separate samples from NV.

However, despite lower calorific values from NV, according to Menucelli et al. (2019) in Brazilian market, HHV values between 16500 and 18000 kJ.kg^{-1} are suitable values for use in bioenergy. Thus, wood from three soils are suitable for use in bioenergy.

2.5 Conclusion

Wood from three soils are suitable for use in bioenergy, since in Brazilian market, HHV values between 16500 and 18000 kJ.kg^{-1} are suitable values for use in bioenergy. Although in literature it is described that extractives and lignin are positively related, and holocellulose is negatively related to calorific value, in our study, wood density seems had a greater influence on calorific results than chemical constituents. It is possible that better water and nutrient availability from NV soil compared with RQ and LV may have led to higher tree growth, which resulted in lower density and therefore lower calorific values.

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References

Arnaud C, Brancheriau L, Sabatier S, Heinz C, Chaix G, Tomazello Filho M. Interactions between the mechanical and hydraulic properties of *Eucalyptus* trees under diferente environmental conditions of fertilization and water availability. BioResources 2019;14(3):7157-7168.

Associação brasileira de normas técnicas. NBR 14929: 2003: Determinação do teor de umidade de cavacos – Métodos por secagem em estufa. Rio de Janeiro: ABNT; 2004.

Associação brasileira de normas técnicas. NBR 8633: 1984: Carvão vegetal – Determinação do poder calorífico. Rio de Janeiro: ABNT; 2004.

Barbosa TL, Oliveira JTS, Rocha SMG, Câmara AP, Vidaurre GB., Rosado AM, Leite FP. Influence of site in the wood quality of Eucalyptus in plantations in Brazil. Southern Forests 2019;81:247–253.

Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura – CEPAGRI, https://www.cpa.unicamp.br/; 2019. [accessed 20 May 2019].

Costa TG, Bianchi ML, Protásio PT, Trugilho PF, Pereira A. Qualidade da madeira de cinco espécies de ocorrência no cerrado para produção de carvão vegetal. Cerne 2014;20(1):37-46.

Cunha GM, Gama-Rodrigues AC, Gama-Rodrigues EF, Moreira GR. Nutrient Cycling in Corymbia citriodora in the State of Rio de Janeiro, Brazil. Floresta e Ambiente 2019; 26(2):1-10.

Dias AC, Arroja, L. Environmental impacts of eucalypt and maritime pine wood production in Portugal. Journal of Cleaner Production 2012;37:368-376.

Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA., WRB/FAO and Soil Taxonomy, https://www.embrapa.br/solos/sibcs/correlacao-com-wrb-fao-e-soil-taxonomy/; 2019. [accessed 20 May 2019].

Empresa brasileira de pesquisa agropecuária – EMBRAPA. Manual de métodos de análises de solo, 2 ed, Rio de Janeiro: Ministério da Agricultura e do Abastecimento; 1997

Gava JL, Gonçalves JLM. Soil atributes and wood quality for pulp production in platations of *Eucalyptus grandis* clones. Sci. Agric. 2008**;**65(3):306-313.

Geromel GKS, Paula NF, Paula RC. Caracterização físico-química da madeira e produção de carvão de Corymbia citriodora. Ciência & Tecnologia: FATEC-JB, Jaboticabal 2011;3:3–6.

Gurgel-Garrido LMA, Siqueira ACMF, Cruz SF, Romanelli RC, Ettori LG, Crestana CSM, Sato AS. Programa de melhoramento genético florestal do Instituto Florestal. IF Série Registros 197;18:1-53.

Hinchee M, Rottmann W, Mullinax L, Zhang C, Cunningham M, Pearson L, Nehra N. Short-rotation woody crops for bioenergy and biofuels applications. In Vitro Cell. Dev. Biol 2009;45(6):619–629.

IPEF – Instituto de pesquisa e estudos florestais. Identificação de Espécies Florestais, http://www.ipef.br/identificacao/cief/especies/citriodora.asp; 2017 [accessed 8 October 2017].

Iwakiri S, Cruz R, Olandoski DP, Brand MA. Utilização de resíduos de serraria na produção de chapas de madeira aglomerada de Eucalyptus saligna, Eucalyptus citriadora e Eucalyptus pilularis. Floresta e Ambiente 2000;7(1):251–256.

McGarigal K, Cushman S, Stafford S. Multivariate Statistics for Wildlife Ecology Research. New York: Springer; 2000.

Melo LEL, da Silva JRM, Napoli A, Lima JT, Paulo FT, Nascimento DFR. Influence of genetic material and radial position on the anatomical structure and basic density of wood from *Eucalyptus* spp. and *Corymbia citriodora*. Scientia Forestalis 2016;44(111):611-621.

Menucelli JR, Amorim EP, Freitas MLM, Zanata M, Cambuim J, Moraes MLT, Yamaji FM, Silva Júnior FG, Longui EL. Potential of Hevea brasiliensis Clones, Eucalyptus pellita and Eucalyptus tereticornis Wood as Raw Materials for Bioenergy Based on Higher Heating Value. BioEnergy Research 2019;14: 1-8.

Orwa C, Jamnadass RH, Kindt R, Mutua A, Simons A. Agroforestree Database: A Tree Reference and Selection Guide Version 4.0, http://www.worldagroforestry.org/af/treedb/; 2009 [accessed 20 May 2019].

Pereira JCD, Sturion JA, Higa AR, Higa RCV, Shimizu JY. Características da madeira de algumas espécies de eucalipto plantadas no Brasil. Colombo: Embrapa Florestas; 2000.

Quirino WF, Vale AT, Andrade AD, Abreu, VLS, Azevedo ADS. Poder calorífico da madeira e de materiais ligno-celulósicos. Revista da madeira 2005;89:100-106.

Raij BV, Cantarella H, Quaggio JA, Furlani AMC. Recomendações de adubação e calagem no Estado de São Paulo. 2.ed. Campinas: Instituto Agronômico; 1996.

Reis CAF, Assis TF, Santos AM, Paludzyszyn-Filho E. Corymbia citriodora: estado da arte de pesquisas no Brasil. Colombo: Embrapa Florestas, 2013.

Sansígolo CA, Ramos ES. Quality of wood and pulp from a clone of *Eucalyptus grandis* planted at three locations. Cerne 2011;17(1):47-60.

Sette Júnior CR, Tomazello Filho M, Silva Júnior FG, Laclau JP. Changes in chemical properties of wood with substitution of K by Na in *Eucalyptus* plantations. Revista Árvore 2014;38(3):569-578.

Severo ETD, Calonego FW, Sangígolo CA. Composição química da madeira de *Eucalyptus citriodora* em função das direcções estruturais. Silva Lusitana 2006;14(1):113-126.

Silva MG, Numazawa S, Araujo MM, Nagaishi TYR, Galvão GR. Carvão de resíduos de indústria madeireira de três espécies florestais exploradas no município de Paragominas, PA. Acta Amazonica 2007;37(1):61-70.

Technical association of pulp and paper industry. Solvent extractives of wood and pulp: T204 cm-97. Atlanta; 1998/1999a.

Technical association of pulp and paper industry. Acid – insoluble lignin in wood and pulp: T222 om-98. Atlanta; 1998/1999b.

Telmo C, Lousada J. Heating values of wood pellets from different species. Biomass Bioenergy 2011;35:2634-2639.

Vieira IG. Estudo de caracteres silviculturais e de produção de óleo essencial de progênies de Corymbia citriodora (Hook) K.D.Hill & L.A.S. Johnson procedente de Anhembi SP - Brasil, Ex. Atherton QLD - Austrália. Piracicaba: Dissertação (Mestrado em Ciências Florestais) - Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo; 2004, p. 80.

Vilas Bôas O, Max JCM, Melo ACG. Crescimento comparativo de espécies de Eucalyptus e Corymbia no município de Marília, SP. Revista Instituto Florestal 2009;21(1):63-72.

Vitti AMS, Brito JO. Óleo Essencial De Eucalipto. Documentos florestais - Escola Superior de Agricultura "Luiz de Queiroz" - Universidade de São Paulo 2003;17:1–26.

Zanuncio AJV, Carvalho AG, Trugilho PF, Monteiro TC. Extractives and energetic properties of wood and charcoal. Revista Árvore 2014;38(2):369-374.

CAPÍTULO 3 - WOOD POTENTIAL OF 33-YEAR-OLD *Corymbia citriodora* (HOOK.) K. D. HILL & L. A. S. JOHNSON FOR PULP AND PAPER3*

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ABSTRACT

The pulp and paper industry have great importance in the Brazilian economy. In the present study, we investigated wood of *Corymbia citriodora* in three soil types: Quartzarenic Neosol, Red Latosol and Red Nitosol. Our objective is to clarify how physical, chemical and water holding capacity differences among three types of soils: Quartzarenic Neosol, Red Latosol and Red Nitosol can cause changes in wood density and anatomical ratios for pulp and paper in *C. citriodora* wood. We note some differences in wood density and anatomical ratios for pulp and paper, but in general, we suggested that *C. citriodora* wood has very high values, and in case of paper production would result in a sheet of high density and rigidity, which is not suitable for general use of writing paper, but it can provide formation of a paper that meets a specific need. In contact with people linked to pulp and paper companies, there is a current interest in *C. citriodora* for hybrids production. Thus, we hope that results of our study can contribute to this approach.

Keywords

Quartzarenic Neosol, Red Latosol and Red Nitosol, Fibers, Wood

3.1 INTRODUCTION

The pulp and paper industry have great importance in the Brazilian economy, according to from the Brazilian Tree Industry - Ibá (2017), this year Brazil was in second position among the world's largest pulp and eighth place in the rankings of the paper producers.

These results can be explained by Brazil's high efficiency and competitiveness in pulp production, largely due to soil and climate conditions and history of investment in forest research and development, carried out by companies in the sector and by research agencies. As a result of these aspects, national pulp production has been growing fast since the early 1990s (Hora, 2019). According to Risi (2015), Brazil presented in 2015 almost 15 million tons / year for pulp and market installed capacity.

Almost all pulp and paper preparation is made from wood of different species (Foekel, 2009), and most of the raw material is wood from *Pinus* and *Eucalyptus* species. Despite all technological development over the years and equipment used in paper production, it should always be considered that there are variations in wood and also those imposed by humans in production (Foekel, 2009). Thus, there is always room for the study of new species, species already employed under different conditions of growth and development, for genetic improvement, for development of new processes or equipment, etc.

Thus, it is essential to study *Eucalyptus* and *Corymbia* species under different conditions in order to find new materials for pulp and paper production. In this context we highlight the planting of *Corymbia citriodora* planted experimentally in units of the Forest Institute (Gurgel-Garrido et al., 1997).

Several characteristics, from soil and climate conditions, type and planting management, tree growth and development, wood characteristics such as density and its cellular variations must be studied to attest wood quality to be used in paper production and cellulose. Foekel (2009) presents some essential characteristics for pulp and paper production, for example: tree volume, wood density, percentage of chemical constituents such as extractives, lignin and holocellulose, the characteristics and proportions of the cells that make up the wood.

Other essential data are obtained from knowledge about wood quality, in particular density, which is defined as the ratio of mass to volume expressed by the international system (SI) in units of kilograms per cubic meter (kg.m^{-3}) (Glass and Zelinka, 2010). Density is used to estimate mechanical properties (Hoadley, 2000), but it is also an important parameter for estimating wood quality as a raw material for pulp and paper industry. However, as in general, higher density is found in regions of adult wood compared to young wood, and according to Foekel (2009), the latter has more appropriate characteristics for paper production. Fiber characteristics such as Runkel Index (Runkel, 1952), obtained from the fiber lumen dimensions and fiber wall thickness are closest parameters for determining paper quality. Additionally, Horn (1978) reports that Runkel index is a microscopic extension of wood density, precisely by using the fiber characteristics mentioned above. Thus, the study of anatomical variations is essential for understanding and choosing species for paper and pulp. For differences in the characteristics of cells, parenchyma, vessels and especially fibers directly influence the quality of raw material for this purpose. Different quality indices can be calculated based on fiber features.

In the present study, we investigated wood of *Corymbia citriodora* (Hook.), K.D. Hill, & L.A.S. Johnson (formerly *Eucalyptus citriodora* Hook.) in three soil types: Quartzarenic Neosol, Red Latosol and Red Nitosol. Our objective is to clarify how physical, chemical and water holding capacity differences among three types of soils: Quartzarenic Neosol, Red Latosol and Red Nitosol can cause changes in wood density and Anatomical ratios for pulp and paper in *C. citriodora* wood.

3.2 MATERIAL AND METHODS

Provenances of the seeds, planting area and sampling

In 1982, *Corymbia citriodora* seeds of open-pollinated plants were collected in commercial plantations in Pederneiras State Forest, located in Pederneiras City, São Paulo State, Brazil (22°27′S, 48°44′W, elevation 500 m), climate is CWa. In 1983, progeny test was established with 56 progenies at the Luiz Antonio Experimental Station (LAES), in Luiz Antônio City, São Paulo (21º40’S, 47º49’W, elevation 550 m) (Gurgel-Garrido et al., 1997). Climate is Aw in the Köppen-Geiger classification (Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura – CEPAGRI, 2019). The average annual rainfall is 1,365 mm and average annual temperature is 21.7º C, with the warmest months occurring in January, February and March, and the coldest months in May, June and July.

The planting was established at a spacing of 3 x 2 m, with one external border rows of the same species, without fertilization. The planting was installed with the same design in three different soil types According to Brazilian system of soil classification - SiBCS (Embrapa, 2019): site 1 has soil classified as Quartzarenic Neosol (symbol is RQ), site 2 as Red Latosol (LV), and site 3 as Red Nitosol (NV). The correspondence between classes of SiBCS compared with WRB/FAO, Soil Taxonomy, categorical order and suborder level of their most recent editions (Embrapa, 2019).

In 2008, LAES team determined height, DBH (diameter at breast height - 1.30 m from the ground), stem shape, using a grading system, with values ranging from one (worst grade, crooked trunks) to five (best grade, straighter trunks) and survival. In 2015, LAES team conducted new growth, shape and survival analyzes, but competition among the trees was added. The 2008 and 2015 information served as basis for us to select 18 trees (one of each progeny), the tallest and largest in diameter, for each type of soil, totaling 54 trees.

In 2016, we felled selected trees, and from each tree, a log, 1 meter in length was cut at the region immediately below the breast height. From logs, a central plank (5 cm thick), and from these planks, we cut three specimens in three radial positions: the nearest part of trunk center, designated as pith, a middle position, and a position close to the bark, designated as bark.

Soil sampling and analysis

We performed physical and soil water retention analysis according to Embrapa (1997). We collect samples at depths between 0–20 cm three points within plantation and then we mixed samples to prepare a composite sample, we repeat the same procedure for each soil type. For texture analysis we determined the percentages of sand, clay and silt. We also determined soil water retention content, and soil bulk density with volumetric cylinder.

Air-dried soil samples were analyzed for phosphorus (P); aluminum (Al); H+Al; aluminum saturation (m%); the basic cations, including potassium (K), calcium (Ca), and magnesium (Mg); sum of the bases Ca, Mg and K (SB); pH; base saturation (V%); micronutrients boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn); cation exchange capacity (CEC); total organic carbon (O.M.). Soil analysis was carried out as per the procedures described by Raij et al. (1996).

Density (ρ12)

Wood density at 12% moisture content was determined according to Glass and Zelinka (2010). The mass and volume at 12% moisture content (MC) were evaluated. Specimens of size 2 cm x 2 cm x 3 cm were conditioned at constant temperature (21°C) and 65% MC, respectively and, in these conditions, the mass was determined using an analytical balance and the volume was estimated by means of measurements of their diameters with an external digital micrometer.

Anatomical analysis

We cut small pieces of wood from each sample for maceration using Franklin's method (Berlyn and Miksche, 1976). Wood fragments were stained with aqueous safranin and mounted temporarily in a solution of water and glycerin (1:1). Samples of 2 cm^3 were softened in boiling water and glycerin (4:1) for 1 hour. From these samples, transverse sections 20μm in thickness were obtained with a sliding microtome. Sections were bleached with sodium hypochlorite (60%), washed thoroughly in water, and stained with 1% safranin (Johansen, 1940).

Measurements followed the recommendations of the IAWA Committee (IAWA, 1989). Quantitative data are based on at least 25 measurements for each feature from each tree, thus fulfilling statistical requirements for the minimum number of measurements. The proportions of fibers, vessels, axial parenchyma and rays in the transverse sections were measured using a 25-point grid for each sample. Anatomical measurements were obtained using an Olympus CX 31 microscope equipped with a camera (Olympus E330 EVOLT) and a computer image analysis software (Image-Pro 6.3).

Anatomical ratios for pulp and paper

From values of length (L), diameter (D), lumen diameter (d) and fiber wall thickness (w) we calculated the following ratios for pulp and paper: Flexibility coefficient (FC), Wall proportion (WP), Runkel ratio (RR), Slenderness ratio (SR), Luce's shape factor (LSF).

$FC = (d/D)$ (Milanez and Foelkel, 1981; Pirralho et al., 2014).

$WP = (2w)/D \times 100$ (Foelkel et al., 1978).

$RR = 2w/d$ (Runkel, 1952).

$SR = L/D$ (Ogbonnaya et al., 1997; Saikia et al., 1997).

$LSF = (D^2 - d^2)/(D^2 + d^2)$ (Luce, 1970).

Data analysis

We initially undertook descriptive statistical analysis and used Box Plot graphics to detect outliers. Thus, values 1.5 times higher than the 3rd quartile and values 1.5 times lower than the 1st quartile were excluded from the analysis. Normality tests were performed to check the distribution of data, and when a normal distribution was not observed, data were square root-transformed. Then, a parametric analysis of variance (one-way analysis of variance - ANOVA) was performed. When a significant difference was observed, Tukey's test was used to identify pairs of significantly different means. We analyzed the radial variation within the same tree and also three radial positions together comparing the results in three soil types.

3.3 RESULTS

We found differences in soil texture according to granulometry analyzes in the three soil types. The RQ has 52% coarse sand, 41% fine sand, 4% clay and 3% silt. The LV has 40% coarse sand, 41% fine sand, 16% clay and 3% silt. The NV presented the lowest amount of coarse sand (6%), fine sand (13%) and the largest amount of clay (52%) and silt (29%) (Table 1).

Table 1 Physical attributes of three soil types (0-20 cm layer) of 33-year-old *Corymbia citriodora* plantings.

Soils	Sand			Clay	Silt	Soil texture
	Coarse	Fine	Total			
			(g.kg^{-1})			
RQ	516	415	930	43	27	Sandy
LV	399	413	812	158	30	Medium
NV	65	130	195	519	286	Clayey

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV).

For chemical attributes we observed differences between pH, organic matter, macronutrient and micronutrient, base saturation. We noticed the most acidic pH in LV, the organic matter is higher in NV. The soils LV and RQ have high Al3 +, phosphorus, potassium, calcium and magnesium have low values. Sulfur has average reference values for three soil types. On the other hand, micronutrients present difference between LV, with high values and NV with low values for copper. In both soils, iron presents high values, and manganese and zinc low values. NV has high values for all macronutrients and micronutrients. According to the reference values the base saturation (V%) is very low for LV and low for RQ and NV soils (Table 2). RQ has higher soil density, while NV has lower density (Table 3).

Table 2 Soil pH, organic matter and mineral nutrients of 33-year-old *Corymbia citriodora* in three soil types (0-20 cm layer).

	pH	O.M	P	Al^{3+}	H+Al	K	Ca	Mg	S	SB	CTC	m%	V%	B	Cu	Fe	Mn	Zn
Soils	CaCl$_2$	g.dm^{-3}	mg.dm^{-3}		mmol$_c$.dm^{-3}									mg.dm^{-3}				
RQ	4.1	7	3	6	29	0.4	2	1	7	3	32	64	9	0.15	0.2	88	0.5	0,1
LV	3.8	10	4	10	56	0.4	2	1	6	3	59	75	5	0.20	1.4	68	0.9	0,1
NV	4.6	24	96	1	92	6.1	62	13	7	81	173	1	47	0.26	14.6	49	94.8	4,4

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV). total organic carbon (O.M.); phosphorus (P); aluminum (Al); H+Al; potassium (K), calcium (Ca), magnesium (Mg); sulfur (S); sum of the bases Ca, Mg and K (SB); cation exchange capacity (CEC); aluminium saturation (m%); base saturation (V%); boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn).

Table 3 Soil water holding capacity and soil density of 33-year-old *Corymbia citriodora* in three soil types (0-20 cm layer).

	Retained water ($dm^3.dm^{-3}$)								
	Tension (MPa)								Soil density
Soils	Saturated	0.003	0.006	0.01	0.03	0.1	0.5	1.5	($kg.dm^{-3}$)
RQ	0.43	0.33	0.22	0.13	0.09	0.07	0.06	0.05	1.85a
LV	0.53	0.39	0.29	0.19	0.14	0.12	0.10	0.10	1.70b
NV	0.63	0.47	0.44	0.38	0.33	0.31	0.29	0.29	1.51c

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV).

The flexibility coefficient gradually decreased from pith to the bark in the three soil types. The wall proportion, Runkel ratio and Luce’s shape factor increased from pith to the bark in the three soil types. While the slenderness ratio showed lower values in pith and higher values and no difference in intermediate and bark positions (Table 5).

Among soil types, flexibility coefficient was higher in NV. The wall proportion showed no differences between LV and RQ soils and a lower value can be observed in LV. Runkel ratio was higher in RQ and lower in NV. slenderness ratio was higher in LV and there was no difference between RQ and NV soils. Luce’s shape factor was lower in NV (Table 4).

Table 4 Radial variation of density and ratios for pulp and paper in 33-year-old *Corymbia citriodora* wood in three soil types.

	Quartzarenic Neosol				Red Latosol				Red Nitosol			
	Pith	Inter	Bark	Mean	Pith	Inter	Bark	Mean	Pith	Inter	Bark	Mean
ρ12	0.85b	0.93a	0.95a	0.91A	0.82c	0.93b	1.01a	0.92A	0.80c	0.85b	0.95a	0.87B
FC	0.31a	0.21b	0.17c	0.22B	0.28a	0.22b	0.18c	0.23B	0.37a	0.28b	0.23c	0.29A
WP	69.70c	78.62b	83.40a	77.24A	71.07c	77.13b	81.20a	76.47A	62.54c	71.63b	76.94a	70.37B
RR	3.03c	4.68b	6.04a	4.58A	3.01c	4.34b	5.07a	4.14B	2.09c	3.38b	4.23a	3.23C
SR	62.55b	65.81a	65.66a	64.67B	62.69b	69.22a	71.11a	67.67A	58.03b	66.37a	66.16a	63.52B
LSF	0.81c	0.90b	0.93a	0.88A	0.83c	0.88b	0.92a	0.88A	0.74c	0.83b	0.88a	0.82B

In the same line, distinct letters differ statistically (P <0.05) by Tukey test. Pith = wood near to the pith. Inter = wood of intermediate position. Bark = wood next to the bark. M = mean between radial positions. Lower case letters for differences between radial positions and upper-case letters for differences between soil types. ρ12 = wood density at 12% moisture content. FC = Flexibility coefficient. WP = Wall proportion. RR = Runkel ratio, SR = Slenderness ratio. LSF = Luce’s shape factor.

Fiber percentage increase gradually from the pith to the bark in RQ. In LV and NV fiber percentage was higher in intermediate and bark position. Vessel percentage did not vary in radial positions in three soil types. Axial parenchyma percentage increase gradually from the pith to the bark in RQ and was higher in pith in LV and NV. Radial parenchyma percentage in RQ soil was higher in intermediate and bark position, decrease from pith to the bark in LV, and did not vary in radial positions in NV (Figure 1). When considering the three positions together, we observed differences in vessel percentages, higher in RQ, and radial parenchyma, higher in LV and NV (Figure 2).

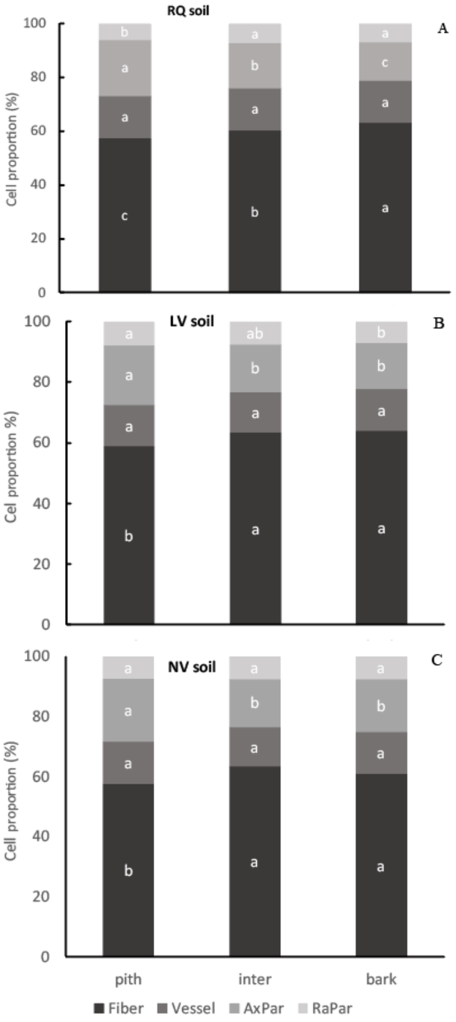

Figure 1. Proportion of cells in 33-year-old *Corymbia citriodora* wood in three soil types. Pith = wood near to the pith. Inter = wood of intermediate position. Bark = wood next to the bark. Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV).

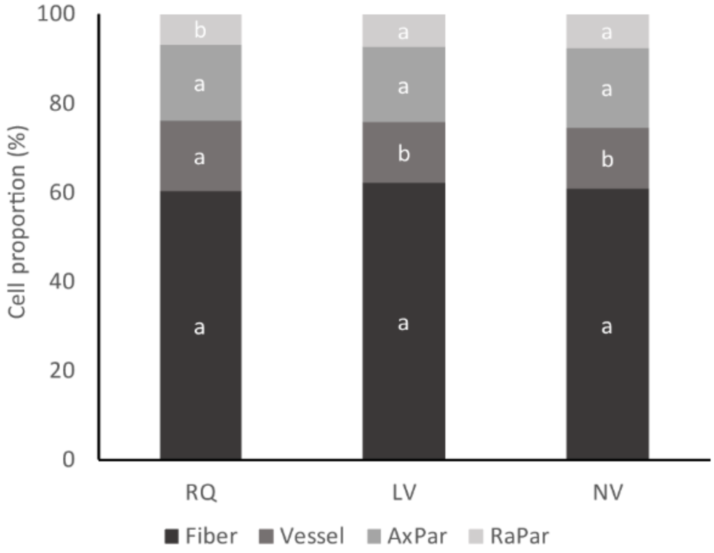

Figure 2. Proportion of cells in 33-year-old *Corymbia citriodora* wood in three soil types. Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV). In each soil the values are mean between radial positions.

3.4 DISCUSSION

In terms of fiber quality to papermaking, wood density followed the pattern commonly reported in literature, with increase toward the bark. Companing soil types, wood from NV trees presented the lowest density, which is theoretically linked to highest quality for pulp and paper.

Flexibility coefficient, with exception of value (0.37) in pith position in NV, classified as a thick wall type, in which fibers collapse very little, have little contact surface, and little union between fibers, all others were below 0.30, which means very thick wall type, in which fibers do not collapse, have very little contact surface, and poor union between fibers.

In wall proportion, the higher this index, the more rigid and resistant to collapse fibers will be (Foelkel, 2009). In this case, wood fibers in RQ and LV trees have higher values than those of NV. However, paper with poor flexibility originating from fibers with very high wall proportion values tends to have lower tensile and burst strength (Boschetti et al., 2015).

Fibers with higher Runkel ratio values are stiffer and less flexible (Ogunjobi et al. 2014) and produce more porous papers compared to lower RR fibers (KIAEI et al., 2014). The lowest RR value was observed in NV, however, it is suggested that values above 2 are classified in grade 5, which characterize low quality material for papermaking (Foelkel, 2009).

According to Agnihotri et al. (2010), the slenderness ratio interferes with paper density and tear resistance. This index is also directly related to pulp digestibility (OHSHIMA et al., 2005). In our study we observed the highest value in LV.

Luce's form factor is also related to final density of paper sheet and may be a property used in species selection for wood quality for paper and pulp (Baldin et al., 2017). The authors studied different paper quality indices in four *Eucalyptus* species, and found lower values than those of *C. citriodora*, even comparing with pith position values (0.81 in RQ), which represents young wood from studie trees. Luce's form factor values reported by Baldin et al. (2017) are: *E. benthamii* (0.50), *E. dunnii* (0.60), *E. grandis* (0.50) and *E. saligna* (0.49), the authors mention these values as means.

Fibers are cells that most occur in wood (Baas et al. 2004, Lachenbruch et al. 2011), and certainly those that most influence pulp and paper quality. However, other cells, vessels and parenchymatics also influence paper material quality. Fiber or other cells broken walls, as well as whole vessel and parenchyma cells, and other debris are often referred to as fines. These cause problems during pulping and refining, as well as further pulp processing (Foekel, 2009), with high quality pulps having lower fines (Fengel and Wegener 1989). Counting the percentage of each cell type, fiber, vessel, or parenchyma is a way of estimating fines amount.

When analyzing different radial positions, it would be obvious to consider wood from intermediate and bark position as lower quality for paper, since in paper and pulp production young trees are used. However, when analyzing the results we reported, in three soils, higher percentages of fibers from intermediate position to the bark. In addition, larger proportions of axial parenchyma in pith, which is youngest wood and theoretically would be used in paper production. However, with higher proportion of radial parenchyma in intermediate and bark positions in RQ and lower in pith in LV. When analyzing three positions together, values also confuse to establishment of quality, since there is a higher proportion of vessels and a lower proportion of radial parenchyma in pith.

3.5 CONCLUSION

In general, we suggested that *C. citriodora* wood has very high values, and in case of paper production would result in a sheet of high density and rigidity, which is not suitable for general use of writing paper, but it can provide formation of a paper that meets a specific need. In contact with people linked to pulp and paper companies, there is a current interest in *C. citriodora* for hybrids production. Thus, we hope that results of our study can contribute to this approach.

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REFERENCES

AGNIHOTRI, A.; DUTT, D.; TYAGI, C. H. Complete characterization of bagasse of early species of Saccharum officiherum-CO 89003 fot pulp and paper making. **Bioresources**, v. 5, n. 2, p. 1197-1214, 2010.

ABNT - ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 11941-02 - **Determinação da densidade básica em madeira**. Rio de Janeiro, 2003. 6p.

BAAS, P.; EWERS, F. W.; DAVIS, S. D.; WHEELER, E. A. Evolution of xylem physiology. In: POOLE, I.; HEMSLEY, A. (eds.). **Evolution of Plant Physiology**. London: Elsevier Academic Press. (Linnaean Society Symposium Series), 2004. p. 273 - 295.

BALDIN, T.; MARCHIORI, J. N. C.; SILVANA NISGOSKI, S.; TALGATTI, M.; DENARDI, L. Anatomia da madeira e potencial de produção de celulose e papel de quatro espécies jovens de Eucalyptus L'Hér. **Ciência da Madeira (Brazilian Journal of Wood Science**, v. 8, n. 2, p. 114-126, 2017.

BERLYN, G. P.; MIKSCHE, J. P. 1976. **Botanical microtechnique and cytochemistry**, Iowa, State University Press, Ames.

BOSCHETTI, W. T. N.; PAES, J. B.; OLIVEIRA, J. T. S.; DUDECKI, L. Características anatômicas para produção de celulose do lenho de reação de árvores inclinadas de eucalipto. **Pesq. agropec. bras.**, v. 50, n. 6, p. 459-467, 2015.

CENTRO DE PESQUISAS METEOROLÓGICAS E CLIMÁTICAS APLICADAS À AGRICULTURA – CEPAGRI. Disponível em: https://www.cpa.unicamp.br/; 2019. Acesso em: 20 Maio 2019.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA – EMBRAPA., **WRB/FAO and Soil Taxonomy**, Disponível em: https://www.embrapa.br/solos/sibcs/correlacao-com-wrb-fao-e-soil-taxonomy/; 2019. Acesso em: 20 Maio 2019.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA – EMBRAPA. **Manual de métodos de análises de solo**, 2 ed, Rio de Janeiro: Ministério da Agricultura e do Abastecimento; 1997.

FENGEL, D.; WEGENER, G. **Wood: chemistry, ultrastructure, reactions**. Berlin: Walter de Gruyter, 1989. 613 p.

FOELKEL, C. E. B. **Eucalyptus online book & newsletter. São Paulo**: Associação Brasileira Técnica de Celulose e Papel, 2009.

FOELKEL, C. E. B.; ZVINAKEVICIUS, C.; ANDRADE, J.; MEDEIROS, S. J. Eucaliptos tropicais na produção de celulose kraft. **Cenibra**, Belo Oriente, n. 68, p. 1-31, 1978.

GLASS, S.; ZELINKA, S. L. Moisture relations and physical properties of wood. *In*: ROSS, R. (Ed.). **Wood handbook – wood as an engineering material**. 100th ed. Madison: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 2010. 508 p.

GURGEL-GARRIDO, L. M. A.; SIQUEIRA, A. C. M. F.; CRUZ, S. F.; ROMANELLI, R. C.; ETTORI, L. G.; CRESTANA, C. S. M.; Sato, A. S. Programa de melhoramento genético florestal do Instituto Florestal**. IF Série Registros**, v. 18, p. 1-53, 1997.

HORA, A. B. Panoramas setoriais 2030: papel e celulose. *In*: **Panoramas setoriais 2030: desafios e oportunidades para o Brasil**. Rio de Janeiro: Banco Nacional de Desenvolvimento Econômico e Social, 2017. p. 79-91.

HORN, R. **Morphology of Pulp Fiber from Hardwoods and Influence on Paper Strength**. USDA Forest Service. Research Paper FPL 312, For. Prod. Lab., Madison, WI, USA. 1978.

HOADLEY, B. **Understanding Wood: A Craftsman's Guide to Wood Technology**. Taunton Press Inc; 2nd Revised edition, 2000.

IAWA COMMITTEE., 1989. IAWA list of microscopic features for hardwood identification.

IAWA Bulletin, 10, 219-332.

JOHANSEN, D., 1940. Plant microtechnique. McGraw Hill, London.

KIAEI, M.; TAJIK, M.; VAYSI, R. 2014. Chemical and biometrical properties of plum wood and its application in pulp and paper production. **Maderas. Ciencia y tecnologia**, v. 16, n. 3, p. 313-322, 2014.

LACHENBRUCH, B.; MOORE, J. R.; EVANS, R. Radial variation in wood structure and function in woody plants, and hypotheses for its occurrence. *In*: MEINZER, F. C.; LACHENBRUCH, B.; DAWSON, T. E. (Eds) **Size-and age-related changes in tree structure and function**. New York: Springer, 2011, p. 121-164.

LUCE, G. E. **The physics and chemistry of wood pulp fibers**. In: STAP, n. 8, TAPPI, New York, 1970, p. 278.

MILANEZ, A.C.; FOELKEL, C.E.B. Processos de deslignificação com oxigênio para a produção de celulose de eucalipto. In: Congresso anual da ABCP, 14., São Paulo. **Anais**... São Paulo: ABTCP. p. 37-110, 1981.

PIRRALHO, M.; FLORES, D.; SOUSA, V. B.; QUILHÓ, T.; KNAPIC, S.; PEREIRA, H. Evaluation on paper making potential of nine *Eucalyptus* species based on wood anatomical features**. Industrial Crops and Products**, v. 54, p. 327–334, 2014.

OGBONNAYA, C. I.; ROY-MACAULEY, H.; NWALOZIE, M. C.; ANNEROSE, D. J. M. Physical and histochemical properties of kenaf (Hibiscus cannabinus L.) grown under water deficit on a sandy soil. **Industrial Crops and Products**, v. 7, p. 9–18, 1997.

OGUNJOBI, K. M.; ADETOGUN, A. C.; SHOFIDIYA, S. A. Investigation of Pulping Potentials of Waste from Conversion of Anogeissus leiocarpus. **Journal of Polymer and Textile Engineering**, v. 1, n. 2, p. 26-30, 2014.

OHSHIMA, J.; YOKOTA, S.; YOSHIZAWA, N.; ONA, T. Representative heights for assessing whole-tree values and the within-tree variations of derived wood properties in Eucalyptus camaldulensis and E. globulus. **Wood Fibre Science**, v. 37, n. 1, p. 51-65, 2005.

RAIJ, B. van; CANTARELLA, H.; QUAGGIO, J.A.; FURLANI, A.M.C. **Recomendações de adubação e calagem no Estado de São Paulo**. 2.ed. Campinas: Instituto Agronômico, 1996. p. 300.

RISI. **Base de dados**. Disponível em: https://www.risiinfo.com/industries/pulp-paper-packaging/. Acesso em: 19 mai. 2019.

RUNKEL, R. O. H. PULP FROM TROPICAL WOOD. **TAAP**, v. 35, n 4, p. 174-178, 1952.

SAIKIA, S. N.; GOSWAMI, T.; ALI, F. Evaluation of pulp and paper making characteristics of certain fast growing plants. **Wood Science and Technology**, v. 31, p. 467–475, 1997.

CONSIDERAÇÕES FINAIS

As três classes de solos apresentaram características distintas entre suas propriedades físicas, químicas e hídricas.

Os solos mais argilosos e com maior disponibilidade de água influenciaram na produtividade e qualidade da madeira de *C. citriodora.*

As classes de solo LV e NV apresentaram maior porcentagem de alburno e maior diâmetro, essas condições são ideais para madeiras empregadas na construção civil, ou na produção de móveis, é interessante que a mesma possua maior porcentagem de cerne do que alburno, pois a maior parte do alburno é perdida com a retirada das costaneiras.

As madeiras com maior densidade básica foram obtidas de solos mais arenosos e com baixa disponibilidade de água, como observados em RQ e LV que corroboraram com a nossa hipótese.

A propriedade física retração volumétrica e as propriedades mecânicas não apresentaram diferenças entre os três tipos de solos. As diferenças foram observadas apenas no sentido radial, com um aumento gradativo no sentido medula-casca.

As madeiras mais homogêneas foram encontradas nos solos RQ e LV, por meio do índice de uniformidade.

As condições edáficas dos solos RQ e LV influenciaram na formação de fibras e vasos com menores comprimentos e diâmetros, paredes celulares mais espessas das fibras e maiores frequências de vasos e raios, este último mais largo em RQ. Estes resultados corroboraram com a nossa hipótese. No sentido radial houve um aumento gradativo no sentido medula-casca para todas as características anatômicas, com exceção para a largura da fibra.

Aos 33 anos a espécie *C. citriodora* mostrou altos teores de extrativos, lignina e holocelulose para os três tipos de solos. Os solos com maior capacidade para a produção de bioenergia foram os solos RQ e LV.

A madeira da espécie *C. citriodora* desenvolvida nos três tipos de solos não apresentou valores de índices para qualidade de papel desejáveis para a produção de papel aos 33 anos de idade.

REFERÊNCIAS

ALMEIDA, G.; BRITO, J. O.; PERRE, P. Alterations in energy properties of eucalyptus wood and bark subjected to torrefaction: the potential of mass loss as a synthetic indicator. **Biores Technol J**, v. 101, n. 24, p. 9778-9784, 2010.

ARNAUD, C et al. Interactions between the mechanical and hydraulic properties of *Eucalyptus* trees under diferente environmental conditions of fertilization and water availability. **BioResources**, v. 14, n. 3, p. 7157-7168, 2019.

ATTIA et al. Modelling carbon and water balance of *Eucalyptus* plantations at regional scale: Effect of climate, soil and genotypes. **Forest Ecology and Management**, v. 449, p. 1-13, 2019.

BARNETT, J. R.; JERONIMIDIS, G. **Wood quality its biological basis**. Blackwell/CRC, Oxford and Boca Raton, 2003, p 1–226.

BORDRON, B et al. Fertilization increases the functional specialization of fine roots in deep soil layers for young Eucalyptus grandis trees. **Forest Ecology and Management**, v. 431, p. 6–16, 2019.

BRAND, M. A. **Energia de Biomassa Florestal**. 01. ed. Rio de Janeiro: Interciência, 2010. p. 114.

BUTLER, J. B. et al. Comparative genomics of Eucalyptus and Corymbia reveals low rates of genome structural rearrangement. **BMC Genomics**, v. 18, n. 1, p. 397, 2017.

CASTRO, F.; WILLIAMSON, G. B.; JESUS, R. M. Radial Variation in the Wood Specific Gravity of Joannesia princeps: The Roles of Age and Diameter. **Biotropica. Assn Trop Biol**, v. 25, n. 2, p. 176-182, 1993.

CASTRO, R. V. et al. The effect of soil nutrients and moisture during ontogeny on apparent wood density of *Eucalyptus grandis*. **Scientic Reports**, v. 10, n. 2530, p. 1-10, 2020.

CUNHA, G. M.; GAMA-RODRIGUES, A. C.; GAMA-RODRIGUES, E. F.; MOREIRA, G. R. Nutrient Cycling in *Corymbia citriodora* in the State of Rio de Janeiro, Brazil. **Floresta e Ambiente**, v. 26, n. 2, p. 1-10, 2019.

DIAS A. C.; ARROJA, L. Environmental impacts of eucalypt and maritime pine wood production in Portugal. **Journal of Cleaner Production**, v.37, p. 368-376, 2012.

DOWNES, G.; DREW, D. Climate and growth influences on wood formation and utilisation. **Southern Forests**, v. 70, n. 2, p. 1-13, 2008.

INDÚSTRIA BRASILEIRA DE ÁRVORES. **Relatório IBÁ 2017**. São Paulo, p. 80, 2017.

EVERT, R. F. Meristemas, Células e Tecidos do Corpo da Planta: sua Estrutura, Função e Desenvolvimento. **Anatomia das Plantas de Esau, tradução da Terceira Edição Americana**. ed. São Paulo: Blucher, 2013. p. 225-263.

FERREIRA, O. P. **Madeira: uso sustentável na construção civil**. São Paulo: Instituto de Pesquisas Tecnológicas, 2003. 60 p.

FOELKEL, C. E. B. **Eucalyptus online book & newsletter. São Paulo**: Associação Brasileira Técnica de Celulose e Papel, 2009.

FONSECA, S. M. da.; RESENDE, M. D. V. de.; ALFENAS, A. C.; GUIMARÃES, L. M. da S.; ASSIS, T. F. de; GRATTAPAGLIA, D. **Manual prático de melhoramento genético do eucalipto**. Viçosa, MG: UFV, 2010. 200 p.

FORESTRY COMMISSION. **Wood as fuel technical supplement. The Biomass Energy Centre**. 2011. Disponível em: <https://www.forestresearch.gov.uk/documents/1958/FR_BEC_Wood_as_Fuel_Technical_Su pplement_2010.pdf > Acessado em: 22 mai. 2019.

GEROMEL, G. K. S.; PAULA, N. F.; PAULA, R. C. Caracterização físico-química da madeira e produção de carvão de *Corymbia citriodora*. **Ciência & Tecnologia**: FATEC-JB, Jaboticabal, v.3, 2011p. 3–6, 2011.

GLASS, S.; ZELINKA, S. L. Moisture relations and physical properties of wood. *In*: ROSS, R. (Ed.). **Wood handbook – wood as an engineering material**. 100th ed. Madison: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 2010. 508 p.

GONÇALVES, J. L. M.; BARROS, N. F.; NAMBIAR, E. K. S.; NOVAIS, R. F. Soil and stand management for short-rotation plantations. *In*: Nambiar EKS, Brown AG, eds. **Management of soil, nutrients and water in tropical plantation forests**. Canberra, Australia: Australian Centre for International Agricultural Research. 1997. p. 379–417.

GONÇALVES, J. L. M.; STAPE, J. L.; LACLAU, J. P.; SMETHURST, P.; GAVA, J. L. Silvicultural effects on the productivity and wood quality of eucalypt plantations. **Forest Ecology and Management**, v. 1993, p. 45-61, 2004.

GONÇALVES, J. L. M.; ALVARES, C.A.; HIGA, A. R.; SILVA, L. D.; ALFENAS, A. C.; STAHL, J.; FERRAZ, S. F. D.; LIMA, W. D. P.; BRANCALION, P. H. S.; HUBNER, A.; BOUILLET, J. P. D.; LACLAU, J. P.; NOUVELLON, Y.; EPRON, D. Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. **Forest Ecology and Management**, v. 301, p. 6-27, 2013.

GONÇALVES, T. A. P. **Contribuição ao conhecimento da anatomia da madeira das famílias: Anacardiaceae, Annonaceae, Aquifoliaceae, Apocynaceae e Araliaceae, através de amostras carbonizadas do lenho de espécies brasileiras**. Seropédica. 2006. 116 f. Monografia (Graduação em

Engenharia Florestal) - Departamento de Silvicultura, Universidade Federal Rural do Rio de Janeiro, Seropédica, 2006.

GREEN, D. W. et al. Mechanical properties of wood. *In*: United State Forest products Laboratory. **Wood handbook: wood as an engineering material**. Madison, 1999. cap 4, p. 1 – 46.

GREET. The Greenhouse Gases, Regulated Emissions, and Energy Use. *In* **Transportation Model, GREET** 1.8d.1, developed by Argonne National Laboratory, Argonne, IL, released August 26, 2010.

GURGEL-GARRIDO, L. M. A.; SIQUEIRA, A. C. M. F.; CRUZ, S. F.; ROMANELLI, R. C.; ETTORI, L. G.; CRESTANA, C. S. M.; Sato, A. S. Programa de melhoramento genético florestal do Instituto Florestal**. IF Série Registros**, v. 18, p. 1-53, 1997.

HINCHEE, M.; ROTTMANN, W.; MULLINAX, L.; ZHANG, C.; CUNNINGHAM, M.; PEARSON, L.; NEHRA, N. Short-rotation woody crops for bioenergy and biofuels applications. **In Vitro Cell. Dev. Biol**, v. 45, n. 6. p. 619–629, 2009.

HILLIS, W. E. Wood quality and utilisation. *In*: HILLIS, W. E.; BROWN, A. G. (eds): **Eucalypts for wood production**. Melbourne: CSIRO, 1978. p. 259–289.

HOADLEY, B. **Understanding Wood: A Craftsman's Guide to Wood Technology**. Taunton Press Inc; 2nd Revised edition, 2000.

HONG, S.; GAN, P.; CHEN, A. Environmental controls on soil pH in planted forest and its response tonitrogen deposition. **Environmental Research**, v. 172, p. 159–165, 2019.

HORA, A. B. Panoramas setoriais 2030: papel e celulose. *In*: **Panoramas setoriais 2030: desafios e oportunidades para o Brasil**. Rio de Janeiro: Banco Nacional de Desenvolvimento Econômico e Social, 2017. p. 79-91.

HORN, R. **Morphology of Pulp Fiber from Hardwoods and Influence on Paper Strength**. USDA Forest Service. Research Paper FPL 312, For. Prod. Lab., Madison, WI, USA. 1978

IWAKIRI, S. et al. Utilização de resíduos de serraria na produção de chapas de madeira aglomerada de Eucalyptus saligna, Eucalyptus citriadora e Eucalyptus pilularis. **Floresta e Ambiente**, v. 7, n. 1, p. 251–256, 2000.

KRETSCHMANN, D. E. **Wood handbook—Wood as an engineering material**. Department of Agriculture, Forest Service, Forest Products Laboratory, 2010. p. 508.

KOLLMANN, F. F. P.; COTÊ, W. A. **Principles of wood science and technology**. Berlim: Springer-Verlag, v. 1, 592p. 1968.

LEPAGE, E. S. Química da madeira. *In*: LEPAGE, E. S. (Coord.). **Manual de preservação de madeiras**. São Paulo: IPT, 1986. v. 1. p. 69-97.

MCKAY, J.K.; CHRISTIAN, C.E.; HARRISON, S.; RICE, K.J. How local is local? A review of practical and conceptual issues in the genetics of restoration. **Restor Ecol**. v. 13, p. 432-440, 2005.

MORAIS, S. A. L.; NASCIMENTO, E. A.; MELO, D. C. Análise da madeira do Pinus oocarpa parte II – caracterização estrutural da lignina de madeira moída. **Revista Árvore**, v. 29, p. 471-478, 2005.

MORI, C. L. S. O.; MORI, F. A.; MENDES, L. M.; SILVA, J. R.M. Caracterização da Madeira de Angico-Vermelho (Anadenanthera Peregrina (Benth) Speng) para Confecção de Móveis. **Brasil Florestal**, v. 23: p. 21-27, 2003.

MOTTA, J. P. **Propriedades tecnológicas da madeira de Tectona grandis L. F. Proveniente do Vale do Rio Doce, Minas Gerais**. 2011. 113 f. Dissertação (Mestrado em Ciências Florestais na Área de Concentração Ciências Florestais) – Programa de Pós-Graduação em Ciências Florestais, Universidade Federal do Espírito Santo, Jerônimo Monteiro, 2011.

NAHUZ, M. A. R. Atividades industriais, usos e aplicações de madeiras no Brasil com ênfase em Pinus e Eucalyptus*. In*: OLIVEIRA, J. T. S.; FIEDLER, N. C.; NOGUEIRA, M. **Tecnologias aplicadas ao setor florestal**. Jerônimo Monteiro, 2007. p. 159-208.

ORWA, C., et al. **Agroforestree Database: A Tree Reference and Selection Guide Version 4.0**. 2009. http://www.worldagroforestry.org/af/treedb/. . Acesso: 20 mai. 2019.

PANSHIN, A. J.; DE ZEEUW, C. **Text book of wood technology**. 4. ed. New York: Mc. Graw Hill, 722p. 1980.

PEREIRA, N. A. et al. Soil physical attributes under *Eucalyptus stands* with non-living and living plants. **Journal of Agricultural Science**, v. 11, n. 3; p. 197-207. 2019.

PLOYET, R. et al. A systems biology view of wood formation in Eucalyptus grandis trees submitted to different potassium and water regimes. **New Phytologist**, v. 222, n. 4, p. 1-17, 2019.

PROTÁSIO, T. P. et al. Relação entre o poder calorífico superior e os componentes elementares e minerais da biomassa vegetal. **Pesquisa Florestal Brasileira**, v. 31, p. 113-122, 2011.

RAO, R. V.; AEBISCHER, D. P.; DENNE. M. P. Latewood density in relation to wood fibre diameter, wall thickness, and fibre and vessel percentages in *Quercus robur*. **IAWA J**, v. 18, p. 127-138, 1997.

REIS, C. A. F. et al. Corymbia citriodora: estado da arte de pesquisas no Brasil. **Empresa Brasileira de Pesquisa Agropecuária Embrapa - Embrapa**, 2013.

RESENDE, R. N et al. Efeito da vaporização na secagem de tábuas de Eucalyptus grandis. **Cerne**, v. 21, n. 1, p. 37-43, 2015.

RISI. **Base de dados**. Disponível em: https://www.risiinfo.com/industries/pulp-paper-packaging/. Acesso em: 19 mai. 2019.

ROWELL R. M. **Handbook of Wood Chemistry and Wood Composites**, CRC Press, Boca Raton, FL, 2013. p. 34-47.

RUNKEL, R. O. H. Pulp from tropical wood. **TAAP**, v. 35, n 4, p. 174-178, 1952.

RYAN et al. Factors controlling Eucalyptus productivity: How water availability and stand structure alter production and carbon allocation. **Forest Ecology and Management**, v. 259, p. 1695–1703, 2010.

SAVIDGE, R. A. Tree growth and wood quality. In: **Wood Quality and Its Biological Basis**. Eds. Barnett JR and Jeronimidis G. Blackwell/CRC, Oxford and Boca Raton, 2003, pp 1–29.

SCHNEIDER, V. E.; PERESIN, D.; TRENTIN, A. C.; BORTOLIN, T. A.; SAMBUICHI, R. H. R. **Diagnóstico dos resíduos orgânicos do setor agrossilvopastoril e agroindústrias associadas: relatório de pesquisa**. Brasília: Ipea, 2012. p. 129.

SILVA, M. G.; NUMAZAWA, S.; ARAUJO, M. M.; NAGAISHI, T. Y. R.; GALVÃO, G. R. Carvão de resíduos de indústria madeireira de três espécies florestais exploradas no município de Paragominas, PA. **Acta Amazonica,** v. 37, n. 1, p. 61-70, 2007.

SILVA, J. C et al. Influência da idade e da posição ao longo do tronco na composição química da madeira de *Eucalyptus grandis*. **Revista Árvore**, v. 29, n. 3, p. 455-460, 2005.

SILVA et al. Fertilization response, light use, and growth efficiency in *Eucalyptus* plantations across soil and climate gradientes in Brazil. **Forests**, v. 7, p. 1-117, 2016.

SILVEIRA, R. L. V. A.; HIGASHI, E. N.; SGARBI, F; MUNIZ, M. R. A. Seja o doutor do seu eucalipto. **Informações agronômicas,** n. 12, p. 1-32, 2001.

SOUZA et al. Genotype-by-environmental interaction in *Corymbia citriodora* (Hook.) K.D. Hill, & L.A.S. Johnson progeny test in Luiz Antonio, Brazil. **Forest Ecology and Management**, v. 460, n. 15, p. 1-8, 2020.

STAPE et al. The Brazil Eucalyptus Potential Productivity Project: Influence of water, nutrientes and stand uniformity on wood production. **Forest Ecology and Management,** v. 259, p. 1684–1694. 2010.

TELMO, C.; LOUSADA, J. Heating values of wood pellets from different species. **Biomass and Bioenergy**, v. 35, p. 2634-2639, 2011.

VALE, A. T.; GENTIL, L. V. **Produção e uso energético de biomassa e resíduos agroflorestais. Tecnologias aplicadas ao setor madeireiro III**. Rio Branco: Suprema, 2008. p.195-241.

VIEIRA, I. G. **Estudo de caracteres silviculturais e de produção de óleo essencial de progênies de Corymbia citriodora (Hook) K.D.Hill & L.A.S. Johnson procedente de Anhembi SP - Brasil, Ex. Atherton QLD - Austrália.** 2004. 80 f. Dissertação (Mestrado em Ciências Florestais) - Escola Superior de Agricultura “Luiz de Queiroz”, Universidade de São Paulo, Piracicaba.

VILAS BÔAS, O.; MAX, J. C. M.; MELO, A. C. G. Crescimento comparativo de espécies de Eucalyptus e Corymbia no município de Marília, SP. **Revista Instituto Florestal**, v. 21, n. 1, p. 63-72, 2009.

VITTI, A. M. S.; BRITO, J. Avaliação do rendimento e do teor de citronelal do óleo essencial de procedências e raças locais de *Eucalyptus citriodora*. **Scientia Forestalis**, n. 56, p. 145-154, 1999.

VITTI, A. M. S.; BRITO, J. O. Óleo Essencial De Eucalipto. **Documentos florestais - Escola Superior de Agricultura “Luiz de Queiroz” - Universidade de São Paulo**, v. 17, n. 0103–4715, p. 1–26, 2003.

WANGAARD, F. F. **The mechanical properties of wood**. London: Chapman & Hall, 1950. p. 377.

WIEDENHOEFT, A. Structure and function of Wood. *In*: **Wood Handbook – Wood as an Engineering Material**: chapter 3. Centennial ed. General technical report FPL; GTR-190. Madison, WI: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, p. 3.1-3.18, 2010.

WOODCOCK, D. W.; SHIER, A. D. Wood specific gravity and its radial variations: the many ways to make a tree. **Trees**, v. 16, p. 437–443, 2002.

ZENID, G. J.; ROMAGNANO, L. F. T.; NAHUZ, M. A. R.; MIRANDA, M. J. A. C.; FERREIRA, O. P.; BRAZOLIN, S. Madeira: uso sustentável na construção civil. São Paulo: **Instituto de Pesquisas Tecnológicas**, v. 2, n. 1, p. 1-103, 2009.