UNIVERSIDADE FEDERAL DE LAVRAS

LUCAS GUIMARÃES PEREIRA

MODELAGEM DO CRESCIMENTO E PROJEÇÃO DA PRODUTIVIDADE DE MADEIRA DE Cedrela odorata NA AMAZÔNIA ORIENTAL: AVALIANDO O MANEJO À LUZ DA DENDROCRONOLOGIA

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Dissertação apresentada à Universidade Federal de Lavras como parte das exigências do Programa de Pós-Graduação em Engenharia Florestal, área de concentração em ecologia, para a obtenção do título de Mestre.

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RESUMO GERAL

O manejo florestal tem sido uma importante atividade econômica na Amazônia oriental datando desde a era colonial. No entanto, somente na década de 70 que o estudo e monitoramento dessa atividade se tornaram mais efetivos com a instalação de parcelas permanentes e aplicação do sistema policíclico. Porém, a aplicação da lei se baseado em dados de curto período dificultou a análise em longo prazo da dinâmica nos intervalos entre um ciclo e outro, superestimando e pressionando as espécies comerciais. A confirmação de espécies com formação de anéis de crescimento anuais nos trópicos pode suprir essa falta informação no manejo florestal. O objetivo do nosso estudo foi avaliar o manejo da espécie *Cedrela odorata* L.. Por meio de parcerias com empresas florestais, o Laboratório de Dendrocronologia da UFLA obteve amostras de madeira dos troncos de árvores de cedro abatidas em áreas de concessão florestal com diferentes tipologias florestais de terra firme no leste da Amazônia: floresta ombrófila aberta, localizada na Floresta Nacional de Altamira, e floresta ombrófila densa, localizada na Floresta Estadual do Paru. As amostras foram preparadas e analisadas seguindo procedimentos clássicos da dendrocronologia. Os dados de anéis de crescimento foram utilizados em duas abordagens consolidadas na literatura para avaliar o manejo florestal: Growth-Oriented Logging (GOL) e projeção de rendimento das árvores no segundo ciclo de corte. Os resultados permitiram reconstruir e simular o crescimento de populações de cedro nas duas áreas de estudo e evidenciaram que os parâmetros utilizados hoje para o manejo florestal não permitem a recuperação do volume extraído no primeiro corte para *C. odorata*, recuperando menos de 30% do volume inicial até o próximo ciclo. Diante disso, esse estudo sugere o um aumento no diâmetro mínimo de corte ou diminuição da intensidade de corte em que essa espécie poderia ser comercializada sem grandes perdas de volume. Os anéis de crescimento podem ser uma ferramenta mais utilizada no monitoramento e definição de manejos específicos de espécies na Amazônia.

Palavras-Chaves: Manejo Florestal, Dendrocronologia, Amazônia Oriental.

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INTRODUÇÃO GERAL

O manejo florestal como forma de atividade econômica é uma das principais atividades na floresta Amazônica datando da à era colonial (BATISTA, 2003; SANTA, FIDANZA, 1899). Atualmente, só no estado do Pará pouco mais de 120 mil ha estão autorizados para o manejo florestal sustentável, que corresponde a um volume de extração de cerca de três milhões de m³ (PARÁ, 2020). Isso gera renda para comunidades adjacentes a área de manejo e movimenta a economia do estado e da região Amazônica (GARRIDO-FILHA, 2002).

A intensificação da exploração florestal na Amazônia ocorreu após a década de 70 devido ao incentivo ao desenvolvimento e o chamado “boom-colapso” (Exploração seguida do abandono da terra) principalmente na porção leste da região, onde os recursos florestais sofreram forte pressão (VERÍSSIMO; PEREIRA, 2014; CASTELO, 2015). Nas décadas seguintes diversos estudos começaram a monitorar a atividades através de parcelas permanentes na região (SILVA, 1993; SILVA ET AL., 1995; ALDER E SILVA, 2000; PHILLIP; VAN GARDINGEN, 2001) e as leis se tornaram mais rígidas, sendo a sustentabilidade o objetivo da atividade econômica (CASTELO, 2015; GARRIDO-FILHA, 2002).

Atualmente, para o manejo florestal as empresas devem seguir os seguintes parâmetros estabelecidos para a região amazônica: Diâmetro mínimo de corte (DMC) ≥ 50 cm, sob um ciclo de corte de 25 a 35 anos, com uma intensidade máxima de corte de 30 m^3/ha e manutenção de 10% das árvores para espécies que não estão ameaçadas e 15% para que estão na lista de vulneráveis, com a possibilidade de alteração mediante nota técnica apresentada pelo responsável técnico (BRASIL, 2006; PARÁ, 2015).

Apesar de todo o critério imposto na retirada de recursos madeireiros, vários grupos de pesquisa em manejo florestal estão questionando a sustentabilidade dos planos de manejo presente na região (GIBSON et al. 2011; PIPONIOT et al. 2019; PUTZ et al. 2012). Os parâmetros foram estabelecidos em um contexto com poucas informações sobre a recuperação de volume de espécies e sítios mediantes a exploração. Desse modo houve uma superestimação da capacidade de recuperação da floresta a depender do ecossistema florestal devido a valores fixos e gerais do ciclo de corte e DMC (DAVID et al., 2019). Nas últimas duas décadas com a obtenção de dados em longo prazo de parcelas permanentes estudos têm sugerido a revisão dos parâmetros gerais definido nas leis para que se ajuste a cada espécie e sítio (DAVID et al, 2019; CASTRO et al, 2021; PUTZ et al. 2012; SCHÖNGART, 2008).

No domínio Amazônia existe aproximadamente 15 tipos de vegetação que vão de campinarana arborizada a floresta ombrófila densa (BRASIL, 2018). A alta diversidade de espécies torna a modelagem do crescimento e produção por espécie e sítio complexa pelas diferenças de estrutura, mortalidade e taxas de crescimento (BRIENEN; ZUIDEMA, 2006a; DAVID et al., 2019).

A comprovação da formação de anéis de crescimento anuais nos trópicos trouxe mais uma ferramenta para o aprimoramento de estudos de manejo por espécie (BRIENEN; SCHÖNGART; ZUIDEMA, 2016; SCHÖNGART et al. 2017; ZUIDEMA; BRIENEN; SCHÖNGART, 2012; WORBES, 2002). Os estudos dos anéis de crescimento podem fornecer dados confiáveis de taxas de crescimento ao longo da vida das árvores, que permitem acompanhar o ciclo de vida destas até a idade de colheita, além de serem dados que podem ser obtidos em um curto período de tempo (STAHLE et al. 2020; BRIENEN; ZUIDEMA, 2006a; ZUIDEMA; BRIENEN; SCHÖNGART, 2012; SCHÖNGART et al., 2017).

Atualmente duas metodologias de avaliação do manejo florestal através dos anéis foram desenvolvidas na Amazônia. O conceito de *Growth-Oriented Logging* (GOL) por Schöngart (2008), o qual busca uma abordagem para melhorar o gerenciamento do manejo florestal definindo o DMC e os ciclos de cortes de acordo com a espécie e local e Brienen e Zuidema (2006a) que buscaram avaliar os rendimentos das árvores no segundo ciclo de corte.

O presente estudo

Este estudo objetivou a avaliar a produtividade a produtividade dentro de um ciclo de corte no manejo madeireiro de *C. odorata* em duas tipologias florestais na Amazônia oriental através dos anéis de crescimento.

(i) Definir ciclo de corte e diâmetro mínimo de corte para cada sítio pela modelagem de crescimento conforme proposto no conceito GOL;

(ii) Avaliar a produção de volume das populações de Cedro após o ciclo de corte, comparando os parâmetros definidos pela modelagem de crescimento e os parâmetros de manejo definidos em Lei;

(iii) Sugerir, com base nos rendimentos de volume futuro, parâmetros que forneçam a recuperação parcial (50%) e total (100%) do volume inicial para *C. odorata*.

REVISÃO BIBLIOGRÁFICA

Manejo Florestal na Amazônia brasileira

A partir da década de 1970 com o avanço do desenvolvimento na região Amazônica, a falta de leis rígidas e o esgotamento de madeiras na região Sul e Sudeste do país resultou em décadas de exploração predatória e desordenada que degradaram grandes áreas florestais no bioma (VERÍSSIMO et al., 1998; ZARIN et al., 2007; CASTELO, 2015). Segundo Veríssimo e Pereira (2014) esse desenvolvimento foi chamado de "boom-colapso", o qual havia o início da exploração predatória dos recursos florestais e após 10 anos com os mesmos já escassos ocorria à migração da atividade para outra região, o que resultava em um colapso ambiental, econômico e social.

O governo brasileiro diante dos altos índices de desmatamentos criou dispositivos legais para a proteção da natureza, como a lei da Política Nacional do Meio Ambiente (6.938 de 1981), que teve como objetivo harmonizar o desenvolvimento econômico e social com a preservação da qualidade do meio ambiente, ou seja, a busca pelo desenvolvimento sustentável (MEDEIROS, 2006; CASTELO, 2015). No manejo florestal a portaria DC 10 de 1975 do IBDF (Antigo IBAMA) já previa o corte seletivo e diâmetro mínimo de corte no manejo florestal, porém, somente na década de 1990, com o Decreto nº 1.282 de 1994 (Revogado pelo Decreto nº 5.975, de 2006), o conceito de sustentabilidade passou a fazer parte da atividade florestal, o qual prevê que a exploração de florestas e de formações sucessoras compreende um regime de Manejo Florestal Sustentável (MFS) (GARRIDO-FILHA, 2002; VERISSÍMO; PEREIRA, 2014).

Com cerca de 180 Mha (20% da área total de floresta) destinadas à produção de madeira na região (FAO, 2011), o MFS na Amazônia passou a ser um dos principais usos de terra, já no período de 1996 a 2003 atingiu uma área de 10 a 20 mil km^2 ano^{-1} m^3 (VAN GARDINGEN; VALLE; THOMPSON, 2006), atualmente, cerca de 11 milhões de m^3 estão sendo extraídos anualmente na Amazônia (BRASIL, 2019a). Consequentemente, houve um direcionamento de grupos de pesquisas a desenvolverem estudos para aperfeiçoar os parâmetros que regulavam a atividade com o objetivo de manter a sustentabilidade e preservação da floresta (SILVA, 1993; SILVA ET AL., 1995; ALDER E SILVA, 2000; PHILLIPS; VAN GARDINGEN, 2001; VALLE ET AL., 2007).

Atualmente, a instrução normativa nº 5, de 11 de dezembro de 2006 do Ministério do Meio Ambiente - MMA, a resolução Nº 406, de 02 de Fevereiro de 2009 do CONAMA e a Instrução normativa nº 05 de 10/09/2015 da SEMAS têm como objetivo estabelecer parâmetros para o plano de manejo, sendo os dois primeiros a nível federal na região Amazônica e o último a nível estadual, no estado do Pará. De modo geral ficou estabelecido que as empresas madeireiras para a execução de suas atividades deveriam se basear nas normas regulatórias que definem parâmetros como: ciclo de corte (Manejo Policíclico), estabelecimento do Diâmetro Mínimo de Corte (DMC), limites de intensidade de colheita, retenção de árvores de semente e proteção de áreas sensíveis. Os seguintes parâmetros foram estabelecidos para a região amazônica: DMC ≥ 50 cm, sob um ciclo de corte de 25 a 35 anos, com uma intensidade máxima de corte de 30 m^3/ha e manutenção de 10% das árvores para cada espécie, com a possibilidade de alteração mediante nota técnica apresentada pelo responsável técnico.

A busca pelo o desempenho ambiental, ou seja, o aumento da produção futura, dos estoques de carbono e das taxas de recuperação, não ficou restrito somente as normas regulatórias. A aplicação de metodologias para substituir o manejo convencional também foi criada. A Exploração de Impacto Reduzido (EIR), que é um conjunto de diretrizes, criada pelas empresas auxilia na busca pela substituição da exploração convencional, a qual não emprega nenhum princípio de planejamento (Inventário Florestal) ou técnicas (ZARIN et al., 2007; IMAZON, 2010; PUTZ et al, 2012). O EIR tem como objetivo minimizar os danos ambientais, ser rentável e, otimizar o tempo das operações (ZARIN ET AL., 2007).

O avanço na legislação e técnicas do manejo florestal na Amazônia possibilitou a aplicação de concessões em florestas públicas (Unidades de conservações) para evitar o desmatamento ilegal (AZEVEDO-RAMOS; SILVA; MERRY, 2015). Atualmente, pouco mais de 1 milhão de hectares estão sob domínio de concessão na Amazônia no âmbito federal e estima-se que outras unidades de conservação também serão incluídas (BRASIL, 2019b).

Desde os primeiros estudos até agora já se passaram aproximadamente 30 anos. Os dados estão mais robustos e as consequências das primeiras explorações já podem ser analisadas. Os resultados mostram que pode haver uma superestimação da capacidade de recuperação da floresta devido a valores fixos e gerais do ciclo de corte e DMC a depender do ecossistema na Amazônia. Além disso, a recuperação do volume da madeira colhida no primeiro ciclo de corte para o segundo ciclo fica abaixo de 50% (CASTRO et al., 2021;

DAVID et al., 2019; PUTZ et al, 2012). Portanto, hoje há uma necessidade de estudos para sugerir ajustes nas projeções e aplicações dos critérios de manejo na Amazônia.

Dendrocronologia nos Trópicos e Subtrópicos

A dendrocronologia como ciência surgiu com Douglass (1914; 1919) que buscou relacionar três grandes áreas de estudo (Astronomia, Meteorologia e Botânica) para observar as variações do sol. Seu estudo comprovou a correlação dos anéis de crescimento anuais com o clima, o que resultou na construção da cronologia de quase 500 anos de *Pinus ponderosa* nos Estados Unidos. Essa descoberta veio acompanhada de seguidos programas de pesquisa em anéis de crescimento no mundo (FRITTS, 1966; 1976), principalmente, no Hemisfério Norte.

Acreditou-se por muito tempo que somente espécies situadas na zona temperada e boreais formavam anéis de crescimento anuais devido ao seu clima com estações bem definidos. A presença de sazonalidade, alta amplitude da temperatura anual e estações frias geram dois tipos de comportamentos anuais na atividade cambial da Árvore: Crescimento e Repouso, o que induz dormência e alteração anatômica (JACOBY, 1989).

Nos trópicos onde a sazonalidade climática ocorre de maneira menos drástica, com baixa amplitude térmica anual tinha-se por hábito acreditar que as árvores cresciam continuamente, sem a formação de anéis anuais de crescimento (LIEBERMAN et al., 1985; DETIENNE, 1989; JACOBY, 1989; WITHMORE, 1990). Estudos prévios descreveram a presença de anéis de crescimento anuais distintos em algumas espécies (GAMBLE, 1981).

Coster (1927) foi um dos primeiros a comprovar a formação de anéis anuais em *Swietenia mahagoni* Jack, *Azadirachta indica* Juss e *Tectona grandis* L.f. no sul da Ásia. Segundo Rozendaal e Zuidema (2011) a formação de anéis anuais em árvores tropicais é comprovada quando elas passam por um momento de dormência cambial em um período do ano devido às condições ambientais desfavoráveis que podem ser em uma estação seca de curta ou longa duração, florestas de várzea no período de inundação e variação de salinidade em Manguezais.

Diante da descoberta do potencial dendrocronológico em algumas espécies tropicais, iniciou-se uma sequência de estudos na região neotropical do hemisfério norte nas décadas 1940 e 1950, onde a primeira cronologia foi construída no México. No hemisfério Sul, mais precisamente no sul e sudeste da Ásia os primeiros estudos iniciaram na década de 20 e 30. Na região subtropical América do sul nos anos 1980 e na região tropical da América Latina os primeiros estudos começaram na década 1960 em El Salvador e na Costa Rica e se estendeu para a região Amazônica na década de 1980 (SCHÖNGART et al, 2017).

Um aumento exponencial de estudos de dendrocronologia nos trópicos tem sido reportado nos últimos 20 anos. As informações contidas nos anéis de crescimento têm contribuído para diversas áreas de conhecimento como arqueologia, história, ecologia, climatologia, hidrologia, etc. (GRANATO-SOUZA et al., 2018; KAENNEL; SCHWEINGRUBER, 1995; ROZENDAAL; ZUIDEMA, 2011; SCHÖNGART et al, 2017; BAKER et al, 2017).

Aplicação da dendrocronologia no manejo sustentável

A aplicação dos anéis de crescimento no manejo florestal não é recente segundo Schöngart et al. (2017), o qual relata a utilização dessa prática ainda no século XIX com o botânico Alemão Dietrich Brandis no Sul da Ásia. Utilizou a espécie *Tectona grandis* para elaborar um plano de manejo a partir da contagem dos anéis de crescimento e definiu um ciclo de corte baseado nas taxas de incremento anuais. Porém, o mito de que espécies tropicais não possuíam anéis de crescimento com resolução anual resultou no não prosseguimento destes estudos nos trópicos.

A falta de informação sobre o crescimento das árvores por espécie tem resultado em dúvidas sobre a aplicação do manejo florestal na Amazônia. Os estudos dos anéis de crescimento podem fornecer dados confiáveis de taxas de crescimento ao longo da vida das árvores, que permitem acompanhar o ciclo de vida destas até a idade de colheita, além de serem dados obtidos em um curto período (BRIENEN; ZUIDEMA, 2006a,b; ROZENDAAL; ZUIDEMA, 2011; SCHÖNGART, 2008).

Na Amazônia brasileira foi desenvolvido por Schöngart (2008) o conceito de *Growth-Oriented Logging* (GOL), o qual busca uma abordagem para melhorar o gerenciamento do manejo florestal definindo o DMC e os ciclos de cortes de acordo com a espécie e local, os quais podem substituir os regulamentos legais (WORBES; SCHÖNGART, 2019). Na Amazônia boliviana, Brienen e Zuidema (2006a) buscaram avaliar os rendimentos das árvores no segundo ciclo de corte. A coleta de discos das árvores que atingiram o DMC de colheita possibilitou obter o comportamento das taxas de crescimento e as considerar como um crescimento “comum” de todas as árvores que chegarão ao DMC. A partir disso foi possível projetar a produção de madeira tanto retrospectivamente, que analisa em qual DAP a árvore estava no ciclo de corte anterior; como prospectivamente, que projeta o crescimento das árvores que estão abaixo do DMC para o próximo ciclo.

Atualmente, vários estudos estão sendo elaborados com a utilização dos anéis de crescimento na Amazônia (ROSA et al., 2017; ANDRADE et al., 2019). O uso de dados de anéis de árvores pode ser uma excelente ferramenta para o uso no manejo florestal, pois fornece dados de um longo tempo em um curto período e possibilita a inclusão da variação de crescimento temporal observada nas projeções de crescimento, o que leva a estimativas mais precisas da produção futura de madeira (BRIENEN; ZUIDEMA, 2006a; BRIENEN; ZUIDEMA, 2007).

O gênero *Cedrela*

Cedrela é um gênero da família Meliaceae, com 17 espécies distribuídas na América Central à América do Sul (PENNINGTON; MUELLNER, 2010). Sua ocorrência está limitada ao chamado Novo Mundo, ou seja, maior parte de suas espécies estão na Região Neotropical das florestas tropicais e subtropicais, mais precisamente do México até o Norte da Argentina e o Sul do Brasil (TOMAZELLO – FILHO; BOTOSSO, LISI, 2000; FLORES; SOUZA; COELHO, 2017). Entre suas espécies encontra-se a *Cedrela odorata L.* uma árvore monoica, decídua, de tamanho médio a grande (40 a 60 metros de altura), com presença de contrafortes que podem chegar até dois metros de altura (ORWA et al., 2009).

Em sua área natural de distribuição pode ser encontrada tanto nas florestas primárias como nas secundárias, sempre-verde e semi-decídua ou floresta tropical de baixa altitude. Preferem solos úmidos, profundos e bem drenados, mas ocorre também em áreas alagáveis. Pode ser encontrada até 1200 m de altitude e sua primeira floração é esperada após 10 a 15 anos, geralmente, ocorre entre os meses de maio a setembro (CAVERS; NAVARRO; LOWE, 2003; ORWA et al., 2009).

Segundo Lorenzi (1998), a *Cedrela odorata* L. está presente em quase todo o território Brasileiro, sendo muito apreciada comercialmente, tanto pelo mercado nacional como internacional. Suas excelentes propriedades físico-mecânicas são apreciadas na confecção de compensado, laminado, mobiliário de luxo, instrumentos musicais, moldura de quadros, construção civil e aeronáutica (CORDERO; BOSHIER, 2003). Diante do seu alto valor comercial, em média R$ 758 o m^3, houve uma superexploração durante dois séculos dos seus indivíduos o que fez com que ela fosse classificada com 'Vulnerável' pela IUCN e ameaçada pelo desmatamento e extração insustentável de madeira em muitas partes de sua área natural (MARK; RIVERS, 2017; CAVERS; NAVARRO; LOWE, 2003, SEMAS, 2016).

Espécies do gênero *Cedrela* são consideradas sensíveis à umidade, ou seja, concentram suas atividades fisiológicas durante as estações chuvosas e dormência cambial em estações secas (PEREIRA et al. 2018, GRANATO-SOUZA et al. 2018; BAKER et al, 2017). Além disso, a prévia comprovação de que os anéis de crescimento das espécies de Cedrela, incluindo *C. odorata*, são anatomicamente distintos e com resolução anual (DÜNISCH; BAUCH; GASPAROTTO, 2002; BRIENEN; ZUIDEMA, 2005; HAMMERSCHLAG et al, 2019) as tornam propícias ao desenvolvimento dos estudos dendrocronológicos (HIETZ; WANEK; DÜNISCH, 2005). O reconhecimento do potencial dendrocronológico despertou o interesse de vários pesquisadores na América do Sul.

Dentre essas áreas estão ligadas a dendroclimatologia a qual utiliza os anéis de crescimento como registros paleoclimáticos dando base para a contextualização das recentes mudanças climáticas diante de um passado recente (200, 300 anos) (BAKER et al. 2017, GRANATO-SOUZA et al. 2018) e como registro para a variabilidade de Oscilação Sul de El Niño (BRIENEN; GLOOR; ZUIDEMA, 2012). Grandes potencialidades das espécies de *Cedrela* também são relatadas para estudos ecológicos (BRIENEN; ZUIDEMA; MARTINEZ-RAMOS, 2009; DÜNISCH; BAUCH; GASPAROTTO, 2002) e para a aplicação do manejo florestal (LOPEZ; VILLALBA; BRAVO, 2013; SCHÖNGART, 2008).

SEGUNDA PARTE

ARTIGO 1

Evaluation of the Brazilian sustainable forest management in the eastern Amazon: a case study of *Cedrela odorata* L. trees

Esse manuscrito será submetido à revista Forest Ecology and Management, posteriormente a esta defesa, e ainda não apresenta lista de autores, sendo apresentado a esta banca da seguinte forma:

ABSTRACT

Forest management is an important activity in the Amazon dating back to the colonial era and intensified in the 70's. This intensification was followed along with the need to monitor the forest and the main method used was the installation of permanent plots. The still short-term data from the plots supported the creation of regulatory parameters for forest management in the Amazon. These parameters may be overexploiting and contributing to the extinction of vulnerable species such as *Cedrela odorata*. Tree rings can be a tool to assess management due to the possibility of evaluating long-term data in a short period of time. The aim of our study was: (1) evaluate the volume projection in two different forest types and observe if it affects the yield within a cutting cycle; (2) to provide a sustainable felling cycle and a minimum cutting diameter for *C. odorata* resulted from the growth rings analysis performed by this study; (3) to evaluate the sustainability of the *C. odorata* management through the volume yielded by the parameters defined in Law and (4) to suggest new sustainable management criteria, based on future volume yields, parameters that provide partial (50%) and total (100%) recovery of the initial volume for *C. odorata* that will help filling the gaps on the lack of information regarding species-specific growth rates in the eastern Amazon. Tree ring data were used in two approaches consolidated in the literature to assess forest management: Growth Oriented Logging (GOL) and projected tree yield in the second harvest cycle. The results made it possible to reconstruct and simulate the growth of cedar reserves in the two study areas and showed that the parameters used today for forest management are unsustainable for *C. odorata*, recovering less than 30% of the initial volume until the next cycle. The parameters defined by the GOL concept were also unsustainable according to future projection. The best yield was found using a minimum cutting diameter of 80 cm with a 30-year-old felling cycle and an intensity of 90%, which reached 100% yield in the next logging. The differences between the sites demonstrate the need for complementary studies to define not only species-specific but also site-specific management.

Key-words: Eastern Amazon, Dendrochronology, Growth modeling, Timber yield projection.

1 INTRODUCTION

Forest management has been an important economic activity in the eastern Amazon dating back to the colonial era (BATISTA, 2003; SANTA; FINDANZA, 1899). Nevertheless, the main studies to monitor the forest dynamics under management began only in the 1970s, with permanent plots and projections simulations of forest structure (ALDER; SILVA, 2000; PHILLIPS ET AL., 2004; SILVA ET AL., 1995). These studies encouraged policy makers to develop laws and regulations towards the sustainable forest management (CASTELO, 2015), what is considered to be a milestone in the pursuit to establish the sustainability tripod in the Brazilian Amazon. Since then, the so-called sustainable management forest has been intensified and the current managed area has been increased to around 120.000 ha only in Pará (Pará, 2020).

Current legislation determines, based a permanent plot data, a polycyclic system and establishes a minimum logging diameter (MLD) (50 cm), felling cycle (FC) (25-35 years), cutting intensity and percentage of remaining trees (BRASIL, 2006; PARÁ, 2015). However, these parameters are based on short-term data, until creation of law, and thus provide general criteria and deterministic predictions that do not include species-specific and site-specific characteristics. This is likely to be causing overexploitation of some species and threatening their perpetuation in the forest (CASTRO ET AL., 2021; DAVID ET AL., 2019; PUTZ ET AL., 2012).

Tree rings provide long-term knowledge on the annual growth rhythm and thus the reconstruction of the growth trajectories for each individual tree in a population, valuable information for the sustainable forest management (BRIENEN AND ZUIDEMA 2006a; SCHÖNGART 2008; STAHLE ET AL., 1999). Dendrochronological studies applied to forest management of tropical tree species are increasing due to the relatively easy assessment of the growth trajectories in uneven aged forests, which allow growth modeling and timber yield projections that consider the variation among tees and stochastic components of forest dynamics, providing species-specific and site-specific management criteria (ANDRADE ET AL., 2019; GROENENDIJK ET AL., 2017; ROSA ET AL., 2017; ROZENDAAL ET AL., 2010).

Cedrela odorata L. trees are known to form clear annual growth rings and have been previously used in dendrochronology for growth modeling analysis and climate reconstructions (BRIENEN; ZUIDEMA 2005; DÜNISCH; BAUCH; GASPAROTTO, 2002;

GRANATO-SOUZA ET AL., 2018, 2020; PEREIRA ET AL., 2018; STAHLE ET AL., 2020), although Baker et al., (2017) found a two rings per year in Suriname. In the eastern Amazon this commercial timber species is well known for its wood quality and low density (0.47 g cm^{-1}) and has historically been used for woodwork and construction of vessels since the colonial era in the 17th and 18th century (CONVENTION ON INTERNATIONAL TRADE IN ENDANGERED SPECIES OF WILD FAUNA AND FLORA, 2007; BATISTA 2003; PENNINGTON, 1981; ZANNE ET AL., 2009). In the last extraction and trade of native wood report report indicated that 1,124 m^3 of C.odorata were extracted in the state of Pará, with a commercial value of $217.19 per m^3 in 2016 (PARÁ, 2016). The high rate of extraction of the species throughout its distribution for more than two centuries and even today has placed *Cedrela odorata* in the IUCN Red List of Threatened Species as vulnerable to extinction in Brazil (MARK; RIVERS, 2017; MARTINELLI; MORAES, 2013).

This study aimed to evaluate the management of *Cedrela odorata* in two forest types in eastern Amazon. We used tree-ring data to (1) to provide a sustainable felling cycle and a minimum cutting diameter for *C. odorata* resulted from the growth rings analysis performed by this study, (2) to evaluate the yield volume of *C. odorata* populations after the cutting cycle, comparing the parameters defined by the growth modeling and the management parameters defined in Law, and (3) to found management criteria, based on future volume yields, that provide partial (50%) and total (100%) recovery of the initial volume for *C. odorata.*

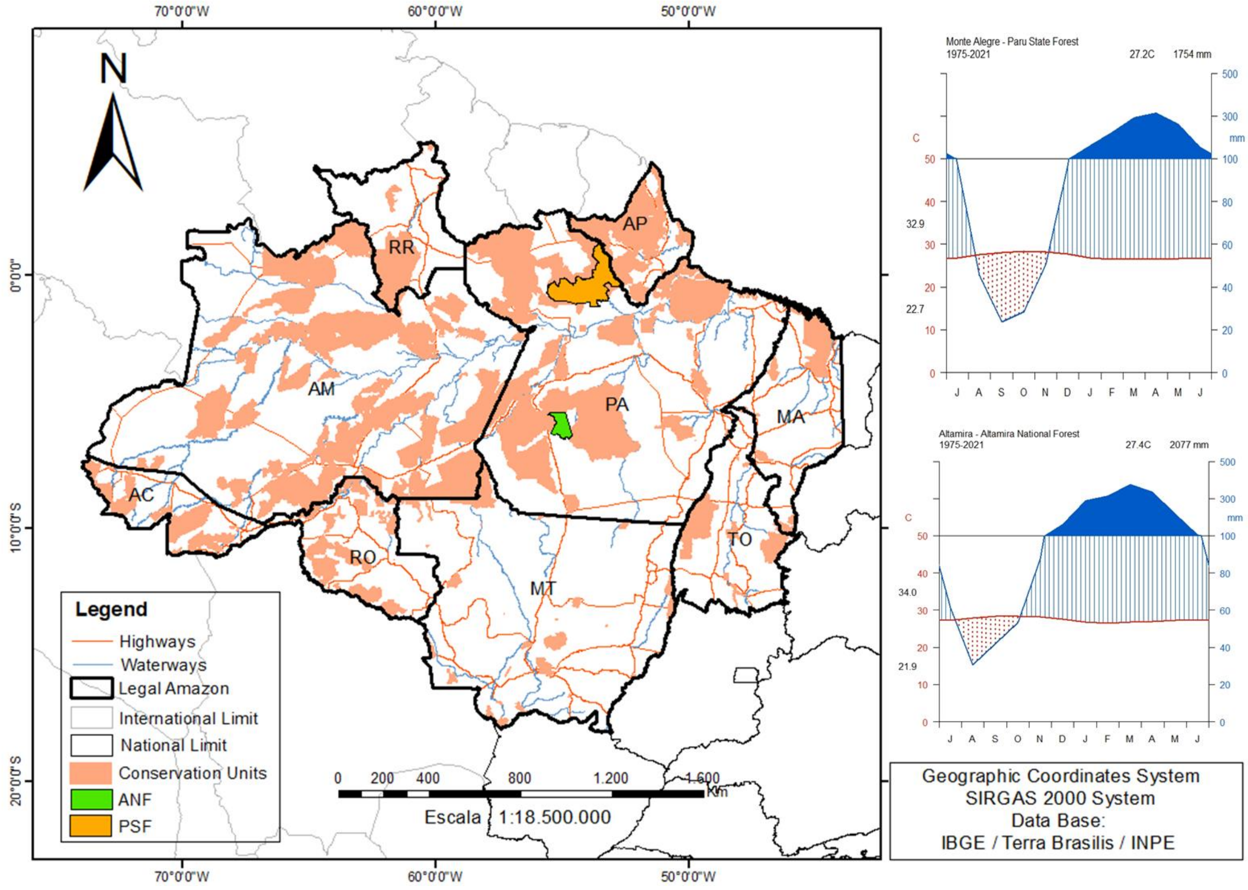
2 METHODS

2.1. Study sites

The samples of *C. odorata* were obtained from two public forests concessions undergoing sustainable logging management in the eastern Amazon, Pará state, Brazil: the Altamira National Forest (ANF) and the Paru State Forest (PSF). These two types of conservative unity allow resource management under a plan. Both forests are characterized by preserved tropical rainforest and have been included in the Annual Plan for Forest Grant, controlled by the Brazilian government (BRASIL, 2020; PARÁ, 2021).

The vegetation differs between sites. The ANF is characterized by Open Submontane Rainforest (IBGE, 2012) and is located close to the “Arc of Deforestation”, where deforestation is occurring most rapidly in the southeastern edge of Amazonia and, hence, more susceptible to human interference and illegal logging operations (Fig.1). The PSF is characterized by Dense Tropical Submontane Rainforest (IBGE, 2012) and has been reported to harbor the tallest tropical hardwoods (*Dinizia excelsa* Ducke) yet documented in the Amazon (GORGENS ET AL., 2019). The regional climate is tropical monsoon (Am), with a short dry season (Aug-Nov), ~ 60 mm), the total precipitation of the wet season (Jan-Jul) is 1641 mm in AFN and 1500 mm in PSF and the annual temperature shows little variation, ranging from 25ºC to 30ºC in two areas (BRASIL, 2020).

Figure 1: Legal Amazon area comprising nine Brazilian states, and their respective conservation units (UC). The UCs related to this study are located in the eastern Amazon in the state of Pará and about 600 km apart in a straight line. The Climatic diagram of the average temperature (gray lines) and precipitation (black bars) come from National Institute of Meteorology (INMET) data from 1961 to 2019.



2.2. Tree-ring data and population structure

All cross sections of *C. odorata* were obtained from trees legally harvested a with at least 50 cm of Diameter at Breast Height (DBH) according to the sustainable management legislation in Para (Pará, 2015) by the companies RRX Mineração e Serviços LTDA (ANF) and CEMAL - Comércio Ecológico de Madeiras LTDA (PSF). We dated the samples with the cross-dating techniques (see GRANATO-SOUZA ET AL., 2018; 2020). The Rio Paru

Cedrela tree ring chronologies are publicly available at the International Tree Ring Data Bank (ITRDB) at NOAA’s Paleoclimatology Program (Rio Paru A - BRA001; Rio Paru B - BRA003). For this study, we selected only the samples that were extracted close to the DBH, therefore, 16 and 49 trees attended these criteria in ANF and PSF, respectively.

We analyzed the density, size distributions and commercial height of *C. odorata* trees to simulations a base population and to test recovery volumes to the next felling cycle. Data were gently provided by the companies of the forest concessions (trees with DBH ≥ 40 cm) that in ANF has an area of 1500 ha and in PSF 3066 ha. The trees with DBH ≥ 40 cm were provided by the environmental agencies in the state of Pará, which in ANF is a Serviço Florestal Brasileiro - SFB (trees with DBH ≤ 30 cm; 96 ha) and in PSF is a Instituto de Desenvolvimento Florestas e Biodiversidade – IDEFLOR-BIO (trees with DBH ≤ 40 cm; 54,4 ha) through the forest inventories of the studied sites. The sampled areas from the inventory performed by environmental agencies were smaller than the areas sampled by logging companies, thus we extrapolated the number of individuals with DBH ≤ 40 cm for the larger areas.

2.3. Growth modeling (GOL-concept)

To define the minimum logging diameter and the felling cycle based on tree-ring data we constructed individual cumulative diameter growth curves by averaging two to four radii per tree to establish the age-growth relationships (BRIENEN; ZUIDEMA, 2006a; SCHÖNGART, 2008). We corrected the difference between the diameter derived from tree rings and the DBH measured in the field. Hollow samples were scanned and we used CooRecorder ® software (CYBIS ELECTRONIC, 2013) to project and estimate the distance to the pith.

Growth relationships (AGE-DBH- and DBH-Height) were determined to calculate the volume per year with form factor provided by law (Eq.1, Table 2) and generate cumulative volume growth (cumulative volume over the life span of a tree) for each study site (SCHÖNGART, 2008). A sigmoidal function (Eq.2, Table 1) relating DBH (independent variable) to age was fitted to model the cumulative mean diameter curve; and a non-linear regression model (Eq.3, Table 1) relating DBH and height (independent variable) (SCHÖNGART ET AL., 2007; SCHÖNGART, 2008).

The current annual increment (CAI) trough cumulative volume (CV) (Eq.4; Table 1) and the mean annual increment (MAI) (Eq.5, Table 1) were calculated. They are important parameters for maximizing timber production and to define the optimal volume production point. For this study, we defined the MLD at the maximum Current Annual Increment for volume (CAI_{vmax}), which means that the species reached its maximum point of production at the site (SCHÖNGART, 2008, ROSA ET AL. 2017). The Felling cycle (FC) is defined as the estimated time (years) for the smaller diameter classes (DBH < 50 cm) of trees to pass through 10-cm diameter classes until reaching the determined MLD (CAI_{vmax}) (Eq.6, Table 1) (SCHÖNGART, ET AL 2007).

Table 1:Equations of growth modeling.

	Equation	Variables
Eq. 1	$V_t = \pi \frac{DBHt^2}{4} H_t(f)$	V_t = commercial volume per year; H_t = Height per year; f = Factor to correct (0,7)
Eq. 2	$D = \frac{b_0}{\left(1 + \left(\frac{b_1}{Age}\right)^{b_2}\right)}$	D= Diameter cumulative; b_0, b_1 and b_2 = correlation coefficient
Eq. 3	$H = \frac{D\ x\ \alpha}{D\ x\ \varepsilon}$	H = height; ε and α = correlation coefficient
Eq. 4	$CAI = CGV_{(t+1)} - CGV_t$	t is any given age (t)
Eq. 5	$MAI = \frac{CGV_t}{t}$	t is any given age (t)
Eq. 6	$Felling\ Cycle = \frac{AGE_{MLD}}{(MLD\ x\ 0{,}1)}$	

2.4. Growth simulations and recruited trees

To estimate forest yeld within one cutting cycle we used bootstrap growth simulations to increase the number of individual growth trajectories and incorporated total autocorrelation (within and among trees) in the calculations (BRIENEN; ZUIDEMA, 2006a, GROENENDIJK, ET AL, 2017). This approach takes into account the ontogenetic growth pattern throughout the lifespan of the tree, i.e., at the juvenile age, simulated growth rate will derive from a juvenile window (BRIENEN; ZUIDEMA; DURING, 2006). This method has proven to be more realistic for considering temporal stochastic structures related to the implied autocorrelation in tree-ring series, improving the estimation of the growth trajectories variability among trees (BRIENEN; ZUIDEMA; DURING, 2006 FOX ET AL. 2001 GROENENDIJK ET AL. 2017). We simulated 1000 growth trajectories curves at each location using the R program (R CORE TEAM, 2020).

Growth trajectories of the trees were used to project the diameter growth of trees below the MLD (<50 cm) during the FC period. To project the growth dynamics, we fixed a mortality rate of 2% based on some studies in others ombrophilous forest in the amazon that ranged from 1.96% to 2.5% (CARVALHO ET AL., 2004; SILVA ET AL., 1995). However, other studies have already proven that mortality rate varies widely between sites and after forest management (DIONISIO ET AL., 2019). To estimate how many individuals would be available for the next cutting cycle, we applied the survival rate suggested by Brienen and Zuidema (2006a) represented by the equation of $(1 - \text{mortality rate})^{\text{Cutting Cycle}}$, which was then multiplied by the density of individuals in each class.

2.5. Timber yield projections

Timber yield projections were estimated based on the calculations of volume from the first and second harvests, which were divided and analyzed in percentage of how much volume was recovered for the second FC. The sustainability of the management criteria for *C. odorata* species was evaluated considering two different scenarios: (1) following the forest management regulations under a polycyclic logging in the eastern Amazon with 50 cm as the MLD under a FC of 30 years (Pará, 2015). (2) Considering the FC and MLD determined by the growth modeling based on tree-ring data (SCHÖNGART, 2008).

The cutting intensity used today is based on the volume of the site, which makes it difficult to apply to a single tree species because it is a high amount. Alternatively, the cutting intensity considering the number of trees cut was used. The maximum harvest intensity was 90% of the harvestable trees, leaving 10% of the remaining trees. Although *C. odorata* is on the list of vulnerable species and by law 15% of the trees should be maintained (BRASIL, 2015), 10% was used assess management in general.

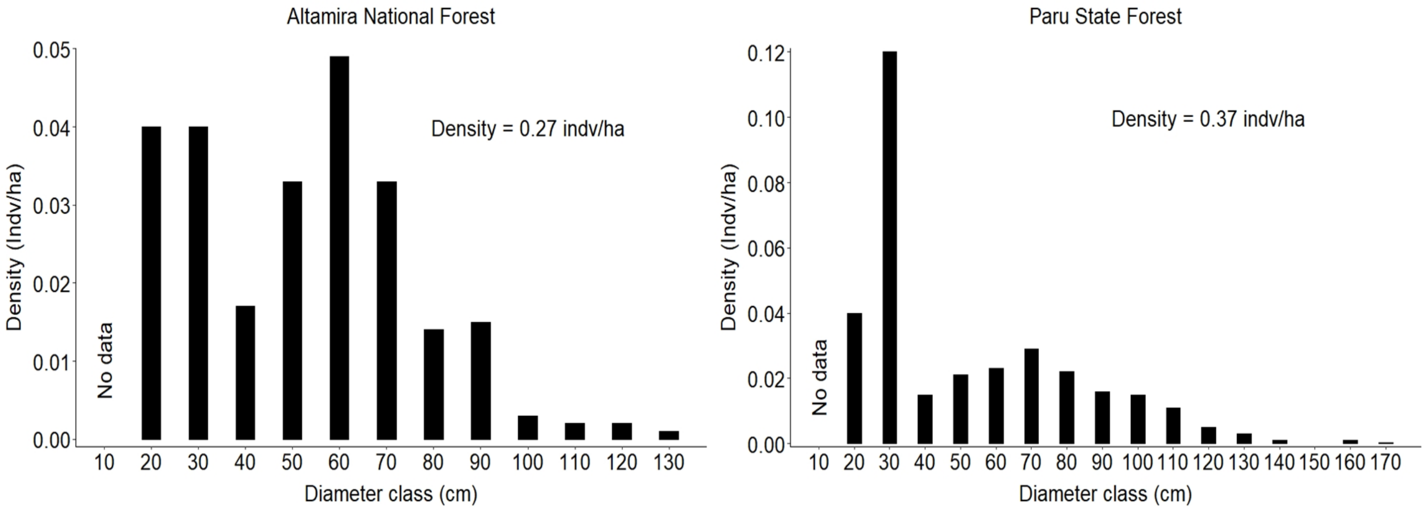
The script of yield projection allowed the choice of the parameter combinations - i.e., to change the MLD, Cutting cycle and intensity values. This was used to test and define a combination that provides partial (50%) or full (100%) recovery. Only one parameter at a time was modified both in the criteria defined in law and in GOL - for example, for tree ring parameters only the intensity was changed and for those of the law only MLD or intensity. When some of these combinations achieved partial or total recovery, we analyzed ten times to observe the variation in the choice of cut trees and the remaining ones at the sites.

3 RESULTS

3.1. Stand structure

C. odorata occurred in low density at both sites (Fig. 2). PSF had higher tree density than ANF, but difference was not significant at $p < 0.05$. In all sites there was a lack of young tree data (DBH <20 cm) and populations did not show the reverse J-shaped diameter distribution (Fig. 3), indicating the low regeneration and the predominance of mature to old trees. These results might have been compromised by the lack of data regarding the presence of juveniles of *C. odorata*, and should not be interpreted as conclusive regarding the species regeneration. Diameter distribution also revealed different forest structure at ANF and PSF. Drastic shifts observed at 80-cm and 100-cm classes at ANF may suggest disturbance events, while the PSF population presented a smooth shape and larger trees (DBH> 150 cm).

Figure 2: Diametric distribution of C. odorata trees in two areas in eastern Amazonia. The data below 40 cm are from the government agency and the data above are from the harvesting company.



3.2. Growth rates and Ages of trees at the MLD

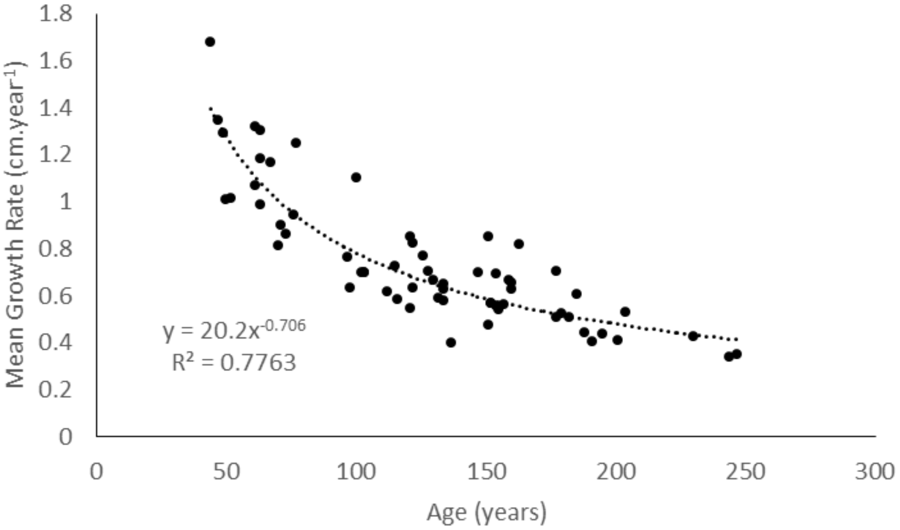
Tree-ring data provided reliable ages and growth rates from *Cedrela* populations from both sites (Table 2). The annual periodicity of stem radial growth and the dating quality from these samples has been previously demonstrated (GRANATO-SOUZA ET AL., 2018; 2020; GUACIARA-SANTOS ET AL., 2020; STAHLE ET AL. 2020). The age structure and growth varied between the *Cedrela* populations. PSF presented slow old growth profile, whereas

ANF presented fast growing younger trees, as tree age and mean growth rate are negatively correlated (Fig. 3).

Table 2: Growth and age characteristics of C. odorata in two sites in the Eastern Amazon.

	Altamira National Forest (ANF)	**Paru Forest State (PFS)**
Samples	16	49
Mean age (year, Min -Max)	76 (49 - 126)	152 (57 - 252)
Mean age at MLD (year, Min Max)	44 (26 - 65)	66 (21 - 166)
Mean diameter rings (cm year $^{-1}$, Min - Max)	75.79 (57.6 - 106)	89.745 (54.1 - 135.2)
Mean diameter growth rate (cm year^{-1} , ± SD)	1.00 ± 0.55	0.57 ± 0.39

Figure 3: Mean growth rate and maximum tree age from 64 sampled trees from this study.



The sites had similar growth patterns but with wide variation in the mean values. The mean growth rates differed 2-fold between the sites, affecting tree-age at MLD. In ANF, average radial growth was 1 cm per year and trees reached harvestable size about 22 years before the trees from PSF, on a mean (Fig.4, Table 2). However, tree age at MLD varied approximately 8-fold at PSF (21 years to 166 years, Table 2). Growth rates were higher in the early years and smaller diametric classes, the typical growth pattern of light-demanding species (Fig 3, 5). In both sites growth rate reaches its maximum in the 20 and 30 cm diameter classes and stabilizes at when diameter reaches the 60 cm class. This growth pattern of *C. odorata* trees is likely related to the moment that the trees reach the canopy of the dense tropical rain forest from the eastern Amazon (BRIENEN; ZUIDEMA, 2006b).

Figure 4: Diameter growth rates per tree age (A and B) and diameter size class (C and D) determined using tree ring data from C. odorata at two sites in eastern Amazonia. Individual growth rates of 16 sampled trees from ANF and 49 from PSF (gray lines); average growth (solid black line) and Confidence interval (dashed black line)..

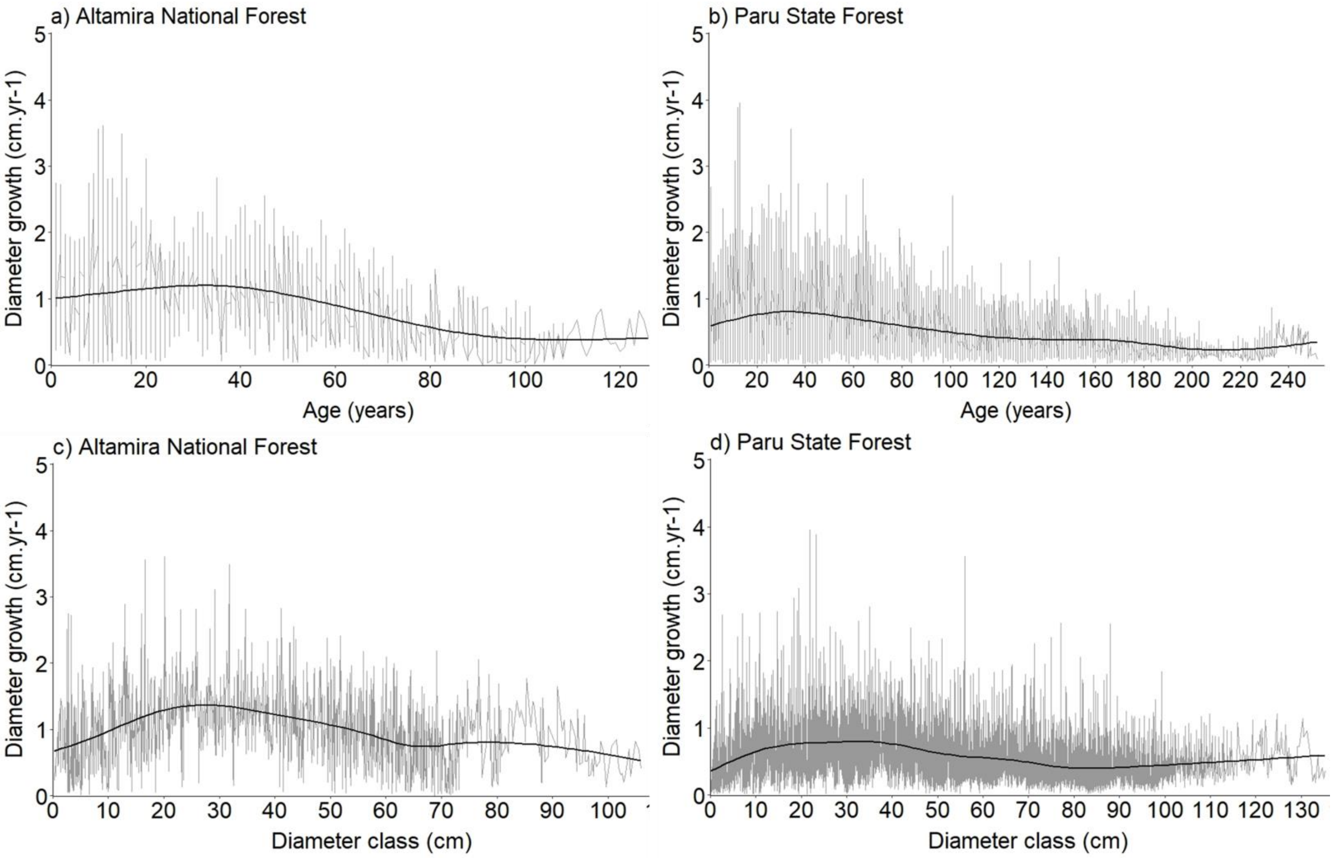
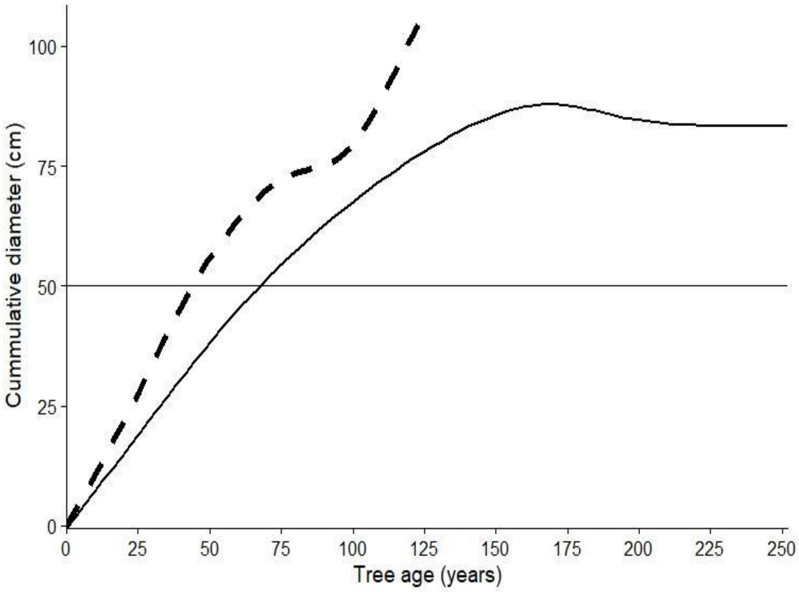


Figure 5: Mean cumulative diameter growth curves from ANF (dashed curve) and PSF (solid curve). Horizontal line indicates the minimum logging diameter threshold of 50 cm established by the Brazilian law.



3.3. Growth modeling parameters

The relationships between tree age and diameter (AGE-DBH) and between diameter and tree height (DBH-Height) were significant at < 0.01 (see Table 4). AGE-DBH relationships were tree species with similar wood densities in different ecosystem (ANDRADE ET AL, 2019; SCHÖNGART, 2008). The overall low DBH-Height relationships could be because the commercial height is measured below tree crown and is poorly related to DBH. DBH-Height relationship at PSF was very low (R^2=0.18), and maybe because it is a height defined by man, with no ecological explanation, that is, it is difficult to correlate with the species' own autoecology. As tree ages, the hypsometric relationship is more affected by the secondary growth in stem diameter rather than the variation in tree height (MARZILIANO ET AL. 2019). A volume equation Berkhout ($V=B_0*DBH^{b1}$) that was used by the forest management company in PSF was also tested, but there were no significant changes in the derived volume growth models (not shown).

Table 3: Regression coefficients of Age-DBH and DBH - Height relations for *Cedrela odorata* growth modeling in two sites in the Eastern Amazon.

	Altamira National Forest		Paru State Forest	
	Age - DBH	DBH-Height	Age - DBH	DBH-Height
a	125.0 ± 6.491***	16.87 ± 1.85 ***	110.743 ± 1.979 ***	17.893 ± 0.512***
b	59.652 ± 4.717 ***	19.41 ± 9.72 *	73.729 ± 2.035***	22.408 ± 2.804***
c	1.389 ± 0.056 ***		1.515 ± 2.035 ***	
R^2	0.87	0.55	0.77	0,18

* p-value < 0.05

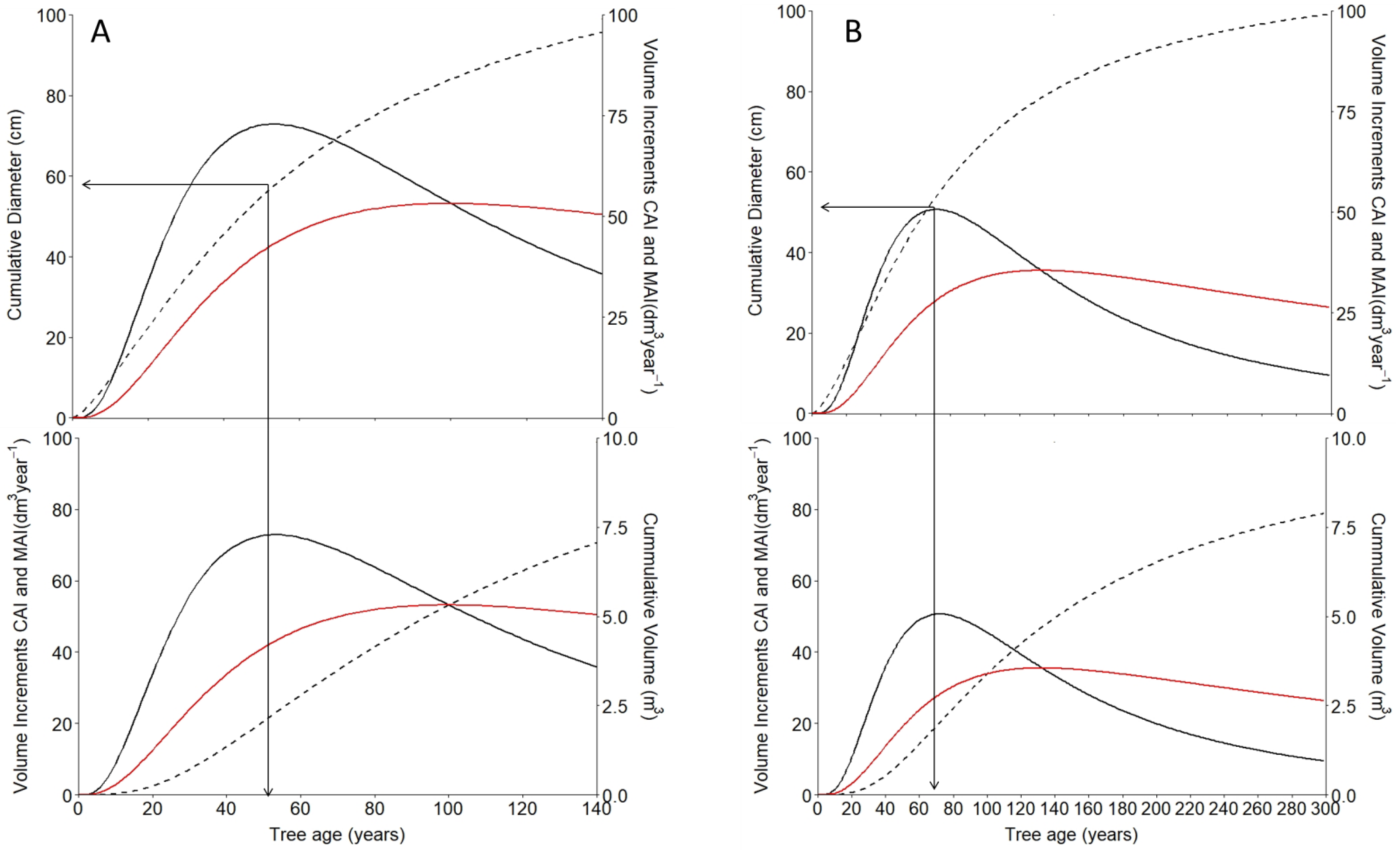
*** p-value < 0.01

The parameters defined by growth modeling (GOL concept, SCHÖNGART, 2008) showed a felling cycle below 25 years and an MLD close to 50 cm. MLD at both sites were within the same diametric classes, but the ages at CAI_{Vmax} varied between sites (Table 5. Fig.5). In ANF, CAI_{Vmax} was achieved an age of 53 years, while at PSF it was at mean age of 71 years. Tree-ring data revealed how long *C. odorata* trees take to reach site-specific determined MLD and how this single information impacts the felling cycle. Site-specific felling cycles determined by growth models indicate 9 years at ANF and 13 years at PSF, that is the mean passage time through 10-cm diameter classes until reaching the site-specific defined MLD. These numbers are expected for low to medium density wood tree species from the Amazon (SCHÖNGART 2008). Mean age at MLD in the model (Table 5) was similar with what we found in the observed data (Table 2), thus our growth model fits well with the data.

Table 4: Estimated management criteria for *Cedrela odorata* in the Eastern Amazon: minimum logging diameter (MLD), felling cycle, maximum current annual increment of volume growth (CAI_{Vmax}), age at CAI_{Vmax} and MLD, and mean age at the MLD threshold determined by the Brazilian law (MLD_{LAW}, 50 cm).

	Altamira National Forest	**Paru State Forest**
MLD (cm)	57 ± 18	53 ± 17
Felling cycle (years)	9 ± 1.628	13 ± 1.933
CAI_{Vmax} (dm^3 $year^{-1}$)	72.890 ± 26.869	50.612 ± 19.007
Age at CAI_{Vmax} (years)	53	71
Age at MLD_{law} (years)	45	65

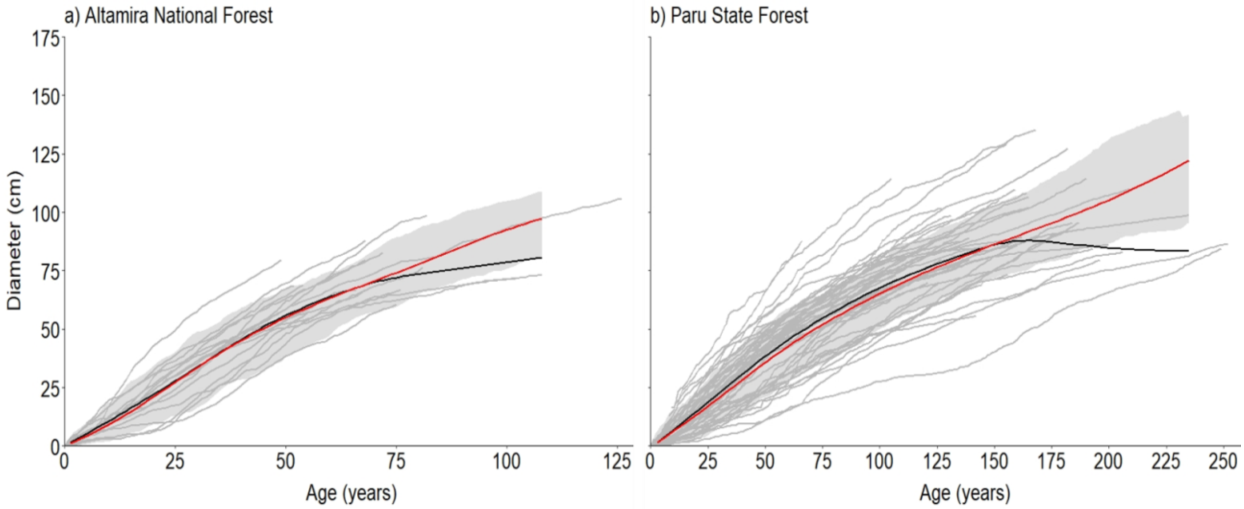
Figure 6: Growth models of *Cedrela odorata* from two sites in eastern Amazon: cumulative diameter and volume increments (dashed black line), current annual increment (CAI, black solid line) and mean annual increment (MAI, red solid line). Arrows indicate the diameter and mean age at CAI_{Vmax} (site-specific determined MLD). A) Altamira National Forest and, B) Paru State forest.



3.3 Volume yield estimation

Growth simulations showed similar behavior to the observed data (Fig. 7). Variation in simulated trees was lower than the observed data, but it incorporated most individuals. The variation of average age to attain the MLD_{LAW} (50 cm) was larger within the sites than between sites for both observed and simulated trees. Diametric window and time lag was tested to choose the best fit to represent the observed growth. In our study we chose a 10 cm diametric window and a 5-year lag time. The maximum age of the simulated individuals was 140 years in ANF and 250 years in PSF. So in PSF we had a simulated age similar to the oldest individual in the observed data.

Figure 7: Growth simulations of *Cedrela odorata* trees in eastern Amazonia. The average of the simulations (solid black line), average of the tree rings (solid red line) and the growth trajectory data of the observed data (solid gray lines).



When applying management criteria determined by growth models (GOL concept, SCHÖNGART, (2008)) and defined by current law to simulation runs, the timber volume recovery was not sustainable (Table 6). Estimated volume yield did not exceed 30% at both sites. In ANF, the yield was higher and with a great volume contribution of individuals below the MLD. In PSF, the recovery was slower, especially in the 13-year felling cycle in which the contribution of new ingrowth was low. These findings reinforce the value of the tree-ring data to project realistic timber yield.

Table 5: Volume yield estimation of *Cedrela odorata* according to two management criteria in eastern Amazonia.

	ANF		PSF	
	GOL	Law	GOL	Law
Felling Cycle (years)	9	30	13	30
New ingrowth (m^3/ha)	0.044	0.130	0.064	0.317
Remaining trees (m^3/ha)	0.039	0.030	0.160	0.123
Total (m^3/ha)	0.083	0.160	0.224	0.540
Yields (%)	**16**	**28**	**10**	**21**

The recruitment dynamics analysis indicated how the trees reach the MLD and which are the main recruiting classes, that is, potential trees for logging in the next cycle (Fig 8). Applying the parameters provided by law, the highest percentage of recruitment is observed for the ANF site (50%), while for the PSF site, the recruitment was lower (39%). In both, the main recruitment class is 30 cm. On the other hand, the parameters defined by the GOL concept, showed low recruitment, only two classes contained possible recruited trees (40 and 50 cm), in this case the main class was 50 cm with 96% at ANF and 63% at PSF. The same occurred in the volume contribution (Table 7). About 46% at ANF and 74% at PSF came from the 30 cm class when we applied the law parameters. While in the GOL model the main class for new ingrowth volume was 50 cm.

Figure 8: Dynamics of recruiting *Cedrela odorata* trees in smaller classes to DBH in eastern Amazonia. The first bars are related to the 30-year felling cycle based on Brazilian legislation and the second bar based on site-specific felling cycles estimated in this study.

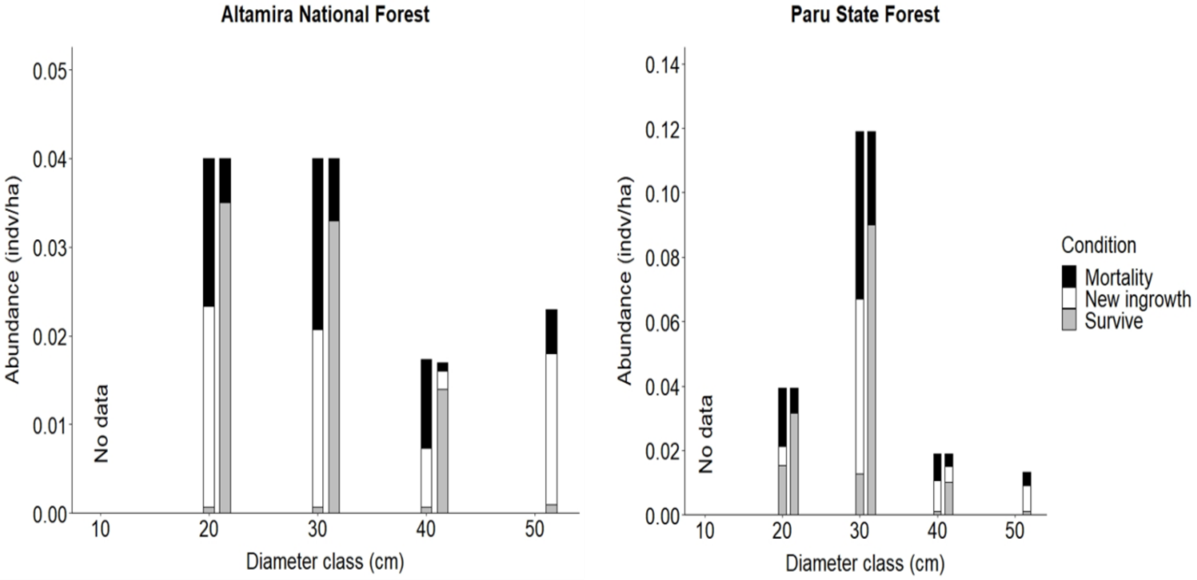
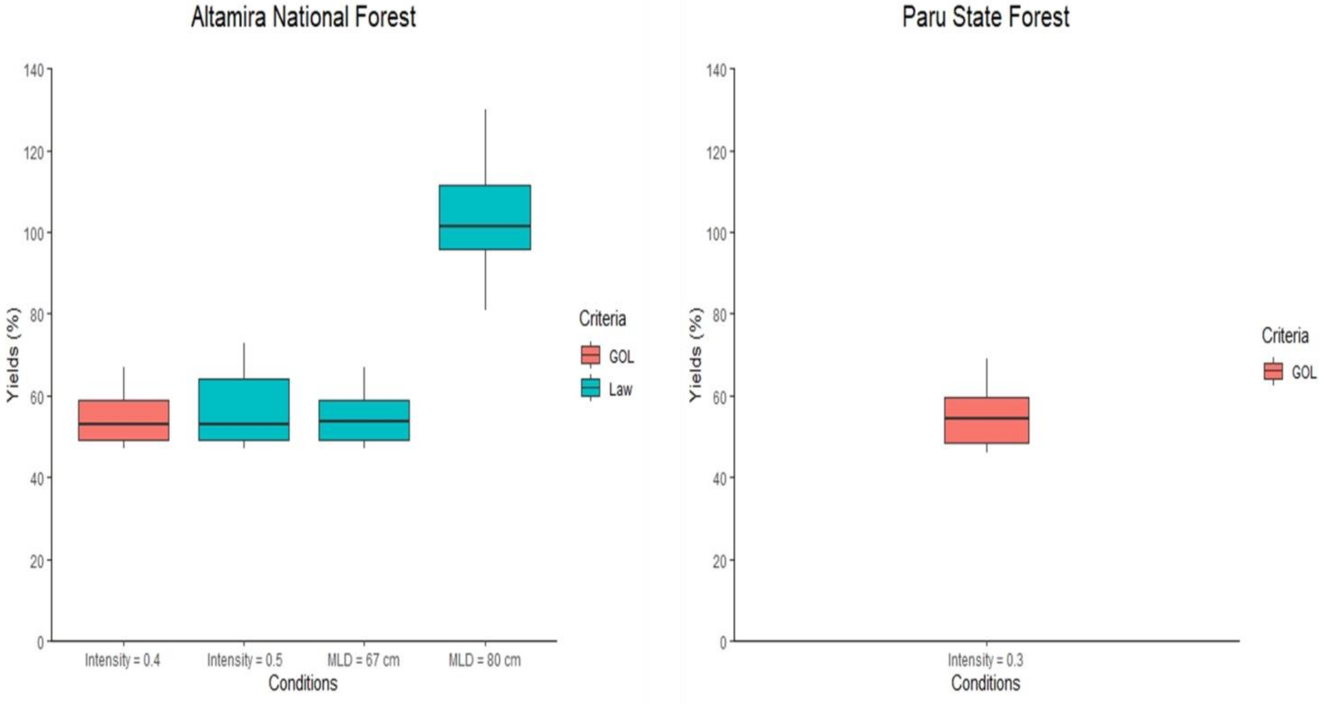


Table 6: Recruitment of stem volume comparing the parameters defined by legislation in the Amazon and those defined by the GOL methods in this study.

	Volume (m³/ha)			
	ANF		PSF	
Class (cm)	GOL	Law	GOL	Law
20		0.04		0.01
30		0.06		0.11
40	0.0001	0.03		0.02
50	0.04		0.02	

We have designed some conditions under which the criteria derived from Brazilian legislation and growth modeling of this study can partially (50%) or full (100%) recover the volume of the first harvest (Fig. 9). The first condition decreased the logging intensity: When we use the GOL-concept with an intensity of 40% (ANF) and 30% (PSF), the volume yield after one felling cycle is around 50% and 60%. While in law parameters the partial volume recover was available when the logging intensity is 50% (ANF). The second condition increased MLD and keeping the logging intensity and the FC. In ANF, at a 17 cm increase in MLD the volume yield recovers over 30 years the partial volume of the first harvest, but when MLD is increase by 30 cm, the recovery is complete. In PSF, as the maximum age of our simulation was 250 years, we were unable to simulate older individuals as we could not estimate future DBH data to define the size at a given age above 250 years.

Figure 9: Analysis of conditions under which two management criteria can be partially or totally sustainable.



4 DISCUSSIONS

The analysis of age structures and size of *C. odorata* populations from two managed public forests provided essential information for the projection of wood production during a felling cycle. We can also observe that site description, old growth trees and well distributed diameter class are strong indicators that the PSF site is a very well preserved forest than ANF.

Despite this, they were similar in terms of *Cedrela's* low density (<1 indv / ha; Schulze, 2008) and low regeneration. The species' vulnerable status on the IUCN red list shows that this valuable wood species may be under pressure and needs an action plan for the rational management of the remaining populations. It is worth mentioning that our results were contrasting to those reported in Bolivia, where the structure had a high number of individuals in the regeneration classes (DBH <20 cm) and a high density (BRIENEN; ZUIDEMA, 2006a). Therefore, interpretation must be cautious, given the intricate processes such as competition (CINTRON, 1990; CUNHA ET AL., 2016), local conditions (BRAZ ET AL, 2012), human and natural disturbances, among others.

However, we must pay attention to the ecology of the species. We can observe that if, on the one hand, there is an absence of individuals in the recruitment classes, and on the other hand, there are larger classes with an abrupt increase in individuals, such as the 60 cm class in ANF and 30 cm in PSF (Fig. 2). This can be explained due to the cohorts formed through disturbances that allowed an increase of light in the forest soil, thus favoring the species (BAKER ET AL. 2005; VLAM ET AL, 2014, 2017; WORBES, 2003). This fact may be more evident at the PSF site than at ANF due to the more closed canopy.

Growth rates of *C. odorata* in eastern Amazonia are high in the early years, a pattern that has been observed for light demanding species in the Amazon (CARVALHO, ET AL. 2004; WITHMORE, 1990). The large difference between the mean growths rates can be associated with a set of factors that affect plant growth that make difficult the comparison at sites: structure of crown, crown illumination, liana load, competition, site conditions (SWAINE; LIEBERMAN; PUTZ, 1987; CUNHA ET AL., 2016). Some studies indicated strong correlation between crown illumination, canopy disturbances and increased growth rates of longed lived pioneer tropical species (CARVALHO ET AL., 2004; CUNHA ET AL., 2016; SILVA ET AL., 1995). In the ANF the predominant forest typology is the open submontane rainforest with possible previous disturbances that facilitate the access of sunlight in the understory when compared to PSF (BRASIL, 2009; BRIENEN; ZUIDEMA; MATÍNEZ-RAMOS, 2009).

Despite the differences in stand structure and the geographical distance between the study sites, *C.odorata* achieved maximum growth rates diameter around the 30 cm diameter class (Fig. 4). This pattern could be related to intrinsic species trait or the size class where trees usually reach the canopy and their reproductive age (ZUIDEMA; BOOT, 2002;

BRIENEN; ZUIDEMA, 2006b). This lifetime growth pattern was also found by Brienen and Zuidema (2006b) in Bolivia, in which young trees that maintained a certain steadiness in growth reached ~30 cm in diameter around 32 years of age. According to the same authors, this constancy in growth is related to a constant light level during the juvenile phase (DBH < 30 cm), showing that despite seeing a difference in the intensity of light by the typology of the forest, younger individuals generally grew under constant light conditions in both sites.

The difference in the age at which species reach the canopy may be related to the availability of light in individuals when they reach the canopy. Cunha and Finger (2013) in southeastern Pará found that *C.odorata* trees with greater light availability at 30 cm reached the MLD 19 years earlier than those with low availability. The difference found in our study was similar in ANF in that the trees reached MLD 22 years earlier. These findings reinforce the need to address site-specific management of the species. The high variation in age at MLD and consequently low relationship between age and size has been reported for other tropical species (BRIENEN; ZUIDEMA, 2006a; WORBES ET AL., 2003). In PSF this variation was high among individuals due to the high sampling effort and heterogeneous light condition that influence the passage time between size classes (BRIENEN; ZUIDEMA, 2006b). In general, our trees reached MLD earlier in the canopy compared to other studies (BRIENEN; ZUIDEMA, 2006b).

Was there a difference between the management parameters determined by growth modeling and those from the law? In a context of controversial opinions and the polemic issues involving forest management in the Amazon, the length of the FC and the MLD determined for *C. odorata* by the growth modeling method must be confirmed by complementary studies. Our results highlight the importance of species-specific management and the potential use of growth rings, the only known reliable method able to incorporate age to hypsometric equations, providing us with information about the ecology of the species over a long period of time (DE RIDDER ET AL., 2013; SCHÖNGART ET AL., 2007, 2008; ROSA ET AL., 2017; SCHÖNGART ET AL., 2017; WORBES; SCHÖNGART, 2019). Despite this, some limitations occurred in the growth models, such as the use of commercial height, which may have caused a low correlation of the DBH-Height relationship, mainly in PSF that contains the largest diameters. This appears to be recurrent in some areas and species in tropical forests, mainly due to the lack of adjustments of species-specific- equations for each species in the Amazon (DE RIDDER ET AL., 2013; ROSA ET AL., 2017).

Are the current forest management parameters sustainable for *Cedrela odorata* in the Earnest amazon? The recovery of timber volume using the current parameters was not sufficient to maintain the *C. odorata's* population in eastern Amazonia. The volume yields for the next harvest of *C. odorata* were unsustainable, less than 30% of the initial available volume. Previous studies with the species have also found similar results in western Amazonia in which the recovery did not reach 20% under a fixed mortality of 2% to recover the initial volume (BRIENEN; ZUIDEMA, 2006a). In other study in the western region of the Brazilian Amazon Braz et al., (2012) projected the volume recovery of C. odorata in three different areas that were also below 50% volume recovery. In that same study, the area with an unbalanced diametric structure similar to that of our sites had a recovery of around 22% of the initial volume. We also found differences in recovery time between sites. In ANF the recovery is faster than in PSF demonstrating the need for specific management studies for species in site (BRAZ ET AL., 2012; PIPONIOT ET AL., 2019; SCHÖNGART, 2008).

The projection of timber yield during the felling cycle for specific species is not an easy task in tropical forests due to the high diversity of species and site conditions mortality, growth and recruitment rates generally increase in the first years after management, mainly for light-demanding species (ÁVIILA ET AL., 2017; CARVALHO ET AL., 2004; DIONISIO ET AL., 2019). These changes may affect the volume recovery of the species in the next felling cycle, but occur only for a short period of time and stabilize. Therefore, several modeling studies fix the mortality and recruitment values to avoid underestimation or overestimation of the species (BRIENEN; ZUIDEMA, 2006a; GROENENDYK ET AL., 2017). Our simulations also used a fixed rate due to the lack of information regarding the behavior of the species of C.odorata and the limitations of our simulation.

Do the parameters defined by the growth rings show higher volume yields in the next cycle? The GOL method resulted in low yields for the populations of *C. odorata* in our study. The application of polycyclic management for helophyte species, such as the case of *C. odorata,* may be suppressing the regeneration and growth of individuals in the forest. The species C. odorata showed rapid growth mainly in an environment with a more open canopy, which is avoided by logging companies that seek reduced impact. Schöngart (2008) argues that the monocyclic system without or with alterations can be more efficient for these species as they would stimulate the regeneration of the species, therefore they should have a period of rotations (period between establishment of the tree until its cut in the diameter that corresponds with the maximum current production by volume). However, for that we need more study on the regeneration of the species so that the volume is recovered. In addition Schöngart (2008) suggests that the method has to be accompanied by an intense silvicultural activity.

Our simulations bring new evidence to discuss the impacts of different management parameters for *C. odorata* in eastern Amazonia. In this study we only manipulated logging intensity and MLD, since other studies have shown that long cutting cycles can be costly for companies and have an increase in accumulated mortality (GROENENDYK ET AL., 2017). In fact, the logging intensity has shown to be the main cause of unsustainable forest management (VAN GARDINGEN; VALLE; THOMPSON, 2006). However, we observed that when we reduced the logged intensity in both scenarios (Law and GOL) the performance only improved from 50% reduction in the cutting intensity. This is an alarming result given that the Pará state legislation "protects" *Cedrela odorata*, classified as vulnerable species, by establishing lower cutting intensity (85% instead of 90%). While current logging intensity is not sustainable and continues to pressure the species, a 50% reduction in intensity could be economically impracticable for managers. Therefore, the best simulated scenario was when we increased the MLD to 80 cm and maintained the cutting intensity of 90% and the felling cycle in 30 years in which the recoil was 100% in ANF. The MLD can decrease if the intensity is 85% and the management will still be sustainable. Braz et al., (2012) it also suggested a total cut of the class above 75 cm and obtained a volume recovery close to 100% after 30 years. Unfortunately, in PSF, due to limitations in our simulations, the maximum age of the simulations was close to the observed data and it is not possible to observe the projection of the older trees, generating unrealistic yield values.

Stimulating the regeneration of this species is necessary. According to Cintron (1990) a large amount of *C. odorata* seedling is found close to older individuals, however due to their intolerance to shade and high competition they present a high mortality. One of the means of increasing density and inducing regeneration of *C. odorata* is by using its seedlings to enrich clearings after exploitation (VIEIRA ET AL., 2018). Silvicultural practices can improve volume yield in the next cutting cycle (AVILA ET AL., 2017; CARVALHO ET AL., 2004;). The species *C. odorata* may have its growth negatively influenced with the increase of lianas after forest management, mainly in ANF that has a high concentration of liana in gap (BRASIL, 2009; CUNHA ET AL., 2016). Practices applied in recruiting classes such as open gaps and liana control can improve the volume yield of the species. They are responsible for most of the volume of the second logging (Table 7)

5 CONCLUSION

The forest management applied with the current parameters is putting pressure and overestimating the recovery capacity of *C. odorata* in a 30-year felling cycle. However, the management criteria cannot be defined only by species, but must be evaluated by the ecology of the species per site. Therefore, changes in the parameters defined for species-specific and site-specific management are ideal for the conservation of the forest. The growth rings proved to be a good tool to contribute to the ecology and projection of the future timber yield. We strongly believe tree-ring data could be successfully added to inventory routines by management groups in the Amazon and would be promising to improve techniques according to the needs of the region

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