MINISTÉRIO DA EDUCAÇÃO
UNIVERSIDADE FEDERAL RURAL DA AMAZÔNIA
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS FLORESTAIS

**RAPHAEL LOBATO PRADO NEVES**

# TRATAMENTOS SILVICULTURAIS EM CLAREIRAS APÓS EXPLORAÇÃO FLORESTAL

BELÉM
2020

**RAPHAEL LOBATO PRADO NEVES**

# TRATAMENTOS SILVICULTURAIS EM CLAREIRAS APÓS EXPLORAÇÃO FLORESTAL

Defesa de tese apresentada à Universidade Federal Rural da Amazônia como parte das exigências para obtenção do título de Doutor em Ciências Florestais, área de concentração Manejo de Ecossistemas Florestais.

**Orientador:** Dr. Gustavo Schwartz

**BELÉM**
**2020**

Dados Internacionais de Catalogação na Publicação (CIP)
Bibliotecas da Universidade Federal Rural da Amazônia
Gerada automaticamente mediante os dados fornecidos pelo(a) autor(a)

---

NEVES, RAPHAEL LOBATO PRADO

TRATAMENTOS SILVICULTURAIS EM CLAREIRAS APÓS EXPLORAÇÃO FLORESTAL / RAPHAEL LOBATO PRADO NEVES. - 2020.

75 f. : il. color.

Tese (Doutorado) - Programa de Pós-Graduação em Ciências Florestais (PPGCF), Campus Universitário de Belém, Universidade Federal Rural Da Amazônia, Belém, 2020.
Orientador: Prof. Dr. GUSTAVO SCHWARTZ

1. SILVICULTURA. 2. CLAREIRAS. 3. ENRIQUCIMENTO. 4. MANEJO. 5. PLANTIO. I. SCHWARTZ, GUSTAVO , *orient.* II. Título

CDD 634.92

---

**RAPHAEL LOBATO PRADO NEVES**

# TRATAMENTOS SILVICULTURAIS EM CLAREIRAS APÓS EXPLORAÇÃO FLORESTAL

Tese apresentada à Universidade Federal Rural da Amazônia como parte das exigências para obtenção do título de Doutor em Ciências Florestais, área de concentração Manejo de Ecossistemas Florestais.
Orientador: Dr. Gustavo Schwartz
Aprovado em 09 de outubro de 2020

**BANCA EXAMINADORA**

Dr. Gustavo Schwartz
Orientador

Marciel José Ferreira

Dr. Marciel José Ferreira
1º Avaliador

Igor do Vale

Dr. Igor do Vale Gonçalves
2º Avaliador

Izildinha S. Miranda

Dra. Izildinha de Souza Miranda
3º Avaliadora

Dr. Rodrigo Geroni Mendes Nascimento
4º Avaliador

## SUMÁRIO

LISTA DE TABELAS ........................................ 4

LISTA DE FIGURAS ........................................ 4

RESUMO ........................................ 8

ABSTRACT ........................................ 9

CONTEXTUALIZAÇÃO ........................................ 10

OBJETIVOS ........................................ 12

QUESTÕES E HIPÓTESES ........................................ 13

Post-harvesting silvicultural treatments in canopy logging gaps: medium-term responses of commercial tree species under tending and enrichment planting ........................................ 19

1. Introduction ........................................ 19
2. Materials and methods ........................................ 21
3. Results ........................................ 26
4. Discussion ........................................ 29
5. Conclusion ........................................ 33
6. References ........................................ 33

Silviculture of high value timber species in the Amazon: managing *Dinizia excelsa* in logging gaps 40

1. Introduction ........................................ 40
2. Materials and methods ........................................ 42
3. Results ........................................ 44
4. Discussion ........................................ 47
5. Conclusion ........................................ 49
6. References ........................................ 50

Silviculture of a very common commercial timber species in the Amazon: managing *Tachigali glauca* in logging gaps ........................................ 57

1. Introduction ........................................ 57
2. Materials and methods ........................................ 59
3. Results ........................................ 61
4. Discussion ........................................ 65
5. Conclusions ........................................ 67
6. References ........................................ 68

CONCLUSÕES GERAIS ........................................ 74

## LISTA DE TABELAS

Capitulo 1

**Tabela 1.** Initial conditions (2006-2007) of the four post-harvesting silvicultural treatments tested (mean ± SD) for seedlings and saplings naturally present or planted in logging gaps in Jari Florestal, Brazil.......................................................................................... 17

**Tabela 2.** Current conditions (2017-2018) of the four post-harvesting silvicultural treatments tested for initial and complementary individuals in logging gaps in Jari Florestal, Brazil...................................................................... 18

Capitulo 2

**Tabela 1.** Measurement year, number of individuals (N), basal area (G), absolut density (ADe) and dominance (ADo) of Dinizia excelsa in the pre-logging and in the annual production unit of 2004 in the forest management are of Jari S.A., Eastern Amazon. PL (pre-logging), SRIL (standard reduced impact logging), TNER (tending of the naturally established regeneration), and EP (enrichment planting)........................................................................................... 36

Capitulo 3

**Tabela 1.** Number of individuals (N), basal area (G), absolut density (ADe) and dominance (ADo) of Tachigali glauca in the forest management are of Jari S.A., Eastern Amazon. PL (pre-logging), SRIL (standard reduced impact logging), TNER (tending of the naturally established regeneration), and EP (enrichment planting)........................................................................................... 49

## LISTA DE FIGURAS

Capítulo 1

**Figura 1.** Mean (± SE) of mortality rates of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments by one, six, and 11 years in logging gaps in the managed forests of Jari company, Pará state, Brazil. Lowercase letters are treatment comparisons and uppercase letters are time comparisons in the GLM repeated measures

ANOVA and post-hoc Tukey’s pairwise test..…………………….......................................................................... 20

**Figura 2.** Mean (± SE) of basal area (m² ha-1) of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments from the initial trees, complementary and the overall individuals (sum of initial and complementary individuals) in logging gaps in the managed forests of Jari company, Pará state, Brazil. Lowercase letters are to comparisons between the initial mean basal areal of treatments and uppercase letter are to mean basal area of complementary and overall in the ANOVA and post-hoc Tukey’s pairwise test........................................................................................................ 21

**Figura 3.** Mean (± SE) of periodic annual increment (PAI) of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments in logging gaps in the managed forests of Jari company, Pará state, Brazil. Lowercase letters are treatment comparisons in ANOVA with post-hoc Tukey’s pairwise test.......................................................... 22

**Figura 4.** Bars representing percentage of individuals per diameter class (left side y-axis) and lines showing basal area (m² ha-1) per diameter class (right y-axis) of the standard reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments for both initial and complementary trees in logging gaps in the managed forests of Jari company, Pará state, Brazil.......................................................................................... 23

**Capítulo 2**

**Figura 1.** Mortality rates of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER) and enrichment planting (EP) treatments over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil.......................................................................................... 38

**Figura 2.** Basal area (mha-¹) of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER) and enrichment planting (EP) treatments over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil…………………… 38

**Figura 3.** Periodic annual diameter (PAI) measured from diameter at breast height (DBH) at 1.3 m from the soil of each individual distributed in gap sizes, treatments and crown exposure classes, over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil. In figure "D" the lower case letters are for comparison between treatments and upper case letters are for crown exposure class comparisons............................... 39

**Figura 4.** Percentage of individuals per diameter class (0-4 cm; 4-8 cm, 8-12 cm and 12-16 cm) distributed in gap sizes, treatments and crown exposure classes, over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil............................................................................ 40

**Capítulo 3**

**Figura 1.** Mortality rates of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER) and enrichment planting (EP) treatments by one, six, and 11 years in logging gaps in the managed forests of Jari company, Eastern Amazon, Brazil.......................................................................................... 51

**Figura 2.** Basal area (m² ha-¹) of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER) and enrichment planting (EP) treatments over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil………………… 51

**Figura 3.** Periodic annual diameter (PAI) mean (± SE) of the diameter at breast height (DBH) at 1.3 m from the soil of each individual distributed in treatments over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil. Lowercase letters are treatment comparisons in ANOVA with post-hoc Tukey's pairwise test.......................................................................................... 52

**Figura 4.** Periodic annual diameter (PAI) mean (± SE) of the DBH at 1.3 m from the soil of each individual distributed in crown exposure classes over 11 years in logging gaps in the managed forests of Jari S.A., Eastern

Amazon, Brazil. Lowercase letters are crown exposure class comparisons in ANOVA with post-hoc Tukey's pairwise test........................................ 52

**Figura 5.** Percentage of individuals per diameter class (0-5 cm; 5-10 cm, 10-15 cm and 15-20 cm) distributed in gap sizes, treatments and crown exposure classes, over 11 years in logging gaps in the managed forests of Jari, Eastern Amazon, Brazil............................................................................. 53

**Figura 6.** Mean (± SD) of periodic annual increment (PAI cm year-1) and Gap area (m²) of the eight logging gap units of enrichment planting treatment in the managed forests of Jari S.A., Eastern Amazon, Brazil. Lowercase letters are PAI (cm year$^{-1}$) mean (± SD) comparisons between logging gap units of EP treatment in ANOVA with post-hoc Tukey's pairwise test............................................................................................................ 53

## RESUMO

O objetivo geral do trabalho foi o de avaliar qual o efeito a médio prazo dos tratamentos silviculturais pós-colheita na sobrevivência, crescimento e estrutura de espécies comerciais, tanto de árvores plantadas quanto as de regeneração natural, ambas conduzidas em clareiras de exploração florestal. Essas clareiras foram abertas nos anos de 2004 e 2006, totalizando 72 clareiras sob diferentes tipos de tratamentos com avaliação ao longo de onze anos na área de manejo florestal da empresa Jari Florestal S.A, situada em Monte Dourado, distrito da cidade de Almerim, Amazônia Oriental, Brasil. Foi avaliado a regeneração natural sem aplicação de nenhum tipo de tratamento silvicultural (SRIL); condução da regeneração natural (TNER); condução de espécies plantadas com e sem remoção prévia de resíduos provenientes da colheita de madeira (EP's). No primeiro artigo foi avaliado a sobrevivência, crescimento e estrutura. Os resultados indicaram maior sobrevivência e crescimento de árvores com tratamento silvicultural pós-colheita quando comparado ao tratamento controle, que reflete os procedimentos padrão de exploração de impacto reduzido. No segundo artigo foi avaliado o efeito do tratamento silvicultural pós-colheita para a espécie *Dinizia excelsa*, uma das mais importantes espécies comerciais da Amazônia e que possui baixa densidade natural. Foi comparado a sobrevivência e o crescimento de árvores de *D. excelsa* em diferentes tamanhos de clareiras, tratamentos e classes de exposição de copa. Foi constatado que não há diferença no crescimento dos indivíduos de acordo com o tamanho da clareira, mas de acordo com a classe de exposição de copa. Apesar da alta mortalidade de indivíduos plantados, estes obtiveram melhor desempenho no crescimento, principalmente aqueles que receberam mais luz solar. A *D. excelsa* é uma espécie que responde muito bem, seja para plantio ou condução da regeneração natural em clareiras. No terceiro artigo buscou-se avaliar a espécie *Tachigali glauca*, também uma importante espécie comercial da Amazônia. O tachi é uma espécie que respondeu muito bem ao tratamento silvicultural, principalmente quando há luz do sol disponível em toda sua copa. Obteve ótimos resultados em sobrevivência e incremento sendo esta espécie recomendada para plantio em clareiras. As clareiras de impacto reduzido ou as clareiras naturais que possuam um mínimo de 200 m² são espaços florestais com alto potencial produtivo e/ou conservacionista. Recomenda-se o uso destes espaços aliado aos tratamentos silviculturais de condução tanto de indivíduos plantados quanto da regeneração natural, auxiliando assim em uma mais rápida produção madeireira associada com a conservação de espécies comerciais.

**PALAVRAS-CHAVE:** condução da regeneração natural; enriquecimento de clareiras; luz solar; tamanho de clareiras; silvicultura tropical.

## ABSTRACT

The general objective of the work was to evaluate the medium-term effect of post-harvest silvicultural treatments on the survival, growth and structure of commercial species, both from planted trees and those from natural regeneration, both conducted in canopy logging gaps. These gaps were opened in 2004 and 2006, totalling 72 gaps under different types of treatments with assessment over 11 years in the forest management area of the company Jari Florestal SA, located in Monte Dourado, district of the city of Almerim, Eastern Amazon, Brazil. Was evaluated natural regeneration without any silvicultural treatment, so-called standard procedures of reduced impact-logging (SRIL); tending of natural established regeneration (TNER); tending of enrichment planted species with and without prior removal of residues from wood harvesting (EP's). In the first article, survival and growth were evaluated. The results indicated greater survival and growth of trees with post-harvest silvicultural treatment when compared to the control treatment, which reflects the standard procedures of reduced impact-logging. Legally adopted in Brazil. In the second article, the effect of post-harvest silvicultural treatment for *Dinizia excels* specie, one of the most important commercial species in the Amazon and which has a low natural density, was evaluated. The survival and growth of *D. excelsa* trees in different gaps sizes, treatments and crown exposure classes were compared. It was found that there is no difference in the growth of individuals according to the gap sizes, but according to the crown exposure class. Despite the high mortality of planted individuals, they performed better in growth, especially those who received more sunlight. *D. excelsa* is a species that responds very well, whether for planting or conducting natural regeneration in gaps. The third article sought to evaluate the species *Tachigali glauca*, also an important commercial species in the Amazon. *T. glauca* is a specie that responded very well to silvicultural treatment, especially when sunlight is available throughout its crown. It obtained excellent results in survival and growth and this specie is recommended for enrichment planting in gaps. Gaps that have a minimum of 200 m² are forest spaces with high productivity and / or conservation potential. It is recommended to use these spaces together with the silvicultural treatments for tending both planted individuals and natural regeneration, thus assisting a faster timber production associated with the conservation of commercial species.

**KEYWORDS:** natural regeneration tending; enrichment planting; sunlight; size of logging gaps; tropical forestry.

## CONTEXTUALIZAÇÃO

Manejo Florestal Sustentável é a administração da floresta para obtenção de benefícios econômicos, sociais e ambientais, respeitando-se os mecanismos de sustentação do ecossistema objeto do manejo e considerando-se, cumulativa ou alternativamente, a utilização de múltiplas espécies madeireiras, de múltiplos produtos e subprodutos não-madeireiros, bem como a utilização de outros bens e serviços florestais. No entanto, nem todos os mecanismos de sustentabilidade das florestas manejadas são adequadamente abordados pelos gestores e pela atual legislação florestal brasileira (BRANDÃO et al., 2018). Portanto, o desafio para a silvicultura tropical é garantir níveis adequados de estoque em crescimento e facilitar a regeneração de espécies de valor comercial, além de serviços ambientais.

O Brasil assumiu compromissos nacionais e internacionais de restaurar e reflorestar, pelo menos, 12 milhões de hectares de florestas até 2030 por meio de sua Contribuição Nacionalmente Determinada (CND), a qual foi apresentada no âmbito da Convenção-Quadro das Nações Unidas sobre Mudança do Clima (Brasil, 2015). Essa é parte da estratégia nacional adotada para reduzir as emissões de gases de efeito estufa (GEE) e promover atividades de menor impacto ambiental (VALLE et al., 2020). Uma destas metas é a criação de mecanismos eficientes que garantam o cumprimento da Lei de Proteção de Vegetação Nativa (BRASIL, 2012), com a recuperação de passivos de Áreas de Preservação Permanente (APPs) e RL (VALLE et al., 2020).

O Governo do estado do Pará instituiu através do decreto de número 941 de 03/08/2020 o Plano Estadual Amazônia Agora (PEAA). O plano considera o incremento de cobertura vegetal secundária para contabilidade das remoções estimadas de GEE, na qual objetiva: §1º ter regeneração da vegetação correspondendo a 5,65 milhões de hectares até o ano de 2030; e/ou §2º ter regeneração de cobertura vegetal correspondendo a 7,41 milhões de hectares para o ano de 2035, caso a implementação do PEAA disponha de recursos externos até 2030.

Parte da recuperação desses passivos deve ocorrer por meio da regeneração natural, o que incluí o manejo de clareiras para plantio e condução da regeneração natural, conforme previsto no Artigo 44 da Instrução Normativa 05 da SEMAS/PA, publicada em 11 de setembro de 2015. O conhecimento da regeneração, recrutamento, crescimento e mortalidade de indivíduos de espécies comerciais em florestas tropicais manejadas é crucial para sua conservação e previsão sobre a produção futura destas florestas. Essas informações dão ao gerente florestal uma imagem muito mais clara sobre a capacidade de recuperação de uma determinada floresta manejada. Isso, portanto, permite ao gerente tomar decisões precisas sobre a melhor forma de manejar sua floresta.

A abertura de clareiras no dossel causadas pela morte natural de árvores são distúrbios comuns de pequena escala e desempenham papel importante na dinâmica da floresta (WHITMORE, 1989). No entanto, clareiras artificiais causadas pelo corte de espécies arbóreas em florestas tropicais têm impactos maiores do que aqueles naturais. As alterações no ambiente florestal causadas pela exploração madeireira podem modificar a trajetória da regeneração natural, crescimento, mortalidade e recrutamento de indivíduos que compõem as comunidades destas florestas (SCHWARTZ et al., 2014; DE AVILA et al., 2017, DIONISIO et al., 2018).

A exploração florestal com técnicas de EIR é baseada em planejamento de operações e treinamento dos recursos humanos. Na EIR deve-se: a) minimizar danos ambientais, conservando serviços ambientais e potencial de exploração futura e; b) reduzir custos operacionais da exploração, aumentando a eficácia do trabalho, e c) reduzir desperdícios. As florestas sob EIR geralmente apresentam uma dinâmica mais alta do que a dinâmica observada em florestas intocadas, devido a operações de exploração como construção de infraestrutura (estradas, trilhas de arraste e pátios de estocagem), corte e arraste de árvores (YGUEL et al., 2019). Essas alterações na floresta muitas vezes promovem melhores condições para o crescimento de espécies remanescentes baseadas na dinâmica da sucessão de indivíduos (COSTA et al., 2020).

Apesar dos significativos avanços obtidos nas formas de exploração madeireira em florestas tropicais primárias, o que inclui a aplicação de EIR, não há sinais de sustentabilidade do sistema silvicultural no longo prazo (SIST e FERREIRA, 2007; VALLE et al., 2007). O que se tem demonstrado por meio de simulações e monitoramento de longo prazo, é que a maior parte das espécies exploradas não é capaz de recuperar os volumes explorados dentro de um ciclo (25-35 anos) completo de corte (REIS et al., 2010). Assim, as florestas tropicais primárias não são capazes de apresentar o mesmo rendimento de madeira no segundo ciclo de corte. Desta forma, a colheita florestal por meio de EIR em florestas tropicais primárias ainda precisa evoluir muito para alcançar uma exploração cíclica sustentável de madeira.

Como possíveis medidas para contornar o problema estão: a) mudança de mercados para espécies de baixa densidade de madeira (REIS et al., 2010); b) redução de volume colhido ou então alongamento do ciclo de corte (HAWTHORNE et al., 2012); c) redução do diâmetro mínimo de corte (DMC) para algumas espécies (SIVIERO et al., 2020b) e d) aplicação de tratamentos silviculturais pós-colheita (DE GRAAF et al., 1999; DAUBER et al., 2005; CARVALHO et al., 2008). As práticas silviculturais pós-colheita para aumentar as taxas de crescimento das espécies arbóreas comerciais, o plantio de espécies de valor econômico (SCHWARTZ et al., 2017b) e o aproveitamento do volume perdido por mortalidade tornam-se fundamentais para equilibrar as perdas de madeira em florestas tropicais devido às colheitas (DIONISIO et al., 2018).

Os diferentes tratamentos silviculturais aplicados após a colheita, favorecem o estabelecimento de regeneração natural e maior produção em florestas tropicais (AZEVEDO et al., 2008; DE AVILA et al., 2017; SCHWARTZ et al., 2017a, 2017b; GOMES et al., 2019). Entre os tratamentos silviculturais pós-colheita estão aqueles que se concentram em garantir a reposição de indivíduos de espécies comerciais para os próximos ciclos de corte via plantio ou condução de regeneração natural. O plantio de espécies comerciais e a condução da regeneração natural encontram ambientes propícios para serem bem-sucedidos dentro das clareiras abertas pela queda de árvores colhidas (KUKKONEN et al., 2008). As técnicas de plantio e condução da regeneração natural vêm se desenvolvendo em diferentes florestas tropicais no mundo, como na Amazônia Oriental (LOPES et al., 2008; SCHWARTZ et al., 2013), Amazônia Ocidental (D'OLIVEIRA E RIBAS, 2011; KARSTEN et al., 2013) e Oeste da África (DOUCET et al., 2009). Assim, estes promissores tratamentos silviculturais têm merecido mais atenção em pesquisas científicas e desenvolvimento tecnológico.

Nesta tese serão abordados os efeitos a médio prazo de tratamentos silviculturais em clareiras oriundas da exploração de impacto reduzido, tanto de árvores comerciais plantadas quanto das de regeneração natural sob diferentes tratamentos, utilizando-se de técnicas que visam aumentar a densidade de espécies exploradas, de espécies com baixa densidade e/ou visando produção madeireira; que mantenham a variabilidade genética através das mudas e/ou sementes nativas; e que ao mesmo tempo conservem *in situ* as espécies podendo ainda ter utilização das mesmas nos próximos ciclos de corte. Conforme regimento geral da UFRA, que instrui escrita nas normas da revista a que serão submetidos, os capítulos/artigos estão no formato da revista *Forest Ecology and Management*.

## OBJETIVOS

### Geral

Avaliar o comportamento de espécies comerciais em clareiras de exploração de impacto reduzido.

### Específicos

**Capítulo 1:**

Avaliar o efeito a médio prazo dos tratamentos silviculturais pós-colheita sobre a mortalidade, o crescimento e a estrutura de espécies comerciais de árvores, tanto plantadas quanto as de regeneração natural, presentes em clareiras de exploração de impacto reduzido.

**Capítulo 2:**

Avaliar o efeito a médio prazo dos tratamentos silviculturais pós-colheita em clareiras de diferentes tamanhos, com uso de árvores da espécie *Dinizia excelsa* plantadas e provenientes da regeneração natural sob diferentes níveis de sombreamento.

**Capítulo 3:**

Avaliar o efeito a médio prazo dos tratamentos silviculturais pós-colheita em clareiras utilizando árvores da espécie *Tachigali glauca* plantadas e provenientes da regeneração natural sob diferentes níveis de sombreamento.

## QUESTÕES E HIPÓTESES

**Capítulo 1:**

**Questão:** Os tratamentos silviculturais pós-colheita influenciam na sobrevivência e crescimento de espécies comerciais madeireiras?

**Hipótese nula:** Os tratamentos silviculturais pós-colheita não influenciam na sobrevivência e crescimento de espécies comerciais em clareiras da exploração de impacto reduzido.

**Hipótese alternativa:** Os tratamentos silviculturais pós-colheita aumentam a sobrevivência e crescimento de espécies comerciais em clareiras da exploração de impacto reduzido.

**Capítulo 2:**

**Questão:** Qual efeito a médio prazo de tratamentos silviculturais em indivíduos de *Dinizia excelsa* em termos de mortalidade e crescimento?

**Hipótese nula:** Os tratamentos silviculturais pós-colheita não influenciam na sobrevivência e crescimento de *D. excelsa* em clareiras da exploração de impacto reduzido.

**Hipótese alternativa:** Árvores de *D. excelsa* não sofrem influência dos tamanhos de clareira, mas terão influência dos níveis de sombreamento, havendo alto crescimento no menor nível de sombreamento, tanto de indivíduos plantados quanto aqueles de regeneração natural.

**Capítulo 3:**

**Questão:** A condução da regeneração natural e enriquecimento de *Tachigali glauca* em clareiras mais a sua condução diminui as taxas de mortalidade e aumenta as de incremento?

**Hipótese nula:** Os tratamentos silviculturais pós-colheita não influenciam na sobrevivência e crescimento de *T. glauca* em clareiras da exploração de impacto reduzido.

**Hipótese alternativa:** Árvores de *T. glauca* terão influência dos níveis de sombreamento, havendo alto crescimento no menor nível de sombreamento, tanto de indivíduos plantados quanto aqueles de regeneração natural.

# REFERÊNCIAS

Azevedo, C. P., Sanquetta, C. R., Silva, J. N. M., Machado, S. A. Efeito de diferentes níveis de exploração e de tratamentos silviculturais sobre a dinâmica da floresta remanescente. **Floresta**, 38, 277-293, 2008.

Brandão, A.D.S., Dionisio, L. F. S., Farias, P. R. S., Schwartz, G., Carvalho, J. O. P. Spatial distribution pattern of Euxylophora paraensis Huber in a natural managed forest in the Eastern Amazon**. Revista de Ciências Agrárias**, 13, e5545, 2018.

BRASIL. Lei nº 12.651, de 25 de maio de 2012, que dispõe sobre a proteção da vegetação nativa. **Diário Oficial da União**, Brasília, DF; 25 maio 2012. Disponível em: http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm.

BRASIL. MINISTÉRIO DO MEIO AMBIENTE. Convenção-**Quadro das Nações Unidas sobre Mudança do Clima** (UNFCCC). Brasília, DF: MMA, 2015.

Carvalho, J.O.P, Silva, J.N.M., Pokorny, B., Sabogal, C., Zweede, J. Systems for SFM. **Tropical Forest**, 18, 9-11, 2008.

Costa, N. S. L.; Jardim, F. C. S.; Gomes, J. M.; Dionisio, L. F. S.; Schwartz, G. Responses in growth and dynamics of the shade-tolerant species Theobroma subincanum to logging gaps in the Eastern Amazon. **Forest Systems**, 29, 003, 2020.

D'Oliveira, M.V.N., Ribas, L.A. Forest regeneration in artificial gaps twelve years after canopy opening in Acre State Western Amazon. **Forest Ecology and Management**, 261, 1722-1731, 2011.

Dauber, E., Fredericksen, T.S., Peña, M. Sustainability of timber harvesting in Bolivian tropical forests. **Forest Ecology and Management**, 214, 294-304, 2005.

De Avila, A.L., Schwartz, G., Ruschel, A.R., Lopes, J.C., Silva, J.N.M., Carvalho, J.O.P., Bauhus, J. Recruitment, growth and recovery of commercial tree species over 30 years following logging and thinning in a tropical rain forest. **Forest Ecology and Management**, 385, 225–235, 2017.

De Graaf, N. R., Poels, R. L. H., Van Rompaey, R. S. A. R. Effect of Silvicultural treatment on growth and mortality of rainforest in Surinam over long periods. **Forest Ecology and Management**, 124, 123–135. 1999.

Dionisio, L.F.S., Schwartz, G., Lopes, J. C., Oliveira, F.A. Growth, mortality, and recruitment of tree species in an Amazonian rainforest over 13 years of reduced impact logging. **Forest Ecology and Management**, 430, 150–156, 2018.

Gomes, J. M., Silva, J. C. F., Vieira, S. B., Carvalho, J. O. P., Oliveira, L. C. L. Q., Queiroz, W. T. Schizolobium parahyba var. amazonicum (Huber ex Ducke) Barneby pode ser utilizada em enriquecimento de clareiras de exploração florestal na Amazônia. **Ciência Florestal**, v. 29, n. 1, p. 417-425, 2019.

Hawthorne, W.D., Sheil, D., Agyeman, V.K., Abu Juam, M., Marshall, C.A.M. Logging scars in Ghanaian high forest: Towards improved models for sustainable production. **Forest Ecology and Management**, 271, 27-36, 2012.

Karsten, R. J., Jovanovic, M., Meilby, H., Perales, E., Reynel, C. Regeneration in canopy gaps of tierra-firme forest in the Peruvian Amazon: Comparing reduced-impact logging and natural, unmanaged forests. **Forest Ecology and Management**, 310, 663-671, 2013.

Kukkonen, M., Rita, H., Hohnwald, S.,Nygren, A. Treefall gaps of certified, conventionally managed and natural forests as regeneration sites for Neotropical timber tree in northern Honduras. **Forest Ecology and Management**, 255, 2163-2176, 2008.

Lopes, J.C.A., Jennings, S.B., Matni, N.M. Planting mahogany in canopy gaps created by commercial harvesting. **Forest Ecology and Management**, 255, 300-307, 2008.

PLANAVEG, Brasil. **Plano Nacional de Recuperação da Vegetação Nativa**. Ministério do Meio Ambiente: Brasília, v. 76, 2017.

Reis, L.P., Ruschel, A. D., Coelho, A.A., Luz, A.S., Martins-da-Silva, C.V. Avaliação do potencial madeireiro na Floresta Nacional do Tapajós, após 28 anos da exploração florestal. **Pesquisa Florestal Brasileira**, 30, 265-281, 2010.

Schwartz, G., Falkowski, V., Peña-Claros, M. Natural regeneration of tree species in the Eastern Amazon: short-term responses after reduced-impact logging. **Forest Ecology and Management**, 390 385, 97–103, 2017a.

Schwartz, G., Lopes, J.C. Logging in the Brazilian Amazon forest: The challenges of reaching sustainable future cutting cycles. In: Daniels, J.A. (Ed.), **Advances in environmental research**, volume 36. Nova, New York, pp. 113-137, 2015.

Schwartz, G., Lopes, J.C.A., Mohren, G.M.J., Peña-Claros, M. Post-harvesting silvicultural treatments in logging gaps: a comparison between enrichment planting and tending of natural regeneration. **Forest Ecology and Management**, 293, 57-64, 2013.

Schwartz, G., Pereira, P. C., Siviero, M. A., Pereira, J. F., Ruschel, A. R., Yared, J. A. Enrichment planting in logging gaps with *Schizolobium parahyba* var. amazonicum (Huber ex Ducke) Barneby: A financially profitable alternative for degraded tropical forests in the Amazon. **Forest Ecology and Management**, 390, 166-172, 2017b.

Sist, P., Ferreira, F.N. Sustainability of reduced-impact logging in the Eastern Amazon. **Forest Ecology and Management**, 243, 199-209, 2007.

Siviero, M. A., Ruschel, A. R., Yared, J. A., de Aguiar, O. J., Pereira, P. C., Vieira, S. B., Sales, A. Harvesting Criteria Application as a Technical and Financial Alternative for Management of Degraded Tropical Forests: A Case Study from Brazilian Amazon. **Diversity**, v. 12, n. 10, p. 373, 2020b.

Siviero, M.A., Yared, J.A.G., Ruschel, A.R., Vieira, S.B., Sales, A.; Pereira, J.F., Aguiar, O.J.R., Brienza Junior, S., Pereira, P.C.G., Berberian, G.A. Manejo de florestas naturais degradadas na Amazônia: Estudo de caso sobre critérios de colheita. **Ciência Florestal**, v. 30, n. 1, p. 43-59, 2020a.

Valle, D., Phillips, P., Vidal, E., Schulze, M., Grogan, J., Sales, M., Gardingen, P. Adaptation of a spatially explicit individual tree-based growth and yield model and long-term comparison between reduced impact and conventional logging in Eastern Amazonia, Brazil. **Forest Ecology and Management**, 243, 187–198, 2007.

Valle, R. S.T.; Alves, L. M., Oliveira, M. F., Feltran-Barbieri, R. **Implicações da legislação brasileira na atividade de plantio de florestas nativas para fins econômicos**. Working paper. São Paulo, Brasil. WRI Brasil, p. 1-24, 2020.

Yguel, B., Piponiot, C., Mirabel, A., Dourdain, A., Hérault, B., Gourletfleury, S., Forget, P. M., Fontaine, C. Beyond species richness and biomass: impact of selective logging and silvicultural treatments on the functional composition of a neotropical forest. **Forest Ecology and Management**, 433: 528-534, 2019.

# Post-harvesting silvicultural treatments in canopy logging gaps: medium-term responses of commercial tree species under tending and enrichment planting[1]

Raphael Lobato Prado Neves[ab], Gustavo Schwartz[b], José do Carmo Alves Lopes[b], Fábio Miranda Leão[c]
[a] Federal Rural University of Amazonia, Av. Presidente Tancredo Neves, 2501, 66077-530, Belém, Pará, Brazil
[b] Embrapa Eastern Amazon, P. O. Box 48, 66095-100, Belém, Pará Brazil
[c] Federal University of Pará, R. Cel. José Porfírio, 2515, 68372-040, Altamira, Pará, Brazil

## Abstract

Technical and scientific information on medium-term effects of post-logging silvicultural interventions on the recovery of harvestable growing stocks are hardly available. To mitigate uncertainties about these effects our study aimed to answer the following question: “What is the medium-term effect of post-harvest silvicultural treatments on mortality, growth, and the structure of commercial tree species in canopy logging gaps under tending and enrichment planting?” we study individuals planted and naturally regenerated in 72 logging gaps opened tree felling during reduced-impact logging among different silvicultural treatments: (1) natural regeneration tending (TNER); (2) enrichment planting in logging gaps (EP1); (3) enrichment planting in logging gaps previously cleaned of harvesting residuals (EP2). Mortality increased through time, EP1 presented the highest mortality rates of all treatments in the first, sixth and 11th year, TNER had the lowest at the same period. TNER and EP2 presented the highest basal area and EP2 the highest periodic annual increment. Effects of the silvicultural treatment TNER were positive, since it presented the highest survival and a high mean basal area of the initial trees. The medium-term effects of silvicultural treatments applied over individuals of commercial trees in logging gaps indicate higher survival and growth that reflected in the structure of treated individuals when compared to standard procedures of reduced impact-logging, these results bring positive outcomes to reach more sustainable future cutting cycles in the Brazilian Amazon and other tropical forests worldwide.

**Keywords:** assisted densification; conservation and timber production; sustainable forest management; tropical forest

## 1. Introduction

The fate of tropical forests has been guided by anthropic activities (Lewis and Maslin,

---

[1] Publicado na revista *Forest Ecology and Management*, DOI: 10.1016/j.foreco.2019.117521

2015; Putz et al., 2012). Species richness simplification in tropical environments has been observed where species have been lost due to a combination of rapid climate change, natural populations isolation in fragmented landscapes, competition against invasive species, and the impact of increasing disturbances due to land use changes (Lewis et al., 2015; Lewis and Maslin, 2015). To conciliate the conservation of forest biodiversity as well as other ecosystem services with economic interests is a big challenge for nations, especially those developing countries with large tropical forests (Chaudhary et al., 2016).

Reduced-impact logging (RIL) has been applied in tropical forests as an important tool to mitigate destructive impacts of conventional logging in order to conserve biodiversity and other ecosystem services as well to reduce deforestation rates (Putz et al., 2012; Schwartz et al., 2012). Although its several benefits, other studies have shown that tree mortality increases after harvesting following all RIL requirements (Bladon et al., 2008; Hautala and Vanha-Majamaa, 2006; Lavoie et al., 2012). Even after the application of RIL, mortality rates increase in response to disturbance effects that can remain up to 11 years after harvesting (Dionisio et al., 2017).

Besides the increased mortality, simulations of future scenarios indicate that the current technological advances in tropical forest management do not guarantee the same volume yields of wood for further harvesting cycles (Avila et al., 2017; Dauber et al., 2005; Dionisio et al., 2017; Hawthorne et al., 2012; Putz et al., 2012; Sist and Ferreira, 2007; Valle et al., 2007). The scarcity of natural regeneration of commercial species in harvested tropical forests (Park et al., 2005; Schwartz et al., 2017a; Van Rheenen et al., 2004), the large amount of timber volume removal per harvest cycle, and the volume of wood lost due to increased post-harvest mortality are crucial factors to prevent successful future harvesting cycles. Evidences show that the current cutting cycle of 25-35 years employed in the Brazilian Amazonian forests with a maximum harvesting volume of 30 $m^3$ $ha^{-1}$ (SEMAS, 2015) cannot be sufficient to allow the recovery of harvested timber volumes (Avila et al., 2017; Dionisio et al., 2018, 2017; Schwartz et al., 2013; Sist and Ferreira, 2007). Non-logged commercial species, however, could be harvested in further cutting cycles to ensure the same forest yields.

Some of the possible alternatives to mitigate this issue includes: a) to change the set of harvested species to lighter wood species (Reis et al., 2010); and b) to apply post-harvesting silvicultural treatments (Dauber et al., 2005) such as tending the natural regeneration and planting commercial species in canopy gaps created by tree felling during harvesting operations (Schwartz et al., 2017b). Silvicultural treatments increase timber production in tropical forests and favor the establishment of natural regeneration and the growth of seedlings potentially able to replace harvested individuals (Avila et al., 2017; Inada et al., 2017; Schwartz et al., 2017b, 2017a, 2013; Vieira et al., 2018; Villegas et al., 2009), but there is a need to assess the costs of silvicultural treatments.

Technical and scientific information on medium-term effects of post-logging silvicultural interventions on the recovery of harvestable growing stocks are hardly available (Petrokofsky et al., 2015) and are empirical or based simply on simulations. In this sense, it becomes necessary a non-empirical silvicultural system for the sustainable management of tropical forest resources (Jardim, 2015). To mitigate uncertainties about the effects of post-harvest silvicultural treatments (Gomes et al., 2019; Lopes et al., 2008; Schwartz et al., 2013; Souza et al., 2015; Taffarel et al., 2014; Vieira et al., 2018) our study aimed to respond the following questions: What is the medium-term effect of post-harvest silvicultural treatments on survival, growth, and the structure of commercial tree species in canopy logging gaps under tending and enrichment planting?

## 2. Materials and methods

### 2.1 Study area and sampling design

Data were obtained from a field experiment carried out in the forest management area of the forestry company Jari Florestal SA under the project 'Logging Gaps Management' coordinated by Embrapa Eastern Amazon in cooperation with Jari Florestal. The study area is located in the Jari valley, Almeirim municipality (1° 9' S, 52° 38' W), Pará state, Brazil. Average annual precipitation is 2200 mm and the annual average temperature is 26 °C. The vegetation is mainly ombrophilous dense forest over yellow latossols (Azevedo, 2006).

Jari Florestal has a total area of 545,535 ha under forest management where harvesting operations follow RIL techniques. A total of 2,997 seedlings and saplings naturally present or planted in 72 gaps created by tree felling due to RIL operations were assigned to assess treatments as follows: (1) standard procedures of RIL (SRIL), (2) tending of the naturally established regeneration (TNER), (3) enrichment planting 1 (EP1), and (4) enrichment planting 2 (EP2).

The experiment was established in 2006 and 2007 in the logging compartments harvested in 2004 and 2006. In SRIL, which served as control, marked individuals were only monitored, with no additional silvicultural treatments, according to the current forest management regulations for forest monitoring in the Brazilian Amazon. In the other three treatments, silvicultural procedures were applied in addition to all steps required to employ RIL.

Tending consisted in the liberation of target individuals against competing tree species and lianas, it was applied over seedlings and saplings of commercial tree species naturally established (TNER) and planted (EP1 and EP2) in all measurement years. In the enrichment planting treatments, all seedlings were planted in a spacing of 2.5 m × 2.5 m using commercial tree species of different ecological groups. EP1 and EP2 differed in terms of planted species, logging compartments, gap ages and removal of logging residuals. EP1 was established in 2-year gaps where no logging residual was removed while EP2 was established in 1-year gaps with complete logging residual removal for further energy production by the forestry company (Table 1).

**Table 1.** Initial conditions (2006-2007) of the four post-harvesting silvicultural treatments tested (mean ± SD) for seedlings and saplings naturally present or planted in logging gaps in Jari Florestal, Brazil (adapted from Schwartz et al., 2016).

| Variable | Standard RIL (SRIL) | Tending of natural regeneration (TNER) | Enrichment planting 1 (EP1) | Enrichment planting 2 (EP2) |
|---|---|---|---|---|
| Number of seedlings and saplings | 436 | 396 | 1520 | 645 |
| Density (number of individuals / $m^2$)(mean ± SD) | 0.070 ± 0.017 | 0.056 ± 0.015 | 0.110 ± 0.035 | 0.109 ± 0.020 |
| Number of species | 34 | 39 | 10 | 5 |
| Number of logging gaps | 15 | 15 | 34 | 8 |
| Size of logging gaps ($m^2$) (mean ± SD) | 395.1 ± 86.3 | 478.4 ± 200.4 | 418.7 ± 97.6 | 754.9 ± 237.7 |
| Age of logging gaps at the beginning of the experiment (years) | 2 | 2 | 2 | 1 |
| Logging compartment | 2004 | 2004 | 2004* | 2006** |
| Logging residuals removed from gaps | No | No | No | Yes |
| Silvicultural treatment | No treatment | Tending the natural regeneration | Enrichment planting and tending | Enrichment planting and tending |

* Species planted in 2006

** Species planted in 2007

The logging gaps used in this experiment were set in terms of size, according to the classification of Jardim et al. (2007) in: 27 small size gaps (200–400 m²), 30 medium size gaps (401-600 m²), and 11 large size gaps (> 600 m²). EP2 has the largest logging gaps with a significant statistical difference of the other three treatments, whose did not differ among them

(SRIL, TNER, and EP1) in size. The tending silvicultural treatments on TNER, EP1, and EP2 were applied annually from 2006 to 2010, 2012, 2017, and 2018. In 2018 the treatments SRIL, TNER, EP1, and EP2 presented 203, 248, 461, and 276 trees, respectively, which remained alive since the experiment beginning (henceforth "Initials"). At the 2017 measurement, new individuals ≥ 300 cm in height that grew naturally inside the monitored logging gaps (henceforth "Complementary") were included and monitored in the experiment. All species of the study are commercial but not necessarily were harvested by the forestry company. The total number of new individuals included in SRIL, TNER, EP1, and EP2 were 51, 44, 129, and 20, respectively (Table 2).

**Table 2.** Current conditions (2017-2018) of the four post-harvesting silvicultural treatments tested for initial and complementary individuals in logging gaps in Jari Florestal, Brazil.

| Variable | Standard RIL (SRIL) | Tending of natural regeneration (TNER) | Enrichment planting 1 (EP1) | Enrichment planting 2 (EP2) |
|---|---|---|---|---|
| Number of alive trees ≥ 300 cm in height since the experiment beginning | 203 | 248 | 462 | 274 |
| Number of complementary trees, included in 2017 | 51 | 44 | 129 | 20 |
| Total number of trees in the experiment | 254 | 292 | 591 | 294 |
| Number of species included in 2017 | 0 | 0 | 15 | 8 |
| Current total number of species | 29 | 34 | 24 | 13 |
| Current number of logging gaps | 15 | 13 | 32 | 8 |
| Total area of logging gaps ($m^2$) | 5,926.61 | 6,587,13 | 13,325.85 | 6,038.93 |

## 2.2 Data analysis

Only individuals with height ≥ 300 cm were used in the analyses carried out in this study. This means that every planted or naturally regenerated seedling that did not reach minimum height of 300 cm by 2010 was not considered in this study. Mortality, diameter at breast height (DBH) at 1.3 m from the soil, periodic annual increment (PAI), basal area, and diameter classes were calculated based on the measurements of the years 2017 for SRIL, TNER, and EP1 and 2018 for EP2, so in this way all treatments were analyzed under the same measurement ages.

Mortality rates were calculated with logging gaps as the sampling units. The annualized mortality rates were calculated using the formula "$m = 1 – (N_{t2} / N_{t1})^{(1/t)}$", where $N_{t1}$ = Number of live trees in the first sampling, $N_{t2}$ = number of trees that survived until the second sampling and t = years between first and second sampling (Sheil et al., 1995). Mortality rates did not follow a normal distribution, thus they were analyzed through a general linear model (GLM) repeated measures ANOVA, with time and treatment as factors and mortality rates as the dependent variable and compared by post-hoc Tukey's pairwise test.

The logging gap area was calculated by the ellipse formula. Logging gap was also the sampling unit to calculate basal area, which was the sum of tree cross sections of each logging gap. Each tree cross section was obtained with the formula $g = \pi * (DBH/2)^2$ in square meters per hectare, where DBH = diameter at breast height. Basal area for the initial, complementary, and the sum of initial and complementary individuals (henceforth "Overall") in each logging gap per treatment were calculated. Once applied the Shapiro-Wilk test, the data on both initial, complementary, and overall trees did not present a normal distribution, which required a Box-Cox transformation, before running ANOVA and the post-hoc Tukey's pairwise test.

Periodic annual diameter (PAI) measured from DBH of each individual was calculated using the formula $PAI = ((DBH_{t2} – DBH_{t1})/n)*365)$, where $DBH_{t1}$ = individual's diameter at the initial sampling, $DBH_{t2}$ = individual's diameter at the final sampling, and n = days between first and second sampling. Individual PAI was the sampling unit, ANOVA ($p < 0.05$ significance level) was performed and compared by the post-hoc Tukey's pairwise test. All analyses were performed using the R version 3.0.2 (2016).

The number of individuals (initial, complementary, and overall trees), in percentages, were set in five diameter classes ranging 5 cm in DBH from 0 up to 25 cm. In addition, the basal area was also set in each of these five diameter classes.

## 3. Results

Mortality increased through time. In the first, sixth and 11th year, EP1 presented the highest mortality rates of all treatments, 7.5, 7.3, and 10.4% year$^{-1}$, respectively. TNER had the lowest mortality rate observed at the same period, with 1.5, 1.6, and 3.3% year$^{-1}$, respectively. There was a significant statistical difference among treatments (repeated measures ANOVA, $p < 0.001$) and time (repeated measures ANOVA, $p < 0.001$), with no significant interaction between treatment and time (repeated measures ANOVA, $p = 0.063$). SRIL and EP2 treatments presented statistical similarity ($p = 0.93$ significance level; Figure 1).

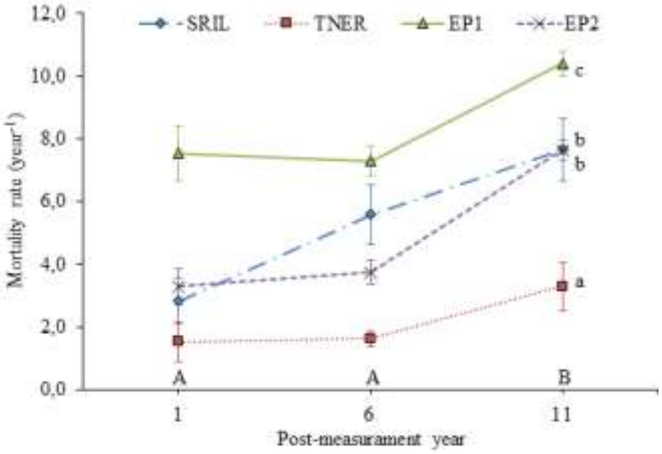

**Figure 1.** Mean (± SE) of mortality rates of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments by one, six, and 11 years in logging gaps in the managed forests of Jari company, Pará state, Brazil. Lowercase letters are treatment comparisons and uppercase letters are time comparisons in the GLM repeated measures ANOVA and post-hoc Tukey's pairwise test.

In terms of basal area of the initial trees 11 years after the experiment started, EP2 presented the highest value (2.47 m² ha$^{-1}$) and SRIL the lowest (1.12 m² ha$^{-1}$). However, for the complementary trees, the highest basal area was observed in SRIL (0.90 m² ha$^{-1}$) and the lowest in the EP2 treatment (0.25 m² ha$^{-1}$). The sum of initial and complementary basal area resulted in TNER (3.14 m² ha$^{-1}$) as having the highest basal area, and SRIL with the lowest (2.01 m² ha$^{-1}$; Figure 2). Comparisons among initial trees presented statistical significant difference ($p < 0.001$) among treatments, except between TNER (2.33 m² ha$^{-1}$) versus EP2 (2.47 m² ha$^{-1}$) and SRIL (1.19 m² ha$^{-1}$) versus EP1 (1.18 m² ha$^{-1}$) that had no statistical differences. No statistical significant differences were found among treatments in the mean basal area of the complementary and overall trees (Figure 2).

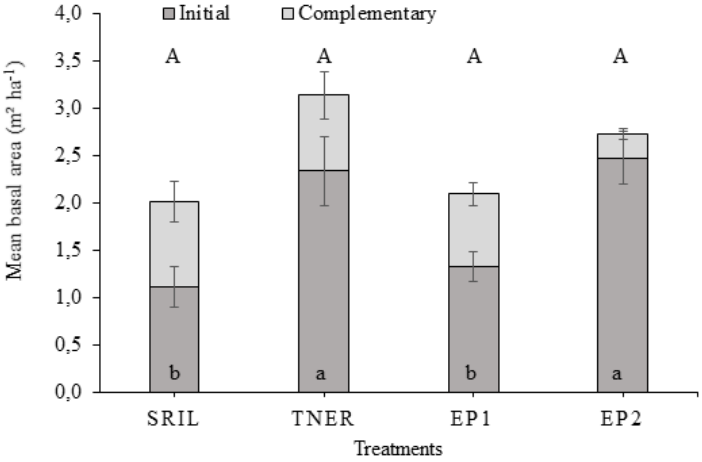

**Figure 2.** Mean (± SE) of basal area (m² ha$^{-1}$) of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments from the initial trees, complementary and the overall individuals (sum of initial and complementary individuals) in logging gaps in the managed forests of Jari company, Pará state, Brazil. Lowercase letters are to comparisons between the initial mean basal areal of treatments and uppercase letter are to mean basal area of complementary and overall in the ANOVA and post-hoc Tukey's pairwise test.

The lowest mean of PAI were observed in the natural regeneration treatments, where SRIL presented half (0.20 cm year$^{-1}$) of the PAI mean observed in TNER (0.41cm year$^{-1}$). EP2 presented the highest PAI mean (0.84 cm year$^{-1}$), four times more than SRIL ($p < 0.05$). Statistical differences were found in all treatments ($p < 0.05$, Figure 3).

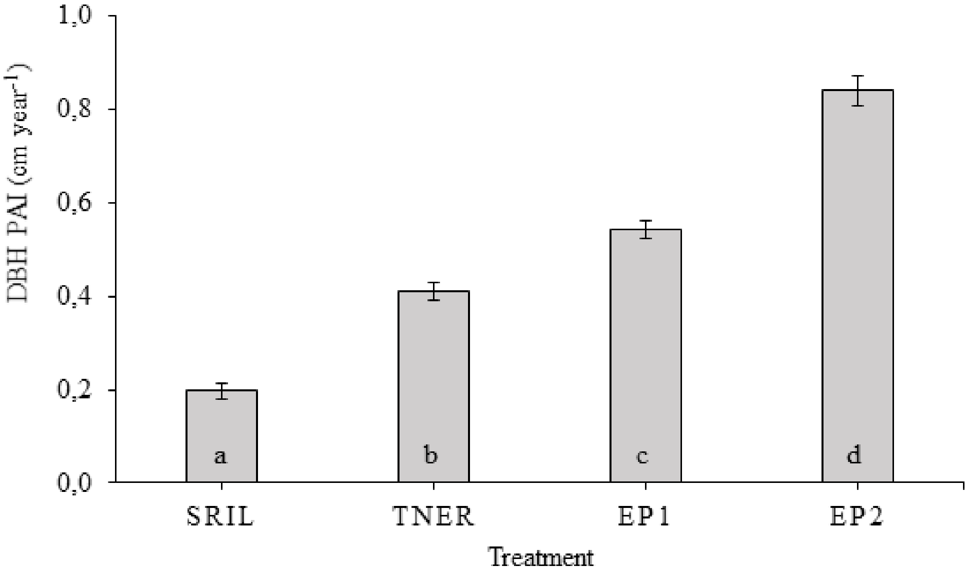

**Figure 3.** Mean (± SE) of periodic annual increment (PAI) of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments in logging gaps in the managed forests of Jari company, Pará state, Brazil. Lowercase letters are treatment comparisons in ANOVA with post-hoc Tukey's pairwise test.

Over 11 years the 0-5 and 5-10 classes presented the highest percentage of the initial trees in all treatments. Meantime the 5-10 and 10-15 classes presented the highest percentage of the complementary trees. Among treatments, SRIL 0-5 cm diameter class presented the highest number of individulas. On the other hand, EP1 showed the highest concentration of individuals in class 5-10 cm of the complementary individuals. The basal area presented a paraboloid tendency for all treatments. However, the classes with the highest concentration of basal area are in the range of 5-15 cm (Figure 4).

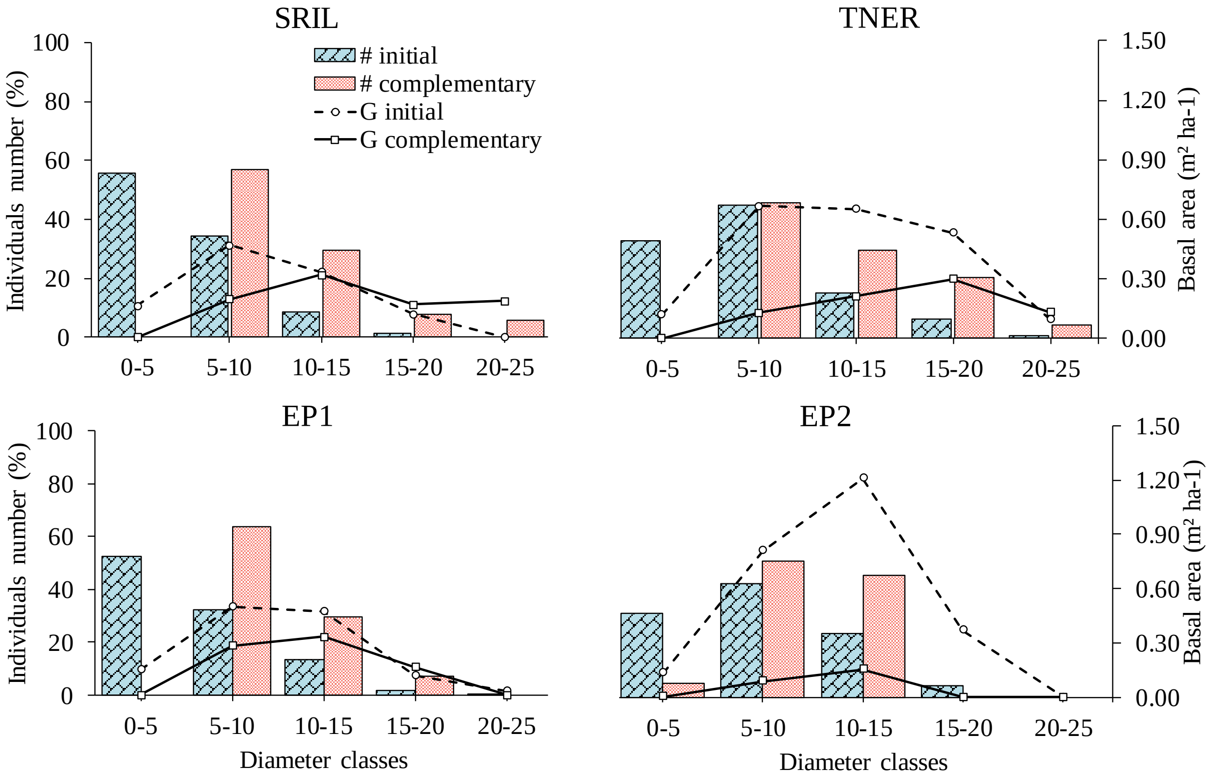

**Figure 4.** Bars representing percentage of individuals per diameter class (left side y-axis) and lines showing basal area (m² ha$^{-1}$) per diameter class (right y-axis) of the standard reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER), enrichment planting 1 (EP1), and enrichment planting 2 (EP2) treatments for both initial and complementary trees in logging gaps in the managed forests of Jari company, Pará state, Brazil.

## 4. Discussion

Effects of the silvicultural treatment TNER were positive, since it presented the highest survival and a high mean basal area of the trees. Furthermore, TNER presented twofold PAI value when compared to SRIL, which is the treatment that reflects the current procedures of reduced impact logging (RIL) legally adopted in the Brazilian Amazon. Tending treatment applied to natural regeneration and enrichment planting in logging gaps are financially profitable options for forest managers and investors (Schwartz et al., 2016) to minimize post-logging losses due to increased mortality observed in managed forests (Dionisio et al., 2017). These silvicultural treatments also help to mitigate the non-recovery of species diversity after logging observed in selectively logged forests (Shima et al., 2018).

The highest TNER survival is probably due to the fact that sampled individuals were already established before the silvicultural treatments had started. Besides this, tending begun to be applied to avoid competition for light against other arboreal individuals and lianas (Schwartz et al., 2016). In this study, TNER was shown to be effective to increase survival of individuals when compared to the other treatments tested. Higher mortality in enrichment planting, like EP1 and EP2, in relation to natural regeneration, like SRIL and TNER is probably due to the rustification phase (Adenesky-Filho et al., 2017).

Although the rustification phase, EP2 and SRIL did not present significant statistical difference in mortality, which can figure as a positive treatment effect of cleaning potential competitors for light and nutrients in enrichment planting. The higher mortality of enrichment planting treatments in relation to tending may be a result of the low quality many planted seedlings. The availability of high quality seedlings of native commercial species is a serious bottleneck for enrichment planting in the Brazilian Amazon. For the success of enrichment planting in logging gaps, it is recommended a rigorous seedling production, with fertilizers, as well as annual cleanings once seedlings planted in the field normally face strong competition (Gomes et al., 2019).

The highest complementary mean basal area in SRIL can be explained by the absence of any silvicultural treatment, which permitted new individuals of commercial species to get established. The fact that there was no tending over the monitored individuals of commercial species (initials) could have allowed competing individuals to over compete them inside logging gaps (Avila et al., 2017; Jardim, 2015). Results on basal area found in this study corroborate Inada et al., (2017), in a comparison among RIL + Line Planting/Slashing (LP/S) of tree species versus conventional logging and versus RIL. After 10 years, stocks were marginally higher in RIL + LP/S plots, with no statistical difference among treatments.

SRIL, TNER, and EP2 presented a similar total area of logging gaps (m²), but the basal area of the initial trees of TNER and EP2 were twice higher than SRIL. The tending treatment benefits both natural regeneration and enrichment planting and may be influenced by gap sizes, since in larger gaps more light illuminates the forest floor, stimulating tree growth (Vatraz et al., 2016). In an experiment with *Cedrela odorata* planted in logging gaps, Vieira et al. (2018) found after five years that tending silvicultural treatment provided higher growth in height of seedlings planted in larger logging gaps (>600 m²).

The canopy height formed by trees that surround a logging gap is crucial for the success of individuals of tree species under any silvicultural treatment. Foresters can also enlarge logging gaps in order to improve success of survival and growth rates of planted or tended individuals of tree species. For example, two gaps with the same area but different surrounding canopy heights will have different sunlight incidence, which will necessarily have effects on the individual performances. *S. parahyba* planted in small gaps (200 m²) can thrive since the surrounding canopy height is not so tall. And this is the case of Schwartz et al. (2017b) where *S. parahyba* was managed in logging gaps surrounded by a short canopy height.

Low densities or absence of the regeneration of commercial species found in three managed forests sampled by Schwartz et al., (2017a) suggest that commercial species are having poor post-harvesting capacity to regenerate in the Eastern Amazon. The enrichment planting in gaps is defined by Schwartz and Lopes (2015) as a type of assisted densification. This means that tree species have their densities increased in their own natural habitats, which can work both for conservation and timber production, as it can increase artificial density up to 60 times compared to the natural densities of many commercial species. Mahogany is an example of rare commercial species that can have its natural densities increased (Lopes et al., 2008).

EP1 started with 10 species in 2006 and reached 24 in 2017, even though one of the planted species had 100% of mortality rate in the period. The high mortality of EP1 trees and the application of cleaning opened space for new individuals of fast-growing species. This explains the entrance of the largest number of commercial species and individuals, mainly in the higher diameter classes, of EP1. This outcome of silvicultural treatment application can mitigate the sequential depletion of species (Putz et al., 2012) through the enrichment planting and augment of the regeneration with the entrance of new species and stock of the most commercial species. Most of the individuals present in higher diameter classes will probably reach the minimum cutting diameter faster than initial trees.

EP2 was the most suitable treatment for the specific purpose of timber production and/or species conservation. Furthermore, the improvement in light conditions caused by silvicultural treatments improved the increase of both growth and stock of commercial species (Inada et al., 2017). Successful enrichment planting in logging gaps confirms the results found in other experiments worldwide with enrichment planting in gaps (Doucet et al., 2009; Gomes et al., 2019, 2010; Lopes et al., 2008; Quédraogo et al., 2014; Schwartz et al., 2013; Taffarel et al., 2014; Vieira et al., 2018). These studies help to reinforce the efficiency of enrichment planting in logging gaps, which comes as a viable silvicultural alternative for managing tropical forests.

Enrichment planting in logging gaps can also work as an active germplasm bank to maintaining the genetic diversity of rare or endangered species (Lopes et al., 2008) and may have potential as seed/seedling orchard. Besides the use in old-growth managed forests, as the forest management area of the forestry company Jari Florestal, such silvicultural treatments can also be applied to recover degraded forests or to improve secondary forests, which are commonly found in the arc of deforestation (Schwartz and Lopes, 2015), a region that concentrates most of the deforestation in the Brazilian Amazon. To have this achievement, it is necessary the development of new public policies to improve the current forest management regulations in the Brazilian Amazon.

Silvicultural treatments also showed positive effects on the structure of individuals in logging gaps. Based on these results, it is hypothesized that the silvicultural treatments will shorten the time required to recover losses caused by RIL. Post-harvest silvicultural treatments could help to mitigate the delay in several tropical forests to recover harvested stocks (Shima et al., 2018).

## 5. Conclusion

The medium-term effects of silvicultural treatments applied over individuals of commercial trees in logging gaps indicate higher survival and growth that reflected in the structure of treated individuals when compared to standard procedures of reduced impact-logging. These results bring positive outcomes to reach more sustainable future cutting cycles in the Brazilian Amazon.

## Acknowledgements

We acknowledge Jari Florestal SA for a very productive partnership, especially to Viviane de Souza Nogueira, Isael Araújo Costa, and all field assistants and technicians engaged in different phases of the experiment. The authors appreciated the comments of two anonymous reviewers for their contribution in improving the quality of the manuscript. The first author is grateful to CNPq (140941/2016-9) on his PhD fellowship.

## 6. References

Adenesky-Filho, E., Maçaneiro, J.P., Vitorino, M.D., 2017. How to select potential species for ecological restoration of rain forest – Southern Brazil. Appl. Ecol. Environ. Res. 15, 1671–1684. https://doi.org/10.15666/aeer/1503_16711684

Avila, A.L. de, Schwartz, G., Ruschel, A.R., Lopes, J. do C., Silva, J.N.M., Carvalho, J.O.P. de, Dormann, C.F., Mazzei, L., Soares, M.H.M., Bauhus, J., 2017. Recruitment, growth and recovery of commercial tree species over 30 years following logging and thinning in a tropical rain forest. For. Ecol. Manage. 385, 225–235. https://doi.org/10.1016/J.FORECO.2016.11.039

Azevedo, C.P. De, 2006. Dinâmica de florestas submetidas a manejo na Amazônia Oriental:

experimentação e simulação.

Begon, M., Townsend, C.R., Harper, J.L., 2009. Ecologia: de indivíduos a ecossistemas.

Bladon, K.D., Lieffers, V.J., Silins, U., Landhäusser, S.M., Blenis, P. V., 2008. Elevated mortality of residual trees following structural retention harvesting in boreal mixedwoods. For. Chron. 84, 70–75. https://doi.org/10.5558/tfc84070-1

Buajan, S., Liu, J.F., He, Z.S., Feng, X.P., Muhammad, A., 2018. Effects of gap size and locations on the regeneration of castanopsis kawakamii in a subtropical natural forest, China. J. Trop. For. Sci. 30, 39–48. https://doi.org/10.26525/jtfs2018.30.1.3948

Chaudhary, A., Burivalova, Z., Koh, L.P., Hellweg, S., 2016. Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. Sci. Rep. 6, 23954. https://doi.org/10.1038/srep23954

Clark, D.A., Clark, D.B., 1992. Life History Diversity of Canopy and Emergent Trees in a Neotropical Rain Forest. Ecol. Monogr. 62, 315–344. https://doi.org/10.2307/2937114

Das Chagas, R.S., Gomes, J.M.Ê., De Carvalho, J.O.P., Ferreira, J.E.R., 2012. Sobrevivência e crescimento de plântulas de Manilkara huberi Chevalier durante cinco anos em clareiras causadas pela exploração de impacto reduzido na Amazônia brasileira. Sci. For. Sci. 40, 417–424.

Dauber, E., Fredericksen, T.S., Peña, M., 2005. Sustainability of timber harvesting in Bolivian tropical forests. For. Ecol. Manage. 214, 294–304. https://doi.org/10.1016/J.FORECO.2005.04.019

Dionisio, L.F.S., Schwartz, G., Lopes, J. do C., Oliveira, F. de A., 2018. Growth, mortality, and recruitment of tree species in an Amazonian rainforest over 13 years of reduced impact logging. For. Ecol. Manage. 430, 150–156. https://doi.org/10.1016/J.FORECO.2018.08.024

Dionisio, L.F.S., Schwartz, G., Mazzei, L., Lopes, J. do C., Santos, G.G.A. dos, Oliveira, F. de A., 2017. Mortality of stocking commercial trees after reduced impact logging in eastern Amazonia. For. Ecol. Manage. 401, 1–7. https://doi.org/10.1016/j.foreco.2017.06.060

Doucet, J.-L., Kouadio, Y.L., Monticelli, D., Lejeune, P., 2009. Enrichment of logging gaps with moabi (Baillonella toxisperma Pierre) in a Central African rain forest. For. Ecol. Manage. 258, 2407–2415. https://doi.org/10.1016/J.FORECO.2009.08.018

Foster, R.B., 1977. Tachigalia versicolor is a suicidal neotropical tree. Nature 268, 624–626. https://doi.org/10.1038/268624b0

Gomes, J.M., Carvalho, J.O.P. de, Silva, M.G. da, Nobre, D.N.V., Taffarel, M., Ferreira, J.E.R., Santos, R.N.J., 2010. Sobrevivência de espécies arbóreas plantadas em clareiras causadas pela colheita de madeira em uma floresta de terra firme no município de Paragominas na Amazônia brasileira. Acta Amaz. 40, 171–178. https://doi.org/10.1590/S0044-59672010000100022

Gomes, J.M., Silva, J.C.F. da, Vieira, S.B., Carvalho, J.O.P. de, Quadros, L.C.L., Queiroz, W.T. de, 2019. Schizolobium parahyba var. amazonicum (Huber ex Ducke) Barneby can be used in enrichment planting in gaps caused by logging in Amazonia. Ciência Florest. 29, 421–428. https://doi.org/10.5902/198050984793

Hautala, H., Vanha-Majamaa, I., 2006. Immediate tree uprooting after retention-felling in a coniferous boreal forest in Fennoscandia. Can. J. For. Res. 36, 3167–3172. https://doi.org/10.1139/x06-193

Hawthorne, W.D., Sheil, D., Agyeman, V.K., Abu Juam, M., Marshall, C.A.M., 2012. Logging scars in Ghanaian high forest: Towards improved models for sustainable production. For. Ecol. Manage. 271, 27–36. https://doi.org/10.1016/j.foreco.2012.01.036

Hu, J., Herbohn, J., Chazdon, R.L., Baynes, J., Vanclay, J., 2020. Silvicultural treatment effects on commercial timber volume and functional composition of a selectively logged Australian tropical forest over 48 years. For. Ecol. Manage. 457, 117690. https://doi.org/10.1016/j.foreco.2019.117690

Inada, T., Hardiwitono, S., Purnomo, S., Putra, I.B.W.., Kitajima, K., Kanzaki, M., 2017. Dynamics of forest regeneration following logging management in a bornea lowland dipterocarp forest. J. Trop. For. Sci. 29, 185–197.

Jardim, F.C. da S., 2015. Natural re generation in tropical forests. Rev. Ciências Agrar. - Amaz. J. Agric. Environ. Sci. 58, 105–113. https://doi.org/10.4322/rca.1676

Jardim, F.C. da S., Serrão, D.R., Nemer, T.C., 2007. Efeito de diferentes tamanhos de clareiras, sobre o crescimento e a mortalidade de espécies arbóreas, em Moju-PA 1. Acta Amaz. 37, 37–48.

Lavoie, S., Ruel, J.C., Bergeron, Y., Harvey, B.D., 2012. Windthrow after group and dispersed tree retention in eastern Canada. For. Ecol. Manage. 269, 158–167. https://doi.org/10.1016/j.foreco.2011.12.018

Lewis, S.L., Edwards, D.P., Galbraith, D., 2015. Increasing human dominance of tropical forests. Science (80-. ). 349, 827–832. https://doi.org/10.1126/science.aaa9932

Lewis, S.L., Maslin, M.A., 2015. Defining the Anthropocene. Nature 519, 171–180. https://doi.org/10.1038/nature14258

Lima, H.C., 2015. Lista do Brasil - Tachigali glauca Tul. [WWW Document]. URL http://floradobrasil.jbrj.gov.br/jabot/FichaPublicaTaxonUC/FichaPublicaTaxonUC.do?id=FB106814 (accessed 3.11.20).

Lopes De Souza, A., Marques De Medeiros, R., Silva Matos, L.M., Silva, K.R., Alves Côrrea, P., de Faria, F.N., 2014. Estratificação volumétrica por classes de ... Rev. Ár 38, 533–541.

Lopes, J. do C.A., Jennings, S.B., Matni, N.M., 2008. Planting mahogany in canopy gaps created by commercial harvesting. For. Ecol. Manage. 255, 300–307. https://doi.org/10.1016/J.FORECO.2007.09.051

Neves, R.L.P., Schwartz, G., Lopes, J. do C.A., Leão, F.M., 2019. Post-harvesting silvicultural treatments in canopy logging gaps: Medium-term responses of commercial tree species under tending and enrichment planting. For. Ecol. Manage. 451, 117521. https://doi.org/10.1016/j.foreco.2019.117521

Odum, E.P., 2006. Fundamentos de ecología.

Park, A., Joaquin Justiniano, M., Fredericksen, T.S., 2005. Natural regeneration and environmental relationships of tree species in logging gaps in a Bolivian tropical forest. For. Ecol. Manage. 217, 147–157. https://doi.org/10.1016/J.FORECO.2005.05.056

Petrokofsky, G., Sist, P., Blanc, L., Doucet, J.-L., Finegan, B., Gourlet-Fleury, S., Healey, J.R., Livoreil, B., Nasi, R., Peña-Claros, M., Putz, F.E., Zhou, W., 2015. Comparative effectiveness of silvicultural interventions for increasing timber production and sustaining conservation values in natural tropical production forests. A systematic review protocol. Environ. Evid. 4, 8. https://doi.org/10.1186/s13750-015-0034-7

Piponiot, C., Rödig, E., Putz, F.E., Rutishauser, E., Sist, P., Ascarrunz, N., Blanc, L., Derroire, G., Descroix, L., Guedes, M.C., Coronado, E.H., Huth, A., Kanashiro, M., Licona, J.C., Mazzei, L., D'Oliveira, M.V.N., Peña-Claros, M., Rodney, K., Shenkin, A., De Souza, C.R., Vidal, E., West, T.A.P., Wortel, V., Hérault, B., 2019. Can timber provision from Amazonian production forests be sustainable? Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/ab195e

Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S., Griscom, B., Palmer, J., Zagt, R., 2012. Sustaining conservation values in selectively logged tropical forests: The attained and the attainable. Conserv. Lett. 5, 296–303. https://doi.org/10.1111/j.1755-263X.2012.00242.x

Quédraogo, D.Y., Fayolle, A., Daïnou, K., Demaret, C., Bourland, N., Lagoute, P., Doucet, J.L., 2014. Enrichment of logging gaps with a high conservation value species (Pericopsis elata) in a central African moist forest. Forests 5, 3031–3047.

https://doi.org/10.3390/f5123031

Reis, L.P., Carvalho, J.O.P. de, Reis, P.C.M. dos, Gomes, J.M., Ruschel, A.R., Silva, M.G. da, 2014. Crescimento de mudas de *Parkia gigantocarpa* Ducke, em um sistema de enriquecimento em clareiras após a colheita de madeira. Ciência Florest. 24, 431–436. https://doi.org/10.5902/1980509814583

Reis, L.P., Ruschel, A.R., Coelho, A.A., Luz, A.S. da, Martins-da-Silva, R.C.V., 2010. Avaliação do potencial madeireiro na Floresta Nacional do Tapajós após 28 anos da exploração florestal. Pesqui. Florest. Bras. 30, 265–281. https://doi.org/10.4336/2010.pfb.30.64.265

Schwartz, G., Bais, A., Peña-Claros, M., Hoogstra-Klein, M., Mohren, G., Arts, B., 2016. Profitability of Silvicultural Treatments in Logging Gaps in the Brazilian Amazon. J. Trop. For. Sci. 28, 68–78.

Schwartz, G., Falkowski, V., Peña-Claros, M., 2017a. Natural regeneration of tree species in the Eastern Amazon: Short-term responses after reduced-impact logging. For. Ecol. Manage. 385, 97–103. https://doi.org/10.1016/J.FORECO.2016.11.036

Schwartz, G., Lopes, J. d. C.A., 2015. Logging in the brazilian amazon forest: The challenges of reaching sustainable future cutting cycles, in: Advances in Environmental Research. pp. 113–138.

Schwartz, G., Lopes, J.C.A., Mohren, G.M.J., Peña-Claros, M., 2013. Post-harvesting silvicultural treatments in logging gaps: A comparison between enrichment planting and tending of natural regeneration. For. Ecol. Manage. 293, 57–64. https://doi.org/10.1016/j.foreco.2012.12.040

Schwartz, G., Peña-Claros, M., Lopes, J.C.A., Mohren, G.M.J., Kanashiro, M., 2012. Mid-term effects of reduced-impact logging on the regeneration of seven tree commercial species in the Eastern Amazon. For. Ecol. Manage. 274, 116–125. https://doi.org/10.1016/j.foreco.2012.02.028

Schwartz, G., Pereira, P.C.G., Siviero, M.A., Pereira, J.F., Ruschel, A.R., Yared, J.A.G., 2017b. Enrichment planting in logging gaps with Schizolobium parahyba var. amazonicum (Huber ex Ducke) Barneby: A financially profitable alternative for degraded tropical forests in the Amazon. For. Ecol. Manage. 390, 166–172. https://doi.org/10.1016/J.FORECO.2017.01.031

SEMAS - Sisflora PA [WWW Document], n.d. URL https://monitoramento.semas.pa.gov.br/sisflora/relatorios.html (accessed 12.7.19).

Sheil, D., Burslem, D.F.R.P., Alder, D., 1995. The Interpretation and Misinterpretation of

Mortality Rate Measures Author ( s ): Douglas Sheil , David F . R . P . Burslem , Denis Alder Published by : British Ecological Society Stable URL : http://www.jstor.org/stable/2261571. Br. Ecol. Soc. 83, 331–333. https://doi.org/10.2307/2261571

Shenkin, A., Bolker, B., Peña-Claros, M., Licona, J.C., Ascarrunz, N., Putz, F.E., 2018. Interactive effects of tree size, crown exposure and logging on drought-induced mortality. Philos. Trans. R. Soc. B Biol. Sci. 373. https://doi.org/10.1098/rstb.2018.0189

Shima, K., Yamada, T., Okuda, T., Fletcher, C., Kassim, A.R., 2018. Dynamics of Tree Species Diversity in Unlogged and Selectively Logged Malaysian Forests. Sci. Rep. 8, 1024. https://doi.org/10.1038/s41598-018-19250-z

Sist, P., Ferreira, F.N., 2007. Sustainability of reduced-impact logging in the Eastern Amazon. For. Ecol. Manage. 243, 199–209. https://doi.org/10.1016/J.FORECO.2007.02.014

Sist, P., Picard, N., Gourlet-Fleury, S., 2003. Sustainable cutting cycle and yields in a lowland mixed dipterocarp forest of Borneo. Ann. For. Sci 60, 803–814. https://doi.org/10.1051/forest:2003075

Souza, D.V., Carvalho, J.O.P. de, Mendes, F.D.S., Melo, L.D.O., Silva, J.N.M., Jardim, F.C. da S., 2015. Crescimento de espécies arbóreas em uma floresta natural de terra firme após a colheita de madeira e tratamentos silviculturais, no município de Paragominas, Pará, Brasil. Ciência Florest. 25, 873–883. https://doi.org/10.5902/1980509820585

Taffarel, M., Gomes, J.M., Carvalho, J.O.P. de, Melo, L. de O., Ferreira, J.E.R., 2014. Efeito da silvicultura pós-colheita na população de Chrysophyllum lucentifolium Cronquist (Goiabão) em uma floresta de terra firme na amazônia brasileira. Rev. Árvore 38, 1045–1054. https://doi.org/10.1590/S0100-67622014000600009

Valle, D., Phillips, P., Vidal, E., Schulze, M., Grogan, J., Sales, M., van Gardingen, P., 2007. Adaptation of a spatially explicit individual tree-based growth and yield model and long-term comparison between reduced-impact and conventional logging in eastern Amazonia, Brazil. For. Ecol. Manage. 243, 187–198. https://doi.org/10.1016/J.FORECO.2007.02.023

Van Rheenen, H.M.P.J.B., Boot, R.G.A., Werger, M.J.A., Ulloa Ulloa, M., 2004. Regeneration of timber trees in a logged tropical forest in North Bolivia. For. Ecol. Manage. 200, 39–48. https://doi.org/10.1016/j.foreco.2004.06.024

Vatraz, S., Olegário Pereira de Carvalho, J., Natalino Macedo Silva, J., da Cunha Castro, T., 2016. Efeito da exploração de impacto reduzido na dinâmica do crescimento de uma floresta natural. Sci. Florestalis 44, 261–271. https://doi.org/10.18671/scifor.v44n109.25

Vieira, S.B., de Carvalho, J.O.P., Gomes, J.M., da Silva, J.C.F., Ruschel, A.R., 2018. Is cedrela odorata L. A species with potential to be used in post-harvesting silviculture in the Brazilian amazonia? Cienc. Florest. 28, 1230–1238. https://doi.org/10.5902/1980509833361

Villegas, Z., Peña-Claros, M., Mostacedo, B., Alarcón, A., J.C.Licona, Leaño, C., Pariona, W., Choque, U., 2009. Silvicultural treatments enhance growth rates of future crop trees in a tropical dry forest. For. Ecol. Manage. 258, 971–977. https://doi.org/10.1016/J.FORECO.2008.10.031

# Silviculture of high value timber species in the Amazon: managing *Dinizia excelsa* in logging gaps

Raphael Lobato Prado Neves[abd], Gustavo Schwartz[b], José do Carmo Alves Lopes[b], Fábio Miranda Leão[c]
[a] Federal Rural University of Amazonia, Av. Presidente Tancredo Neves, 2501, 66077-530, Belém, Pará, Brazil
[b] Embrapa Eastern Amazon, P. O. Box 48, 66095-100, Belém, Pará Brazil
[c] Federal University of Pará, S. Cel. José Porfírio, 2515, 68372-040, Altamira, Pará, Brazil
[d] State Secretary for Environment and Sustainability, Ln Lomas Valentinas, 2717, 66093-677, Belém, Pará, Brazil

## Abstract

*Dinizia excelsa*, one of the most important species traded in the Brazilian Amazon due to the high commercial value of its timber, was analyzed through the medium-term effect of post-harvesting silvicultural treatments in canopy logging gaps of different sizes under tending and enrichment planting under different crown exposure. We hypothesized that individual effects will have low or neither influence from gap sizes, but will have influence on the crown exposure class. A total of 244 seedlings and saplings of *Dinizia excelsa* naturally present or planted in 43 gaps were assigned to assess the species medium-term responses to the following treatments: (1) standard procedures of RIL (SRIL) or control, (2) tending of the naturally established regeneration (TNER) and (3) enrichment planting (EP). There is better survival and growth in enrichment planting (EP) and tending of natural regeneration (TNER) in canopy logging gaps when compared to SRIL, which is the treatment that reflects the current procedures of reduced impact logging (RIL) legally adopted in the Brazilian Amazon. There is no difference in the growth of individuals according to the gap sizes, but according to their crown exposure class. Despite the high mortality of planted individuals (EP), there was a better performance in growth, especially those individuals who received more sunlight. These results bring positive outcomes to reach more sustainable future cutting cycles to *D. excelsa* specie in the Brazilian Amazon.

**Keywords:** assisted densification; conservation and timber production; sustainable forest management; tropical forest.

## 1. Introduction

*Dinizia excelsa* Ducke (family Fabaceae), a tree species with wide geographical distribution in the Eastern Amazon, is now represented by the tallest alive tree in the whole biome, measuring 88 m in height and 5.5 m in diameter (Gorgens et al., 2019). *Dinizia excelsa* figures currently as one of the most important commercial species traded in the Brazilian

Amazon due to its high timber value (Lopes De Souza et al., 2014). According Secretary for Environment and Sustainability of Pará state, Brazil, a total of 1,486,952.87 m³ of *D. excelsa* was traded in a recent period of 10 years (01/January/2006 to 21/February/2016) with monetary values of US$ 52,501,435.82, which gives a mean price of US$35.85 ± 6.42 SD (BRL/USD exchange rate of 15/February/2020, SEMAS/PA, 2020).

Despite of the substantial harvested timber volumes in the Brazilian Amazon, *D. excelsa* presents naturally low densities of individuals because of its light requirements, only found in canopy gaps opened by forest disturbances (Cysneiros et al., 2018). Forest disturbances, including those caused by logging, that create canopy gaps, can be used as an efficient way of conserving low density or rare tree species (Gomes et al., 2019; Neves et al., 2019; Schwartz and Lopes, 2015; Vieira et al., 2018). In this context, the application of silvicultural treatments can also work as an effective procedure for a more sustainable economic use of these species (Gomes et al., 2019; Schwartz et al., 2016).

Post-harvesting silvicultural treatments applied over individuals in canopy logging gaps, as tending and enrichment planting, bring positive outcomes in order to reach more sustainable future cutting cycles in tropical native forests (Doucet et al., 2009; Gomes et al., 2019, 2010; Lopes et al., 2008; Neves et al., 2019; Quédraogo et al., 2014; Schwartz et al., 2013; Taffarel et al., 2014; Vieira et al., 2018). Tending consists in the liberation of target individuals against competing non-commercial tree species and lianas, providing better light availability to improve survival and more rapid growth (Brokaw 1985, Brown & Whitmore 1992). Therefore, these silvicultural treatments applied to *D. excelsa* can also contribute to increase the species' natural low densities through assisted densification (Schwartz and Lopes, 2015) that can result in increments on timber production ensuring the species conservation in further cutting cycles.

The tree species regeneration inside micro-environments as canopy gaps is higher in large gaps than small gaps (Buajan et al., 2018). The canopy height formed by surrounding trees of a logging gap is determinant variable, even more important than gap size, for the success of tree species individuals under any silvicultural treatment. Schwartz et al. (2017) studying showed the successful performance of the pioneer species *Schyzolobium parahyba* var. *amazonica* planted in small managed logging gaps (200 m²) surrounded short canopy height. So, treated individuals of commercial species in logging gaps can thrive since the surrounding canopy height is not so tall, what optimizes sunlight incidence. One of the methods used to categorize sunlight incidence over trees is the crown exposure class system (CEC) of Shenkin et al. (2018), adapted of Clark and Clark (1992).

In the Brazilian Amazon, managers have invested little or even no resources in post-harvest treatments in Sustainable Forest Management Plans (SFMP). Research with positive outcomes, including positive cost-benefit analyses, of studies about post-harvesting silvicultural treatments in canopy logging gaps (Gomes et al., 2019, 2010; Neves et al., 2019; Schwartz et al., 2016, 2013; Vieira et al., 2018) with high value commercial species as *D. excelsa*, can increase the interest of managers. Thus, the objective of this study was to analyze the medium-term effect of post-harvesting silvicultural treatments in canopy logging gaps of different sizes under tending and enrichment planting with *D. excelsa* individuals under different crown exposure. We hypothesized that, after application of the silvicultural treatments on trees in logging gaps, individual effects will have low or neither influence from gap sizes, but will have influence on the crown exposure class, mainly with high growth in the highest CEC, regardless gap sizes.

## 2. Materials and methods

### 2.1. *Study area*

Data were collected in a field experiment carried out in the forest management area of the forestry company Jari Florestal SA under the project ‘Logging Gaps Management’ coordinated by Embrapa Eastern Amazon in cooperation with Jari Florestal. The company has a total forest management area of 545,535 ha and all harvesting operations follow RIL techniques. The study area is located in the Jari valley, Almeirim municipality (1° 9' S, 52° 38' W), Pará state, Brazil. Average annual precipitation is 2200 mm and the annual average temperature is 26 °C. The vegetation is mainly ombrophilous dense forest or *terra firme* forest, where the most common soils are yellow latossols (Azevedo, 2006).

### 2.2. Experimental design

A total of 244 seedlings and saplings of *Dinizia excelsa* naturally present or planted in 43 gaps created by tree felling under RIL were assigned to assess the species medium-term responses to the following treatments: (1) standard procedures of RIL (SRIL) or control, (2) tending of the naturally established regeneration (TNER) and (3) enrichment planting (EP). All seedlings and saplings had 40-80 cm in height.

The experiment was established in 2006 in the logging compartments harvested in 2004. In SRIL, individuals of commercial species were only monitored, with no additional silvicultural treatments, following the current forest regulations for forest monitoring in the Brazilian Amazon. In the other two treatments, silvicultural procedures were applied in addition to all steps required for RIL. Tending consisted in the liberation of target individuals against competing individuals of tree species and lianas. This treatment was applied over and around seedlings and saplings of commercial tree species naturally established (TNER) and planted (EP), annually from 2006 to 2010, 2012 and 2017. In the EP treatment all seedlings were transplanted from the annual production unit (APU) to the logging gaps in a planting spacing of 2.5 m × 2.5 m inside in 2-year-old logging gaps.

According to the pre-logging inventory (PL) done in 2003, as the standard procedures of RIL require, the annual production unit (APU) area of 7,600 ha presented 5,300 *D. excelsa* individuals (N). Pre-logging absolute density (ADe), dominance (ADo) and basal area (G) of *Dinizia excelsa* were calculated (Table 1). Forest characteristics as volume, species composition, diameter structure and diversity indexes of the study area (annual production unit) of the study area are available in Lopes De Souza et al. (2014).

Table 1: Measurement year, number of individuals (N), basal area (G), absolut density (ADe) and dominance (ADo) of *Dinizia excelsa* in the pre-logging and in the annual production unit of 2004 in the forest management are of Jari S.A., Eastern Amazon. PL (pre-logging), SRIL (standard reduced impact logging), TNER (tending of the naturally established regeneration), and EP (enrichment planting).

| | PL* | SRIL | TNER | EP |
|---|---|---|---|---|
| Measurement year | 2003 | 2006 | 2006 | 2006 |
| Number of individuals in 2006 | 5300 | 57 | 45 | 142 |
| Number of individuals in 2017 | - | 39 | 36 | 72 |
| Area (ha) | 7600 | 0.593 | 0.659 | 1.333 |
| G ($m^2 ha^{-1}$) | 0.49 | 0.06 | 0.14 | 0.26 |
| ADe (ind $ha^{-1}$) | 0.7 | 65.8 | 54.65 | 54.78 |
| ADo ($m^2 ha^{-1}$) | 0.49 | 0.1 | 0.21 | 0.2 |

* The *D. excelsa* Pre-logging (PL) information is to the year 2003

In 2017 only individuals that reached ≥ 300 cm in height in the measurement of 2012 were included in the analyses, so the total number of *D. excelsa* individuals was 20, 32 and 65 for SRIL, TNER and EP, respectively.

Mortality rates were calculated using the formula “m = 1 – (Nt2 / Nt1)(1/t)”, where Nt1 = Number of live trees in the first sampling, Nt2 = number of trees that survived until the second sampling and t = years between first and second sampling (Sheil et al., 1995). The logging gap area was calculated by the ellipse formula. The basal area was the sum of tree cross sections of each treatment. Each tree cross section was obtained with the formula $g = \pi * (DBH/2)^2$ in square meters per hectare, where DBH = diameter at breast height. The number of individuals in percentages, were set in diameter class ranging 4 cm in DBH from 0 up to 16 cm. Percentage of individuals per diameter class (0-4 cm; 4-8 cm, 8-12 cm and 12-16 cm) distributed in gap sizes, treatments and crown exposure classes, over 11 years in logging gaps in the managed forests of Jari S.A.

Periodic annual diameter (PAI) was obtained from diameter at breast height (DBH) at 1.3 m from the soil of each individual through the formula PAI = ((DBHt2 – DBHt1)/n)*365), where DBHt1 = individual's diameter at the initial sampling, DBHt2 = individual's diameter at the final sampling, and n = days between first and second sampling. The 117 individuals of *D. excelsa*, which reached minimum height of 300 cm by 2012, were compared by treatment, gap size (GS) and crown exposure class (CEC). SRIL, TNER and EP presented respectively 20, 32 and 65 individuals. To permit gap size comparisons, the individuals were set in: 59 individuals in small size gaps (200–400 $m^2$) and 58 individuals in large size gaps (> 400 $m^2$). The crown exposure of all seedlings and saplings were classified since the beginner of the study before and after the application or not of tending silvicultural treatment, the classification was divided in classes according to Clark & Clark (1992) in: 1 (no direct light, 51 individuals), 2 (some lateral light, 39 individuals) and 3 (10–90% overhead light, 27 individuals).

Once applied the Shapiro-Wilk test on PAI by treatment, gap size and crown exposure class, the data did not present a residual normal distribution (p normal < 0.01). This required a Box-Cox transformation, before running ANOVA and the post-hoc Tukey's pairwise test to gap sizes, treatments and crown exposure class. Besides these analyzes, a two-way ANOVA and the post-hoc Tukey's pairwise were tested too to the treatments versus crown exposure class. All analyses were performed using the R version 3.0.2 (2016).

## 3. Results

Mortality rates of the natural regeneration treatments remained constant, except EP in the initial years of the experiment. Over 11 years EP presented the highest mortality rate (6% $year^{-1}$) while TNER had the lowest rate (2% $year^{-1}$, Figure 1).

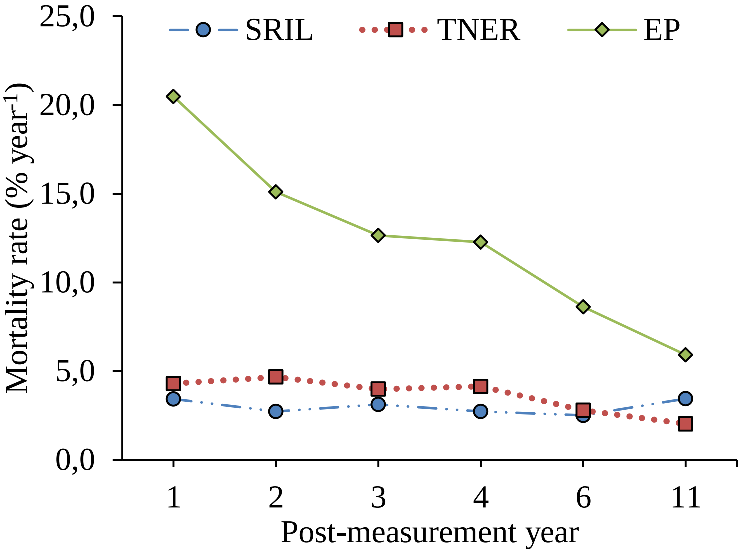

Figure 1: Mortality rates of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER) and enrichment planting (EP) treatments over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil.

The highest basal areas were observed in large gaps, EP treatment and crown exposure class (CEC) 3. The lowest basal area was observed in small gap sizes, SRIL treatment and to CEC 1 (Figure 2).

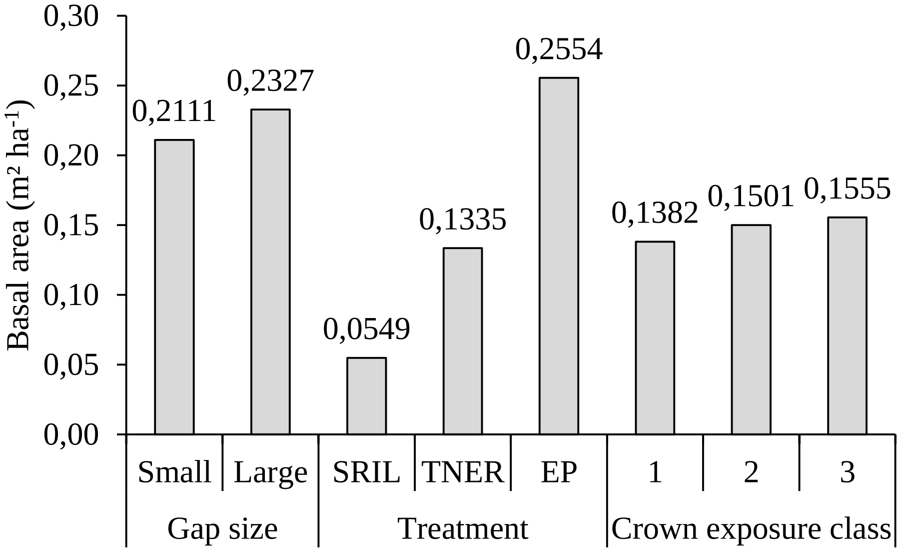

Figure 2: Basal area (m² ha$^{-1}$) of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER) and enrichment planting (EP) treatments over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil.

Taking into consideration only the PAI effect on gap sizes, there was no statistical difference between gap sizes (ANOVA, p = 0,171, Fig. 3A). EP presented an average PAI (0.79

cm year$^{-1}$) four times greater than SRIL (0.19 cm year$^{-1}$, ANOVA, $p < 0.001$, Fig. 3B) and TNER had PAI (0.5 cm year$^{-1}$) almost threefold larger than SRIL (ANOVA, $p < 0.001$, Fig. 3B). SRIL, TNER and EP presented statistical difference between them (ANOVA, $p < 0.001$, Fig. 3B). CEC 3 was more than twice (0.88 cm year$^{-1}$) higher than CEC 1 (0.42 cm year$^{-1}$, ANOVA, $p < 0.001$, Fig. 3C) and CEC 2 was almost twice than CEC 1 (0.42 cm year$^{-1}$, ANOVA, $p < 0.001$, Fig. 3C). The crown exposure class 1, 2 and 3 presented statistical difference between them (ANOVA, $p < 0.001$).

There was interaction of treatments versus crown exposure class (Two-way ANOVA, $p < 0.001$). CEC 1 presented the lowest means of the three treatments (0.14, 0.46, 0.64 cm year$^{-1}$, respectively to SRIL, TNER and EP). CEC 3 presented the highest means (0.43, 0.69, 0.95 cm year$^{-1}$, respectively to SRIL, TNER and EP, Fig. 3D). EP showed the highest means in all crown exposure classes, and SRIL the lowest.

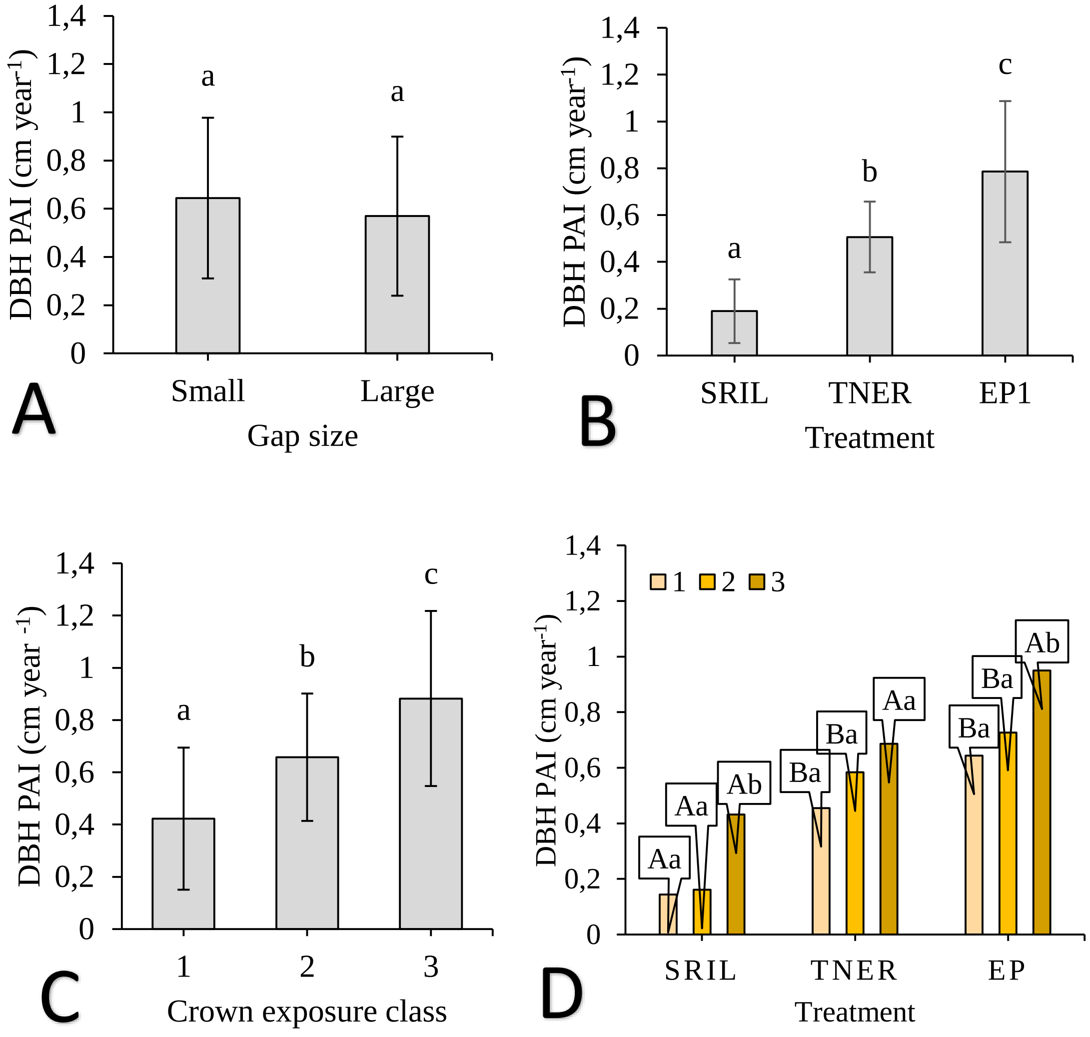

Figure 3: Periodic annual diameter (PAI) measured from diameter at breast height (DBH) at 1.3 m from the soil of each individual distributed in gap sizes, treatments (SRIL: Standard Procedures of RIL, TNER: Tending of

Natural Established Regeneration, EP: Enrichment Planting) and crown exposure classes (1: no direct light, 2: some lateral light, and 3: 10–90% overhead light), over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil. In figure "D" lower cases indicate differencesin treatments and upper case letters are for crown exposure class comparisons.

Large gaps, treatments where tending was applied (TNER and EP) and individuals with some lateral light and 10–90% overhead light (CEC = 2 and 3), reached the fourth diameter class (12-16 cm). SRIL, small gaps and the first crown exposure class did not pass of the third diameter class (8-12 cm).

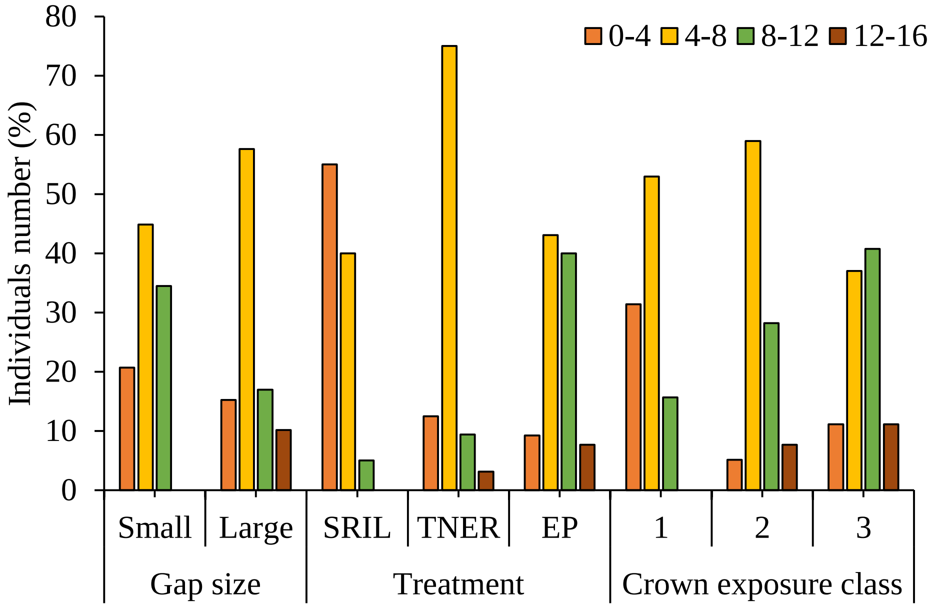

Figure 4. Percentage of individuals per diameter class (0-4 cm; 4-8 cm, 8-12 cm and 12-16 cm) distributed in gap sizes, treatments and crown exposure classes, over 11 years in logging gaps in the managed forests of Jari S.A., Eastern Amazon, Brazil.

## 4. Discussion

Growth was higher in enrichment planting (EP) and tending of natural regeneration (TNER) in logging gaps when compared to SRIL, which is the treatment that reflects the current procedures of RIL legally adopted in the Brazilian Amazon. There is no difference in growth of individuals according in relation to gap size, but according to their crown exposure class. Despite the high mortality of planted individuals (EP), in this treatment individuals had better performance in growth, especially those with higher crown exposure class (CEC). These outcomes are positive in order to increase the low natural densities of *D. excelsa* and to improve its performances in survival, growth and structure.

The better survival of *D. excelsa* in SRIL and TNER in comparison to EP is probably due to the acclimatation phase and even may be a result of the low quality of many planted seedlings. The availability of high-quality seedlings of native commercial species has been a serious bottleneck to permit enrichment planting in managed forests of the Brazilian Amazon (Neves et al., 2019). For the success of enrichment planting in logging gaps, it is recommended a rigorous seedling production, with fertilizers, as well as annual cleanings once seedlings planted in the field normally face strong competition (Gomes et al., 2019).

Was observed after RIL over time the occurrence of new logging gaps. According Dionisio et al. (2017), mortality rates increase in the first five years after logging and the effects of RIL remain up to seven years after RIL. Therefore, these logging gaps that are created over time could be used to apply post-harvesting silvicultural treatments, after all, the entire structure of the RIL are recent created, such as the drag roads, and are available for tending and enrichment planting, optimizing the species conservation and the timber production. To achieve this, it is necessary the development of new public policies to improve the current forest management regulations in the Brazilian Amazon (Neves et al., 2019).

It was remarkable the occurrence of high natural regeneration in the annual production unit (APU). Also noteworthy, based on observations of logging gaps and their surroundings, significant amount of *D. excelsa* regeneration in the following years after the RIL. We suppose that there was a disturbance in the past in which an adequate edaphoclimatic condition was created for this high occurrence. The high mortality observed in the first four years strongly decreased in EP. So the density will be higher if combined the techniques of: (a) replanting seedlings from the nursery; (b) after RIL, logging gaps as well as skid trails, and log decks can be used, aiming at saving nursery costs and mitigating the effects of the seedling rustification process; and (c) tending the seedlings naturally present in gaps, these so-called complementary trees (Neves et al., 2019).

*Dinizia excelsa* presented good growth performance where tending was applied however, there was no difference in increment by gap sizes. This finding contradicted what was expected, a high diameter growth of trees in larger gaps. The more sunlight incidence inside logging gaps, the better is trees growth, which fact explains the higher basal area of treatments with tending (TNER and EP). Even small logging gaps could be used to grow *D. excelsa* by forestry companies, which can represent economic advantages in terms of silvicultural costs. Regarding the silvicultural treatment, TNER presented the highest cost-benefit relation (Schwartz et al., 2016), so it can be widely applied under lower cost in managed forests rich in natural regeneration of commercial species, as can be observed in the present study.

Sunlight is the main limiting factor for plant growth and survival, so in evolutionary terms, it determines the plant’s survival strategy in a forest (Begon et al., 2009; Odum, 2006).

Light-demanding species, such as *D. excelsa*, tolerate certain shading levels, however, they grow faster under overhead light, as showed in this current study. The increment of the EP with CEC 3 performed better due to the high mortality of the other planted species (Neves et al., 2019; Schwartz et al., 2013), generating less competition, allied to the fact that there was the silvicultural treatment of tending (competition cleaning) in these gaps. As in TNER there is low mortality (Neves et al., 2019; Schwartz et al., 2013), there is a greater number of individuals competing in the area, so this justifies its lower growth compared to EP that had the highest mortality and highest growth. Successful enrichment planting in logging gaps confirms the results found in other experiments worldwide with enrichment planting in gaps (Doucet et al., 2009; Gomes et al., 2019, 2010; Lopes et al., 2008; Neves et al., 2019; Quédraogo et al., 2014; Schwartz et al., 2013; Taffarel et al., 2014; Vieira et al., 2018). These studies reinforce the efficiency of enrichment planting in logging gaps, which comes as a viable silvicultural alternative for managing tropical forests.

Individuals with some lateral light and 10–90% overhead light (CEC 2 and 3) of the treatments where tending was applied (TNER and EP) reached the fourth diameter class (12-16 cm) and presented the highest means of PAI (cm year$^{-1}$). SRIL and CEC 1 were not higher than the third diameter class (8-12 cm) and presented the lowest means of PAI. This positive effect reinforces the importance of improving post-harvesting silvicultural treatments in forest management plans. Besides this, the positive outcomes could be extrapolated and tested in species of the same ecological group. For example, species of the same ecological group under TNER and EP treatments and with better sunlight incidence in canopy logging gaps can shorten the time required to recover timber losses caused by RIL (Neves et al., 2019) and help to mitigate the delay in several tropical forests to recover harvested stocks (Hu et al., 2020; Shima et al., 2018).

The dominance of *D. excelsa* in treatments with tending was twice higher than the standard procedures of RIL. Schwartz et al. (2016) found the best cost-benefit relation for TNER, but the authors considered a set of species in their study, which included some slow-growth species. In this study we focused on the light-demanding species *D. excelsa*, which presented a high silvicultural performance.

## 5. Conclusion

Individuals of *Dinizia excelsa* presented better survival and growth under post-harvesting silvicultural treatments of tending both planted and naturally regenerated individuals. Growth of individuals did not respond to differences in gap sizes, but according to crown exposure, individuals with overhead light has higher growth.

## Acknowledgements

We acknowledge Jari Florestal SA for a very productive partnership, especially to Viviane de Souza Nogueira, Isael Araújo Costa, and all field assistants and technicians engaged in different phases of the experiment. The first author is grateful to Conselho Nacional de Desenvolvimento Científico e Tecnológico (140941/2016-9) on his PhD Fellowship.

## 6. References

Adenesky-Filho, E., Maçaneiro, J.P., Vitorino, M.D., 2017. How to select potential species for ecological restoration of rain forest – Southern Brazil. Appl. Ecol. Environ. Res. 15, 1671–1684. https://doi.org/10.15666/aeer/1503_16711684

Avila, A.L. de, Schwartz, G., Ruschel, A.R., Lopes, J. do C., Silva, J.N.M., Carvalho, J.O.P. de, Dormann, C.F., Mazzei, L., Soares, M.H.M., Bauhus, J., 2017. Recruitment, growth and recovery of commercial tree species over 30 years following logging and thinning in a tropical rain forest. For. Ecol. Manage. 385, 225–235. https://doi.org/10.1016/J.FORECO.2016.11.039

Azevedo, C.P. De, 2006. Dinâmica de florestas submetidas a manejo na Amazônia Oriental: experimentação e simulação.

Begon, M., Townsend, C.R., Harper, J.L., 2009. Ecologia: de indivíduos a ecossistemas.

Bladon, K.D., Lieffers, V.J., Silins, U., Landhäusser, S.M., Blenis, P. V., 2008. Elevated mortality of residual trees following structural retention harvesting in boreal mixedwoods. For. Chron. 84, 70–75. https://doi.org/10.5558/tfc84070-1

Buajan, S., Liu, J.F., He, Z.S., Feng, X.P., Muhammad, A., 2018. Effects of gap size and locations on the regeneration of castanopsis kawakamii in a subtropical natural forest, China. J. Trop. For. Sci. 30, 39–48. https://doi.org/10.26525/jtfs2018.30.1.3948

Chaudhary, A., Burivalova, Z., Koh, L.P., Hellweg, S., 2016. Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. Sci. Rep. 6, 23954. https://doi.org/10.1038/srep23954

Clark, D.A., Clark, D.B., 1992. Life History Diversity of Canopy and Emergent Trees in a Neotropical Rain Forest. Ecol. Monogr. 62, 315–344. https://doi.org/10.2307/2937114

Das Chagas, R.S., Gomes, J.M.Ê., De Carvalho, J.O.P., Ferreira, J.E.R., 2012. Sobrevivência e crescimento de plântulas de Manilkara huberi Chevalier durante cinco anos em clareiras causadas pela exploração de impacto reduzido na Amazônia brasileira. Sci. For. Sci. 40, 417–424.

Dauber, E., Fredericksen, T.S., Peña, M., 2005. Sustainability of timber harvesting in Bolivian tropical forests. For. Ecol. Manage. 214, 294–304. https://doi.org/10.1016/J.FORECO.2005.04.019

Dionisio, L.F.S., Schwartz, G., Lopes, J. do C., Oliveira, F. de A., 2018. Growth, mortality, and recruitment of tree species in an Amazonian rainforest over 13 years of reduced impact logging. For. Ecol. Manage. 430, 150–156. https://doi.org/10.1016/J.FORECO.2018.08.024

Dionisio, L.F.S., Schwartz, G., Mazzei, L., Lopes, J. do C., Santos, G.G.A. dos, Oliveira, F. de A., 2017. Mortality of stocking commercial trees after reduced impact logging in eastern Amazonia. For. Ecol. Manage. 401, 1–7. https://doi.org/10.1016/j.foreco.2017.06.060

Doucet, J.-L., Kouadio, Y.L., Monticelli, D., Lejeune, P., 2009. Enrichment of logging gaps with moabi (Baillonella toxisperma Pierre) in a Central African rain forest. For. Ecol. Manage. 258, 2407–2415. https://doi.org/10.1016/J.FORECO.2009.08.018

Foster, R.B., 1977. Tachigalia versicolor is a suicidal neotropical tree. Nature 268, 624–626. https://doi.org/10.1038/268624b0

Gomes, J.M., Carvalho, J.O.P. de, Silva, M.G. da, Nobre, D.N.V., Taffarel, M., Ferreira, J.E.R., Santos, R.N.J., 2010. Sobrevivência de espécies arbóreas plantadas em clareiras causadas pela colheita de madeira em uma floresta de terra firme no município de Paragominas na Amazônia brasileira. Acta Amaz. 40, 171–178. https://doi.org/10.1590/S0044-59672010000100022

Gomes, J.M., Silva, J.C.F. da, Vieira, S.B., Carvalho, J.O.P. de, Quadros, L.C.L., Queiroz, W.T. de, 2019. Schizolobium parahyba var. amazonicum (Huber ex Ducke) Barneby can be used in enrichment planting in gaps caused by logging in Amazonia. Ciência Florest. 29, 421–428. https://doi.org/10.5902/198050984793

Hautala, H., Vanha-Majamaa, I., 2006. Immediate tree uprooting after retention-felling in a coniferous boreal forest in Fennoscandia. Can. J. For. Res. 36, 3167–3172. https://doi.org/10.1139/x06-193

Hawthorne, W.D., Sheil, D., Agyeman, V.K., Abu Juam, M., Marshall, C.A.M., 2012. Logging scars in Ghanaian high forest: Towards improved models for sustainable production. For. Ecol. Manage. 271, 27–36. https://doi.org/10.1016/j.foreco.2012.01.036

Hu, J., Herbohn, J., Chazdon, R.L., Baynes, J., Vanclay, J., 2020. Silvicultural treatment effects on commercial timber volume and functional composition of a selectively logged Australian tropical forest over 48 years. For. Ecol. Manage. 457, 117690. https://doi.org/10.1016/j.foreco.2019.117690

Inada, T., Hardiwitono, S., Purnomo, S., Putra, I.B.W.., Kitajima, K., Kanzaki, M., 2017. Dynamics of forest regeneration following logging management in a bornea lowland dipterocarp forest. J. Trop. For. Sci. 29, 185–197.

Jardim, F.C. da S., 2015. Natural re generation in tropical forests. Rev. Ciências Agrar. - Amaz. J. Agric. Environ. Sci. 58, 105–113. https://doi.org/10.4322/rca.1676

Jardim, F.C. da S., Serrão, D.R., Nemer, T.C., 2007. Efeito de diferentes tamanhos de clareiras, sobre o crescimento e a mortalidade de espécies arbóreas, em Moju-PA 1. Acta Amaz. 37, 37–48.

Lavoie, S., Ruel, J.C., Bergeron, Y., Harvey, B.D., 2012. Windthrow after group and dispersed tree retention in eastern Canada. For. Ecol. Manage. 269, 158–167. https://doi.org/10.1016/j.foreco.2011.12.018

Lewis, S.L., Edwards, D.P., Galbraith, D., 2015. Increasing human dominance of tropical forests. Science (80-. ). 349, 827–832. https://doi.org/10.1126/science.aaa9932

Lewis, S.L., Maslin, M.A., 2015. Defining the Anthropocene. Nature 519, 171–180. https://doi.org/10.1038/nature14258

Lima, H.C., 2015. Lista do Brasil - Tachigali glauca Tul. [WWW Document]. URL http://floradobrasil.jbrj.gov.br/jabot/FichaPublicaTaxonUC/FichaPublicaTaxonUC.do?id=FB106814 (accessed 3.11.20).

Lopes De Souza, A., Marques De Medeiros, R., Silva Matos, L.M., Silva, K.R., Alves Côrrea, P., de Faria, F.N., 2014. Estratificação volumétrica por classes de ... Rev. Ár 38, 533–541.

Lopes, J. do C.A., Jennings, S.B., Matni, N.M., 2008. Planting mahogany in canopy gaps created by commercial harvesting. For. Ecol. Manage. 255, 300–307. https://doi.org/10.1016/J.FORECO.2007.09.051

Neves, R.L.P., Schwartz, G., Lopes, J. do C.A., Leão, F.M., 2019. Post-harvesting silvicultural treatments in canopy logging gaps: Medium-term responses of commercial tree species under tending and enrichment planting. For. Ecol. Manage. 451, 117521. https://doi.org/10.1016/j.foreco.2019.117521

Odum, E.P., 2006. Fundamentos de ecología.

Park, A., Joaquin Justiniano, M., Fredericksen, T.S., 2005. Natural regeneration and environmental relationships of tree species in logging gaps in a Bolivian tropical forest. For. Ecol. Manage. 217, 147–157. https://doi.org/10.1016/J.FORECO.2005.05.056

Petrokofsky, G., Sist, P., Blanc, L., Doucet, J.-L., Finegan, B., Gourlet-Fleury, S., Healey, J.R., Livoreil, B., Nasi, R., Peña-Claros, M., Putz, F.E., Zhou, W., 2015. Comparative effectiveness of silvicultural interventions for increasing timber production and sustaining conservation values in natural tropical production forests. A systematic review protocol. Environ. Evid. 4, 8. https://doi.org/10.1186/s13750-015-0034-7

Piponiot, C., Rödig, E., Putz, F.E., Rutishauser, E., Sist, P., Ascarrunz, N., Blanc, L., Derroire, G., Descroix, L., Guedes, M.C., Coronado, E.H., Huth, A., Kanashiro, M., Licona, J.C., Mazzei, L., D'Oliveira, M.V.N., Peña-Claros, M., Rodney, K., Shenkin, A., De Souza, C.R., Vidal, E., West, T.A.P., Wortel, V., Hérault, B., 2019. Can timber provision from Amazonian production forests be sustainable? Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/ab195e

Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S., Griscom, B., Palmer, J., Zagt, R., 2012. Sustaining conservation values in selectively logged tropical forests: The attained and the attainable. Conserv. Lett. 5, 296–303. https://doi.org/10.1111/j.1755-263X.2012.00242.x

Quédraogo, D.Y., Fayolle, A., Daïnou, K., Demaret, C., Bourland, N., Lagoute, P., Doucet, J.L., 2014. Enrichment of logging gaps with a high conservation value species (Pericopsis elata) in a central African moist forest. Forests 5, 3031–3047. https://doi.org/10.3390/f5123031

Reis, L.P., Carvalho, J.O.P. de, Reis, P.C.M. dos, Gomes, J.M., Ruschel, A.R., Silva, M.G. da, 2014. Crescimento de mudas de *Parkia gigantocarpa* Ducke, em um sistema de enriquecimento em clareiras após a colheita de madeira. Ciência Florest. 24, 431–436. https://doi.org/10.5902/1980509814583

Reis, L.P., Ruschel, A.R., Coelho, A.A., Luz, A.S. da, Martins-da-Silva, R.C.V., 2010. Avaliação do potencial madeireiro na Floresta Nacional do Tapajós após 28 anos da exploração florestal. Pesqui. Florest. Bras. 30, 265–281. https://doi.org/10.4336/2010.pfb.30.64.265

Schwartz, G., Bais, A., Peña-Claros, M., Hoogstra-Klein, M., Mohren, G., Arts, B., 2016. Profitability of Silvicultural Treatments in Logging Gaps in the Brazilian Amazon. J. Trop. For. Sci. 28, 68–78.

Schwartz, G., Falkowski, V., Peña-Claros, M., 2017a. Natural regeneration of tree species in the Eastern Amazon: Short-term responses after reduced-impact logging. For. Ecol. Manage. 385, 97–103. https://doi.org/10.1016/J.FORECO.2016.11.036

Schwartz, G., Lopes, J. d. C.A., 2015. Logging in the brazilian amazon forest: The challenges of reaching sustainable future cutting cycles, in: Advances in Environmental Research. pp. 113–138.

Schwartz, G., Lopes, J.C.A., Mohren, G.M.J., Peña-Claros, M., 2013. Post-harvesting silvicultural treatments in logging gaps: A comparison between enrichment planting and tending of natural regeneration. For. Ecol. Manage. 293, 57–64. https://doi.org/10.1016/j.foreco.2012.12.040

Schwartz, G., Peña-Claros, M., Lopes, J.C.A., Mohren, G.M.J., Kanashiro, M., 2012. Mid-term effects of reduced-impact logging on the regeneration of seven tree commercial species in the Eastern Amazon. For. Ecol. Manage. 274, 116–125. https://doi.org/10.1016/j.foreco.2012.02.028

Schwartz, G., Pereira, P.C.G., Siviero, M.A., Pereira, J.F., Ruschel, A.R., Yared, J.A.G., 2017b. Enrichment planting in logging gaps with Schizolobium parahyba var. amazonicum (Huber ex Ducke) Barneby: A financially profitable alternative for degraded tropical forests in the Amazon. For. Ecol. Manage. 390, 166–172. https://doi.org/10.1016/J.FORECO.2017.01.031

SEMAS - Sisflora PA [WWW Document], n.d. URL https://monitoramento.semas.pa.gov.br/sisflora/relatorios.html (accessed 12.7.19).

Sheil, D., Burslem, D.F.R.P., Alder, D., 1995. The Interpretation and Misinterpretation of Mortality Rate Measures Author ( s ): Douglas Sheil , David F . R . P . Burslem , Denis Alder Published by : British Ecological Society Stable URL : http://www.jstor.org/stable/2261571. Br. Ecol. Soc. 83, 331–333. https://doi.org/10.2307/2261571

Shenkin, A., Bolker, B., Peña-Claros, M., Licona, J.C., Ascarrunz, N., Putz, F.E., 2018. Interactive effects of tree size, crown exposure and logging on drought-induced mortality. Philos. Trans. R. Soc. B Biol. Sci. 373. https://doi.org/10.1098/rstb.2018.0189

Shima, K., Yamada, T., Okuda, T., Fletcher, C., Kassim, A.R., 2018. Dynamics of Tree Species Diversity in Unlogged and Selectively Logged Malaysian Forests. Sci. Rep. 8, 1024. https://doi.org/10.1038/s41598-018-19250-z

Sist, P., Ferreira, F.N., 2007. Sustainability of reduced-impact logging in the Eastern Amazon. For. Ecol. Manage. 243, 199–209. https://doi.org/10.1016/J.FORECO.2007.02.014

Sist, P., Picard, N., Gourlet-Fleury, S., 2003. Sustainable cutting cycle and yields in a lowland mixed dipterocarp forest of Borneo. Ann. For. Sci 60, 803–814. https://doi.org/10.1051/forest:2003075

Souza, D.V., Carvalho, J.O.P. de, Mendes, F.D.S., Melo, L.D.O., Silva, J.N.M., Jardim, F.C. da S., 2015. Crescimento de espécies arbóreas em uma floresta natural de terra firme após a colheita de madeira e tratamentos silviculturais, no município de Paragominas, Pará, Brasil. Ciência Florest. 25, 873–883. https://doi.org/10.5902/1980509820585

Taffarel, M., Gomes, J.M., Carvalho, J.O.P. de, Melo, L. de O., Ferreira, J.E.R., 2014. Efeito da silvicultura pós-colheita na população de Chrysophyllum lucentifolium Cronquist (Goiabão) em uma floresta de terra firme na amazônia brasileira. Rev. Árvore 38, 1045–1054. https://doi.org/10.1590/S0100-67622014000600009

Valle, D., Phillips, P., Vidal, E., Schulze, M., Grogan, J., Sales, M., van Gardingen, P., 2007. Adaptation of a spatially explicit individual tree-based growth and yield model and long-term comparison between reduced-impact and conventional logging in eastern Amazonia, Brazil. For. Ecol. Manage. 243, 187–198. https://doi.org/10.1016/J.FORECO.2007.02.023

Van Rheenen, H.M.P.J.B., Boot, R.G.A., Werger, M.J.A., Ulloa Ulloa, M., 2004. Regeneration of timber trees in a logged tropical forest in North Bolivia. For. Ecol. Manage. 200, 39–48. https://doi.org/10.1016/j.foreco.2004.06.024

Vatraz, S., Olegário Pereira de Carvalho, J., Natalino Macedo Silva, J., da Cunha Castro, T., 2016. Efeito da exploração de impacto reduzido na dinâmica do crescimento de uma floresta natural. Sci. Florestalis 44, 261–271. https://doi.org/10.18671/scifor.v44n109.25

Vieira, S.B., de Carvalho, J.O.P., Gomes, J.M., da Silva, J.C.F., Ruschel, A.R., 2018. Is cedrela odorata L. A species with potential to be used in post-harvesting silviculture in the Brazilian amazonia? Cienc. Florest. 28, 1230–1238. https://doi.org/10.5902/1980509833361

Villegas, Z., Peña-Claros, M., Mostacedo, B., Alarcón, A., J.C.Licona, Leaño, C., Pariona, W., Choque, U., 2009. Silvicultural treatments enhance growth rates of future crop trees in a tropical dry forest. For. Ecol. Manage. 258, 971–977. https://doi.org/10.1016/J.FORECO.2008.10.031

# Silviculture of a very common commercial timber species in the Amazon: managing *Tachigali glauca* in logging gaps[2]

Raphael Lobato Prado Neves[abd], Gustavo Schwartz[b], José do Carmo Alves Lopes[b], Fábio Miranda Leão[c]
[a] Federal Rural University of Amazonia, Av. Presidente Tancredo Neves, 2501, 66077-530, Belém, Pará, Brazil
[b] Embrapa Eastern Amazon, P. O. Box 48, 66095-100, Belém, Pará Brazil
[c] Federal University of Pará, S. Cel. José Porfírio, 2515, 68372-040, Altamira, Pará, Brazil
[d] State Secretary for Environment and Sustainability, Ln Lomas Valentinas, 2717, 66093-677, Belém, Pará, Brazil

## Abstract

The objective of this paper was analyze the medium-term effects of post-harvesting silvicultural treatments over growth and survival of *Tachigali glauca* individuals planted or naturally established in canopy logging gaps. under tending and enrichment planting with different crown exposure intensities. A total of 181 *Tachigali glauca* individuals were used in the experiment. Part of them was naturally present while other was planted in 26 gaps created by tree felling in order to evaluate the specie medium-term responses to the following treatments: (1) standard procedures of RIL (SRIL) or control, (2) tending of the naturally established regeneration (TNER) and (3) enrichment planting (EP). Effects of the EP silvicultural treatment were positive to *T. glauca*, since it presented high survival and growth of the trees present in canopy logging gaps. Furthermore, EP presented PAI value almost four times greater than SRIL, which is the treatment that reflects the current procedures required for the employment of reduced impact logging (RIL) in the Brazilian Amazon. The EP growth is reflected in percentage of individuals in the fourth diameter class (15-20) and means that EP trees are growing faster than trees of the other two treatments.

**Keywords:** assisted densification; conservation and timber production; sustainable forest management; tropical forest.

## 1. Introduction

“*Can timber provision from Amazonian production forests be sustainable?*”. Piponiot et al. (2019) approached the question with simulations finding that, regardless the cutting cycle duration and logging intensities, selectively logged forests are unlikely to meet timber demands over the long term as timber stocks are predicted to steadily decline. Moreover, 40–50 years is

---

[2] Artigo a ser submetido na revista *Forest Ecology and Management*

not time enough for  mixed dipterocarp tropical forests in Kalimantan, Indonesia to recover original species composition after logging (Shima et al., 2018).

Some alternatives to mitigate such tropical forest issues are the application of post-harvesting silvicultural treatments in canopy logging gaps, as tending and enrichment planting. These treatments bring positive outcomes to reach more sustainable future cutting cycles (Doucet et al., 2009; Gomes et al., 2019, 2010; Lopes et al., 2008; Neves et al., 2019; Quédraogo et al., 2014; Schwartz et al., 2013; Taffarel et al., 2014; Vieira et al., 2018). Tending consists in the liberation of target individuals against competing tree species and lianas, providing better light availability to improve survival and more rapid growth (Brokaw 1985, Brown & Whitmore 1992).

Higher light availability promoted by tending tends to benefit mainly individuals of pioneer and light-demanding species, as the case of *Tachigali glauca* Tul. in three managed forests sampled by Schwartz et al. (2017a). *T. glauca* is an monocarpic (Foster, 1977), fast-grow and light-demanding endemic tree species in Brazil that occurs naturally not only in the North region of Brazil (states of Acre, Amazonas, Amapá, Pará, Rondônia and Roraima), but also in its Northeast (state of Maranhão) and Midwest regions (state of Mato Grosso) (Lima, 2015). To Pará state, in 10 years (01/Jan/2006-21/Feb/2016), 14,415.92 m³ of *T. glauca* timber was traded by 453.012,10 USD (1,954,656.46 BRL, rate of 11/Mar/2020), with an average price of 31.29 USD (“SEMAS - Sisflora PA,” n.d.). Schwartz et al. (2016), in a profitability analysis of a set of species, including *T. glauca*, found the best cost-benefit relation in the treatment of tending of the naturally established regeneration. So, the treatments will improve the wood trade

In the current Sustainable Forest Management Plans (SFMP) in the Brazilian Amazon, almost no investments have been addressed to post-harvest treatments. In this sense, new public policies to improve the current forest management regulations in the Brazilian Amazon (Neves et al., 2019) using commercial species as *T. glauca* can call the forest managers attention to invest in silvicultural techniques, especially over pioneer and light-demanding species. Thus, the objective of this paper was to analyze medium-term effects of post-harvesting silvicultural treatments over growth and survival of *T. glauca* individuals planted or naturally established in canopy logging gaps under tending and enrichment planting with different crown exposure to sunlight. According to the *T. glauca* characteristics of be a fast-growing and light-demanding tree species, it is hypothesized that, after application of silvicultural treatments on logging gaps, the individuals will respond positively in growth and survival.

## 2. Materials and methods

### *2.1. Study area*

Data were collected from a field experiment carried out in the forest management area of the forestry company Jari Florestal SA under the project 'Logging Gaps Management' coordinated by Embrapa Eastern Amazon in cooperation with Jari Florestal S.A. The study area is located in the Jari valley, Almeirim municipality (1° 9' S, 52° 38' W), Pará state, Brazil. Average annual precipitation is 2200 mm and the annual average temperature is 26 °C. The most common vegetation type is ombrophilous dense forest popularly as *terra firme* forest, where the most dominant soils are yellow latossols (Azevedo, 2006).

Jari Florestal has a total area under forest management of 545,535 ha and all harvesting operations follow RIL techniques. A total of 181 seedlings and saplings of *Tachigali glauca* were used in the experiment. Part of them was naturally present while others were planted in 26 gaps created by tree felling in order to evaluate the specie medium-term responses to the following treatments: (1) standard procedures of RIL (SRIL) or control, (2) tending of the naturally established regeneration (TNER) and (3) enrichment planting with tending the planted seedlings (EP). All seedlings and saplings had 40-80 cm in height.

### *2.2. Experimental design*

The experiment was established in 2006 and 2007 in the logging compartments harvested in 2004 and 2006. In SRIL, marked individuals were only monitored, with no additional silvicultural treatments, according to the current forest management regulations in the Brazilian Amazon. In the other two treatments, post-harvesting silvicultural procedures were applied in addition to all steps required to employ RIL.

Tending consisted in the liberation of target individuals against competing individuals of tree species, commonly pioneers, and lianas. This treatment was applied over seedlings and saplings of commercial tree species naturally established (TNER) and planted (EP) in all measurement years. EP treatment was established in 1-year-old gaps with complete logging residual removal for further energy production by the forestry company and every seedling was planted in spacing of 2.5 m × 2.5 m inside the logging gaps.

According to the pre-logging inventory (PL) done in 2005, as the standard procedures of RIL, the annual production unit (APU) had an area of 7,600 ha and 6,555 individuals of *T. glauca* individuals, all above 35 cm in DBH. Based on this information, it was possible to calculate the pre-logging absolute density (ADe), dominance (ADo) and basal area (G) of *T. glauca*. Forest characteristics as volume, species composition, diameter structure, and diversity indexes of the study area (annual production unit) are available in Lopes De Souza et al. (2014), Neves et al. (2019), and Schwartz et al. (2013). The dendrological variables for treatments were based on data collected in 2018.

In 2018, all trees that reached ≥ 300 cm in height in 2012 were included in the analyses, totalizing 31, 16 and 115 trees in SRIL, TNER and EP, respectively (Table 1). This means that every planted or naturally regenerated seedling < 300 cm in height in 2012 was not considered in this study.

Table 1: Number of individuals (N), basal area (G), absolut density (ADe) and dominance (ADo) of *Tachigali glauca* in the forest management area of Jari SA, Eastern Amazon, Brazil. PL (pre-logging), SRIL (standard reduced impact logging/control), TNER (tending of the naturally established regeneration), and EP (enrichment planting).

| | PL* | SRIL | TNER | EP |
|---|---|---|---|---|
| Initial measurement year | 2005 | 2006 | 2006 | 2006 |
| Number of individuals in the initial measurement year | 6555 | 35 | 17 | 129 |
| Number of individuals in the last data collect | uninformed | 31 | 16 | 115 |
| Area (ha) | 7600 | 0.593 | 0.659 | 0.604 |
| G ($m^2\ ha^{-1}$) | 0.15 | 0.10 | 0.14 | 1.77 |
| ADe ($ind\ ha^{-1}$) | 0.9 | 57.4 | 25.8 | 190.4 |
| ADo ($m^2\ ha^{-1}$) | 0.64 | 0.1 | 0.21 | 0.43 |

* The *T. glauca* Pre-logging (PL) information in 2005.

Mortality rate (m) was calculated through the formula “m = 1 – (Nt2 / Nt1)(1/t)”, where Nt1 = Number of live trees in the first sampling, Nt2 = number of trees that survived until the second sampling and t = years between first and second sampling (Sheil et al., 1995). The logging gap area was calculated by the ellipse formula. The basal area was the sum of tree cross sections of each treatment. Each tree cross section was obtained with the formula $g = \pi * (DBH/2)^2$ in square meters per hectare, where DBH = diameter at breast height at 1.3 m from the soil.

Periodic annual diameter (PAI) measured from the DBH of each individual was calculated using the formula PAI = ((DBHt2 – DBHt1)/n)*365), where DBHt1 = individual's diameter at the initial sampling, DBHt2 = individual's diameter at the final sampling, and n = days between first and second sampling. The 117 individual PAI of *T. glauca*, which reached minimum height of 300 cm by 2012, were compared by treatment and crown exposure class (CEC). The individuals crown exposure class were assigned with the system of Clark & Clark (1992): CEC 1 (no direct light, 8 individuals), CEC 2 (some lateral light, 37 individuals) and CEC 3 (10–90% overhead light, 101 individuals).

Once applied the Shapiro-Wilk test on PAI by treatment and crown exposure class, the data did not present a residual normal distribution ($p$ normal $< 0.05$), which required a square root transformation, before running ANOVA and the post-hoc Tukey's pairwise test to treatments and crown exposure class. The number of individuals, in percentage, were set in four diameter class ranging 5 cm in DBH from 0 up to 20 cm.

The PAI of each individual present in the eight gaps of the EP treatment was also compared by ANOVA with post-hoc Tukey's pairwise test. The area, in square meters, of the eight logging gaps was: EP1 = 827.81 m$^2$; EP2 = 785.4 m$^2$; EP3 = 1278.63 m$^2$ (the largest gap); EP4 = 632.25 m$^2$; EP5 = 572.56 m$^2$; EP6 = 523.08 m$^2$ (the smallest gap); EP7 = 643.24 m$^2$ and EP8 = 775.97 m$^2$). All analyses were performed using the R version 3.0.2 (2016).

## 3. Results

Mortality rates of all treatments were lower than 2%, with only one death in TNER treatment (0.55% year$^{-1}$). The highest mortality rate was to SRIL treatment (1.10% year$^{-1}$, Figure 1).

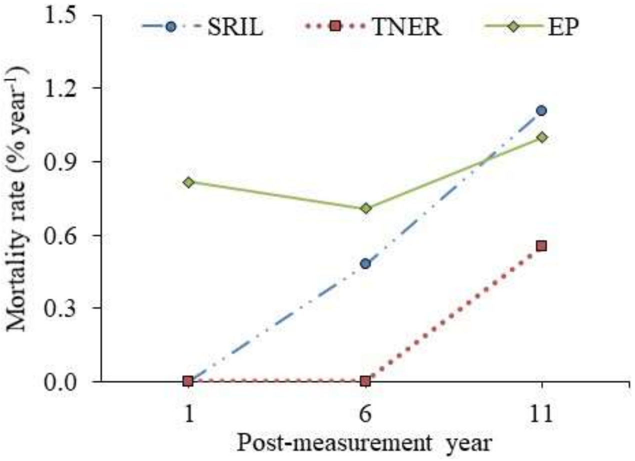

**Figure 1.** Mortality rates of standard procedures of reduced-impact logging (SRIL), tending of the naturally established regeneration (TNER) and enrichment planting (EP) treatments by one, six and 11 years in logging gaps in the managed forests of Jari company, Eastern Amazon, Brazil.

The highest basal area was observed in EP treatment (1.7704 m² ha$^{-1}$) and in individuals under crown exposure class 3 (1.7455 m² ha$^{-1}$). The lowest basal area was observed in SRIL treatment (0.1026 m² ha$^{-1}$) and in CEC 1 (0.0107 m² ha$^{-1}$, Figure 2).

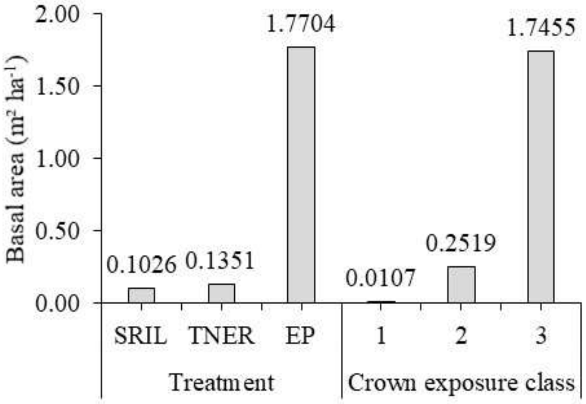

Figure 2: Basal area (m² ha$^{-1}$) of treatments (SRIL: Standard Procedures of RIL, TNER: Tending of Natural Established Regeneration, EP: Enrichment Planting) and crown exposure classes (1: no direct light, 2: some lateral light, and 3: 10–90% overhead light), over 11 years in logging gaps in the managed forests of Jari, Eastern Amazon, Brazil.

Considering PAI of each treatment, the EP mean (0.98 cm year$^{-1}$) was almost four times greater than SRIL (0.25 cm year$^{-1}$, ANOVA, $p < 0.001$); and TNER (0.56 cm year$^{-1}$) was twice greater than SRIL (0.25 cm year$^{-1}$, ANOVA, $p < 0.001$). SRIL, TNER and EP presented statistical differences among them (ANOVA, $F_{2;143} = 56.76$, $p < 0.001$, Figure 3).

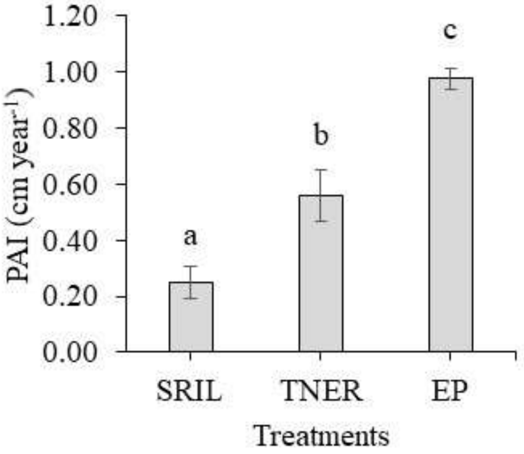

Figure 3: Periodic annual diameter (PAI) mean (± SE) of the diameter at breast height (DBH) at 1.3 m from the soil of each individual per treatment over 11 years in logging gaps in the managed forests of Jari, Eastern Amazon, Brazil. Letters indicate differences in ANOVA with post-hoc Tukey's pairwise test.

PAI (cm year$^{-1}$) in relation to the crown exposure class (CEC), the treatments presented a substantial difference among their means (ANOVA, $F_{2;143} = 83.34$, $p < 0.001$, Figure 4). CEC 3 (1.02 cm year$^{-1}$) was almost 15 times higher than CEC 1 (0.07 cm year$^{-1}$, ANOVA, $p < 0.001$) and CEC 2 (0.48 cm year$^{-1}$) was six times higher than CEC 1 (0.07 cm year$^{-1}$, ANOVA, $p < 0.001$; Figure 4).

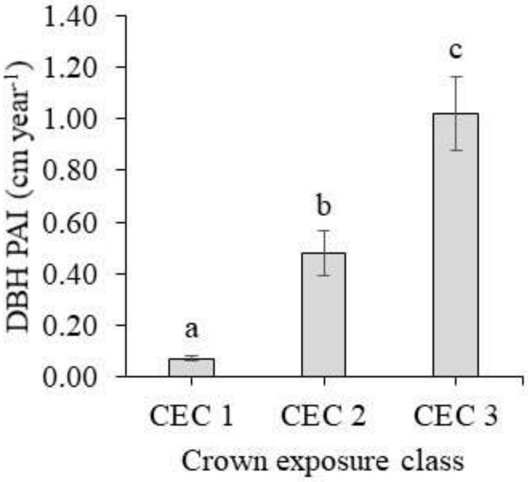

Figure 4: Periodic annual diameter (PAI) mean (± SE) of the DBH at 1.3 m from the soil of each individual distributed in crown exposure classes over 11 years in logging gaps in the managed forests of Jari, Eastern Amazon, Brazil. Letters indicate differences in ANOVA with post-hoc Tukey's pairwise test.

Individuals under tending treatments (TNER and EP) and with some lateral light and

10–90% overhead light (2 and 3 crown exposure class), reached the fourth diameter class (15-20 cm), while SRIL individuals and those with CEC 1 did not pass over the third diameter class (10-15 cm, Figure 5).

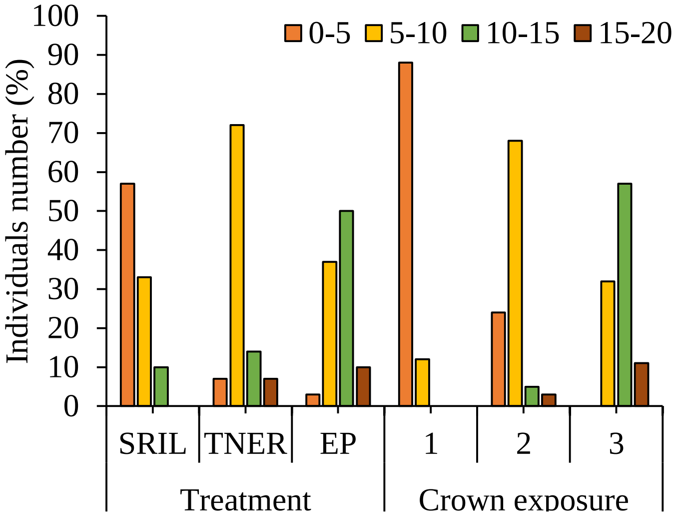

**Figure 5.** Percentage of individuals per diameter class (0-5 cm; 5-10 cm, 10-15 cm and 15-20 cm) distributed in treatments (SRIL: Standard Procedures of RIL, TNER: Tending of Natural Established Regeneration, EP: Enrichment Planting) and crown exposure classes (1: no direct light, 2: some lateral light, and 3: 10–90% overhead light), over 11 years in logging gaps in the managed forests of Jari, Eastern Amazon, Brazil.

The logging gap EP3 (area = 1,278.63 m²) and EP4 (area = 632.25 m²) presented the highest PAI means (1.16 and 1.24 cm year$^{-1}$ respectively). The logging gap EP7 (area = 643.24 m²) presented the lowest PAI mean (0.66 cm year $^{-1}$). There were statistical differences between EP 7 from EP4 and EP3 (ANOVA, $F_{7;103} = 4.16$, $p < 0.01$, Figure 6).

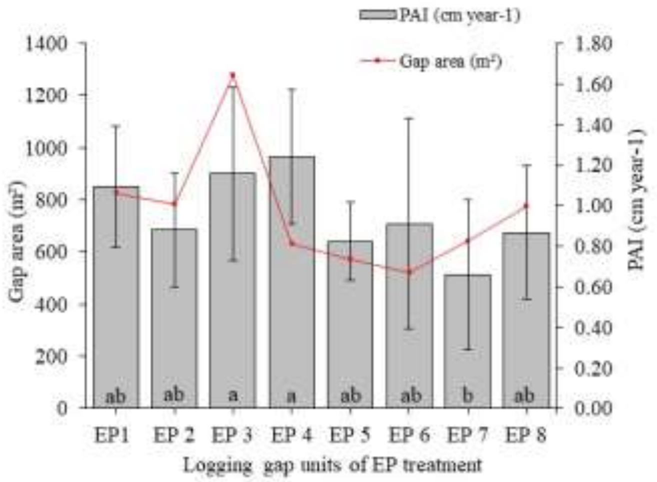

**Figure 6.** Mean (± SD) of periodic annual increment (PAI cm year-1) and Gap area (m²) of the eight logging gap units of enrichment planting treatment in the managed forests of Jari, Eastern Amazon, Brazil. Letters indicate differences in ANOVA with post-hoc Tukey’s pairwise test.

## 4. Discussion

Effects of the silvicultural treatment enrichment planting (EP) were positive to *Tachigali glauca*, since it presented high survival and growth of the trees present in canopy logging gaps. EP presented PAI value almost four times greater than SRIL, which is the treatment that reflects the current procedures required for the employment of reduced impact logging (RIL) in the Brazilian Amazon. The EP growth also showed as the percentage of individuals in the fourth diameter class (15-20), where EP trees grew much faster than trees of the two other treatments.

For the success of enrichment planting in logging gaps it is essential the production of high quality seedlings, with fertilizers, as well as annual cleanings once seedlings planted in the field normally face strong competition (Gomes et al., 2019; Schwartz et al., 2013). However, in the present study the seedlings possibly had low quality and was not utilized fertilizer, only annual cleanings were applied, therefore, it was expected low survival in enrichment planting treatments of canopy logging gaps (Neves et al., 2019) mainly due to the rustification phase, (Adenesky-Filho et al., 2017; Neves et al., 2019), which is the phase in which the plant takes to adapt to the new edaphoclimatic conditions. However, the EP treatment presented low mortality rate, which may be a positive effect of the silvicultural treatment.

Mortality rates vary among species and diameter classes, however, the average mortality rate for the three treatments (0.88% year-1), with an emphasis on TNER treatment with only one dead tree (0.55 year -1), is within the range of values reported in tropical forests in the Amazon and Southeast Asia, with annual mortality rates ranging between 1% and 2% per year in unexplored natural tropical forests (Swaine et al., 1987), with values generally higher for recently harvested forests and decreasing over time (Dionisio et al., 2017; Dionisio et al., 2018). It is expected mortality rate of individuals lower than 20% in forests under silvicultural treatments. For example, Neves et al. (2019) reported mortality rates of individuals of commercial species ranging from 3% to 10% per year in forests under different silvicultural treatments at the Jari company 11 years after harvest. Das Chagas et al. (2012) and Gomes et al. (2010) reported mortality rates of 19% and 14% of planted individuals in logging gaps five and one year after harvesting, respectively. The highest mortality rates are observed during the first period of two to seven years after RIL (Shenkin et al., 2015; Dionisio et al., 2018), and the mortality rates stabilize afterwards, between 5 years and 10 years (Dionisio et al., 2018, 2017; Sist et al., 2003) or after 15 years post-harvest (Avila et al., 2017).

It is expected over time after RIL the opening of new canopy gaps by the tree fall of remaining trees. According Dionisio et al. (2017) and Sist et al. (2003), the mortality rate of remaining trees is higher in the first five years after logging and its effects remain up to 10 years. These new gaps could also be used in the application of post-harvesting silvicultural treatments, after all, there is the entire structure of the RIL, such as the drag roads, optimizing the species conservation and the timber production.

EP presented a basal area 13 times greater or 92% larger than the standard procedures of RIL, which is a positive effect of the treatment of *T. glauca* in logging gaps. These results were only possible due to the increase in planting density. Neves et al. (2019) also observed that the enrichment with commercial species on logging gaps by the company Jari, significantly increased the basal area of individuals. The authors reinforce that these treatments bring positive results to achieve future more sustainable cutting cycles in the Brazilian Amazon.

Light intensity had also positive influence over the increase growth in diameter. The evolutionary strategy of light-demanding species, such as *T. glauca*, consists of a greater investment in secondary growth (diameter) than primary growth (height), due to the photosynthetically active radiation that reaches the forest floor. Such process becomes more intense as it increases the canopy opening through disturbances caused by human activities such as selective logging (Jardim et al., 2007; Reis et al., 2014) and silvicultural treatments (Gomes et al., 2010; Neves et al., 2019; Schwartz et al., 2017b, 2013; Vieira et al., 2018).

Radiation is the main limiting factor for plant survival, so it determines the plant's survival strategy in a forest (Begon et al., 2009; Odum, 2006). Light-demanding species, such as *T. glauca*, present better development in environments with greater sunlight incidence, as was found in the current study. The PAI of EP and crown exposure class number three (CEC 3) performed better due to the high mortality of the other planted species (Neves et al., 2019; Schwartz et al., 2013), diminishing competition, allied to the fact that there was the tending in these gaps. As in TNER there is low mortality (Neves et al., 2019; Schwartz et al., 2013), there is a greater number of natural regeneration competing in the area, so this justifies its lower growth in diameter compared to the EP, but is needed an evaluation of others factors as growth in height for example.

Forest disturbances which result in canopy logging gaps, can be used as an effective way to conserve rare tree species (low density of individuals) and / or those with low natural regeneration and slow growth (Neves et al., 2019). According to Schwartz and Lopes ( 2015) increasing the density of individuals of rare species in logging gaps can function as an artificial refuge for endangered species, maintaining their genetic diversity. This is possible through assisted densification (artificial increase in the number of individuals per unit area of tree species in their own natural habitats), a procedure that can help to ensure the third cutting cycle (Dionisio et al. (2017).

Successful enrichment planting in logging gaps confirms the results found in other experiments worldwide with enrichment planting in gaps (Doucet et al., 2009; Gomes et al., 2019, 2010; Lopes et al., 2008; Neves et al., 2019; Quédraogo et al., 2014; Schwartz et al., 2013; Taffarel et al., 2014; Vieira et al., 2018). These studies corroborate the efficiency of enrichment planting in logging gaps, which comes as a viable silvicultural alternative for managing tropical forests. Regarding the silvicultural treatment, TNER presented the highest cost-benefit relation (Schwartz et al., 2016), so it can be widely applied under low cost in managed forests rich in natural regeneration of commercial species, as the case of the study area in the Jari's managed forests.

Individuals with some lateral light and 10–90% overhead light (2 and 3 crown exposure class) of the treatments where tending was applied (TNER and EP) reached the fourth diameter class (15-20 cm) and presented the highest PAI (cm year$^{-1}$). SRIL and the first crown exposure class (CEC 1) had no individuals above third diameter class (10-15 cm) and presented the lowest means of PAI (cm year$^{-1}$), this was expected because *T. glauca* is a light-demanding specie. This positive effect reinforces the importance of improving post-harvesting silvicultural treatments in forest management plans. Besides this, its positive outcomes can be expanded and tested in species of the same ecological group. For example, species of the same ecological group subjected to TNER and EP treatments allied to better sunlight incidence in canopy logging gaps could shorten the time required to recover losses caused by RIL (Neves et al., 2019) and help to mitigate the delay in several tropical forests to recover harvested stock (Hu et al., 2020; Shima et al., 2018).

The dominance of *T. glauca* in EP treatment (0.43 m² ha$^{-1}$) is four times greater than dominance of SRIL, TNER (0.21 m² ha$^{-1}$) is twice than SRIL (0.10 m² ha$^{-1}$). But in EP, *T. glauca* was planted with only four other species having a high density in the gap, while in the other treatments, its density was much lower. Schwartz et al. (2016) found the best cost-benefit relation for TNER, but the authors considered a set of species in their study, which included some slow-growth species. In this study we focused on the light-demanding species *T. glauca*, which presented a high silvicultural performance.

## 5. Conclusions

*Tachigali glauca* presented better survival and growth in the highest crown exposure classes and in canopy logging gaps under enrichment planting treatment in comparisons to lowest crown exposure classes and in gaps under standard procedures of reduced impact logging treatment.

## Acknowledgements

We acknowledge Jari Florestal SA for a very productive partnership, especially to Viviane de Souza Nogueira, Isael Araújo Costa, and all field assistants and technicians engaged in different phases of the experiment. The first author is grateful to Conselho Nacional de Desenvolvimento Científico e Tecnológico (140941/2016-9) on his PhD Fellowship.

## 6. References

Adenesky-Filho, E., Maçaneiro, J.P., Vitorino, M.D., 2017. How to select potential species for ecological restoration of rain forest – Southern Brazil. Appl. Ecol. Environ. Res. 15, 1671–1684. https://doi.org/10.15666/aeer/1503_16711684

Avila, A.L. de, Schwartz, G., Ruschel, A.R., Lopes, J. do C., Silva, J.N.M., Carvalho, J.O.P. de, Dormann, C.F., Mazzei, L., Soares, M.H.M., Bauhus, J., 2017. Recruitment, growth and recovery of commercial tree species over 30 years following logging and thinning in a tropical rain forest. For. Ecol. Manage. 385, 225–235. https://doi.org/10.1016/J.FORECO.2016.11.039

Azevedo, C.P. De, 2006. Dinâmica de florestas submetidas a manejo na Amazônia Oriental: experimentação e simulação.

Begon, M., Townsend, C.R., Harper, J.L., 2009. Ecologia: de indivíduos a ecossistemas.

Bladon, K.D., Lieffers, V.J., Silins, U., Landhäusser, S.M., Blenis, P. V., 2008. Elevated mortality of residual trees following structural retention harvesting in boreal mixedwoods. For. Chron. 84, 70–75. https://doi.org/10.5558/tfc84070-1

Buajan, S., Liu, J.F., He, Z.S., Feng, X.P., Muhammad, A., 2018. Effects of gap size and locations on the regeneration of castanopsis kawakamii in a subtropical natural forest, China. J. Trop. For. Sci. 30, 39–48. https://doi.org/10.26525/jtfs2018.30.1.3948

Chaudhary, A., Burivalova, Z., Koh, L.P., Hellweg, S., 2016. Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. Sci. Rep. 6, 23954. https://doi.org/10.1038/srep23954

Clark, D.A., Clark, D.B., 1992. Life History Diversity of Canopy and Emergent Trees in a Neotropical Rain Forest. Ecol. Monogr. 62, 315–344. https://doi.org/10.2307/2937114

Das Chagas, R.S., Gomes, J.M.Ê., De Carvalho, J.O.P., Ferreira, J.E.R., 2012. Sobrevivência e crescimento de plântulas de Manilkara huberi Chevalier durante cinco anos em clareiras causadas pela exploração de impacto reduzido na Amazônia brasileira. Sci. For. Sci. 40, 417–424.

Dauber, E., Fredericksen, T.S., Peña, M., 2005. Sustainability of timber harvesting in Bolivian tropical forests. For. Ecol. Manage. 214, 294–304. https://doi.org/10.1016/J.FORECO.2005.04.019

Dionisio, L.F.S., Schwartz, G., Lopes, J. do C., Oliveira, F. de A., 2018. Growth, mortality, and recruitment of tree species in an Amazonian rainforest over 13 years of reduced impact logging. For. Ecol. Manage. 430, 150–156. https://doi.org/10.1016/J.FORECO.2018.08.024

Dionisio, L.F.S., Schwartz, G., Mazzei, L., Lopes, J. do C., Santos, G.G.A. dos, Oliveira, F. de A., 2017. Mortality of stocking commercial trees after reduced impact logging in eastern Amazonia. For. Ecol. Manage. 401, 1–7. https://doi.org/10.1016/j.foreco.2017.06.060

Doucet, J.-L., Kouadio, Y.L., Monticelli, D., Lejeune, P., 2009. Enrichment of logging gaps with moabi (Baillonella toxisperma Pierre) in a Central African rain forest. For. Ecol. Manage. 258, 2407–2415. https://doi.org/10.1016/J.FORECO.2009.08.018

Foster, R.B., 1977. Tachigalia versicolor is a suicidal neotropical tree. Nature 268, 624–626. https://doi.org/10.1038/268624b0

Gomes, J.M., Carvalho, J.O.P. de, Silva, M.G. da, Nobre, D.N.V., Taffarel, M., Ferreira, J.E.R., Santos, R.N.J., 2010. Sobrevivência de espécies arbóreas plantadas em clareiras causadas pela colheita de madeira em uma floresta de terra firme no município de Paragominas na Amazônia brasileira. Acta Amaz. 40, 171–178. https://doi.org/10.1590/S0044-59672010000100022

Gomes, J.M., Silva, J.C.F. da, Vieira, S.B., Carvalho, J.O.P. de, Quadros, L.C.L., Queiroz, W.T. de, 2019. Schizolobium parahyba var. amazonicum (Huber ex Ducke) Barneby can be used in enrichment planting in gaps caused by logging in Amazonia. Ciência Florest. 29, 421–428. https://doi.org/10.5902/198050984793

Hautala, H., Vanha-Majamaa, I., 2006. Immediate tree uprooting after retention-felling in a coniferous boreal forest in Fennoscandia. Can. J. For. Res. 36, 3167–3172. https://doi.org/10.1139/x06-193

Hawthorne, W.D., Sheil, D., Agyeman, V.K., Abu Juam, M., Marshall, C.A.M., 2012. Logging scars in Ghanaian high forest: Towards improved models for sustainable production. For. Ecol. Manage. 271, 27–36. https://doi.org/10.1016/j.foreco.2012.01.036

Hu, J., Herbohn, J., Chazdon, R.L., Baynes, J., Vanclay, J., 2020. Silvicultural treatment effects on commercial timber volume and functional composition of a selectively logged Australian tropical forest over 48 years. For. Ecol. Manage. 457, 117690. https://doi.org/10.1016/j.foreco.2019.117690

Inada, T., Hardiwitono, S., Purnomo, S., Putra, I.B.W.., Kitajima, K., Kanzaki, M., 2017. Dynamics of forest regeneration following logging management in a bornea lowland dipterocarp forest. J. Trop. For. Sci. 29, 185–197.

Jardim, F.C. da S., 2015. Natural re generation in tropical forests. Rev. Ciências Agrar. - Amaz. J. Agric. Environ. Sci. 58, 105–113. https://doi.org/10.4322/rca.1676

Jardim, F.C. da S., Serrão, D.R., Nemer, T.C., 2007. Efeito de diferentes tamanhos de clareiras, sobre o crescimento e a mortalidade de espécies arbóreas, em Moju-PA 1. Acta Amaz. 37, 37–48.

Lavoie, S., Ruel, J.C., Bergeron, Y., Harvey, B.D., 2012. Windthrow after group and dispersed tree retention in eastern Canada. For. Ecol. Manage. 269, 158–167. https://doi.org/10.1016/j.foreco.2011.12.018

Lewis, S.L., Edwards, D.P., Galbraith, D., 2015. Increasing human dominance of tropical forests. Science (80-. ). 349, 827–832. https://doi.org/10.1126/science.aaa9932

Lewis, S.L., Maslin, M.A., 2015. Defining the Anthropocene. Nature 519, 171–180. https://doi.org/10.1038/nature14258

Lima, H.C., 2015. Lista do Brasil - Tachigali glauca Tul. [WWW Document]. URL http://floradobrasil.jbrj.gov.br/jabot/FichaPublicaTaxonUC/FichaPublicaTaxonUC.do?id=FB106814 (accessed 3.11.20).

Lopes De Souza, A., Marques De Medeiros, R., Silva Matos, L.M., Silva, K.R., Alves Côrrea, P., de Faria, F.N., 2014. Estratificação volumétrica por classes de ... Rev. Ár 38, 533–541.

Lopes, J. do C.A., Jennings, S.B., Matni, N.M., 2008. Planting mahogany in canopy gaps created by commercial harvesting. For. Ecol. Manage. 255, 300–307. https://doi.org/10.1016/J.FORECO.2007.09.051

Neves, R.L.P., Schwartz, G., Lopes, J. do C.A., Leão, F.M., 2019. Post-harvesting silvicultural treatments in canopy logging gaps: Medium-term responses of commercial tree species under tending and enrichment planting. For. Ecol. Manage. 451, 117521. https://doi.org/10.1016/j.foreco.2019.117521

Odum, E.P., 2006. Fundamentos de ecología.

Park, A., Joaquin Justiniano, M., Fredericksen, T.S., 2005. Natural regeneration and environmental relationships of tree species in logging gaps in a Bolivian tropical forest.

For. Ecol. Manage. 217, 147–157. https://doi.org/10.1016/J.FORECO.2005.05.056

Petrokofsky, G., Sist, P., Blanc, L., Doucet, J.-L., Finegan, B., Gourlet-Fleury, S., Healey, J.R., Livoreil, B., Nasi, R., Peña-Claros, M., Putz, F.E., Zhou, W., 2015. Comparative effectiveness of silvicultural interventions for increasing timber production and sustaining conservation values in natural tropical production forests. A systematic review protocol. Environ. Evid. 4, 8. https://doi.org/10.1186/s13750-015-0034-7

Piponiot, C., Rödig, E., Putz, F.E., Rutishauser, E., Sist, P., Ascarrunz, N., Blanc, L., Derroire, G., Descroix, L., Guedes, M.C., Coronado, E.H., Huth, A., Kanashiro, M., Licona, J.C., Mazzei, L., D'Oliveira, M.V.N., Peña-Claros, M., Rodney, K., Shenkin, A., De Souza, C.R., Vidal, E., West, T.A.P., Wortel, V., Hérault, B., 2019. Can timber provision from Amazonian production forests be sustainable? Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/ab195e

Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S., Griscom, B., Palmer, J., Zagt, R., 2012. Sustaining conservation values in selectively logged tropical forests: The attained and the attainable. Conserv. Lett. 5, 296–303. https://doi.org/10.1111/j.1755-263X.2012.00242.x

Quédraogo, D.Y., Fayolle, A., Daïnou, K., Demaret, C., Bourland, N., Lagoute, P., Doucet, J.L., 2014. Enrichment of logging gaps with a high conservation value species (Pericopsis elata) in a central African moist forest. Forests 5, 3031–3047. https://doi.org/10.3390/f5123031

Reis, L.P., Carvalho, J.O.P. de, Reis, P.C.M. dos, Gomes, J.M., Ruschel, A.R., Silva, M.G. da, 2014. Crescimento de mudas de *Parkia gigantocarpa* Ducke, em um sistema de enriquecimento em clareiras após a colheita de madeira. Ciência Florest. 24, 431–436. https://doi.org/10.5902/1980509814583

Reis, L.P., Ruschel, A.R., Coelho, A.A., Luz, A.S. da, Martins-da-Silva, R.C.V., 2010. Avaliação do potencial madeireiro na Floresta Nacional do Tapajós após 28 anos da exploração florestal. Pesqui. Florest. Bras. 30, 265–281. https://doi.org/10.4336/2010.pfb.30.64.265

Schwartz, G., Bais, A., Peña-Claros, M., Hoogstra-Klein, M., Mohren, G., Arts, B., 2016. Profitability of Silvicultural Treatments in Logging Gaps in the Brazilian Amazon. J. Trop. For. Sci. 28, 68–78.

Schwartz, G., Falkowski, V., Peña-Claros, M., 2017a. Natural regeneration of tree species in the Eastern Amazon: Short-term responses after reduced-impact logging. For. Ecol. Manage. 385, 97–103. https://doi.org/10.1016/J.FORECO.2016.11.036

Schwartz, G., Lopes, J. d. C.A., 2015. Logging in the brazilian amazon forest: The challenges of reaching sustainable future cutting cycles, in: Advances in Environmental Research. pp. 113–138.

Schwartz, G., Lopes, J.C.A., Mohren, G.M.J., Peña-Claros, M., 2013. Post-harvesting silvicultural treatments in logging gaps: A comparison between enrichment planting and tending of natural regeneration. For. Ecol. Manage. 293, 57–64. https://doi.org/10.1016/j.foreco.2012.12.040

Schwartz, G., Peña-Claros, M., Lopes, J.C.A., Mohren, G.M.J., Kanashiro, M., 2012. Mid-term effects of reduced-impact logging on the regeneration of seven tree commercial species in the Eastern Amazon. For. Ecol. Manage. 274, 116–125. https://doi.org/10.1016/j.foreco.2012.02.028

Schwartz, G., Pereira, P.C.G., Siviero, M.A., Pereira, J.F., Ruschel, A.R., Yared, J.A.G., 2017b. Enrichment planting in logging gaps with Schizolobium parahyba var. amazonicum (Huber ex Ducke) Barneby: A financially profitable alternative for degraded tropical forests in the Amazon. For. Ecol. Manage. 390, 166–172. https://doi.org/10.1016/J.FORECO.2017.01.031

SEMAS - Sisflora PA [WWW Document], n.d. URL https://monitoramento.semas.pa.gov.br/sisflora/relatorios.html (accessed 12.7.19).

Sheil, D., Burslem, D.F.R.P., Alder, D., 1995. The Interpretation and Misinterpretation of Mortality Rate Measures Author ( s ): Douglas Sheil , David F . R . P . Burslem , Denis Alder Published by : British Ecological Society Stable URL : http://www.jstor.org/stable/2261571. Br. Ecol. Soc. 83, 331–333. https://doi.org/10.2307/2261571

Shenkin, A., Bolker, B., Peña-Claros, M., Licona, J.C., Ascarrunz, N., Putz, F.E., 2018. Interactive effects of tree size, crown exposure and logging on drought-induced mortality. Philos. Trans. R. Soc. B Biol. Sci. 373. https://doi.org/10.1098/rstb.2018.0189

Shima, K., Yamada, T., Okuda, T., Fletcher, C., Kassim, A.R., 2018. Dynamics of Tree Species Diversity in Unlogged and Selectively Logged Malaysian Forests. Sci. Rep. 8, 1024. https://doi.org/10.1038/s41598-018-19250-z

Sist, P., Ferreira, F.N., 2007. Sustainability of reduced-impact logging in the Eastern Amazon. For. Ecol. Manage. 243, 199–209. https://doi.org/10.1016/J.FORECO.2007.02.014

Sist, P., Picard, N., Gourlet-Fleury, S., 2003. Sustainable cutting cycle and yields in a lowland mixed dipterocarp forest of Borneo. Ann. For. Sci 60, 803–814. https://doi.org/10.1051/forest:2003075

Souza, D.V., Carvalho, J.O.P. de, Mendes, F.D.S., Melo, L.D.O., Silva, J.N.M., Jardim, F.C. da S., 2015. Crescimento de espécies arbóreas em uma floresta natural de terra firme após a colheita de madeira e tratamentos silviculturais, no município de Paragominas, Pará, Brasil. Ciência Florest. 25, 873–883. https://doi.org/10.5902/1980509820585

Taffarel, M., Gomes, J.M., Carvalho, J.O.P. de, Melo, L. de O., Ferreira, J.E.R., 2014. Efeito da silvicultura pós-colheita na população de Chrysophyllum lucentifolium Cronquist (Goiabão) em uma floresta de terra firme na amazônia brasileira. Rev. Árvore 38, 1045–1054. https://doi.org/10.1590/S0100-67622014000600009

Valle, D., Phillips, P., Vidal, E., Schulze, M., Grogan, J., Sales, M., van Gardingen, P., 2007. Adaptation of a spatially explicit individual tree-based growth and yield model and long-term comparison between reduced-impact and conventional logging in eastern Amazonia, Brazil. For. Ecol. Manage. 243, 187–198. https://doi.org/10.1016/J.FORECO.2007.02.023

Van Rheenen, H.M.P.J.B., Boot, R.G.A., Werger, M.J.A., Ulloa Ulloa, M., 2004. Regeneration of timber trees in a logged tropical forest in North Bolivia. For. Ecol. Manage. 200, 39–48. https://doi.org/10.1016/j.foreco.2004.06.024

Vatraz, S., Olegário Pereira de Carvalho, J., Natalino Macedo Silva, J., da Cunha Castro, T., 2016. Efeito da exploração de impacto reduzido na dinâmica do crescimento de uma floresta natural. Sci. Florestalis 44, 261–271. https://doi.org/10.18671/scifor.v44n109.25

Vieira, S.B., de Carvalho, J.O.P., Gomes, J.M., da Silva, J.C.F., Ruschel, A.R., 2018. Is cedrela odorata L. A species with potential to be used in post-harvesting silviculture in the Brazilian amazonia? Cienc. Florest. 28, 1230–1238. https://doi.org/10.5902/1980509833361

Villegas, Z., Peña-Claros, M., Mostacedo, B., Alarcón, A., J.C.Licona, Leaño, C., Pariona, W., Choque, U., 2009. Silvicultural treatments enhance growth rates of future crop trees in a tropical dry forest. For. Ecol. Manage. 258, 971–977. https://doi.org/10.1016/J.FORECO.2008.10.031

## CONCLUSÕES E SUGESTÕES PARA PRÓXIMOS ESTUDOS

De um modo geral nós podemos perceber que os tratamentos silviculturais pós-colheita influenciam positivamente na sobrevivência e crescimento de espécies comerciais da Amazônia. Algumas implicações/potencialidades dos tratamentos pós-colheita em clareiras são:

- Aliar produção madeireira com a conservação de espécies de baixa densidade da Amazônia, principalmente as demandantes de luz;
- Os nossos resultados a médio prazo, demonstraram que podemos produzir e/ou conservar em um espaço de tempo menor que o que acontece naturalmente após o preconizado hoje na Exploração de Impacto Reduzido (EIR);
- Há a possibilidade de utilizarmos as clareiras como pomar de sementes e mudas;
- Há a possibilidade de uso dessas clareiras como zonas de produtos florestais não madeireiros;
- Conforme outro trabalho do mesmo projeto, foi mostrado que a EIR gera mortalidade em até 11 anos após a exploração, por isso há ainda clareiras que são resquícios de ações antrópicas que podem ser utilizadas, afinal já há toda a estrutura de ramais, pátios, clareiras etc, só precisa ser incorporado os tratamentos para que haja essa otimização do uso de clareiras provenientes da EIR;
- Apresenta potencial econômico, principalmente com espécies de crescimento rápido como o Paricá;
- Podemos aproveitar para criação de zonas como Banco Ativo de Germoplasma *in situ*, onde iremos dedicar às espécies de baixa densidade na área e/ou aquelas ameaçadas ou em risco;
- Na área de estudo temos ensaios que envolvem tanto a floresta primária quanto área degradada pela extração de cascalho, por exemplo, então estas técnicas podem ser estudadas para aplicação também em florestas secundárias e/ou áreas degradadas;
- A metodologia pode ser aplicada preferencialmente no período pré-chuvoso ou chuvoso, este fato irá favorecer aos trabalhadores que, geralmente, são demitidos no período de embargo.