Post-harvesting natural regeneration of *Theobroma subincanum* Mart. (Cupuí) (Malvaceae) inside and around logging gaps

Regeneração natural pós-colheita de Theobroma subincanum (Cupuí) (Malvaceae) Mart. dentro e ao redor de clareiras

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Abstract: The natural regeneration dynamics of *Theobroma subincanum* Mart. (Malvaceae) around canopy gaps created by tree felling due to selective logging was assessed. For that, an experiment located in the Experimental Field of Embrapa Eastern Amazon in Moju municipality, PA, Brazil was carried out. Nine logging gaps were selected, and four strips of 10 m x 50 m were installed in each of these gaps following the cardinal directions. These plots were split in five 10 m x 10 m plots numbered from 1 to 5 from the gap's border toward the forest. In plots 1, 3, and 5 and in the gap's center 2 m x 2 m plots were installed to monitor individuals ≥ 10 cm in height and < 5 cm in DBH. In most of the variation factors analized, *Theobroma subincanum* presented higher recruitment rate in period 1 (1998-2000), since the competition for light were less intense. In period 2 (2000-2010), under a possible lower luminosity and higher competition, RR was lower for all factors analyzed. In relation to gap size, *T. subincanum* presented the best results in RR around medium size gaps. The distance of 20 m in relation to the gap center, with intermediary sunlight condititions, *T. subincanum* presented higher RR. The population of *T. subincanum* had better performance under intermediate light conditions.

Keywords: Shade-tolerant species; Forest management; Reduced impact logging; Recruitment; Mortality.

Resumo: *A dinâmica de regeneração natural de Theobroma subincanum Mart. (Malvaceae) dentro e ao redor de clareiras criadas pela derrubada de árvores da exploração de impacto reduzido (EIR) foi avaliada. Para tanto, foi realizado um experimento localizado no Campo Experimental da Embrapa Amazônia Oriental no município de Moju, PA, Brasil. Após seleção de nove clareiras, foi traçado quatro faixas de 10 m x 50 m nas direções cardeais. Nas faixas foi subdividido cinco parcelas de 10 m x 10 m numeradas de 1 a 5, partindo da clareira em direção à floresta. Nas parcelas 1, 3 e 5 e no centro da clareira, parcelas de 2 m x 2 m foram instaladas para monitorar indivíduos de indivíduos ≥ 10 cm de altura e <5 cm no DAP. Na maioria dos fatores de variação analisados, Theobroma subincanum apresentou maior taxa de recrutamento no período 1 (1998-2000), uma vez que a competição por luz foi menos intensa. No período 2 (2000-2010), sob uma possível menor luminosidade e maior competição, o RR foi menor para todos os fatores analisados. Em relação ao tamanho das clareiras, T. subincanum apresentou os melhores resultados no RR em torno das clareiras médias. A distância de 20 m em relação ao centro da clareira, com condições intermediárias de insolação, T. subincanum apresentou maior RR. A população de T. subincanum teve melhor desempenho sob condições intermediárias de luz.*

Palavras-chave: *Espécies tolerantes à sombra; Manejo florestal; Exploração de impacto reduzido; Recrutamento; Mortalidade.*

INTRODUCTION

Species responses to natural disturbances have been used for a long time to guide and improve silvicultural systems (HART and KLEINMAN, 2018). The sustainability of the application of these systems in tropical forests for timber production is strongly supported by the natural regeneration of the harvested species, whose mechanisms have been investigated by foresters and ecologists (JARDIM, 2015, AGUIAR *et al*., 2019). Canopy gaps are a type of natural disturbance essential to promote the regeneration and dynamics of tropical forests. During logging activities, the tree felling for timber production creates canopy gaps (logging gaps) in similar ways how these gaps are naturally formed in non-logged forests. These antropic disturbance can have a role as important as the natural canopy gaps have for the regeneration and dynamics of tropical forests (BROKAW, 1982; MARCHESINI *et al*., 2009; DE CARVALHO *et al*., 2017). Besides this, it is expected that in forests under sustainable management disturbances cause micro-climate changes. Such disturbances are caused by the establishment of logging infrastructure as roads, skid trail, and log decks as well as tree cutting and logs dragging.

When the forest canopy is opened, due to natural causes or logging activities, more sunlight reaches the forest floor. This increase in sunlight incidence has a positive influence in growth, recruitment, and mortality of individuals that compose the after-logging remaining communities (SCHWARTZ *et al*., 2014; DARRIGO *et al*., 2016; DE AVILA *et al*., 2017; DIONISIO *et al*., 2018).

According to the resources partitioning hypothesis, the canopy gaps provide a gradient of conditions and resources for seedlings and saplings of tree species from its center towards the borders (RICKLEFS, 1977; DENSLOW, 1980). Logging gap center offers high amounts of sunlight while in borders the light availability is substantially lower. The resources partitioning suggests that different tree species can regenerate towards a resources gradient inside canopy gaps based on their ecological features, which creates the possibility of co-existence among tree species belonging to different ecological groups inside or around canopy gaps (DENSLOW, 1980; ZHANG *et al*., 2013, NEVES *et al*., 2019).

The size of a canopy gap is determined by various factors such as: disturbance magnitude, felled tree size, felling direction, and number of fallen neighboring due to the harvested tree. The community of tree species inside and around a canopy gap is directly affect by the canopy gap size. This will determine the regeneration community that will develop, as a response to selective pressures and competition, since the different species present different responses in growth, according to their genetic background, ecological features, and response capacity to variable light availability (ALMEIDA and JARDIM, 2012).

Theobroma subincanum Mart., commonly known in Eastern Amazon as *cupuí*, is a fruit tree species native from the Amazon region. Its geographical distribution spreads out in almost all the biome. The species' fruits, although having lower economic importance than *T. cacao* (cocoa) and *T. grandiflorum* (cupuaçu), are consumed fresh or as juice by the local populations (CAVALCANTE, 2010). *T. subincanum* belongs to the family Malvaceae and it is normally found in *terra firme* highland forests, and its timber can be used in rustic buildings (GAMA *et al*., 2003). An economic use of this species can increase the alternative of uses of forest resources and aggregate value to the managed forests through the management and trading of the *T. subincanum* timber and non-timber products.

The knowledge on growing of tree species, mainly those with economic importance, is fundamental for the adequate management of production forests. Studies on population dynamics provide information about the species stability, rates of growth, recruitment, and mortality of the population, as well as the relations of the species in the forest community (MARTINS *et al*., 2018). The regeneration, recruitment and mortality medium-term effects of remnant *T. subincanum* trees, inside and around canopy logging gaps, were assessed in an eastern Amazon tropical forest, submitted to reduced impact logging 12 years early. The present study aimed to respond the following questions: (a) Does the light gradient between the interval of gap center and the forest understory affect the recruitment, mortality, and regeneration of *T. subincanum*? (b) Are the recruitment, mortality, and regeneration rate influenced over time after logging and by canopy gap size?

MATERIALS AND METHODS

Study area

The experiment was carried out in the Experimental Field of Moju. The area belongs to Embrapa Eastern Amazon and it is located at Km 30 of the PA 150 highway, municipality of Moju, Pará state, Brazil (latitudes 2°07’30”S to 2°12’06”S and longitudes 48°46’57”W to 48°48’30”W). The region’s climate is Ami (warm and humid), according to the Köppen classification, annual pluviometric precipitation is irregularly distributed and varies from 2,000 to 3,000 mm. The average relative humidity is 85%, with monthly average temperatures of e 21 ºC and 33 ºC (LOPES *et al*., 2001).

The study area’s relief is plain, with slopes of 3%, and the most common soils are Distrofic Yellow Latosols, with different textures. There are also Red-Yellow Podzols, Gley low humid and Plintossols. The native vegetation is mainly Ombrophilous Dense Forest, where there are trees with 25-35 m in height and understory palms (LOPES *et al*., 2001).

Experimental design

The experiment about the influence of logging gaps on the natural regeneration of *Theobroma subincanum* was established in 1998, one year after the primary forest had been harvested under techniques of reduced impact logging (RIL). Nine logging gaps opened by tree felling due to RIL were selected and their areas were calculated by the ellipse formula (Figure 1). These areas varied from 231 to 748 m^2, where logging gaps were divided in three size classes: small (200 – 400 m^2), medium (401 - 600 m^2), and large gaps (> 600 m^2). Three logging gaps were selected for each size class.

In each logging gap four 10 x 50 m strips were set. Each of the four strips started in logging gap's border towards the forest and directed to the cardinal points (North, South, East, and West). Moreover, each strip was divided in five 10 x 10 m permanent plots (Figure 1).

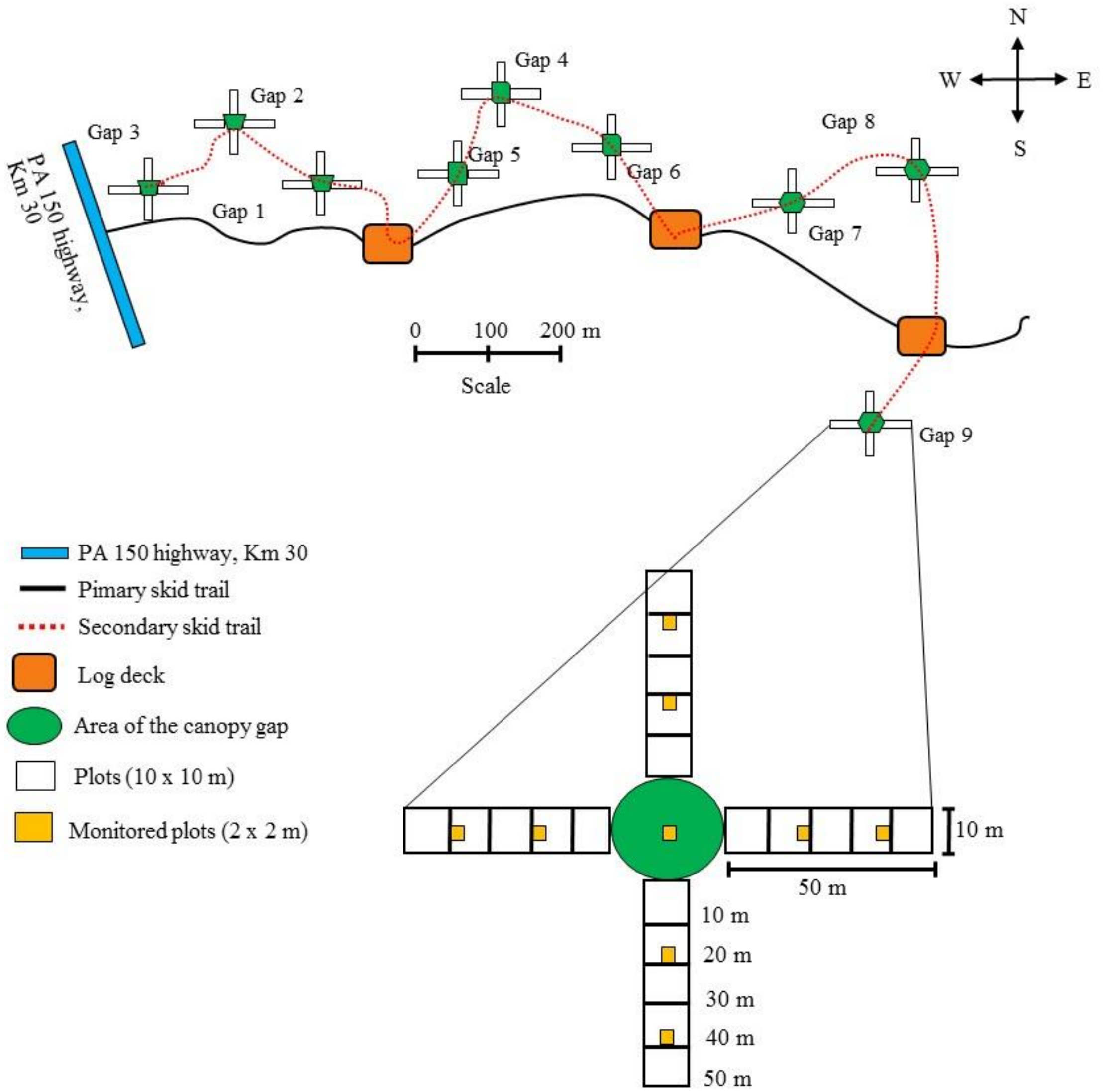

Figure 1. The nine selected logging gaps and a stretch of the four strips s*et al*ong to the cardinal points and divided in five sampling plots of 10, 20, 30, 40 e 50 m of distance from the canopy gaps' border for the monitoring of *Theobroma subincanum* individuals ≥ 5 cm in DBH after reduced impact logging in the Experimental Field of Moju, Eastern Amazon, Brazil.

After installing permanent plots, individuals of *T. subincanum* with DBH ≥ 5 cm were identified and measured during the years of 1998, 1999, 2000, 2001, 2007, and 2010, totaling six measurements in 12 years of monitoring (Table 1). The choice of *T. subincanum* was based on the fact that the species is highly representative in the Amazon, because of the following features: a) wide geographical distribution in almost all the Amazon; and b) shade-tolerant species, characteristic shared by most of tree species in this biome (Nascimento and Carvalho, 2012). In addition, *T. subincanum* has the commercial potential of producing timber and fruits.

In the plots of the center, 20 m and 40 m from the canopy gaps' border, were established 2 m x 2 m subplots. In each one of these subplots all individuals ≥ 10 cm in height and < 5 cm in DBH were measured in height. The diameter of all individuals ≥ 5 cm in DBH was also measured in the years of 1998, 1999, 2000, 2001, 2007, and 2010, totaling 12 years of monitoring (Table 1).

Table 1. Measurement years, time after reduced impact logging (RIL), number of logging gaps, and number of *Theobroma subincanum* individuals < 5 cm in DBH sampled in a managed forest in the Experimental Field of Moju, Eastern Amazon, Brazil.

Years of measurement/re-measurement	Time after RIL (years)	Number of logging gaps	Number of individuals
1998-1999	1	9	60
1998-2000	2	9	57
1998-2001	3	9	212
1998-2007	9	9	71
1998-2010	12	9	26

Data analysis

The population dynamics of *T. subincanum* was analyzed in order to determine recruitment and mortality of individuals ≥ 10 cm in height and DBH < 5 cm. These variables were evaluated in relation to gap size (small, medium, and large); in gap center and 20 and 40 m distant from the gap' border in cardinal directions; and in the monitoring period (1, 2, 3, 9, and 12 years). Post-logging density of individuals was obtained for the nine gaps. In this way, the rates of recruitment, mortality, and regeneration of the remnant individuals were calculated for the period of 12 years through the below equations respectively:

Recruitment rate (%)

Recruitment rate was calculated by formula (1):

$$R(\%) = (n/A_0) \text{ x } 100 \qquad (1)$$

Where: R(%) = recruitment rate (in percentage), n = number of individuals recruited at the end of the period; A_0 = number of individuals alive at the beginning of monitoring.

Mortality rate (%)

Mortality rate was calculated by formula (2):

$$M(\%) = (m/A_0) \text{ x } 100 \qquad (2)$$

Where: M(%) = mortalidade rate (in percentage), m= number of individuals dead at the end of the monitoring period; and A_0 = number of individuals alive at the beginning of monitoring.

Regeneration rate

The regeneration rate was calculated calculated according Jardim (1986), which expresses possible flutuactions in the absolute density of species, group of species, or even the forest. For its calculation, equation 3 was used:

$$RG = \left[\left(\frac{A_1}{A_0}\right) - 1\right] \text{ x } 100 \qquad (3)$$

Where: RG = natural regeneration rate; A_1 = final absolute density; and A_2 = initial absolute density.

Data were analyzed through the repeated measures Analysis of Variance (ANOVA) in a Generalized Linear Model (GLM), for the variables “gap size” (small, medium, and large) and the experiment period (12 years) on the dependent variables: Natural recruitment, mortality and regeneration rate. In cases of significant differences between treatments, the post-hoc Tukey test was used to compare means. The analyses were run in the statistical software R, version 3.5.1 (R Development Core Team, 2018), at $p < 0.05$ of probability.

RESULTS

Recruitment, mortality, and regeneration in relation to the monitoring period

There was a significant difference for the rates of regeneration (p = 0.004), recruitment (p = 0.001), and mortality (p = 0.041). In relation to the after-logging period, the variables were influenced by the canopy closure along 12 years of monitoring (Figure 2). One year after logging, the population of *Theobroma subincanum* present a regeneration rate of zero, since the both recruitment rate and mortality rate were 15%. In the second and third year, *T. subincanum* presented a positive regeneration, due to the recruitment rate of 138.3% higher than the mortality rate of 11.7%. Nine years after logging, the density of individuals decreased, the recruitment was lower than mortality (Figure 2).

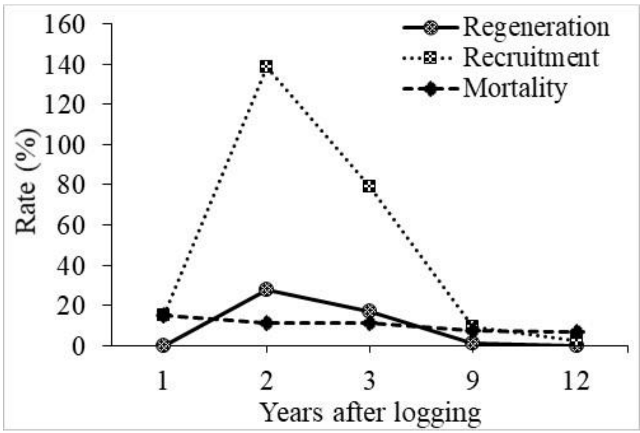

Figure 2. Natural regeneration, recruitment, and mortality rate of *Theobroma subincanum* individuals < 5 cm in DBH sampled in a managed forest in the Experimental Field of Moju, Eastern Amazon, Brazil.

Recrutiment rate presented difference between 2, 3, and 9 years in relation to 1 and 12 years. However, the first and last periods presented lower average values. Regarding recruitment, 12 years presented the lowest average value with no difference between this period and the others, 2, 3, and 9 years were different of the first year. For mortality, there was no difference among 2, 3, and 9 years in relation to 1 and 12 years, but they presented within difference, where the first year had the highest mean. According to the results, *T. subincanum* had the best development in intermediate conditions. The best average values of regeneration rate was observed in 2 and 3 years after logging.

Rate of regeneration, recruitment, and mortality in relation to gap size

Concerning the regeneration, in relation to the gap size show that in small gaps the population of *T. subincanum*, in 1, 9, and 12 years presented a negative regeneration rate, due to recruitment lower than mortality. In 2 and 3 years the population incresed. On the other hand, medium gaps presented positive regeneration rate in the nine first years and negative in 12 years after logging. In large gaps the regeneration rate was negative in the first and last period and positive in 2, 3, and 9 years after logging. All gap sizes ananlyzes during 2, 3, and 9 years had positive regeneration rates and negative 12 years after longging (Figure 3).

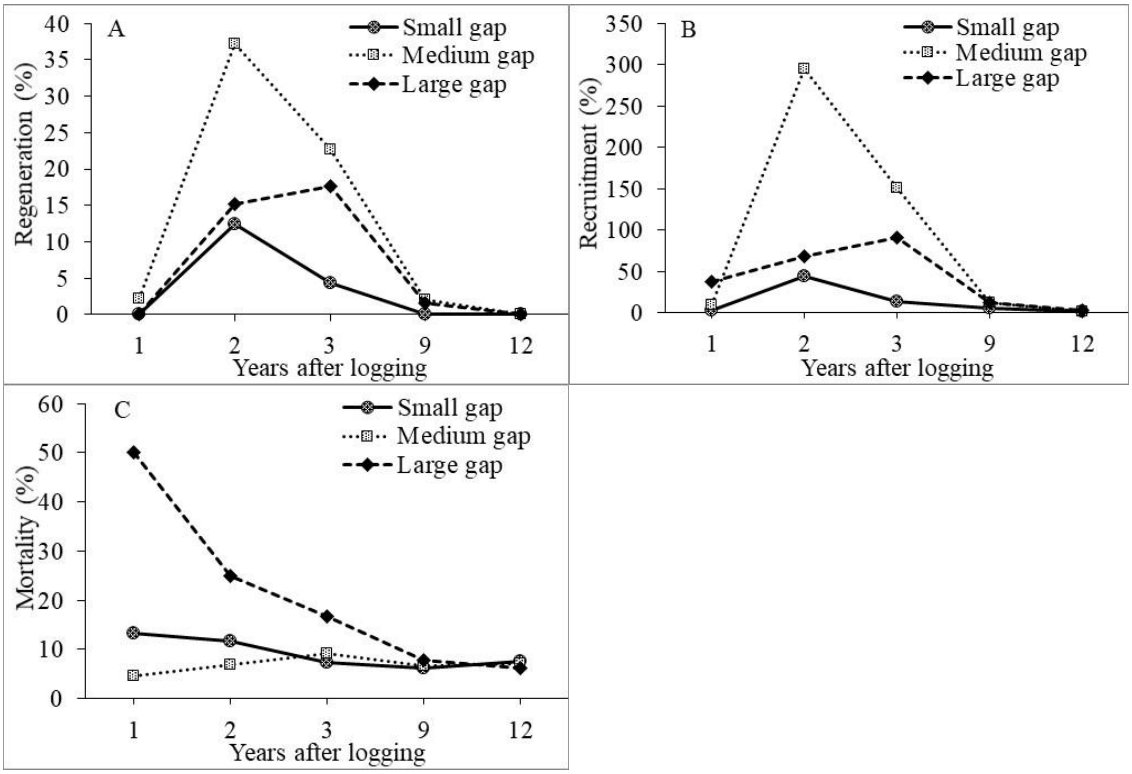

Figure 3. Rates of regeneration, recruitment, and mortality in relation to gap size in a managed forest after reduced impact logging in the Experimental Field of Moju, Eastern Amazon, Brazil.

In the small and medium gaps the regeneration rate was higher 2 years after logging and in the large gaps the regeneration rate was higher after 3 years. However, the medium gap presented the highest average value of the regeneration rate, 37.13% in relation to the other two gap sizes. In intermediate conditions, the population of *T. subincanum* presents the highest regeneration.

Rate of regeneration, recruitment, and mortality of *Theobroma subincanum* in relation to the distance from gap center

The recruitment rate in the two first periods (1998-1999) and (1998-2000) in the gap's center was zero, so there was a dynamic balance of the population, between recruitment and mortality (Figure 4). At the distance of 20 m in relation to the gap's border, in the nine first years, the regeneration rate was positive, with higher recruitment than mortality. Twelve years after logging the regeneration rate was negative. At the distance of 40 m in relation to the gap's border, in the first and twelve years the regeneration rate was negative and the the other periods (2, 3, and 9 years) the rate was positive. In the gap's center, the regneration rate was negative as well as the other distances. This corroborates other results with lower luminosity with lower regeneration.

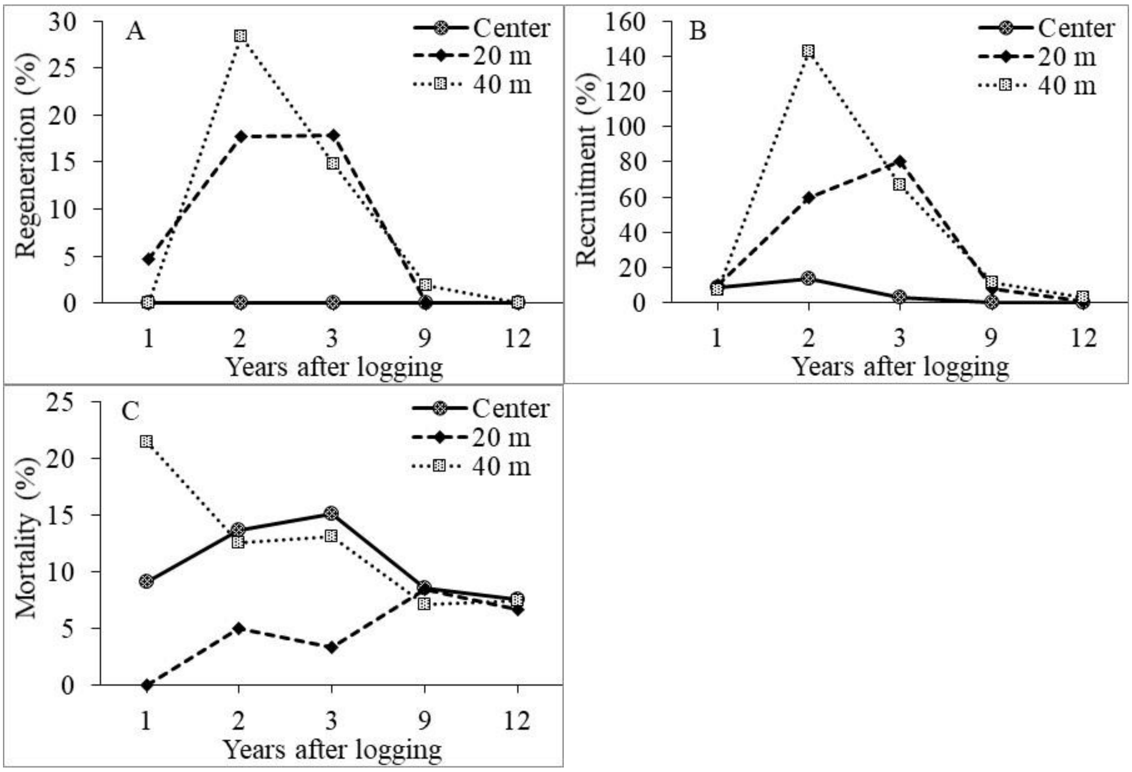

Figure 4. Rates of regeneration, recruitment, and mortality of *Theobroma subincanum* in relation to the gap's center, 20 m, and 40 m from the gap's border toward the forest in a managed forest after reduced impact logging (RIL) in the Experimental Field of Moju, Eastern Amazon, Brazil.

DISCUSSION

Theobroma subincanum is a very slow-growing species and, when seedlings and sapling, occupies the lower and medium forest strata (AZEVEDO *et al*., 2008), up to find ideal luminosity conditions to grow and attain the canopy. During the first year after logging, where the luminosity conditions are highest, *T. subincanum* did not find the best conditions for its establishment. At the end of 12 yeras of monitoring, the forest became better structured with consequent higher intra and inter-specific competition for light, which results in higher mortality in the periods 1 and 5. Concerning periods 2, 3 and 4, the species found the best conditions of luminosity and competition for its establhisment, which resulted in higher recruitment.

The medium-term responses on mortality rates to *T. subincanum* are similar to the values founded in Amazon tropical rainforest, as the case of the study of Dionisio *et al*. (2017; 2018), where mortality is generally higher for recently harvested forests and tend to decrease over time (BLADON *et al*., 2008; HAUTALA and VANHA-MAJAMAA, 2006; LAVOIE *et al*., 2012), stabilizing between 5 to 10 years (SIST *et al*., 2003). Neves *et al*. (2020) comparing medium-term responses of post-harvesting silvicultural treatments in canopy logging gaps founded similar results to standard procedures of reduced-impact logging (RIL), which this treatment served as the control treatment, they reported mortality rates 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% five and one year after harvesting, respectively.

Medium size gaps presented higher regeneration rate, showing the *T. subincanum* better develops in intermediate conditions of light. In large gaps, the recruitment rate, even though with no statistical differences from the small gaps, presented higher average value. This is because the ecological group belonging the species benefits from the high luminosity conditions provided by logging gaps (GOMES *et al*, 2010).

Environmental conditions in the plots vary as the sunlight decreased from the gap's center toward the forest, which reflecte din the population of *T. subincanum* (VITOUSEK; DENSLOW, 1986). Based on the Tukey test at 5% of probability, there was no significant difference between regeneration and recruitment rates for the distances of 20 m e 40 m, but only between the means of the gap's center and 20 m of distance. In terms of mortality, it did no present statistical difference between the gap's center and 20 m, but the distance of 40 m was statistically different from the other two.

The distance of 20 m in relations to the gap center, where the luminosity conditions are intermediary, *T. subincanum* presented the highest average values of RR. This is an indication that the species has its best growing performance under intermediate conditions of light.

In a study carried out by Vieira and Gandolfi (2006) in the municipality of Iracemápolis, SP, Brazil, with the species *Centrolobium tomentosum* (Fabaceae), *Cordia myxa* (Boraginaceae), and *Melia azedarach* (Meliaceae), observed a decrease in the number of individuals and species in relation to the increase in height toward the ecological succession process. This decrease, however, can be a consequence of intra and inter-specific competition, seedlings predation, intolerance to the environmental conditions. With the canopy closure between 9 and 12 years after reduced impact logging (RIL), the solar radiation insidence inside the forest decreased, which resulted in mortality increase. This result can be an indication of the shade-intolerance of *T. subincanum*, but it can also be related to the strong inter-specific competition, mainly by light, water, and nutrients, which results high densities of individuals inside logging gaps (NEMER and JARDIM, 2004).

Structural features of logging gaps, such as size and shape, work as additional factors in the building of habitats for the different species colonization (DENSLOW; HARTSHORN, 1994). Thus the different areas of the logging gap receiving sunlight will determine the mosaics that will further compose the forest (WHITMORE, 1978). In this sense, gap size has influence in the species composition and in the way how different species colonize it (WHITMORE, 1996). Therefore, the gap's structure works as the main factor to determine microclimate and substrate conditions (DENSLOW; HARTSHORN, 1994).

In general, what may explain the higher rates of regeneration and recruitment in the first 3 years after logging is the fact that there is a greater incidence of light in the logging gaps. Studies show that increasing the availability of light promotes rapid growth in logging gaps and stimulate the natural regeneration of native species (GOMES *et al*., 2019; QUÉDRAOGO *et al*., 2014; TAFFAREL *et al*., 2014; VIEIRA *et al*., 2018). This fact is reinforced according to the regeneration and recruitment rates at 9 and 12 years old, in which there is less light incidence due to the logging gaps having already closed their canopy. An alternative to continue promoting regeneration and recruitment in the shortest possible time is the use of post-harvest silvicultural treatments in canopy logging gaps (LOPES *et al*., 2008; SCHWARTZ *et al*., 2013; NEVES *et al*., 2019).

CONCLUSIONS

In most of the variation factors analized, *Theobroma subincanum* presented higher recruitment rate in period 1 (1998-2000), since the competition for light were less intense. In period 2 (2000-2010), under a possible lower luminosity and higher competition, RR was lower for all factors analyzed. In relation to gap size, *T. subincanum* presented the best results in RR around medium size gaps. The distance of 20 m in relation to the gap center, with intermediary sunlight condititions, *T. subincanum* presented higher RR. The population of *T. subincanum* had better performance under intermediate light conditions.

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