



Responses in growth and dynamics of the shade-tolerant species *Theobroma subincanum* to logging gaps in the Eastern Amazon

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Abstract

Aim of study: To assess responses of the shade-tolerant species *Theobroma subincanum* in relation to canopy gaps created by reduced impact logging (RIL).

Materials and methods: A managed forest in the municipality of Moju, Pará state, Brazil, harvested in 1997 through RIL was monitored during 12 years (1998-2010). Nine logging gaps were selected and classified in small, medium, and large. Four 10 m x 50 m strips starting from the gap's border towards the forest and following the directions of cardinal points were installed. Each strip was divided in five 10 m x 10 m plots. Density, diameter distribution (DBH \geq 5 cm with intervals = 5 cm), and diameter growth were measured.

Main results: No significant changes in seedling density of *T. subincanum* were found, and its diameter distribution followed the reverse "J" shape during all monitoring time. *T. subincanum* presented diameter growth of 0.15 cm year⁻¹ with highest Periodic Annual Increment in diameter up to three years, and stabilization in nine years after RIL. The species responded to a growth gradient inversely proportional to the gap's border distance ($p = 0.001$) but not to gap size and plots direction in cardinal points around the gap.

Research highlights: Shade-tolerant species such as *T. subincanum* have sensible and positive growth responses to disturbances caused by RIL even when seedlings received low amounts of indirect sunlight. These positive responses should be considered in the management of production forests.

Key words: Ecological group; forest management; diameter distribution; reduced impact logging (RIL).

Authors' contributions: Original idea: FCSJ and NSLC. Study design: FCSJ. Data collection: FCSJ and NSLC. Data analysis: LFSJ, NSLC, and GS. Manuscript preparation and revisions: LFSJ, JMG, NSLC, and GS.

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Introduction

Forests under selective logging usually present higher dynamics than untouched forests, due to logging operations as infrastructure construction (roads, skid trails, and log decks) and tree cut and dragging (Yguel *et al.*, 2019). In forests under sustainable management, that includes techniques to minimize logging impacts, better conditions for growth of remnant stands based on the dynamics of individuals succession are often promoted.

Knowledge on replacement capacity of harvested stocks and tree growth at the individual and stand levels (Abiyu *et al.*, 2018) is fundamental for the adoption of forest management and conservation. This permits managers to have more precise control of cutting cycles according to the specific characteristics of each forest (Dionisio *et al.*, 2018), and also to plan forest activities for commercial production.

Canopy gaps originated from natural tree deaths normally occur as small scale disturbances, with an important role on forest regeneration and dynamics (Whitmore, 1989; Neves *et al.*, 2019). On the other hand, canopy gaps created by tree felling for harvesting, or logging gaps, are in average larger than canopy gaps created by natural disturbances. The forest environment alterations caused by logging gaps can modify the natural regeneration trajectory, growth, mortality, and recruitment of individuals that compose the forest community (Schwartz *et al.*, 2014; Darrigo *et al.*, 2016; Dionisio *et al.*, 2017).

Several variables determine the logging gap's size such as tree's size, tree felling direction, and number of neighbor trees fallen during cutting operations. Gap size differences result in substantial changes in selective pressure, competition, and spatial distribution over the regenerating individuals and species (Grogan *et al.*, 2008; Schwartz *et al.*, 2017). These individuals and species can present significant variation in growth, based on their genetic background and on the ecological alterations caused by logging, with more light entrance reaching the forest floor. The creation of logging gaps is one of the main factors to determine growth and survivorship of individuals from smaller diameter classes. So, growth of these individuals becomes a parameter to be taken into account in forest management, since it influences floristic composition and individuals' spatial distribution (Schwartz *et al.*, 2017).

Species responses to natural disturbances have been used for decades to support decision making in silvicultural systems. Small canopy gaps, as those formed by a branch fall, do not promote enough microclimatic conditions for the establishment of pioneer species. In small canopy gaps, shade-tolerant species normally fill the gap by branches side growing, growing of smaller individuals, and individuals belonging to the seedlings bank. On the other side, larger gaps offer better conditions for colonizers and pioneer species establishment. Shade-tolerant species can also take advantage of larger gaps, however, under such conditions they are usually outcompeted by pioneer and light-demanding species (Whitmore, 1989; Jardim, 2015).

Theobroma subincanum Mart., commonly known in the Brazilian Amazon as *cupuí*, is an important fruit species of the family Malvaceae (Alverson *et al.*, 1999; Whitlock *et al.*, 2000). The species is mainly geographically distributed in tropical forests from Mexico to Southern Amazon in *terra firme* forests (Rivas *et al.*, 2013; Dardengo *et al.*, 2016). *T. subincanum* presents aggregate spatial distribution and, as a shade-tolerant species, has a population structure continuous and descending over diameter classes (Jardim, 2015). Its

fruits present high food potential, they are consumed by local populations as fresh fruits or juice, and seeds are often used to prepare homemade chocolate. Fruits of *T. subincanum* also attract seed dispersers as mammals and birds. Besides its food and ecological importance, the wood of *T. subincanum* is used for rustic buildings. The economic use of this species can increase alternatives of forest resources use and aggregate value to the forest by the management and trade of its timber and non-timber products.

This study, therefore, had the objective to assess the effects of forest harvesting and logging gaps size on growth of seedlings belonging to a remnant population of *T. subincanum* in a forest monitored during 12 years after RIL in the Eastern Amazon.

Materials and methods

Study area

The experiment was carried out in the Experimental Field of Moju, belonging to Embrapa Eastern Amazon and located at Km 30 of the PA 150 highway, municipality of Moju, Pará state, Brazil, between the latitudes 2°07'30"S and 2°12'06"S and longitudes 48°46'57"W and 48°48'30"W. The region's climate is Ami (warm and humid), according to the Köppen classification (Alvares *et al.*, 2013). Annual rainfall varies from 2,000 to 3,000 mm, irregularly distributed and the average relative humidity is 85%, with monthly average temperatures from 21 °C to 33 °C. The relief is plain, with slopes of 3% where Distrofic Yellow Latosols are the most common soils in the area, in different textures there are also Red-Yellow Podzols, Gley low humid, and Plintossols. The original vegetation of the study area is Ombrophilous Dense Forest (IBGE, 2012).

Study design

The experiment about the influence of logging gaps on the dynamics of *Theobroma subincanum* was established in 1998, one year after the conserved forest had been harvested under techniques of reduced impact logging (RIL) in 1997. Nine logging gaps opened by tree felling due to RIL were selected, where a minimum distance of 150 m between them was kept as a buffer zone to avoid possible influences on each other. Gap's areas were calculated by the ellipse formula, and varied from 231 to 748 m². In addition, logging gaps were divided in three size classes: small (200 – 400 m²), medium (401 - 600 m²), and large gaps (>600 m²). Three logging gaps were selected in each size class.

Four 10 m x 50 m strips starting from the logging gap's border towards the forest were established around every logging gap. Each one of the four strips was

directed to the cardinal points North, South, East, and West. In addition, all strips were divided in five 10 m x 10 m permanent plots (Fig. 1).

After installing the permanent plots, individuals of *T. subincanum* with DBH \geq 5 cm were identified and measured during the years 1998, 1999, 2000, 2001, 2007, and 2010, totaling six measurements in 12 years of monitoring (Table 1).

Data analysis

Density (seedlings m⁻²) of *T. subincanum*, with the 10 x 10 m² plot as the sampling unit, was calculated in relation to the distances from the gap's border into the forest. Individuals of *T. subincanum* were divided in six diameter classes from DBH \geq 5 cm with intervals of 5 cm. The six diameter classes were: 5.0 – 9.9 cm

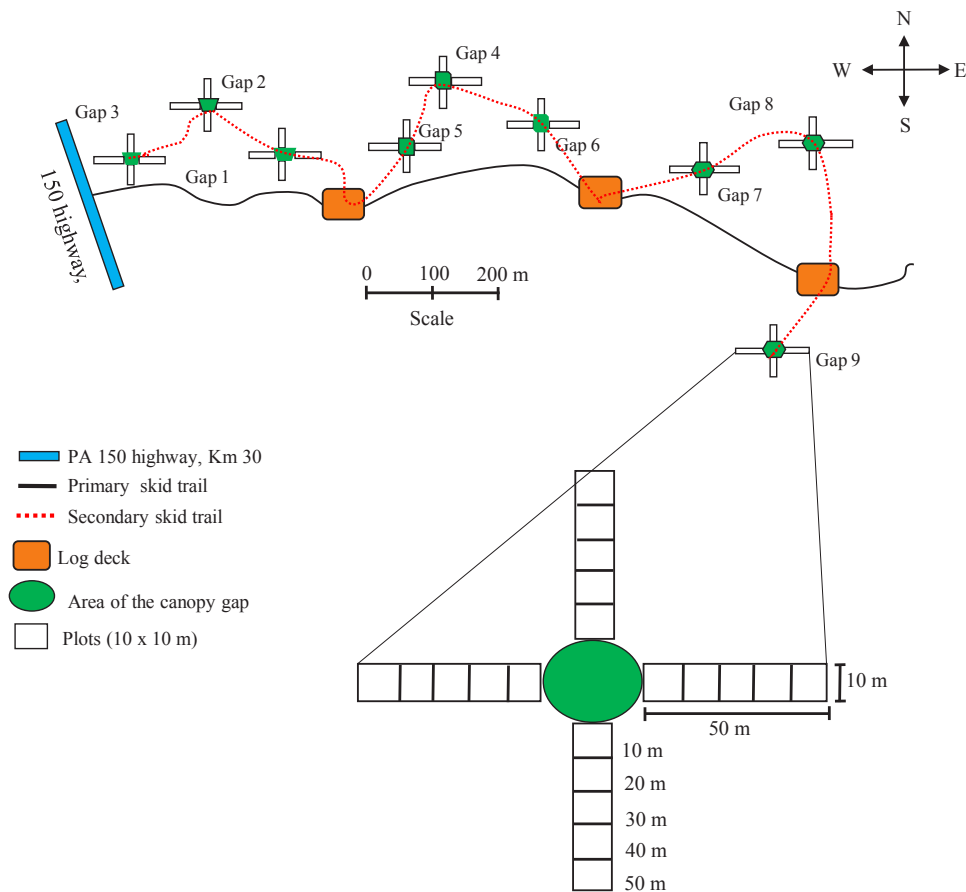


Figure 1. Stretch of the four strips set along to the cardinal points (North, South, East, and West) and divided in five sampling plots of 10, 20, 30, 40 e 50 m of distance from the canopy gaps' border for the monitoring of *Theobroma subincanum* individuals \geq 5 cm in DBH after reduced impact logging in the Experimental Field of Moju, Eastern Amazon, Brazil.

Table 1. Years of measurement and re-measurement after reduced impact logging (RIL), number of logging gaps, and number of *Theobroma subincanum* seedlings sampled in a managed forest in the Experimental Field of Moju, Eastern Amazon, Brazil

Years of measurement/ re-measurement	Years after RIL	Number of logging gaps	Number of seedlings
1998-1999	1	9	27
1998-2000	2	9	28
1998-2001	3	9	29
1998-2007	9	9	30
1998-2010	12	9	32

(1), 10.0 – 14.9 cm (2), 15.0 – 19.9 cm (3), 20.0 – 24.9 cm (4), 25.0 – 29.9 cm (5), and ≥ 30.0 cm (6). For comparisons, this distribution was done twice: in 1998 and 2010 (one year and 12 years after logging).

The diameter growth was calculated by the difference between diameters measured only in the alive trees along all five monitoring periods (1998-1999, 1998-2000, 1998-2001, 1998-2007, and 1998-2010), according to the formula $(DBH_{final} - DBH_{initial})/T_{(time)}$. From this measure, the Periodic Annual Increment in diameter (PAIdbh) was calculated.

The analysis of variance (ANOVA) was done through a Generalized Linear Model (GLM) for gap's size (small, medium, and large), distance in relation to the gap's border (plots far away 10, 20, 30, 40, and 50 m from the gap's border), and the time of experiment monitoring (12 years) on the dependent variable (PAIdbh). The data were analyzed through repeated measures ANOVA and, in case of significant differences among treatments, the post-hoc Tukey test was applied to compare means. All statistical analyses were run with the software R version 3.6.1 (R Development Core Team, 2019), at $p < 0.05$ of significance.

Results

Seedling density and diameter distribution of *Theobroma subincanum*

Seedling density in relation to the distance of the gap's border decreased up to 30 m from the gap's border, regardless the year after logging. The number of individuals per plot reduced from 7.00 at 10 m to 3.00 at 30 m from the gap's border. Density increased again at 40 m and 50 m after logging (Fig. 2).

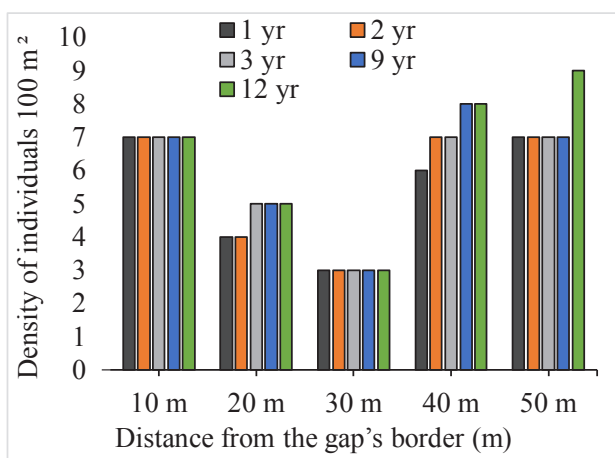


Figure 2. Seedling density of seedlings ≥ 5 cm in DBH of the species *Theobroma subincanum* in relation to seedlings' distances from the gap's border towards the forest in a managed forest after RIL in the Experimental Field of Moju, Eastern Amazon, Brazil.

In the first measurement after RIL (1998), the seedling density of *Theobroma subincanum* with $DBH \geq 5$ cm, regardless the treatment, was 15.00 seedlings ha^{-1} and in the last, 12 years after RIL (2010), was 17.78 seedlings ha^{-1} (Fig. 3). Although varying among diameter classes, the diameter distribution of *T. subincanum* maintained an increasing shape in the two first classes (5.0-9.9 and 10.0-14.9) and a decreasing shape in the third class forwards (15.0 cm) during the entire monitoring period (Fig. 3). The largest changes in the distribution of individuals were observed in the first class (decrease) and in the third and fourth class (increase).

PAIdbh in relation to distance from logging gap's border and time after RIL

There was a significant difference in the Periodic Annual Increment in diameter (PAIdbh) of *T. subincanum* in relation to the distance of the individual to the gap's border ($p = 0.001$). The shorter is distance of the individual from the gap's border the higher is its PAIdbh (Fig. 4). There was a significant difference in the two first years after RIL among all plot distances in relation to the gap's border (10, 20, 30, 40, and 50 m). The 10 m distance presented higher increment (0.75 $cm\ year^{-1}$, $F_{4,63} = 4.97$, $p = 0.002$) in the two first years. The year following RIL also influenced positively the seedlings growth ($p = 0.001$). PAIdbh was significantly higher in the first year after the application of RIL and decreased significantly from the second year after logging. From nine years after logging onwards, growth stagnated where no more differences in PAIdbh were observed in both plots distance from the gaps' border and time ($p = 0.161$). At the end of 12 years of monitoring, the seedlings had an average increase of 1.82 cm in diameter, which represented an average PAIdbh of 0.15 $cm\ year^{-1}$.

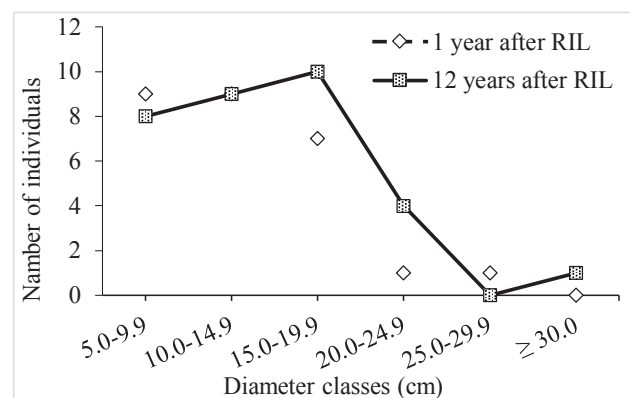


Figure 3. Diameter distribution of *Theobroma subincanum* from $DBH \geq 5$ cm and intervals of $DBH = 5$ cm one year and 12 years after reduced impact logging (RIL) in a managed forest after RIL in the Experimental Field of Moju, Eastern Amazon, Brazil.

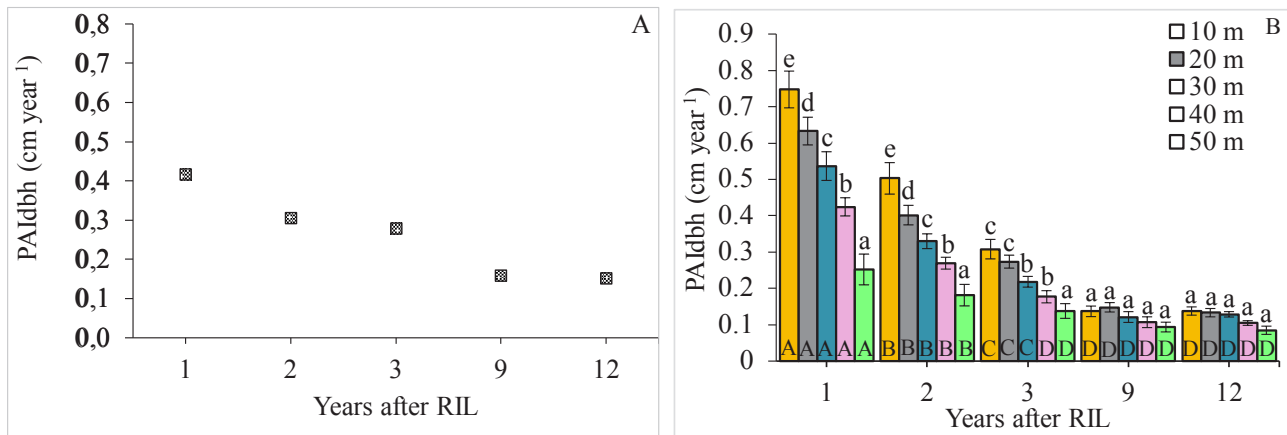


Figure 4. Mean of the Periodic Annual Increment in diameter (PAIdbh) of *Theobroma subincanum* along 12 years of monitoring following reduced impact logging (RIL) (A) and plots distances in relation to the gaps' border (B) in a managed forest after RIL in the Experimental Field of Moju, Eastern Amazon, Brazil. Means followed by the same letter do not differ statistically each other, lower cases indicate differences among distances in the same year while upper cases indicate differences in time in the same distance (ANOVA followed by the post-hoc Tukey test, $p < 5\%$).

PAIdbh in relation to gap size and plots direction in cardinal points

In relation to gap size, seedlings placed around small, medium, and large logging gaps did not present significant differences in PAIdbh ($p = 0.308$). Growth was higher during the three first years for all gap sizes (Fig. 5a). Seedlings around medium size gaps had higher PAIdbh in the two first years, however this was not statistically significant. Regarding cardinal points, there was no significant differences in PAIdbh ($p = 0.503$) in relation to each direction. Growth was highest in the first year after logging in all cardinal directions and started decreasing in response to canopy closing (Fig. 5b).

Discussion

Seedling density and diameter distribution of *Theobroma subincanum*

Seedling density of *Theobroma subincanum* had no relation with distances from the gap's border. The density of individuals reduced in the first 30 m and, from the distance of 40 m it increased again. This result shows that the distance from the gap's border had influence on *T. subincanum* growth (Fig. 4), but not on its density (Fig. 2).

The density of individuals of *T. subincanum* did not have any significant change during 12 years of monitoring (Fig. 3). A stable density indicates that recruitment

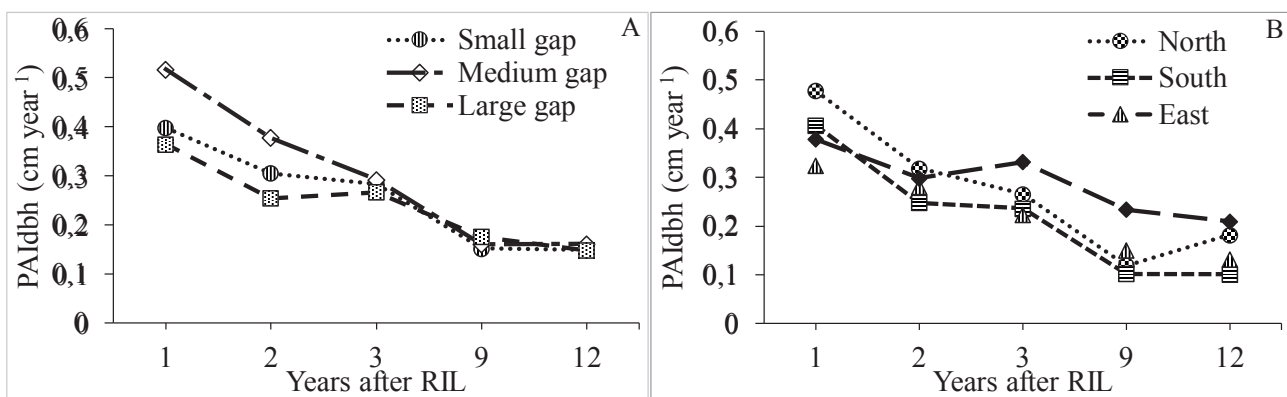


Figure 5. (a) Periodic Annual Increment in diameter (PAIdbh) in relation to gap size (small, medium, and large) and (b) Periodic Annual Increment in diameter (PAIdbh) in relation to cardinal points (North, South, East, West) of the species *Theobroma subincanum* in a managed forest after reduced impact logging (RIL) in the Experimental Field of Moju, Eastern Amazon, Brazil. Differences among gap size and cardinal points are not significant ($p > 0.05$) for all years after treatment.

and mortality rate were constant over time. Hence, the influence of logging gaps on *T. subincanum* was restricted to trees' growth and not to population dynamics, at least when considered individuals ≥ 5 cm in DBH. This is an indication that the species takes indirect advantage of canopy gaps caused by the fall of harvested trees.

The diameter distribution of *T. subincanum* in different periods showed the presence of seedlings in all classes, one and 12 years after logging, with no steep alteration along time. One year after logging, the number of individuals in the two first diameter classes (5.0-9.9 and 10.0-14.9) remained stable, distributed in a decreasing pattern from the third class forwards (15.0-19.9). Twelve years after logging, the number of individuals in class 5.0-9.9 diminished as a consequence of mortality and switch of individuals to upper diameter classes (Fig. 3). This distribution pattern is proper of shade-tolerant species. Although shade-tolerant species grow in conditions of close canopy and understory, they benefit from direct or indirect sunlight coming from canopy gaps, as well as direct light flecks that cross canopy and attain the soil (Jardim, 2015). Individuals of *T. subincanum* were distributed according to a reverse "J" shape, the most common distribution pattern of native tropical forests. This curve indicates a population dynamic balance of a shade-tolerant species, where most of the individuals are concentrated in smaller diameter classes.

PAIdbh in relation to distance from logging gap's border and time after RIL

In all analyzed plots, *T. subincanum* obtained higher growth in the first year of monitoring, which is related to higher availability of sun radiation reaching the forest floor. However, the longer is the plot distance from the border the lower is PAIdbh. According to Jardim (2015), shade-tolerant species benefit from the solar radiation coming from logging gaps, as well as small flecks of direct solar radiation coming from logging gaps or forest canopy. In studies carried out in the Tapajós National Forest, Eastern Amazon, Schwartz *et al.* (2012) observed that individuals of shade-tolerant species under total illumination obtained better growth rates than those under partial or with no illumination. Shade-tolerant species are sensible to low quantities of light, as even those plots far 40 and 50 m away from the gaps' border, two years after RIL, still presented statistical differences from each other. The difference in growth between the 40 and 50 m plots only disappeared in the third year after RIL (Fig. 4).

Theobroma subincanum stabilized its growth in diameter nine years after logging. According to Dionisio *et*

al. (2017, 2018) growth, mortality, and recruitment rates in managed forests under RIL in the Eastern Amazon stabilize between seven and eleven years after logging.

PAIdbh in relation to gap size and plots direction in cardinal points

The lack of difference in PAIdbh of *T. subincanum* when compared to gap size shows that small gaps, even when opened by branches fall, are sufficient to speed up growth of shade-tolerant species. Although the literature shows influence of gap size on species richness and growth, *T. subincanum* did not respond to this variable. This can be a pattern of responses of shade-tolerant species to light (Schwartz *et al.*, 2012). While pioneer species demand high amounts of light to grow, shade-tolerant species need minimum amounts of light to develop. Any small increase in light is enough to trigger positive growth responses from shade-tolerant species. Large gaps promote higher germination and growth of individuals belonging to pioneer and light-demanding species and promote growth of shade-tolerant species. On the other hand, small and medium size gaps have low influence on germination and growth of pioneer and light-demanding species, but still promote growth of shade-tolerant species (Brokaw, 1985; Kobe *et al.*, 1995).

Like gap size, the plots direction following cardinal points also did not interfere on *T. subincanum* growth. The dissimilar light availability in different cardinal points around the logging gap due to sunlight movements was not sufficient to promote different responses in growth of *T. subincanum*. Light incidence had great effect on *T. subincanum* growth, but not in relation to cardinal points around the gap. The location of a given individual inside a canopy gap can reflect on its growth, where there are differences in sunlight incidence in function of daytime (Denslow, 1980; Barton, 1984; Jardim, 2015), but not inside the forest immediately around the gap. Despite the fact that individuals of *T. subincanum* grew better in a light gradient, they did not respond to their location in cardinal points.

Conclusions

There were no changes in density and population structure of the shade-tolerant species *Theobroma subincanum* distributed in different distances around different size logging gaps created by reduced impact logging (RIL). The species presented diameter distribution in reverse "J" shape, which remained unchanged along 12 years of monitoring after RIL, only with in-

dividuals moving to higher diameter classes by growing. There was higher growth, measured in Periodic Annual Increment in diameter (PAI_{dbh}), of *T. subincanum* up to three years after RIL, and a further stabilization nine years after logging.

Individuals of *T. subincanum* responded to the higher entrance of indirect sunlight caused by the canopy gap, they presented a growing gradient inversely proportional to the distance from the gap's border. No differences in growing responses were observed in individuals of *T. subincanum* in relation to gap size and the plots direction in cardinal points around the canopy gap.

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