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The continuous timber production over cutting cycles in the Brazilian Amazon depends on volumes of species not harvested in previous cuts

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ABSTRACT

Can heavily logged Amazonian dense forests produce commercial timber for a second harvest under a 25–35-year cutting cycle? To address this question, we evaluated the forest capacity to recover the volume extracted 32 years after heavy logging (90 m^3 ha^{-1}) in a 144-ha research area located in the Tapajós National Forest, Brazil (03°18′31″ to 03°19′21″ S; 54°56′28″ to 54°56′15″ W). Abundance (number of trees ha^{-1}), basal area (m^2 ha^{-1}) and volume (m^3 ha^{-1}) were assessed in two censuses, one year before logging (1981) and 32 years after logging (2014) to evaluate the status of the timber stock. Canopy openings caused by logging and silvicultural treatments increased sunlight in the forest and boosted the growth of trees 5–45 cm in DBH. Light-demanding species accounted for most of the increase in density and timber volume in the study area after logging. Our findings indicated that 32 years after the first cut, the forest was not able to replace the volume extracted. Considering the present Brazilian forest management regulations, which allow a logging intensity of 30 m^3 ha^{-1} in a 35-year cutting cycle, this volume could only be harvested if new species not logged in the first cut were included in the new species logging list.

1. Introduction

Sustainable forest management is considered by many scholars as the best alternative to conserving tropical forests and assuring that the forests environmental, social and economic functions are maintained. As far as timber production is concerned, to assure long-term timber yields in tropical forests, it is important to evaluate the recovery of species diversity and composition (Hu et al., 2018), recruitment, mortality and growing stock of commercial species (Avila et al., 2017; Dionisio et al., 2017). Timber yields also depend on the recovery rates of previously extracted species and on the potential markets of non-logged species by the time of future harvests (Jardim and Soares, 2010).

One of the main concerns on the management of tropical forests for timber production is the stock reduction after the first harvest, which is frequently observed worldwide (Dauber et al., 2005; Keller et al., 2007; Valle et al., 2007; Rozendaal et al., 2010; Hawthorne et al., 2012). Another question to be considered is the low recruitment rates of commercial species, which decreases timber yield (Avila et al., 2017; Roopsind et al., 2017).

Simulations carried out by van Gardingen et al., (2006) and Valle et al., (2007) in the Brazilian Amazon involving the entire species community have indicated that the studied forests do not recover their initial volume stock in 30-year cutting cycles. Similar conclusions were drawn by Rozendaal et al. (2010) and Hawthorne et al., (2012) in the Bolivian Amazon and in Ghana, West Africa, for simulated 40-year cutting cycles. Moreover, studies involving species specific populations (eg. Andrade et al. 2019; David et al., 2019; Ferreira et al., 2020) suggest 100-year cutting cycles, depending on the ecological features of each tree species, which makes it difficult to maintain the same composition of harvested species in each cycle.

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Logging intensity also influences the recovery time of the commercial timber stock. Heavy logging and intensive thinning have a negative impact on the recovery of the commercial volume stock (Avila et al., 2017; Roopsind et al., 2017; Andrade, 2020). As a consequence of this, the cutting cycle should be extended to allow the recovery of the volume stock of the species harvested, or the allowable cut should be completed with the volume of species not logged in the previous cut.

The high productive potential of dense rain forests in the Amazon is unquestionable, but the maintenance of their timber yields remains as a great challenge for forest managers. Forest research has certainly had great advance in this direction, by proposing cutting cycles of 25–35 years, which are currently adopted by the Brazilian forest management legislation for the Amazon region (Brasil, 2006). These cutting cycles are based on the growth and yield prognoses obtained from permanent sample plots data (Silva et al., 1995; Silva et al., 1996; Alder et al., 2012), representative of the entire tree community (Castro et al., 2019; Ferreira et al., 2020).

A promising alternative to ensure continuous timber yields is to diversify the number of harvested species, including those not harvested in the first cutting, considering their ecological and economic characteristics (van Gardingen et al., 2006; Keller et al., 2007; Alder et al., 2012; Avila et al., 2017). Another approach to achieve long-term production in tropical forests is to apply post-harvesting silvicultural treatments. They are treatments aiming to boost growth of remaining commercial and potential species (Dauber et al., 2005; Brienen and Zuidema, 2006; Rozendaal et al., 2010; Putz et al., 2012; David et al., 2019) and ensure their natural regeneration (Dauber et al., 2005; Peña-Claros et al., 2008; Krisnawati and Wahjono, 2010; Darrigo et al., 2016; Hogan et al., 2018; Neves et al., 2019). Nevertheless, most studies on silvicultural treatments in tropical forests consider only the growth or mortality of the remaining individuals (eg. de Graaf et al., 1999; Wadsworth and Zweede, 2006; Peña-Claros et al., 2008; Villegas et al., 2009; David et al., 2019). Other studies assess the costs (Costa et al., 2001), but few investigate the economic profitability of silvicultural treatments in tropical forests. Gräfe et al. (2020) examined the costs and profitability sensitivity of liberation treatments in two Caribbean (Belize and Trinidad and Tobago) and two South American (Guyana and Suriname) countries. The authors concluded that investments in silvicultural treatments bring considerable financial risk. Therefore, without a reliable response on the matter, the suggestion of adding new species to each cutting cycle comes as a safe procedure.

In this paper we evaluated the ability of a *terra firme* rain forest of the Brazilian Amazon, heavily logged and treated by poison girdling silvicultural treatment, to recover its original stock 32 years after the harvesting operations in order to answer the following research questions: i) Does the forest as a whole recover its original timber stock? ii) Do the tree species extracted recover their original timber stock? iii) Is the forest able to produce enough commercial timber for the next cutting cycle?

2. Material and methods

2.1. Study area

The experimental area comprises 144 ha of Dense Ombrophilous Forest (IBGE, 2012) located in the Tapajós National Forest, municipality of Belterra, state of Pará, Brazil, between the geographic coordinates 03°18′31″ to 03°19′21″ South and 54°56′28″ to 54°56′15″ West. Topography is mostly flat. Climate is “Am” according to the Köppen classification. Annual average temperature is 27 °C, relative humidity is 87%, and the cumulative annual rainfall is 1758 mm (INMET, 2020). The most common soils in the region are Dystrophic Yellow Latosol and Dystrophic Yellow Argisol (Oliveira Junior and Correa, 2001).

2.2. Forest inventories data

Data comes from two inventories at 100% intensity carried out in the 144-ha experimental area and from 48 permanent sample plots (PSP) of 0.25 ha (total of 12 ha sampled) also established in the 144-ha area, randomly distributed with a minimum distance of 50 m between them (see further details in Appendix A.1-supplementary material). In the first 100% inventory conducted in 1981, all trees with DBH (diameter at breast height) $\geq$ 45 cm were measured. In the second 100% inventory that was carried out in 2014, all trees with DBH $\geq$ 25 cm were measured.

To compare the forest structure between the two occasions we complemented the database with data of trees 5.0–44.9 cm DBH measured in the 1981 PSPs assessment. The 2014 database was complemented with trees 5.0–24.9 cm DBH of the PSPs measured in 2012, the closest year to 2014.

All trees measured were identified to species level whenever possible in the area by a parabotanist from the IAN Herbarium (Embrapa Eastern Amazon). Botanical specimens were collected from less common trees for late identification in the IAN Herbarium.

In 1982, logging was carried out in the 144-ha experimental area applying techniques to reduce impacts such as stock survey (100% inventory), climber cutting, directional felling and skid trails planning. A crawler tractor was used to open the logging decks and a rubber skidder was utilized to extract logs from the forest to the logging decks (Carvalho et al., 1984). Thirty-six commercial species with a minimum felling diameter of 55 cm were harvested. The average volume and number of trees extracted was 90 m^3 ha^{-1} and 12 trees ha^{-1}, respectively (Carvalho, 1987). Twelve years after logging, in 1994, silvicultural treatments (refinement by poison girdling of non-commercial species) applied over the logged area reduced the original basal area to 53% of 19 non-commercial species, aiming to boost growth of the remaining commercial species (Costa et al., 2001; Avila et al. 2017). Due to identification issues, two species of the genus *Qualea* (*Q. gracilior* Pilg. and *Q. paraensis* Ducke) and one of the genus *Ruizterania* (*R. albiflora* (Warm.) Marc.-Berti.) were grouped as *Qualea* spp. Thus, in calculations and analyzes, 36 species, instead of 38, were considered as logged in 1982.

2.3. Interviews with sawmill owners

To evaluate the potential stock for future harvests, 53 commercial species were selected according to a survey based on questionnaires applied in the eight biggest sawmills from the 25 operating in the municipalities of Santarém and Belterra, Brazilian Amazon in 2014. The survey indicated: the species processed by sawmills (the sawmill owners were asked to list all species they processed in their sawmills); origin of the timber (forest management projects or traditional exploitation); the most demanded species by buyers; and the most commercialized species, both in the national and in international markets (the sawmill owners were asked to list the countries that bought their timber). All the 53 species listed by the sawmill owners had their timber traded (Brasil, 2020). So, all 53 species were considered potential for the next harvest once having available stock. All of these species were also considered commercial by Piponiot et al. (2019). Out of these 53 species, only two (*Dalbergia spruceana* Benth. and *Euxylophora paraensis* Huber) were not recorded in the 100% intensity forest inventory of 2014. More survey details are shown in Appendix A.3, supplementary material.

2.4. Data analysis

Comparative analyses of abundance (number of trees ha^{-1}), basal area (m^2 ha^{-1}) and volume (m^3 ha^{-1}) in the period of 1981 (one year before logging) to 2014 (32 years after logging) were carried out to evaluate whether the forest recovered its original volume stock. Such analyses also considered the distribution of the number of trees, basal area and volume per diameter classes, for the entire tree community and, separately, for the species harvested in 1982.

Analyses of density, basal area and volume distributions considered 10-cm class intervals starting with 5 cm DBH for density and basal area, and the minimum of 15 cm for volume. Two volume equations developed for the Tapajós National Forest (Silva et al., 1984; Silva and Araújo, 1984) were used, one for trees sizing 15 cm – 45 cm DBH ($V = -0.0994 + 0.00091941\ DBH^2$ ($R^2 = 0.96$, and $S_{yx} = 12\%$)); and another one for trees with DBH ≥ 45 cm ($V = \text{Exp}\ (-7.6281 + 2.1809\ \ln\ (DBH)$ ($R^2 = 0.84$ and $S_{xy} = 16\%$)).

Timber stock available for a second harvest was determined using data of the 2014 stock survey (100% inventory), and considered trees with DBH ≥ 50 cm from 34 species whose timber is currently processed at sawmills in the Santarém region, and traded in the national and international markets. For this evaluation, we considered the criteria established in the Normative Instruction 5/2006 of the Brazilian Ministry of the Environment – MMA (Brasil, 2006) and in Normative Instruction 1/2015 of MMA (Brasil, 2015a). According to these regulations, logging is only allowed if the species' density is at least four trees (DAP ≥ 50 cm) per 100 ha. For those that meet this criterion, 10% must be kept as seed bearers. If the species is classified as vulnerable to extinction the numbers change to five trees per 100 ha and 15% must be kept as seed bearers. We also considered the Article 23 of the Normative Instruction 5/2015 of Pará State Secretary for the Environment and Sustainability, which established the Maximum Felling Diameter (200 cm) for each managed species (SEMAS, 2015).

The species studied were classified into two large ecological groups (shade-tolerant and light-demanding species), according to their characteristics, following the proposition of Swaine and Whitmore (1988), to determine which ecological group was most affected or benefited by the logging and silvicultural treatments.

3. Results

3.1. Stock recovery of the tree community

Abundance, basal area and volume recovered their initial status in DBH classes smaller than 45 cm. This was not the case of the DBH class 45–54.9 cm that recovered only abundance and basal area. As far as volume is concerned, no DBH class above 45 cm recovered the initial stock (Fig. 1).

Thirty-two years after logging, only 60.8% of the volume of trees with DBH > 45 cm was restored (Table 1). On the other hand, the abundance of these large trees recovered by 91.9% in the same period, indicating that in managed forests, the recovery in abundance is faster than the recovery in basal area and volume. As for the whole community (all tree species ≥ 45 cm in DBH), it did not recover the initial stock in abundance, basal area and volume (Table 1).

3.2. Recovery of the harvested species

The timber species harvested over 55.0 cm DBH did not recover their abundance (Fig. 2A; Fig. 2B), basal area (Fig. 2C) and volume (Fig. 2D). The recovery of abundance (Fig. 2B) and basal area (Fig. 2C) occurred,

Table 1
Total number of trees, abundance, basal area and volume of trees with DBH ≥ 45 cm one year before (1981) and 32 years after logging (2014) in a 144-ha experimental area logged in 1982 in the Tapajós National Forest, Eastern Amazon, Brazil.

Variable	1981	2014	Recovery (%)
Number of trees	5731	5267	91.9
Abundance (trees ha^{-1})	39.80	36.58	91.9
Basal area (m^2 ha^{-1})	17.62	12.00	68.9
Volume (m^3 ha^{-1})	210.40	127.86	60.8

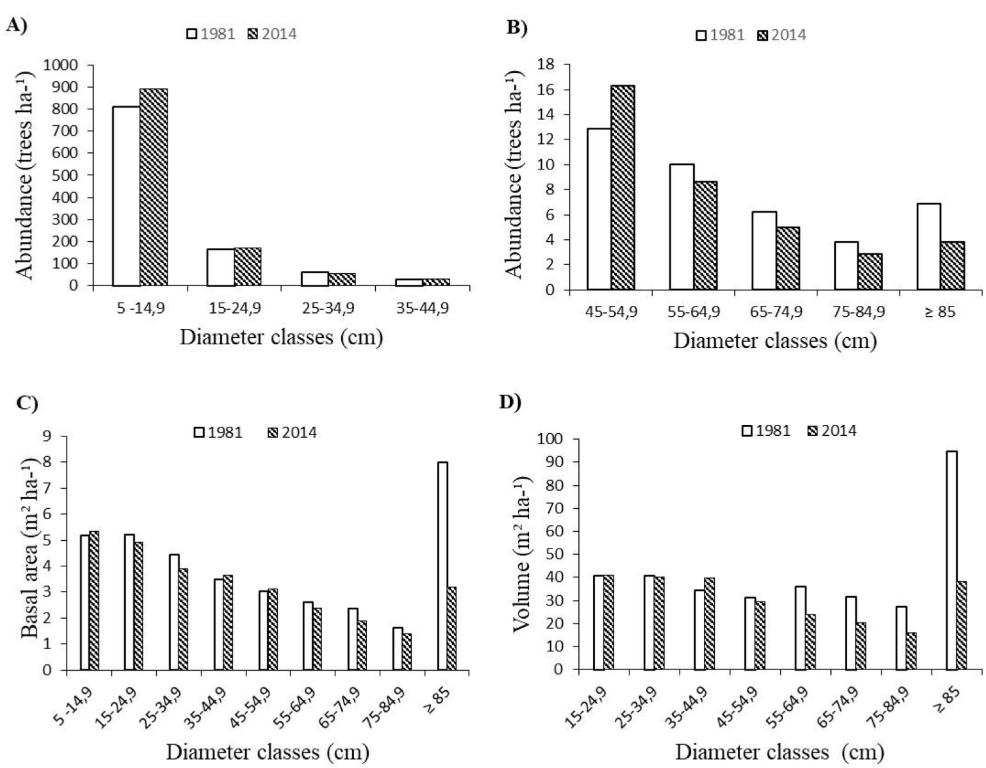

Fig. 1. Pre-logging (1981) and 32 years after logging (2014) abundance (trees ha^{-1}) of the diameter classes < 45 cm (A) and ≥ 45 cm (B), basal area (m^2 ha^{-1}) (C) and volume (m^3 ha^{-1}) (D) of trees per diameter class of a managed forest in the Tapajós National Forest, Eastern Amazon, Brazil. Note that the "y" axis in (A) and (B) is not the same.

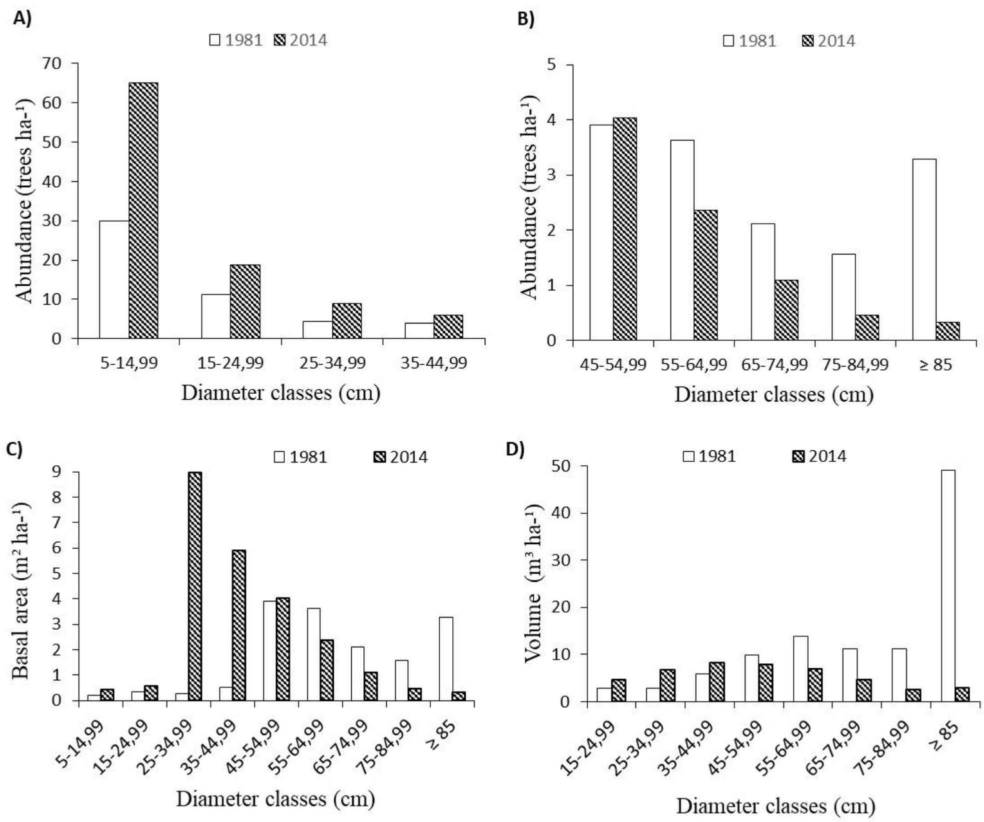

Fig. 2. Pre-logging (1981) and 32 years after logging (2014) abundance (trees ha^{-1}) of the diameter classes < 45 cm (A) and ≥ 45 cm (B), basal area (m^2 ha^{-1}) (C) and volume (m^3 ha^{-1}) (D) per diameter class of the harvested species in 1982 in the Tapajós National Forest, Eastern Amazon, Brazil.

however, in the 45.0–54.9 cm DBH class, due to the remaining stock of trees in this class and to the ingrowth of trees from lower size classes during the post-harvest period.

Ten timber species with the highest volume harvested did not recover their original volume 32 years after logging (Fig. 3). *Carapa guianensis* Aubl. had the best recovery (46%) whereas the remaining nine species did not reach 30% of their initial volume stock. Only five out of 36 species harvested in 1982 recovered their pre-logging abundance and volume stocks: *Astronium lecointei* Ducke, *Bowdichia nitida* Spruce ex Benth., *Jacaranda copaia* (Aubl.) D. Don, *Parkia multijuga* Benth. and *Vatairea guianensis* Aubl. (Appendix A.6, supplementary material). Except for *A. lecointei* which is shade-tolerant, the others are light-demanding and relatively fast growing species. This feature can

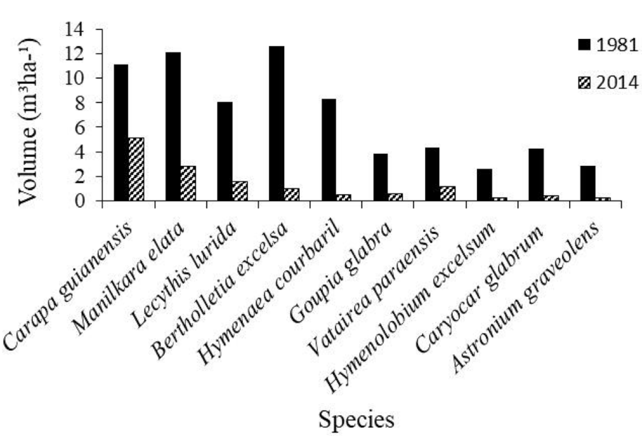

Fig. 3. Pre-logging (1981) and 32-years post-logging (2014) volume stock of trees ≥ 45 cm in DBH of 10 species with the highest timber volume harvested in 1982 in the Tapajós National Forest, Eastern Amazon, Brazil.

explain recuperation of their stock. *A. lecointei* benefitted from the canopy opening after logging. Three of these species were listed as processed in the interviewed sawmills: *A. lecointei* was processed in six sawmills with 70% of demand by buyers, in relation to the other species processed in the sawmill, being traded in both local and national markets; *B. nitida* was processed in two sawmills with 40% of demand by buyers, also traded in both local and national markets; *V. guianensis* was less demanded by buyers and traded only in the local market (Appendix A.3, supplementary material).

Besides recovering the communitýs initial stock, the forest canopy was in a dynamic balance containing large trees of both light-demanding and shade-tolerant species.

3.3. Potential stock for the second cutting (DAP ≥ 50 cm)

Thirty-four species currently processed in local sawmills in the municipalities of Belterra and Santarém compose the potential volume for the second harvest (~39 m^3 ha^{-1}). This is higher than the maximum annual allowable cut of 30 m^3 ha^{-1} established by the Brazilian Government (Normative Instruction 5/2006) for a 35-year cutting cycle. Twelve species logged in the first cut met the criteria established for harvesting in the second cut (Brasil, 2006; 2015a). These species contributed with 37% of the potential number of trees and 25% of the potential volume available for logging (Appendix A.7, supplementary material).

Four species (*Carapa guianensis, Couratari stellata* A.C.Sm, *Manilkara elata* (Allemão ex Miq) Monach) and *Pouteria bilocularis* (H.J.P. Winkl.) Baehni were responsible for 54% of the harvestable volume in 2014. They are highly demanded by buyers and have a high percentage of sales in the local market. *C. guianensis* and *M. elata* are also widely traded in the national market and, according to the interviewed sawmill owners, they are also traded in the international market (Appendix A.3, supplementary material). Both species were logged in 1982.

Twenty-two commercial species were not harvested in 1982. This represents 75% of the total volume available for the next harvest. Some species such as *Couratari* spp., which were not logged in 1982, due to lack of market, can now be commercialized. If the second harvest included only the species harvested in 1982, the available volume would drop to only 16.98 m^3 ha^{-1}, fivefold lower than that of the first harvest (90 m^3 ha^{-1}).

Ten species harvested in the first cutting did not yield sufficient volume to meet the principle of the continuous timber production by the time of the second harvest (trees DBH $\geq$ 50 cm). Those were *Handroanthus impetiginosus* (Mart.ex DC) Mattos, *Sextonia rubra* Van der Werff, *Aniba canelilla* (Kunth) Mez, *Erisma uncinatum* Warm, *Dinizia excelsa* Ducke, *Roupala montana* Aubl., *Swartzia grandifolia* Bong. ex Benth, *Simarouba amara* Aubl, *Qualea* spp. and *Bowdichia nitida*.

The 16 species more demanded by buyers (preference $\geq$ 55%) and that are rated as potentially harvestable in the next cutting cycle had a volume of 21.93 m^3 ha^{-1} in 2014, representing 73% of the maximum volume allowed to harvest. Fifteen species were considered more marketable in the local market (preference $\geq$ 55%) with a volume of 27.11 m^3 ha^{-1} in 2014, representing 90% of the maximum volume allowed for harvesting (Appendix A.3, supplementary material).

According to the sawmill owners interviewed and considering the categories of timber prices established by the Finance Department of the state of Pará, Brazilian Amazon (Brasil, 2015b – Appendix A.4, supplementary material), the volume available for the next harvest could yield USD 2,790.80 per hectare. This income assumes the entire volume of timber (38.96 m^3 ha^{-1}) sold in the local market (Appendix A.5, supplementary material). However, considering that the legislation allows a maximum harvest of 30 m^3 ha^{-1}, the sawmills could obtain up to USD 2,148.97 per hectare in the local market.

Also according to sawmill owners responses, only nine species (*Astronium lecointei, Bagassa guianensis, Carapa guianensis, Cordia goeldiana, Handroanthus serratifolius, Hymenaea courbaril, Hymenolobium excelsum, Manilkara elata* and *Vochysia maxima*) among the 34 selected for the second harvest were sold to other Brazilian states (national market). If the timber of these nine species (7.38 m^3 ha^{-1}) was sold on the local market, the sawmills would raise USD 631.06 per hectare, but once sold in the national market (other Brazilian states) they could raise up to USD 6,316.21 per hectare. Fourteen species were indicated by the interviewed sawmill owners as exported to some countries in North America, Asia and Europe (Appendix A.3, supplementary material), but we did not get reliable information on timber prices of those species in the international market.

4. Discussion

4.1. Recovery of the original timber stock of the forest community

Harvesting in the experimental area followed the Brazilian environmental regulations of 1982 and was planned in detail, i.e., complied with the principles of reduced impact logging. The regulations, at that time, prescribed a minimum felling diameter of 45 cm for any species and had no restrictions on the harvesting intensity (*cf.* Brasil, 1965). The volume harvested (90 m^3 ha^{-1}; Carvalho, 1987) was threefold higher than the maximum logging intensity allowed by the current management regulations (cf. Brasil, 2006). Despite these flexible environmental restrictions, only 38 species were selected. The forest still did not recover its original timber stock in 32 years, due to the high logging intensity applied in a 30–35-year cutting cycle. In Suriname, under the same post-logging period of the present study, Roopsind et al. (2017) found a negative effect of high logging intensity over the initial timber stock. The prediction models used by the authors showed that the probability of the forest to recover its timber stock in 32 years was 82% under low logging intensity (15 m^3 ha^{-1}), 80% with medium intensity (23 m^3 ha^{-1}) and <70% with high intensity (46 m^3 ha^{-1}). Likewise, Piponiot et al. (2019) evaluated data from 15 different sites in the Brazilian Amazon, Peruvian Amazon and French Guiana, with different logging intensities, and found that heavier logging intensities did not allow volume recovery during a cutting cycle. The results obtained by Gaui et al. (2019) in a natural forest in central Amazonia suggest that trees with DBH greater than 40 cm assure stock for a new cutting cycle. If canopy do not recover completely, the timber stock may be exhausted. The authors claim that higher logging intensities do not allow the floristic composition to recover in an interval up to 25 years. Growth rates in the Amazonian rain forests are quite low and this is also true in other tropical rain forest elsewhere. Thus, a compromise must exist between logging intensities and the length of the cutting cycles.

Brienen and Zuidema (2006) pointed out that the recovery time of the harvested volumes is not only determined by the growth rates of each species, but also by the number of remaining trees present in the diameter classes below the minimum felling diameter. Dauber et al. (2005) drew similar conclusions, but taking into account the influence of these factors on the yield of the second cutting cycle. Furthermore, the mortality rates of residual trees also affect both the time needed for the harvested volume to recover (Brienen and Zuidema, 2006) and the production of future cutting cycles in tropical forests (Dionisio et al., 2017).

In the present study, the number of trees and basal area of the 45–55 cm size class recovered for both the timber trees community and the harvested species group. This was the only size class that recovered the volume stock. Trees of the classes immediately below the minimum felling diameter presented faster responses in growth due to the increased solar radiation as result of canopy opening caused by logging. Therefore, these trees grew into the 45–55 cm diameter class.

4.2. Recovery of the original timber stock per species

The non-recovery of timber stock for a second harvest has also been reported elsewhere in tropical rain forests (e.g. Dauber et al., 2005; Rozendaal et al., 2010; Hawthorne et al., 2012; Gourlet-Fleury et al., 2013; Roopsind et al., 2018). A simulation study of three species harvested in a Bolivian tropical forest showed that the recovery of the initial volume would not reach 50% in 40 years (Rozendaal et al., 2010). In another research in Bolivia, the recovery of timber stock of commercial species was also lower than the expected for a 20-year cutting cycle (Brienen and Zuidema, 2006). Other predictions indicated that cutting cycles under 60 years were not sufficient for harvested species to recover their original timber stock (Sist et al., 2003; Van Gardingen et al., 2006; Schulze et al., 2008). Hence, longer cutting cycles are essential for a complete timber stock recovery of harvested species in tropical rain forests (Brienen and Zuidema, 2006; Rozendaal et al., 2010).

4.3. Commercial timber production for the next harvest

Our study revealed how important is to consider timber markets changes in the selection of species for harvesting in forest management projects. The available stock for the second harvest was composed mainly by current commercial species, which were not marketable by the time of the first harvest. This new timber stock composition would be enough to ensure timber production in the next cutting cycle (see also van Gardingen et al., 2006; Keller et al., 2007; Alder et al., 2012; Avila et al., 2017).

Manilkara elata, Carapa guianensis and *Goupia glabra* Aubl., harvested in the first cutting cycle, comprised 34% of the available timber stock for the second harvest. These species still did not recover their initial stocks. However, after 32 years, trees from diameter classes below the minimum felling diameter accumulated enough trees over 50 cm DBH. This made possible to include these species in the second cutting list.

One strategy to assure long-term timber production is to promote a significant set of species to complete the list of commercial species for harvesting in each cutting cycle. This would allow enough time for the species harvested in the previous cutting cycle to replace their initial timber stocks (Avila et al., 2017). Post-harvesting silviculture can promote timber stocks recovery more rapidly (Dauber et al., 2005; Wadsworth and Zweede, 2006; Rozendaal et al., 2010; Avila et al. 2015; David et al., 2019), since the slow growth and low recruitment rates restrict the replacement of the volume stock in tropical forests (Avila et al., 2017; de Graaf et al., 1999). Silvicultural treatments, such as crown liberation thinning (Peña-Claros et al., 2008; Villegas et al., 2009) and enrichment planting in logging gaps (Schwartz et al., 2017; Neves et al., 2019) are promising alternatives that can speed up the volume stock recovery (Villegas et al., 2009; Putz et al., 2012) and may reduce the cutting cycle (Krisnawati and Wahjono, 2010). It is known that post-harvest silviculture is beneficial for timber yields in tropical rainforests, and can also provide employment, ecosystem services and potentially biodiversity benefits (Cerullo and Edwards 2018).

Timber production can be sustainable in the long-term if species selected for logging are changed and diversified along the cutting cycles, as we suggest in the present study. Thus, the second and subsequent harvests depend on the quantity and quality of trees below the minimum felling diameter to allow a continuous timber production. When we consider only trees with DBH $\geq$ 45 cm, the forest did not recover its abundance, basal area and volume 32 years after the first harvest. This was also the case of Piponiot (2019), who evaluated trees with DBH $\geq$ 50 cm in 15 different sites in the Amazon. They found that low intensity loggings do not provide enough timber and the high intensity loggings do not allow volume recovery during a cutting cycle, concluding that selective logging in Amazonian forests cannot provide enough timber to meet even the current long-term demand. The authors, however, did not evaluate trees with DBH $<$ 50 cm as we did in our study, so we found that a considerable number of trees, basal area and volume are concentrated in size classes below 45 cm. For instance, in the diameter class 35–44.9 cm, the basal area in 2014 was six times higher than one year before logging in 1981. This clearly indicates that the study forest is recovering its structure, and is able to supply trees with minimum felling diameter $\geq$ 55 cm for the next harvests. It is well known that in tropical forests, the highest number of trees is concentrated in the smaller size classes, which fits a negative exponential function (De Liocourt, 1898; Leak, 2002; Picard and Gasparotto, 2016). In the study area, openings caused by harvesting and the silvicultural treatments, increased solar radiation inside the forest and boosted growth of small trees (5–45 cm DBH). Indeed, most of the increase in growth and number of trees was driven by light-demanding species.

4.4. Implications for forest management

Various studies have focused on determining the time needed for tropical forests to recover from timber extraction (e.g. Avila et al., 2018, Ferreira et al., 2020). Some of these studies (e.g. Sist et al., 2003; Van Gardingen et al., 2006; Schulze et al., 2008; Rozendaal et al., 2010; Piponiot et al., 2019) emphasize that cutting cycles shorter than 60 years do not allow logged species to recover their initial volume stock. The recovering time depends on several factors such as, logging intensity or volume harvested (Keller et al. 2007; Roopsind et al. 2017), growth responses of different species (Silva et al., 1995; Carvalho et al., 2004), recruitment and mortality (Avila et al., 2017; Dionisio et al, 2017), silvicultural treatments (Sist et al. 2003; Krisnawati and Wahjono, 2010; Schwartz et al., 2012; David et al., 2019) and damage (Gourlet-Fleury et al., 2013; Andrade et al., 2020).

According to David et al. (2019) and Ferreira et al., (2020), in the Brazilian Amazon, due to its great diversity of tree species, it is necessary to establish minimum felling diameter and cutting cycle for each individual species. Those authors also point out that once processing information on species minimum felling diameter and cutting cycle, also including structure and diversity of each forest, decision makers would have sufficient elements to establish more sustainable polycyclic silvicultural systems for Amazonian forests.

The current silvicultural approach applied in managed *terra firme* forests in the Brazilian Amazon is a polycyclic system (Silva, 1993; Yared et al., 2000; Alder et al., 2012), in which part of the commercial trees reaching the minimum felling diameter are removed in specific time intervals (cutting cycles). The present Brazilian forest management legislation establishes cutting cycles of 25–35 years and a maximum annual allowable cut of 30 m^3 ha^{-1} for the *terra firme* forests (Brasil, 2006). The volume extracted in the first cut was the triple of what is currently allowed. If the present annual allowable cut was applied 32 years ago, it is most likely that the recovery of the volume extracted would have been more feasible to achieve. It is also possible that promoting a second harvest within already-logged areas have more limited carbon and biodiversity consequences relative to harvesting timber in undisturbed forests.

Based on the 2014 stock survey, harvesting 34 commercial species would be a good choice, since there would be a more diversified composition of the volume extracted, thus avoiding logging pressure over a few species. Nonetheless, to meet the maximum annual allowable cut of 30 m^3 ha^{-1}, only the volume of six shade-tolerant species *viz. Apuleia leiocarpa* var. *molaris* (Spruce ex Benth) K, *Carapa guianensis*, *Couratari stellata*, *Manilkara elata*, *Pouteria bilocularis* and *Trattinickia burseraefolia* Mart.) and four light-demanding species (*Cordia goeldiana* Huber, *Goupia glabra*, *Pseudopiptadenia suaveolens* (Miq.) J.W Grimes and *Vatairea paraenses* Ducke) would have been enough for the second harvest. These 10 species sum up a total volume of 29 m^3 ha^{-1}.

5. Conclusions

Thirty-two years after logging, the 144-ha experimental area in the Tapajós National Forest presented sufficient timber for the next harvest, under lower yields, in accordance to the present Brazilian forest management regulations. The stock was composed mostly by species not harvested in the first logging. Therefore, replacing some harvested species by new ones not harvested in the first logging becomes an important alternative to maintain continuous timber production in tropical forests of the Brazilian Amazon.

Considering the high logging intensity (90 m^3 ha^{-1}) applied, which was threefold higher than the present annual allowable cut (30 m^3 ha^{-1}), and only the species logged in the first cut, the 32-year period post-logging was not enough for the forest to recover its original abundance, basal area and volume. On the other hand, our study showed that a second harvest would be possible if new commercial species not logged in the first cut were added to compose potential volume to harvest. Encouraging a second harvest over managed forests can also help decrease logging pressure on unlogged primary forests, though this remains a key avenue for future enquiry.

CRediT authorship contribution statement

Tatiana da Cunha Castro: Investigation, Writing - original draft, Formal analysis, Visualization. **João Olegário Pereira de Carvalho:** Conceptualization, Writing - review & editing, Supervision, Project administration. **Gustavo Schwartz:** Writing - review & editing. **José Natalino Macedo Silva:** Writing - review & editing. **Ademir Roberto Ruschel:** Data curation, Writing - review & editing. **Lucas José Mazzei de Freitas:** Writing - review & editing. **Jaqueline Macedo Gomes:** Investigation. **Roseane de Siqueira Pinto:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2021.119124.

References

Alder, D., Silva, J.N.M., Carvalho, J.O.P., Lopes, J.C., Ruschel, A.R., 2012. The cohort-empirical modelling strategy and its application to forest management for Tapajos Forest, Para, Brazilian Amazon. Bois et forêts des tropiques 314 (4), 17–23.

Andrade, D.F.C., Ruschel, A.R., Schwartz, G., Carvalho, J.O.P., Humphries, S., Gama, J.R. V., 2020. Forest resilience to fire in eastern Amazon depends on the intensity of pre-fire disturbance. For. Ecol. Manage. 472, e118258. https://doi.org/10.1016/j.foreco.2019.02.030.

Andrade, V.H.F., Machado, S.A., Filho, A.F., Botosso, P.C., Miranda, B.P., Schongart, J., 2019. Growth models for two commercial tree species in upland forests of the Southern Brazilian Amazon. For. Ecol. Manage. 438, 215–223. https://doi.org/10.1016/j.foreco.2019.02.030.

Avila, A.L., Ruschel, A.R., Carvalho, J.O.P., Mazzei, L., Silva, J.N.M., Lopes, J.C., Araujo, M.M., Dormann, C.F., Bauhus, J., 2015. Medium-term dynamics of tree species composition in response to silvicultural intervention intensities in a tropical rain forest. Biol. Conserv. 191, 577–586. https://doi.org/10.1016/j.biocon.2015.08.004.

Avila, A.L., van der Sande, M.T., Dormann, C.F., Peña-Claros, M., Pooter, L., Mazzei, L., Ruschel, A.R., Silva, J.N.M., Carvalho, J.O.P., Bauhus, J., 2018. Disturbance intensity is a stronger driver of biomass recovery than remaining tree-community atributes in a managed Amazonian forest. J. Appl. Ecol. 55, 1647–1657. https://doi.org/10.1111/1365-2664.13134.

Avila, A.L., Schwartz, G., Ruschel, A.R., Lopes, J.C., Silva, J.N.M., Carvalho, J.O.P., 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.

Brasil, 1965. Lei 4771 de 15 de setembro de 1965 – constitui o Código Florestal Brasileiro.

Brasil, 2006. Instrução Normativa n° 5, de 11 de dezembro de 2006. Diário Oficial [da] República Federativa do Brasil, n. 238, Seção 1, p.155-159.

Brasil, 2015a. Instrução Normativa n° 1, de 12 de fevereiro 2015. Diário Oficial [da] República Federativa do Brasil, n.31, Seção 1, 67p.

Brasil, 2015b. Portaria SEFA No.5 de 2015. Secretaria de Estado da Fazenda. Boletim de preços mínimos de mercado. https://www.legisweb.com.br/legislacao/?id=280619. Accessed on December 22, 2020.

Brasil, 2020. Espécies madeireiras de interesse comercial. SFB – Serviço Florestal Brasileiro: SNIF – Sistema Nacional de Informações Florestais. http://snif.florestal.gov.br/pt-br/especies-florestais?modal=1&tipo=tableau. (Accessed on December 25, 2020).

Brienen, R.J.W., Zuidema, P.A., 2006. The use of tree rings in tropical forest management: Projecting timber yields of four Bolivian tree species. For. Ecol. Manage. 226, 256–267. https://doi.org/10.1016/j.foreco.2006.01.038.

Carvalho, J.O.P., Silva, J.N.M., Lopes, J.C.A., Costa, H.B. 1984. Manejo de florestas naturais do trópico úmido com referência espacial à Floresta Nacional do Tapajós no estado do Pará. Belém, 14p. (Embrapa-Cpatu. Documentos, 26).

Carvalho, J.O.P., 1987. Subsídios para o manejo de florestas naturais na Amazônia brasileira: resultados de pesquisa da EMBRAPA/IBDF-PNPF. Embrapa-CPATU, 35p. (Embrapa-CPATU. Documentos, 43).

Carvalho, J.O.P., Silva, J.N.M., Lopes, J.C.A., 2004. Growth rate of a terra firme rain forest in Brazilian Amazonia over an eight-year period in response to logging. Acta Amazonica 34, 209–217. https://doi.org/10.1590/S0044-59672004000200009.

Cerullo, G.R., Edwards, D.P., 2018. Actively restoring resilience in selectively logged tropical forests. J. Appl. Ecol. 56, 107–118. https://doi.org/10.1111/1365-2664.13262.

Castro, T.C., Ruschel, A.R., Carvalho, J.O.P., Ramos, E.M.L.S., Gomes, J.M., 2019. Representatividade e precisão na estimativa da densidade e área basal na Floresta Nacional do Tapajós. Nativa 7, 312–316. https://doi.org/10.31413/nativa.v7i3.6921.

Costa, D.H.M., Silva, S.M.A., Silva J.N.M., 2001. Efetividade e custo do desbaste com aplicação de arboricida em floresta natural na região do Tapajós, Pará e Jari, Amapá. In: J.N.M. Silva, J.O.P. Carvalho, J.A.G. Yared. (Org.). A Silvicultura na Amazônia Oriental. Belém: Embrapa Amazônia Oriental/DIFID, v.1, p.339–352.

Darrigo, M.R., Venticinque, E.M., Santos, F.A.M., 2016. Effects of reduced impact logging on the forest regeneration in the central Amazonia. For. Ecol. Manage. 360, 52–59. https://doi.org/10.1016/j.foreco.2015.10.012.

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.

David, H.C., Carvalho, J.O.P., Pires, I.P., Santos, L.S., Barbosa, E.S., Braga, N.S., 2019. A 20-year tree liberation experiment in the Amazon: Highlights for diameter growth rates and species-specific management. For. Ecol. Manage. 453, e117584. https://doi.org/10.1016/j.foreco.2019.117584.

de Graaf, N.R., Poels, R.L.H., Van Rompaey, R.S.A.R., 1999. Effect of silvicultural treatment on growth and mortality of rainforest in Surinam over long periods. For. Ecol. Manage. 124, 123±135. https://doi.org/10.1016/S0378-1127(99)00057-2.

De Liocourt. F., 1898. De l'aḿenagement des sapinières. Bulletin Société Forestière de Franche-Comté et Belfort. Bulletin trimestriel, 6:369–405. http://infodoc.agroparistech.fr/index.php?lvl=notice display&id=181924.

Dionisio, L.F.S., Schwartz, G., Mazzei, L., Lopes, J.C., Santos, G.G.A., Oliveira, F.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.

Ferreira, T.M.C., Carvalho, J.O.P., Emmert, F., Ruschel, A.R., Nascimento, R.G.M., 2020. How long does the Amazon rainforest take to grow commercially sized trees? An estimation methodology for Manilkara elata (Allemão ex Miq.). Monach. For. Ecol. Manage. 473, e118333. https://doi.org/10.1016/j.foreco.2020.118333.

Gaui, T.D., Costa, F.R.C., Souza, F.C., Amaral, M.R.M., Carvalho, D.C., Reis, F.Q., Higuchi, N., 2019. Long-term effect of selective logging on floristic composition: A 25 year experiment in the Brazilian Amazon. For. Ecol. Manage. 440, 258–266. https://doi.org/10.1016/j.foreco.2019.02.033.

Gourlet-Fleury, S., Beina, D., Fayolle, A., Ouédraogo, D.Y., Mortier, F., Bénédet, F., Closset-kopp, D., Decocq, G., 2013. Silvicultural disturbance has little impact on tree species diversity in a Central African moist forest. For. Ecol. Manage. 304, 322–332. https://doi.org/10.1016/j.foreco.2013.05.021.

Gräfe, S., Eckelmann, C.M., Playfair, M., Oatham, M.P., Pacheco, R., Bremner, Q., Kohl, M., 2020. Future crop tree release treatments in neotropical forests – an empirical study on the sensitivity of the economic profitability. For. Policy Econ. 121, 102329. https://doi.org/10.1016/j.forpol.2020.102329.

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.

Hogan, J.A., Herault, B., Bachelot, B., Gorel, A., Jounieaux, M., Baraloto, C., 2018. Understanding the recruitment response of juvenile neotropical trees to logging intensity using functional traits. Ecol. Appl. 0 (0), 1–13. https://doi.org/10.1002/eap.1776.

Hu, J., Herbohn, J., Chazdon, R.L., Baynes, J., Wills, J., Meadows, J., Sohel, Md.S.I., 2018. Recovery of species composition over 46 years in a logged Australian tropical forest following different intensity silvicultural treatments. For. Ecol. Manage. 409, 660–666. https://doi.org/10.1016/j.foreco.2017.11.061.

IBGE (Instituto Brasileiro de Geografia e Estatística)., 2012. Manual técnico da vegetação brasileira. Rio de Janeiro: DEDIT/CDDI. 92p.

INMET (Instituto Nacional de Meteorologia. Ministério da Agricultura, Pecuária e Abastecimento). 2020. https://portal.inmet.gov.br (accessed October 12, 2020).

Jardim, F.C.S., Soares, M.S., 2010. Comportamento de *Sterculia pruriens* (Aubl.) Schum. em floresta tropical manejada em Moju-PA. Acta Amazonica 40, 535–542. https://doi.org/10.1590/S0044-59672010000300012.

Keller, M., Asner, G.P., Blate, G., Mcglocklin, J., Merry, F., Peña-Claros, M., Zweede, J., 2007. Timber production in selectively logged tropical forests in South America. Front. Ecol. Environ. 5, 213–216.

Krisnawati, H., Wahjono, D., 2010. Effect of post-logging silvicultural treatment on growth rates of residual stand in a tropical forest. J. For. Res. 7, 112–212.

Leak, W.B., 2002. Origin of sigmoid diameter distributions. Res. Pap. NE-718. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 10p.

Neves, R.L.P., Schwartz, G., Lopes, J.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.

Oliveira Junior, R.C., Correa, J.R.V., 2001. Caracterização dos solos do município de Belterra, Estado do Pará. Belém: Embrapa Amazônia Oriental, 1-39. (Documentos, 88).

Peña-Claros, M., Peters, E.M., Justiniano, M.J., Bongers, F., Blate, G.M., Fredericksen, T. S., Putz, F.E., 2008. Regeneration of commercial tree species following silvicultural treatments in a moist tropical forest. For. Ecol. Manage. 255, 1283–1293. https://doi.org/10.1016/j.foreco.2007.10.033.

Picard, N., Gasparotto, D., 2016. Liocourt's law for tree diameter distribution in forest stands. Ann. For. Sci. 73, 751–755. https://doi.org/10.1007/s13595-016-0563-4.

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., 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, 064014. https://doi.org/10.1088/1748-9326/ab195e.

Putz, F.E., Zuidema, P.A., Synnot, 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. Conservat. Lett. 5, 296–303 https://doi.org/10.111/j.1755-263X.2012.00242.x.

Roopsind, A., Wortel, V., Hanoeman, W., Putz, F.E., 2017. Quantifying uncertainty about forest recovery 32-years after selective logging in Suriname. For. Ecol. Manage. 391, 246–255. https://doi.org/10.1016/j.foreco.2017.02.026.

Roopsind, A., Caughlin, T.T., van der Hout, P., Arets, E., Putz, F.E., 2018. Trade-offs between carbon stocks and timber recovery in tropical forests are mediated by logging intensity. Global Change Biol. 24, 2862–2874. https://doi.org/10.1111/gcb.14155.

Rozendaal, D.M.A., Soliz-gamboa, C.C., Zuidema, P.A., 2010. Timber yield projections for tropical tree species: the influence of fast juvenile growth on timber volume recovery. For. Ecol. Manage. 259, 2292–2300. https://doi.org/10.1016/j.foreco.2010.02.030.

Schulze, M., Grogan, J., Uhl, C., Lentini, M., Vidal, E., 2008. Evaluating ipê (*Tabebuia*, Bignoniaceae) logging in Amazonia: sustainable management or catalyst for forest degradation? Biol. Conserv. 141, 2071–2085. https://doi.org/10.1016/j.biocon.2008.06.003.

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., 2017. 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, 2015. Instrução Normativa n°05, de setembro de 2015. Secretaria de Meio Ambiente e Sustentabilidade (SEMAS), Pará. https://semas.pa.gov.br (accessed on 30 Oct 2020).

Silva, J.N.M., 1993. Possibilidades para a produção sustentada de madeira em floresta densa de terra-firme da Amazônia brasileira (Prospects of sustained timber production in dense terra firme forest on the Brazilian Amazon). Curitiba: EMBRAPA-CNPF, 36p. (EMBRAPA-CNPF, Documentos, 23).

Silva, J.N.M., Araújo, S.M., 1984. Equação de volume para árvores de menor diâmetro na Floresta Nacional do Tapajós. Boletim de Pesquisa Florestal 8 (9), 6–25.

Silva, J.N.M., Carvalho, J.O.P., Lopes, J.C.A., Carvalho, M.S.P., 1984. Equação de volume para a Floresta Nacional do Tapajós. Boletim de Pesquisa Florestal 8 (9), 50–63.

Silva, J.N.M., Carvalho, J.O.P., Lopes, J.C.A., Almeida, B.F., Costa, D.H.M., Oliveira, L.C., Vanclay, J.K., Skovsgaard, J.P., 1995. Growth and yield of a tropical rain forest in the Brazilian Amazon 13 years after logging. For. Ecol. Manage. 71, 267–274. https://doi.org/10.1016/0378-1127(94)06106-S.

Silva, J.N.M., Carvalho, J.O.P., Lopes, J.C.A., Oliveira, R.P., Oliveira, L.C., 1996. Growth and yield studies in the Tapajós region, central Brazilian Amazon. Commonwealth Forestry Rev. 75 (4), 325–329.

Sist, P., Sheil, D., Kartawinata, K., Priyadi, H., 2003. Reduced impact logging in Indonesian Borneo: some results confirming the need for new silvicultural prescriptions. For. Ecol. Manage. 179, 415–427. https://doi.org/10.1016/S0378-1127(02)00533-9.

Swaine, M.D., Whitmore, T.C., 1988. On the definition of ecological species groups in tropical rain forests. Vegetatio 75, 81–86.

Valle, D., Phillips, P., Vidal, E., Schulze, M., Grogan, J., Sales, M., van Gardigen, 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 Gardingen, P.R., Valle, D., Thompson, I., 2006. Evaluation of yield regulation options for primary forest in Tapajos National Forest. Brazil. For. Ecol. Manage. 231, 184–195. https://doi.org/10.1016/j.foreco.2006.05.047.

Villegas, Z., Peña-Claros, M., Mostacedo, B., Alarcon, A., Licona, J.C., 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 (6), 971–977. https://doi.org/10.1016/j.foreco.2008.10.031.

Wadsworth, F.H., Zweede, J.C., 2006. Liberation: Acceptable production of tropical Forest timber. For. Ecol. Manage. 233, 45–51. https://doi.org/10.1016/j.foreco.2006.05.072.

Yared, J.A.G., Carvalho, J.O.P., Silva, J.N.M., Kanashiro, M., Marques, L.C.T. 2000. Contributions of the Tropical Forestry Project - International Cooperation Brazil/United Kingdom (Contribuições do Projeto Silvicultura Tropical - Cooperação Internacional Brasil/Reino Unido). Belém: Embrapa Amazônia Oriental/DFID, 2000. 28p. (Embrapa Amazônia Oriental. Documentos, 52).