PROFITABILITY OF SILVICULTURAL TREATMENTS IN LOGGING GAPS IN THE BRAZILIAN AMAZON

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SCHWARTZ G, BAIS ALS, PEÑA-CLAROS M, HOOGSTRA-KLEIN MA, MOHREN GMJ & ARTS BJM. 2016. Profitability of silvicultural treatments in logging gaps in the Brazilian Amazon. Many harvested timber species of tropical forests have not been regenerating sufficiently and have thus made post-harvesting silvicultural treatments necessary. This study analysed the profitability of sawnwood produced through four treatments in seedlings and saplings naturally present or planted in logging gaps. The treatments were (1) standard procedures of reduced-impact logging or control, (2) tending of the naturally established regeneration, (3) enrichment planting 1 (EP-1) and (4) enrichment planting 2 (EP-2). In EP-1 seedlings were planted in 2-year-old gaps keeping logging residuals inside the gap while in EP-2 seedlings were planted in 1-year-old gaps with residuals removed. Species of EP-2 had higher financial value and growth rates than species in EP-1. Growth rates of treated individuals were projected in 30 and 60 years to simulate sawnwood production. With increases of 25 and 50% in growth rates, 500% in timber prices, and interest rates of 4 and 6% year^{-1}, tending and enrichment planting could profit at year 60. These silvicultural treatments, with technological improvements, can become even more financially profitable for forest managers and investors.

Keywords: Polycyclic silvicultural system, cost-benefit analysis, enrichment planting, forest natural regeneration, NPV

INTRODUCTION

In the Brazilian Amazon, harvesting over managed forests follows a polycyclic silvicultural system which aims for continuous timber production and protection of ecosystem goods and services in harvested areas. This polycyclic silvicultural system has been substantially improved over the last decades, especially with the adoption of reduced-impact logging (RIL) techniques. RIL was introduced in the management of tropical forests to avoid unnecessary damage on the remaining trees and improve the efficiency in harvesting operations through careful and detailed operations (Putz et al. 2008). RIL, when applied in tropical managed forests, is more environment-friendly than the so-called conventional logging, with less destructive effects on animal and plant communities (Imai et al. 2009). RIL techniques can improve post-harvesting survival rates of standing trees (Pereira et al. 2002), increasing chances of these individuals to become available in future cutting cycles (Macpherson et al. 2012). Despite the environmental advantages, RIL usually requires higher investments than conventional logging (Medjibe & Putz 2012). However, it normally becomes more profitable than conventional logging in the long term (Boltz et al. 2001).

Long-term simulations of future timber yields suggest, however, that the harvested species will not be able to produce the same timber volumes of those produced in the first cutting cycle by the length of a complete cutting cycle (30 years), as required by the Brazilian regulations. The main reason for this is that it is impossible for the remaining trees to recover the first cycle harvested volume by the time of the second cutting cycle (Sist & Ferreira 2007, Valle et al. 2007). Moreover, the scarce natural regeneration of timber species in managed tropical forests can result in even lower yields in the third and further cutting cycles (Mostacedo

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& Fredericksen 1999, Van Rheenen et al. 2004, Park et al. 2005).

For adequate regeneration of timber species, it is essential to maintain seed trees to ensure new individuals in the populations of harvested species. Hence, the Brazilian forest management regulations require that 10% of harvestable individuals per species (or at least 3 adults species^{-1} 100 ha^{-1}) remain not felled. These legal procedures, however, are not enough for ensuring sufficient regeneration of the currently harvested species in the Brazilian Amazon (Sist & Ferreira 2007, Valle et al. 2007).

Due to problems of regeneration of timber species and uncertainties of future timber yields, post-harvesting silvicultural treatments have been suggested to ensure timber species regeneration for future harvesting cycles (Fredericksen & Pariona 2002, Schwartz et al. 2012, 2014). These include (1) tending of seedlings and saplings of commercial species naturally established through liberation from competitors and lianas and (2) enrichment planting. Both treatments are applied in gaps created by logging (Lopes et al. 2008, Doucet et al. 2009, Schwartz et al. 2013). The objectives of this study were firstly to compare the profitability of sawnwood produced through three post-harvesting silvicultural treatments with the current standard RIL practices where no post-harvesting silvicultural treatments were applied and, secondly, to compare the long-term profitability of such treatments over scenarios differing in growth rates, interest rates and timber prices.

MATERIALS AND METHODS

Study area and experimental design

The data on survival and growth rates used in this study were from a field experiment carried out in the forest management area of Jari Florestal SA under the project 'Gap Management' coordinated by Jari Florestal and Embrapa Eastern Amazon. The study area is in the Jari valley, Almeirim municipality (1° 9' S, 52° 38' W), Pará state, Brazil. Average annual precipitation is 2200 mm and the annual average temperature, 26 °C. The vegetation is mainly ombrophilous dense forest or terra firme forest over yellow latossols (Azevedo 2006). The total area under the management of Jari Florestal SA is 545,535 ha where harvesting operations follow RIL techniques. The company currently sells certified timber of 27 species under the regulations of the Forest Stewardship Council to domestic and international markets.

A total of 2997 seedlings (individuals < 3 m in height) and saplings (individuals ≥ 3 m in height) naturally present or planted in 72 gaps created by RIL were assigned to test for mortality, growth rate and profitability in four treatments as follows: (1) standard procedures of RIL, (2) tending of the naturally established regeneration, (3) enrichment planting 1 (EP-1) and (4) enrichment planting 2 (EP-2). The experiment was established in 2006 and 2007 in logging compartments harvested in 2004 and 2006 (Table 1). In the treatment of standard RIL, which served as control, marked individuals were only monitored, with no additional silvicultural treatments, according to the current forest management regulations for forest monitoring in Brazil. The other three treatments were applied in addition to all procedures required by RIL. Tending (liberation against competing plants and lianas) was applied for seedlings and saplings of commercial species naturally established in the gaps. In the enrichment planting, all seedlings were planted at a spacing of 2.5 m × 2.5 m using commercial tree species. EP-1 and EP-2 differed in terms of planted species, logging compartments, gap ages and removal of logging residuals. EP-1 was established in gaps created at 2 years with no residual removal while EP-2 was established in 1-year gaps with complete logging residual removal for energy production (Table 1). The liberation against competing vegetation growth, except in standard RIL and mortality measurements, was taken at 6, 12, 18, 24, 36, and 48 months after treatments (Schwartz et al. 2013).

Yield projections

Future timber yields at the end of the second and third cutting cycles (30 and 60 years respectively) were projected by simulating long-term growth of the most dominant individual(s) in each gap. For the standard RIL, it was assumed that the possible number of trees reaching the minimum cutting diameter of 45 cm was one individual per gap ≤ 455 m^2, two in gaps > 455 and ≤ 680 m^2, and

Table 1 Characteristics of the four treatments used for seedlings and saplings naturally present or planted in logging gaps tested

Variable	Standard RIL	Tending	Enrichment planting 1	Enrichment planting 2
Initial number of seedlings and saplings	436	396	1520	645
Density (number of individuals m^{-2})	0.070 ± 0.017	0.056 ± 0.015	0.110 ± 0.035	0.109 ± 0.020
Number of species	34	39	10	5
Number of logging gaps	15	15	34	8
Size of logging gaps (m^2)	424.4 ± 99.9	481.4 ± 103.9	433.7 ± 134.5	754.9 ± 237.7
Age of logging gaps (years)	2	2	2	1
Logging compartment	2004	2004	2004	2006
Logging residuals removed from gaps	No	No	No	Yes
Silvicultural treatment	No treatment	Tending the natural regeneration	Enrichment planting and tending	Enrichment planting and tending

RIL = reduced-impact logging

three in gaps > 680 m^2. On the other hand, the expected number of harvestable trees in the other three treatments was one harvestable tree (45 cm in diameter) per 100 m^2. This densification of harvestable individuals was due to silvicultural treatments applied in logging gaps to ensure better survival and growth rates of treated individuals (Azevedo et al. 2009, Souza et al. 2010). Long-term growth projections were based on (1) observed growth rates in the first 5 years for EP-2 and 6 years for the rest of the treatments, applied over individuals up to 20 cm in diameter at breast height (dbh) and (2) average annual diameter increment of adult commercial tree species, applied after a given individual had attained 20 cm in dbh. The latter data were obtained from literature (Silva et al. 1996, Schulze 2003, Phillips et al. 2004, Azevedo et al. 2008, Sebbenn et al. 2008) and datasets from Embrapa Eastern Amazon (Table 2). In terms of mortality, it was assumed that dominant individuals in each gap would remain alive, attaining harvestable sizes, so mortality rates were out of the projections. Individuals that reached the commercial size (≥ 45 cm in dbh) at 30 and 60 years had the projected diameters converted into volume estimates, according to the diameter-based volume equations available at Globallometree (2015) for the research region. For species without diameter-based volume equations, we applied equation 1 which was developed by Silva et al. (1985) for the Tapajos National Forest, Eastern Amazon.

$$\text{Volume} = E^{-7.62812 + 2.1809 \times \ln(\text{dbh})} \qquad (1)$$

The estimated volume of roundwood was converted into sawnwood volume by multiplying the estimated roundwood yield by 55% which was the assumed processing efficiency within 30 to 60 years from the present. The current average processing efficiency value in the region is 42% (Lentini et al. 2005).

Net present value

Net present value was used as measurement unit to estimate the profitability of the treatments. The net present value is a common economic tool for presenting forest profitability using discounted cash flow analysis. It is calculated by adding all discounted benefits and costs over each harvesting according to equation 2:

$$NPV = \sum_{t=0}^{n}\left(\frac{B_t}{(1+r)^t} - \frac{C_t}{(1+r)^t}\right) \qquad (2)$$

where NPV = net present value, B_t = revenue in year t, C_t = cost in year t, r = discount rate $year^{-1}$ (in percentage), t = year when revenue or

Table 2 Species with number of dominant individuals in logging gaps at the last measurement, individuals reaching the minimum cutting diameter (45 cm in dbh) at 60 years (in brackets) per treatment, average growth rates of individuals < 20 cm in dbh (mean ± SD) and average growth rates of trees ≥ 20 cm in dbh and market prices for sawnwood

Species	Standard RIL	Tending	Enrichment planting 1	Enrichment planting 2	Growth rate of individuals < 20 cm in dbh (cm $year^{-1}$ ± SD)	Growth rate of individuals ≥ 20 cm in dbh (cm $year^{-1}$)	Sawnwood price (USD m^{-3})
Anacardium giganteum	–	–	37 (0)	–	0.68 ± 0.28	0.54	297
Bagassa guianensis	–	–	31 (1)	–	1.04 ± 0.51	0.47	401
Bombacopsis nervosa	1 (1)	–	–	–	0.94	0.64	210
Carapa guianensis	–	–	44 (0)	–	0.90 ± 0.37	0.45	422
Cedrela odorata	–	–	–	2 (2)	1.20	0.94	268
Dinizia excelsa	2 (0)	–	9 (0)	–	0.91 ± 0.28	0.53	452
Enterolobium schomburgkii	–	–	–	2 (0)	0.68	0.52	161
Goupia glabra	–	1 (0)	–	–	0.80	0.60	163
Humiria balsamifera	–	1 (0)	–	–	1.12	0.69	176
Hymenaea courbaril	–	–	4 (0)	–	0.50	0.47	483
Hymenolobium flavum	–	1 (0)	–	–	0.03	0.69	236
Jacaranda copaia	1 (0)	–	–	–	0.53	0.66	422
Jacaranda copaia var. *spectabilis*	–	3 (0)	–	–	0.95	0.54	422
Laetia procera	9 (0)	32 (0)	–	–	1.29 ± 0.36	0.42	326
Parkia pendula	–	–	–	9 (7)	1.14 ± 0.37	0.73	326
Parkia reticulata	1 (1)	–	–	–	0.79	0.73	111
Parkia sp.	1 (1)	1 (1)	–	–	1.57	0.69	111
Qualea albiflora	–	3 (0)	–	–	0.24	0.70	326
Schefflera morototoni	–	5 (5)	–	–	1.56 ± 0.54	0.76	326
Sclerolobium guianense	1 (1)	–	–	–	1.49	0.69	112
Tachigali myrmecophila	2 (2)	5 (5)	–	43 (43)	1.18 ± 0.30	1.16	315
Tapirira guianensis	–	3 (3)	–	–	1.61	0.66	326
Terminalia amazonia	1 (1)	–	–	–	0.97	0.90	87
Trattinnickia rhoifolia	–	7 (5)	–	–	0.92 ± 0.31	0.85	84
Trattinnickia sp.	–	2 (2)	–	–	0.95	0.85	84
Virola melinonii	–	1 (0)	–	–	0.53		149
Vochysia vismiifolia	–	1 (1)	–	–	1.79	0.72	336
Vouacapoua americana	–	–	–	2 (0)	0.43	0.69	181
Total	19 (7)	66 (23)	127 (1)	56 (52)		–	-

RIL = reduced-impact logging, dbh = diameter at breast height; SD = standard deviation cost occurs and n = time for having revenues. If the outcome of the net present value for a given forest was zero or negative, the cost over the cutting cycle was equal to or greater than the benefits. However, if the outcome of the net present value was larger than zero, then the investment was expected to be profitable (Klemperer 2003).

Discount rate

The appropriate discount rate is crucial for determining the net present value of investment, especially the power of discounting in relation to benefits and costs (Livingstone & Tribe 1995). One way to choose the discount rate is to determine the opportunity cost of the capital needed for investment, i.e. the rate in which capital needed for the forestry investment may return if it is invested elsewhere (Row et al. 1981). Thus, the discount rate used in the projections of this study was the long-term interest rate adopted by the National Development Bank of Brazil, namely, 6% per year.

Costs and benefits

Future benefits of the post-harvesting silvicultural treatments applied in logging gaps were based on growth and timber yields simulations of dominant individuals per logging gap. A given tree will be harvested when it attains minimum cutting diameter of 45 cm at year 30 or 60. The benefits were calculated by multiplying the estimated timber volumes (m^3) of sawnwood by their prices, for each species, in the domestic market and subtracting the costs of harvesting, transport and processing. The average timber prices of sawnwood m^{-3} were obtained from SEMA (2014) and Pereira et al. (2010) (Table 2). The costs of harvesting and wood processing were obtained from Pereira et al. (2010) and Jari Florestal. The net benefits ha^{-1}, i.e. net present value ha^{-1}, were calculated for the sawnwood produced by each treatment at years 30 and 60.

The costs of harvesting, transport and processing were assumed to be constant over time of the cost-benefit projections. For calculating the establishment and maintenance costs of each treatment, the following costs were considered: seedling production, gap selection and mapping, seedling selection, gap preparation, seedling transport and transplanting, labour and transport of workers (Table 3). The transport costs to cover the distances from the supplier of seedlings to the base (65 km) and from the base to the management unit (12 km) were based on costs of renting vehicles and their fuel consumption. Equipment costs included shovels, diggers and machetes. For maintenance costs of the treatments, labour was estimated based on the time required for liberating plants inside gaps against competing vegetation (Table 3). Average establishment and maintenance costs per treatment were calculated as per gap ha^{-1}, using an average of 3.44 logging gaps ha^{-1}, according to the forest management plans of Jari Florestal.

Sensitivity analysis

Sensitivity analysis was used to evaluate the profitability of sawnwood produced through each of the four post-harvesting silvicultural treatments under different scenarios. The scenarios differed in (1) increases of 25 and 50% in growth rates of individuals ≥ 20 cm in dbh, (2) interest rates of 4 and 6% and (3) increases of 250 and 500% in timber prices in 30 years and 250, 500 and 750% in 60 years. The different timber prices used in the simulations were based on the increase of the average price for roundwood in the Brazilian Amazon, i.e. 250% in 20 years. Average prices increased from USD32 m^{-3} in 1989 (Verissimo et al. 1992) to USD111 m^{-3} in 2009 (Pereira et al. 2010).

RESULTS

The treatment of standard RIL had no cost of establishment and maintenance since silvicultural interventions (investments) were not required for this treatment. The establishment costs in EP-1 were 14 times higher than tending due to the costs of seedling production, gap preparation, transport and transplanting. Establishment costs in EP-2 were threefold lower than in EP-1 due to reduced costs of seedling production and transport. All seedlings used in EP-2 were produced at the main base of the management area and not purchased from external suppliers. Besides the lower costs in seedling production and transport, gap preparation also presented lower costs in EP-2 than in EP-1. The logging residuals such as trunk pieces and branches of

Table 3 Average costs of establishment and maintenance (USD ha^{-1}) over 4 years for four treatments: standard reduced-impact logging (RIL), tending, enrichment planting 1, and enrichment planting 2 in logging gaps in the Jari valley, Pará, Brazil

Activity	Standard RIL	Tending	Enrichment planting 1	Enrichment planting 2
Seedling production	0	0	123.46	61.75
Gap selection	0	1.65	1.65	1.65
Personnel	0	1.00	1.00	1.00
Transport	0	0.65	0.65	0.65
Gap mapping	0	7.22	7.22	7.22
Personnel	0	3.78	3.78	3.78
Transport	0	3.44	3.44	3.44
Selection of seedlings	0	9.22	0	0
Personnel	0	5.47	0	0
Transport	0	3.75	0	0
Gap preparation	0	0	44.86	20.98
Personnel	0	0	21.16	8.46
Transport	0	0	18.64	7.46
Equipment	0	0	5.06	5.06
Transport of seedlings and transplanting	0	0	77.81	11.70
Personnel	0	0	24.66	3.72
Transport	0	0	53.15	7.98
Total establishment cost	0	18.09	255.00	103.30
Maintenance cost at year 1	0	35.98	35.98	35.98
Maintenance cost at year 2	0	41.38	41.38	41.38
Maintenance cost at year 3	0	45.55	45.55	45.55
Maintenance cost at year 4	0	22.46	22.46	22.46
Total establishment and maintenance costs	0	163.46	400.37	248.67

the gaps used in EP-2 were removed and used by the forestry company for energy production. Hence, a much shorter time was spent for gap preparation. The maintenance costs were the same for both treatments, representing 89% of the total costs of tending, 36% of EP-1 and 58% of EP-2.

All net present values of standard RIL, including simulations, were positive. Considering an increase of 25% in the growth rates of individuals ≥ 20 cm in dbh, sawnwood produced at 60 years through EP-2 was more profitable than the other three treatments at 60 years. Tending was also more profitable than standard RIL, except for the sawnwood produced under an interest rate of 6% with no timber prices increase (Table 4a). With 50% increase in the growth rates of individuals ≥ 20 cm dbh, results showed the same tendency as the 25% increase in growth rates. The difference was that EP-1 became profitable over any timber price increase at an interest rate of 4% in relation to standard RIL. EP-1, under an interest rate of 6% in 60 years, was only profitable if the timber prices increased by 500% (Table 4b). At increased growth rate of 50%, EP-2 was much more profitable than the other three treatments at 60 years (Table 4b).

DISCUSSION

Post-harvesting silvicultural treatments of tending naturally established regeneration and enrichment planting in logging gaps tended

Table 4 Net present value (USD ha^{-1}) of sawnwood produced through four post-harvesting silvicultural treatments in 30 and 60 years when growth rates of individuals ≥ 20 cm in dbh increase of (a) 25% and (b) 50% under different long-term interest rates and increases in timber prices

(a) Increase of 25% in the growth rates of treated individuals ≥ 20 cm in dbh

Interest rate (%)/ increase in imber prices (%)	Standard RIL	Tending	Enrichment planting 1	Enrichment planting 2	Standard RIL	Tending	Enrichment planting 1	Enrichment planting 2
	30 years				60 years			
4/0	Nil	Nil	Nil	-231.71	28.53	120.24	-286.49	1,445.06
4/250	Nil	Nil	Nil	-198.93	153.56	1178.38	55.80	7304.37
4/500	–	–	–	–	278.59	2236.53	398.08	13,163.68
6/0	Nil	Nil	Nil	-236.02	9.10	-64.43	-355.50	300.01
6/250	Nil	Nil	Nil	-230.11	48.97	273.00	-246.34	2168.52
6/500	–	–	–	–	88.84	610.44	-137.19	4037.02

RIL = reduced-impact logging; Nil = no individuals reached the minimum cutting diameter by the harvesting time; trees were harvested at ≥ 45 cm in dbh

(b) Increase of 50% in the growth rates of treated individuals ≥ 20 cm in dbh

Interest rate (%)/ increase in timber prices (%)	Standard RIL	Tending	Enrichment planting 1	Enrichment planting 2	Standard RIL	Tending	Enrichment planting 1	Enrichment planting 2
	30 years				60 years			
4/0	Nil	Nil	Nil	-170	28.53	240.30	-144.74	1,058.97
4/250	Nil	Nil	Nil	77.75	153.56	1,745.79	655.63	5577.05
4/500	–	–	–	–	278.59	3251.28	1456.00	10,095.14
6/0	Nil	Nil	Nil	-224.90	9.10	-26.15	-310.30	176.89
6/250	Nil	Nil	Nil	-180.29	48.97	453.95	-55.06	1617.68
6/500	–	–	–	–	88.84	934.04	200.17	3058.48

RIL = reduced-impact logging, Nil = no individuals reached the minimum cutting diameter by the harvesting time; trees were harvested at ≥ 45 cm in dbh to be profitable if growth rates of individuals ≥ 20 cm dbh and timber prices increased over time. Tended or planted individuals growing under overhead sun in logging gaps must grow, in average, faster than untreated trees in primary forests (where data for simulations in this study came from). It is expected that growth rates of individuals under silvicultural treatments become higher than those observed in monitoring permanent plots of primary forests (Schwartz et al. 2013). Thus, tended or planted individuals could be harvested earlier, i.e. within a 30-year cutting cycle.

Reducing costs

Lower costs can be possible under better understanding and improvement of tending and planting treatments applied in logging gaps. The costs of enrichment planting observed in this study were similar to USD378.00 ha^{-1} recorded by Lopes et al. (2008) in southern Amazon but much higher than the USD22.80 ha^{-1} in Cameroon (Doucet et al. 2009) or USD40.00 ha^{-1} in Fazenda Cauaxi, eastern Amazon (Schulze 2008). Seedling production was the highest cost for establishing, i.e. USD123.46 ha^{-1} in EP-1 and USD61.75 ha^{-1} in EP-2. In this study the total costs of establishment and maintenance varied from USD163.46 ha^{-1} in tending to USD400.37 ha^{-1} in EP-1 (Table 3). In a commercial scale, costs could decrease even more, given that the establishment cost of the treatments in this study was based on an experimental situation. The cost for seedlings production decreases once forest companies maintain nurseries in their own management areas. This study clearly showed the differences in costs of seedling production and transport in two different enrichment planting arrangements. The cost of seedlings purchased from an external supplier in EP-1 was twice higher than the cost of seedlings produced at the management area for EP-2 (Table 3).

Planting costs can be substantially reduced by direct sowing of seeds (Van Rheenen et al. 2004) inside logging gaps instead of producing, transporting and planting seedlings. Hence, maintenance expenses in all treatments can also be reduced. Instead of applying liberation twice a year, a single annual liberation against competing individuals along the first four years should be enough (Schulze 2008, Doucet et al. 2009). In this study, one liberation event per year in the first four maintenance years would reduce the cost by 26% in tending, 11% in EP-1 and 17% in EP-2.

The costs for gap preparation in enrichment planting can be lowered through removal of logging residuals for energy production or other purposes. The cost of gap preparation for EP-1 (USD44.66 ha^{-1}) were twofold higher for EP-2 (USD20.98 ha^{-1}). The vegetation that naturally regenerated in the 2-year-old logging gaps in EP-1 was much taller compared with that present in the 1-year-old logging gaps in EP-2. Thus, 2-year-old loggings gaps are recommended for tending natural regeneration, while 1-year-old logging gaps are better for enrichment planting. Tending could also be applied over natural regeneration in logging gaps older than 2 years. Establishment costs would be higher, but saplings would be taller, demanding a shorter time up to the next cutting cycle.

Increasing benefits

The benefits of applying tending and enrichment planting in logging gaps can be increased by favouring the most valuable and fast-growing species (Tonini et al. 2008, Gomes et al. 2010). In EP-1, three highly valuable species, *Hymenaea courbaril*, *Dinizia excelsa* and *Tabebuia serratifolia*, were planted. Most of the individuals of *H. courbaril* and *D. excelsa* reached dominant positions by the last measurement, but none of the *T. serratifolia* did. An option to increase benefits of post-harvesting silvicultural treatments is to cut or girdle other dominant individuals, even the commercial ones, to favour individuals of the most valuable species (Pariona et al. 2003, Wadsworth & Zweede 2006). Many gaps in EP-1 had *Anacardium giganteum* as the most dominant individual which decreased chances of *T. serratifolia*, *H. courbaril* and *D. excelsa* (all producing more expensive timber than *A. giganteum*) to take dominant positions. For tending treatment, cutting or girdling the dominant *Laetia procera* or *Trattinnickia rhoifolia* can give dominance to the highly valuable *Jacaranda copaia* var. *spectabilis* and *D. excelsa.* On the other hand, in EP-2, the most common dominant species was *Tachigali myrmecophila*, which had the second highest price among the species planted in EP-2 (Table 2).

Sensitivity analysis

Profitability of tested silvicultural treatments can only be possible under increased growth rates of individuals ≥ 20 cm dbh which can also reduce harvesting time. Even with increases of 25 and 50% in growth rates of individuals ≥ 20 cm dbh, only a few individuals of EP-2 reached the minimum cutting diameter in 30 years. If the tendency of increasing timber prices remains, all silvicultural treatments will be profitable in 60 years, which becomes a financially-viable alternative of investment. Nevertheless, investments in silvicultural treatments must also consider uncertainties in the Brazilian Amazon such as illegal logging, landuse rights and short concession periods of forest management.

Besides timber production, the post-harvest silvicultural treatments tackled in this study can also work as a tool for conserving rare or threatened timber species (Schulze et al. 2008, Reis et al. 2010). In EP-1, for example, extremely low densities of *Bagassa guainensis* and *T. serratifolia* were planted. Therefore, in the long run, these treatments can bring additional ecological value for managed forests where they are applied.

CONCLUSIONS

Increases in growth rates and timber prices were the main factors determining the profitability of sawnwood produced through silvicultural treatments of tending the natural regeneration, EP-1 and EP-2. The higher expected profitability of EP-2 in relation to EP-1 was due to the use of newer logging gaps, lower cost in seedling production and the choice of faster growing species as well as higher market-value species. Older gaps demanded more labour due to advanced natural regeneration. Thus, tending is recommended because it can be more profitable once the managed forest can provide, through natural regeneration, timber species with higher market prices.

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