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Article

The Contribution of Multiple Use Forest Management to Small Farmers' Annual Incomes in the Eastern Amazon

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Abstract: Small-scale farmers in the Brazilian Amazon collectively hold tenure over more than 12 million ha of permanent forest reserves, as required by the Forest Code. The trade-off between forest conservation and other land uses entails opportunity costs for them and for the country, which have not been sufficiently studied. We assessed the potential income generated by multiple use forest management for farmers and compared it to the income potentially derived from six other agricultural land uses. Income from the forest was from (i) logging, carried out by a logging company in partnership with farmers' associations; and (ii) harvesting the seeds of *Carapa guianensis* (local name *andiroba*) for the production of oil. We then compared the income generated by multiple-use forest management with the income from different types of agrarian systems. According to our calculations in this study, the mean annual economic benefits from multiple forest use are the same as the least productive agrarian system, but only 25% of the annual income generated by the most productive system. Although the income generated by logging may be considered low when calculated on an annual basis and compared to incomes generated by agriculture, the one-time payment after logging is significant (US$5,800 to US$33,508) and could be used to implement more intensive and productive cropping systems such as planting black pepper. The income from forest management could also be used to establish permanent fields in deforested areas for highly productive annual crops using conservation agriculture techniques. These techniques are alternatives to the traditional land use based on periodic clearing of the forest. Nevertheless, the shift in current practices towards adoption of more sustainable conservation agriculture techniques will also require the technical and legal support of the State to help small farmers apply these alternatives, which aim to integrate forest management in sustainable agricultural production systems.

Keywords: multiple-use forest management; community forestry; Amazon; non-timber forest products; small farming

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1. Introduction

Forest communities and small farmers in the Brazilian Amazon are important actors in the sustainable management of the forest, as they control nearly 60% of public forests in the Brazilian Amazon [1]. Although the potential of community forest management (CFM) to increase the standard of living of rural communities and to fight poverty has been widely assessed in the literature [2–4], fewer studies have examined the specificity of Brazilian Amazon conditions [5–7]. One particularity of Amazonian rural economies is the interplay between agriculture and forest management. Government sponsored colonization of the Brazilian Amazon started in the early 1970s and led to the creation of more than 500,000 km^2 of agrarian settlements occupied by small farmers [8]. Each colonist family usually received a 100 ha land unit. The current Brazilian forest code states that in Amazonia, 50% to 80% of land holdings must remain as permanent forest reserve where forest management plans can be executed only after approval by authorities. However, in practice, many land holdings have already been deforested beyond these limits. The colonization of the Brazilian Amazon has destroyed nearly 18% of the Amazon forest, corresponding to about 70 million ha [9]. Deforestation continues mainly in three states (Pará, Mato Grosso and Rondônia) where the main roads connecting the Amazon states with the economic heart of the south were opened during the colonization of the region [9].

As a result of government policies, satellite monitoring and on the ground enforcement, the deforestation rate in the Brazilian Amazon has decreased considerably over a period of six years to reach its lowest level in 2012: 400,000 ha $year^{-1}$ *versus* 2.7 million ha $year^{-1}$ in 2004 [9]. This represents a 76% reduction in comparison with the mean deforestation rate recorded for the period 1995–2006—close to the country's commitment to reduce deforestation in the Amazon region by 80% by 2020 using the 1995–2006 period as a baseline. Part of this decrease is the result of several government measures to fight deforestation including establishing protected areas, using command-and-control measures, introducing economic instruments including payments for environmental services, and creating policies that affect the drivers of deforestation [10,11]. However, the most recent assessment of deforestation in the Brazilian Amazon revealed a 30% increase in comparison with the rate measured in 2012 [12]. The main reasons for this increase have not been yet rigorously investigated.

More than 12 million ha of permanent forest reserves are estimated to be still held by small farmers in agricultural settlements [13]. Promoting sustainable forest management and incorporating it in agrarian production systems will play a key role in the fight against deforestation in the near future. For more than 40 years, settlers in the Amazon have been pursuing the same strategy: they clear the forest to grow food crops (principally maize, rice and cassava). After two or three years, the soil loses its fertility and the land becomes unproductive. The farmers then convert their plots into pasture, since ranching is the most profitable short term activity. To meet their need for cultivated land, they then cut down more trees, clearing up to three hectares per year, which is the legal limit. If each of the 460,000 smallholder farming families [11] cleared just one hectare of forest per year, the total would reach 4600 km^2, exceeding the 3900 km^2 target set for 2020. It is consequently vital that the smallholder farmers have access to technology and practices that succeed in making their systems more productive and help them manage soil fertility more effectively. This requires the creation of mixed forestry-farming-ranching systems that enhance the economic value of natural forest at the same time as protecting it, and also increase agricultural productivity.

Because it is almost impossible for rural populations to implement forest management plans involving logging themselves, partnerships between communities and logging companies have been considered as a possible way to promote sustainable forest management in agricultural settlements in the Brazilian Amazon [8]. In such partnerships, farmers sell their standing timber to a logging company, which is then responsible for drawing up a forest management plan, submitting it to authorities for approval, and finally for implementing the plan (see [6–8] for further details).

In the context of community and family forest management, multiple forest use has been considered as a possible pathway to increase the incomes of forest communities while conserving the ecological functions of forest ecosystems [14,15]. One of the expected advantages of combining timber harvesting with NTFPs is generating alternative income during the timber rotation cycle, which usually corresponds to a period of at least 30 years (Garcia-Fernandez *et al.* 2008, Sist *et al.* 2008). Although multiple forest management practices are still common worldwide, their adoption in formal forest management models, especially in the tropics, has serious technical and economic limitations [16]. In the Amazon, multiple use forest management has high potential, as more than 40% of timber species also provide non-timber products [17], some of the main products on existing markets being *andiroba* oil (*Carapa guianensis* Aubl.), *cumaru* seeds (*Dipteryx odorata* Aubl. Willd), copaiba oil (*Copaifera* spp.) and Brazil nuts (*Bertholletia a excels* Humb. and Bonpl). Nevertheless, yet the potential role of multiple forest management for settlement communities and the conditions for its successful incorporation in agrarian production systems are still very poorly known and poorly documented [8].

The present study builds on the results of a research and development project implemented in the Moju agrarian settlement near the city of Santarém, in the state of Pará (Brazil). Our aim was to assess both the contribution of multiple use forest management project to small farmers' income and the conditions that favor or limit the development of forest management systems by small farmers in the Brazilian Amazon.

2. Material and Methods

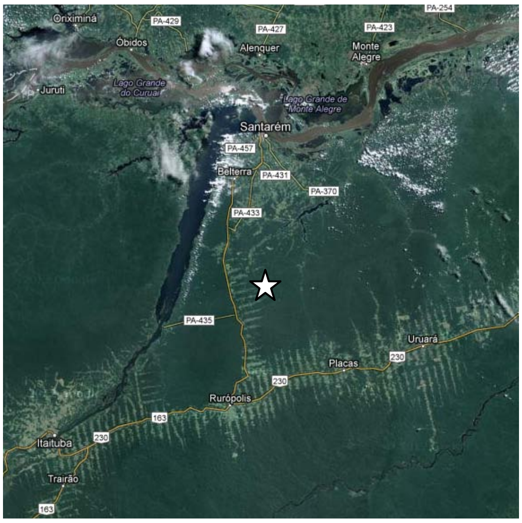
2.1. Study Area

The study was conducted in the agrarian project settlement Mojú officially created in 1996 by the National Institute of Colonization and Agrarian Reform (INCRA) in the municipalities of Santarém and Placas as part of the development policies for the Amazon region in the 1970s. The original vegetation type is tropical *terra firme* forest. The settlement is located about 15 km east of Highway BR-163. The main access routes to the settlement are secondary roads that leave this highway, mainly between km 108 and km 145 (Figure 1a,b). The colonization of the region started in the late 1970s along the main BR-163 highway running north south from Santarém to Cuiaba. In 1970, a national forest (Flona Tapajos) covering about 600,000 ha was created on the west side of the BR-163, while on the east side, secondary roads were opened at 5 km intervals. Between 1976 and 1985, farmers settled the first 10 km-wide strip along the secondary roads (Figure 1a) with the support of INCRA (road construction, credit to the farmers, official land tenure documents) whereas the following phase of colonization (1985–1999) received significantly less financial and technical support from the government. The last phase (1998–2010) of colonization benefited from partnerships between farmers and forest companies for the execution of forest management plans within the forest reserve of each farm unit. Before 2001, the Brazilian forest code allowed farmers to deforest 50% of their land unit for agricultural production, but this provision changed in 2001, and from then on, 80% of the land holdings had to remain as permanent forest reserve. The farmers are allowed to carry out selective logging in their forest reserve with a 30 year rotation cycle, but only after a forest management plan has been approved by the State environmental agency. The settlement covers an area of 152,686 ha and has 1635 families. The farmers are diverse origins, with a high proportion from the western part of Pará State and the Northeast Region of Brazil. Each family received a 100 ha land unit from INCRA. Families organized themselves in associations and cooperatives—determined by geographic proximity-which the inhabitants call a community ("*comunidade*"). Currently, the settlement has 27 such communities. In 2000, to promote sustainable forest management plans in forest reserves of Mojú settlements, INCRA and IBAMA (Environmental agency of the Ministry of Environment) negotiated partnerships between a family-owned forestry company, MAFLOPS (empresa de MAnejo FLOrestal e Prestação de Serviços), and the farmers' associations, establishing the responsibilities of each party as well as the price per cubic meter of timber harvested. For the forestry company, these partnerships were a way to access timber resources on a long term basis without the need to acquire large areas of forest. For the famers, the partnerships were a way to generate income from their forest reserves, which represent more than 60% of the land units, with minimum technical and financial investment. The present study was conducted in one of these communities, represented by an association called ACOPRASA (Associação dos Produtores Rurais da Comunidade de Santo Antônio) that groups 46 families.

In the framework of the partnerships, MAFLOPS develops and implements management plans that are submitted for approval to the State Department of the Environment-SEMA. At the time of our study (2008), four annual production units (APU) had been delimited in the forest reserves of all farm units, but only APUs 1, 2 and 3 had been selectively logged, with APU 4 still waiting to be approved for harvesting by SEMA. Each APU grouped between 8 and 19 forest reserves, each in a land unit and covered an area ranging from 518 ha (APU 1) to 1271 ha (APU 4) (Table 1). To minimize damage to the forest stand and to ensure faster recovery of timber stock, harvesting operations were carried out following Reduced-Impact Logging (RIL) techniques [18,19]. Before logging, MAFLOPS conducted inventories of all timber trees as well as tree species that provide non-timber forest products. All the timber species above 45 cm dbh (diameter at breast height, *i.e.*, 1.30 m from the ground) were inventoried, while for NTFP tree species, the minimum dbh inventoried was 20 cm. These inventories provided basic information on the abundance of species and their distribution. In the study area, 75 timber species were selectively logged and the minimum diameter cutting limit ranged from 50 to 60 cm depending on the species. In 2008, each farmer in the association received 30 Brazilian Reais (R$) or US$16 for each cubic meter of timber extracted from his/her forest reserve. All monetary values in Brazilian Reais (R$) were converted to US dollars (US$) using the mean annual rate of 2008 (mean rate calculated on monthly basis of R$0.54 per dollar).

Figure 1. Location of the study sites and the permanent sample plots; (**a**) Map of Brazil showing the location of the agrarian settlement Mojú (white star); (**b**) detail of the region of the study site Mojú (white star); (source, **a**: [20]; **b**: google earth).

(**a**)



(**b**)

Table 1. Main characteristics of the farms in the Moju settlement.

APU	Number of Farm Units	Mean Area of the farm unit Mean (SD) ha	Mean Deforested Area of the farm unit (ha)	Mean area (SD) of the Forest Reserve (ha)
1	8	84.8 (10.3)	16.9 (2.1)	64.8 (10.0)
2	11	89.5 (10.0)	17.8 (1.9)	69.7 (7.9)
3	11	83.9 (9.3)	16.8 (1.8)	66.1 (7.7)
4	19	83.6 (13.0)	9.8 (4.8)	66.9 (10.4)

2.2. Methods

Recovery of Timber Stocks after Logging

To assess the recovery of timber stocks after logging, 18 permanent plots (PP), of one ha each (40 m × 250 m) were selected in six of the 100 ha land units belonging to farmers who were members of the Acoprasa association and located in the three Annual Production Units (1, 2 and 3) harvested in 2001, 2004 and 2008 respectively. Each APU was therefore represented by two farm land units (a total of 6 farms) and six plots (a total of 18 plots). In each plot, a field technician (botanist) from the Embrapa herbarium identified all trees with dbh ≥10 cm by their scientific name, measured their girth, and numbered and mapped them using *x* and *y* coordinates. Based on these inventories, we calculated the number (N) of harvestable timber trees per hectare in each plot at 20, 30, 35, 40, 50 and 60 years after the first logging operation, using the following equation:

$$N = N_a (1 - m)^t \times 0.7 \quad (1)$$

where N_a is the number of potential crop trees at the time the plot inventory was conducted, m the mortality rate, t the number of years after logging (20, 35, 40, 50, 60) and 0.7 the harvesting rate (harvestable trees inventoried before logging/harvested trees during felling) observed in the study area and in the region in general [21].

Tree mortality during the first 2–5 years following logging is usually higher than in unlogged primary forest and generally results from the higher mortality rate of injured trees, particularly severely injured trees [21–24]. For this reason, our simulations did not include severely injured potential crop trees, since we considered that there was a high probability that these trees would die within the current felling cycle or develop defects that would be incompatible with future commercial use. We applied a 1% mortality rate, which is consistent with studies of intact trees in logged and unlogged forest [21]. Several studies on the dynamics of neotropical forests report post-logging tree diameter growth varying from 2.5 to 6 mm year^{-1} [21–23,25,26]. In the absence of any post-logging silvicultural treatments, growth rates usually decrease with time. Considering the two main parameters (variability of growth rates among stands, and time) we simulated the following three different growth rate scenarios, all with a 1% annual mortality rate:

- SC1: Growth rate of 2.0 mm;
- SC2: Growth rate of 3.5 mm;
- SC3: Growth rate of 5.0 mm.

2.3. Monitoring of Carapa Guianensis Seeds and Oil Production

2.3.1. The Species *Carapa guianensis* (*Meliaceae*)

Carapa guianensis, or andiroba as it is known in Brazil, is represented by medium to large trees up to 35 m (max. 55) tall, with straight and cylindrical boles with diameters at breast height that do not usually exceed 80 to 100 cm. The species is found in the Caribbean, in Central America south of Honduras, and in many parts of the northern Amazon region while the related *C. procera* is found in both Latin America and tropical Africa [27]. Its fruit is a four-valved woody capsule that generally splits open when it matures, falls, and hits the ground [28]. *Carapa guianensis* is a masting tree but does not produce fruit every year. It may be the dominant species in flooded or swampy forests but can also be found in well-drained soil in *terra firme* forest at a relatively high density (3–4 trees/ha, [29]). In the Amazon region, *Carapa guianensis* is valued for both the oil extracted from its seeds and its mahogany-like timber [30]. This species is therefore a good example of a multiple use timber species and a good species to assess possible compatibility between timber harvesting and seed collection for oil production or trade-offs between these two uses [29].

2.3.2. Monitoring of Fruit and Seed Production of *Carapa Guianensis*

To assess the annual production of fruits and seeds by *Carapa guianensis*, we sampled 100 trees in three adjacent farm units. Sampling was designed with the aim of having at least 10 individuals in each dbh class. However, in practice it was not possible to find more than three trees with dbh greater than 60 cm. Trees with severe injuries to the bole and/or with an incomplete crown was not included in this study. We also excluded trees whose crowns overlap with conspecifics in order to be sure of the origin of each seed and fruit. For each of the 100 trees, we measured dbh, the shape of the crown and its position using codes defined by Dawkins [31], the height to the first major branch and the total tree height. From 7 March to 16 May 2009, a mast fruiting period, we monitored the production of fruits and seeds of these 100 *Carapa guianensis* trees at weekly intervals. Each week during this period, fruit and seed production was quantified beneath each tree. The seeds collected by farmers were then processed using the traditional manual method (see Shanley and Medina [30] for more details on the method). We monitored the production of oil as a way of assessing productivity.

2.4. Assessment of Logging Fees

Considering that all the costs of planning and execution of the forest management plan were the entire responsibility of MAFLOPS, the farmers' profits from timber extraction were calculated based on the volume extracted from each farm's forest reserve in APU 2 and 3 only, as these data were not available for APU 1, which was harvested in 2003, nor for APU 4, which had not yet been harvested at the time of the study.

2.4.1. Assessment of Incomes from *Carapa Guianensis* Oil Production

In the framework of the project, *andiroba* oil production was experimented with only a few families of the ACOPRASA association who agreed to carry out a first trial. A cost and benefit analysis in these particular conditions (no former experience in oil production and very little involvement of the whole community) would have given unrepresentative results. For that reason, to collect data on labor productivity, costs and market prices (Table 2), we carried out an assessment in a neighboring forest community located in the FLONA (Floresta Nacional) Tapajos. This assessment was based on interviews of the community leaders involved in the production of *andiroba* oil and the analysis of financial reports produced by the community. We selected this community because of its proximity and its long experience in producing *andiroba* oil. We applied these data in the specific conditions of the Santo Antonio community, taking into account the density of *andiroba* trees in the farm unit to estimate the production of fruits, the cost of collecting the seeds produced and the quantity of oil produced from the collected seeds (Table 2). We only considered the traditional method of production described in detail in Shanley and Medina [30] because it was the decision of the community to use this method. According to this method, the seeds collected in the forest are first washed in running water, and only those with no sign of fungal attacks or parasites are selected for oil production. The seeds are then boiled in water for several hours and then set out in the sun to start the drying process which can last between 15 and 25 days depending on the weather and on the drying method [30]. Once the seeds are dried, they are cut open with a knife to remove the pulp, which is then pressed to collect the oil. Industrial processing of the seeds involves breaking them into small pieces and then pressing the oil out with a hydraulic press. The main variables used in the cost assessment of seed collection and oil production are listed in Table 2.

Table 2. Parameters used to assess the cost and the benefits of andiroba oil production.

Operations		**Cost Description**	**Values**
Harvesting	Material	Bags	1 R$/bag (50 kg)
	Labor Costs	Collect of Seeds	1 man/day/bag
Production	Labor Costs	Washing and cooking	1 man/bag
		Breaking seeds and pulp removal from seeds	0.67 man/bag
		Pulp manipulation	4 men/day
		Total	5.67 men/day
Management	General (meetings, phone calls, ocumentation)		144 R$/year
Commercialization	Transport to markets	Local-Regional Markets (Scenarios 1 and 2)	1.5 R$/L
		National-International markets (Scenarios 3 and 4)	3.3 R$/L
	Labor		2 men/year (for each annual production
	Containers costs	Flasks	28 R$/L
		Gallons	1 R$/L

Economic benefits were calculated for each farm unit based on our assessment of oil production as a proportion of the number Carapa trees in each farm land unit. This made it possible for us to compare the income from oil with annual income from timber production. During our production survey, we observed that 66% of the *Carapa guianensis* trees we monitored produced fruits with a mean of 5.8 kg of healthy seeds per tree. The productivity observed during our monitoring of oil production in the Community was 1 liter (L) of oil produced from 8 kg of seeds which is within the productivity rates reported in the literature, which range from 3 to 12 kg of seeds for 1 L of oil [30,32]. These figures were therefore used to calculate the corresponding quantity of oil for each farm unit according to the following equation:

$$Prod\ (liter) = \frac{N \times 0.66\ \times 5.8}{8} \qquad (2)$$

where *Prod* (*L*) is the production of oil for a given farm unit and *N* is the number of *Carapa guianensis* trees with a dbh >20 cm in the same farm unit.

One year after our survey, we observed that seed production was almost non-existent and so we did not continue to monitor fruit and seed production during this period. In the western Amazon, Klimas, *et al.* [29] observed that during poor seed masting production, the proportion of trees producing fruits was only 10%. We therefore used this rate to assess seed production during poor masting fruit production, using the equation above but replacing 0.66 by 0.10.

Based on the information collected during interviews with farmers of the São Domingo and Santo Antonio communities, *andiroba* oil can be sold on a small-scale to local-regional markets and on a large-scale to national and international market. In the local-regional market, the oil is sold in small quantities in small plastic bottles for R$80 L^{-1} in the local markets of Santarém or to drugstores. They can also be sold in larger quantities to industry in one liter recycled plastic bottles for R$25 L^{-1}. On the national and international market, the oil is usually sold in much larger quantities (minimum one gallon (4 L) for R$50 L^{-1} or R$12 L^{-1} to cosmetic companies. To assess the costs and benefits of *andiroba* oil production for both a massive mast fruiting period and a poor fruit production period, we ran the four following scenarios:

1. Oil sold on the local-regional market for R$80 L^{-1} (US$ 44 L^{-1}) in small plastic flasks;
2. Oil sold on the national-international market for R$50 L^{-1} (US$ 27 L^{-1});
3. Oil sold on the local-regional market for R$25 L^{-1} (US$ 14 L^{-1}) sold in recycled water plastic bottles;
4. Oil sold on the national-international market for R$12 L^{-1} (US$ 6.5 L^{-1}).

To assess the economic viability of each scenario, we calculated the daily net income generated by each scenario and compared it to the daily income of an agricultural worker, which was R$20 a day (US$11a day) in 2008. We considered a scenario to be economically sustainable if the daily income generated was higher than R$20. Because the density of *Carapa guianensis* trees can vary considerably from one farm unit to another, we limited our simulation to farm units in which at least 10 trees had been inventoried in each forest reserve. Our sample comprised 35 farm units representing a total forest area of 2345 ha and including 3592 *Carapa guianensis* trees.

2.4.2. Assessment of Agricultural Systems

Using the methodology described by Dufumier [33], we conducted interviews based on semi-structured questionnaires with 72 farmers, which enabled us to identify the following six main farm production systems:

1. A family farm with annual crops grown for self-consumption in which the income is supplemented by selling labor to other farmers;
2. A family farm with annual crops grown for self-consumption, production of cassava for sale, but no income from selling labor outside the farm;

3. (2) + Production of black pepper (*Piper nigrum*). There are two main subtypes: (a) pepper plantations without fusariosis (*Fusarium solani* f. sp. *piperis*) and (b) with fusariosis which give lower yields;
4. Intensive pepper production only using external labor;
5. (2) + cattle ranching with two subtypes (a) extensive cattle ranching with low pressure on pastures and (b) intensive cattle ranching with high pressure on pastures;
6. Family system mainly based on cattle ranching with the same subtypes as in 5 above.

The questionnaire also modelled the economic performance of each production system. The economic indicators selected for the model were annual family income (AFI), calculated using the following equation:

$$AFI = GI - CI - Re \quad (3)$$

where GI is gross agricultural income, CI are the costs of agricultural inputs, A the amortization of equipment, and Re other costs, such as contracted wages, rents, interest on loans, and taxes.

3. Results

3.1. Logging Intensity, Main Commercial Tree Species and Recovery of Timber Stocks

A total of 69,651 trees were inventoried in the four Annual Production Units before logging. Because the size of the APU varied from 518 ha to 1161 ha (Table 1), the number of trees inventoried also varied from 11,561 trees in APU 1 to 22,690 in APU 4. The most abundant timber species were *Manilkara huberi* (Ducke) Standl. (Sapotaceae) and *Carapa guianensis*, which represented almost 20% of all the trees inventoried in the four APUs (Table 3). The mean volumes harvested in the farm units were 937 m^3 and 1061 m^3 in APU 2 and APU 3 respectively, with no significant difference among the four (t-test, $t = 1.7$, $df = 20$, $p > 0.05$). The mean logging intensities in APUs 2 and 3 were 13 m^3/ha and 16 m^3/ha, both representing three harvested trees ha^{-1}. In APUs 2 and 3, a mean of 66% of the trees inventoried as harvestable were in fact harvested.

In the 18 sample plots selected in the three APUs, the mean density of trees with dbh ≥10 cm and the basal area were respectively 457 trees ha^{-1} and 22.4 m^2 ha^{-1} (Table 4). Although the mean tree density in the plots in APU 3 was lower than in APUs 1 and 2, this difference was not statistically significant (ANOVA, $F = 3.55$, $df = 2$, $p = 0.26$, Table 4). However, there was a significant difference in the mean basal area (ANOVA, $F = 3.96$, $df = 2$, $p = 0.04$), with a lower basal area in APU 3 than in APU 1 and APU 2 (Table 4).

Table 3. Density and relative abundance (% of the total number of trees inventoried = 69,651) of the dominant timber species in the four Annual Production Unit; the list includes the 10 most abundant timber species in each APU.

Names	***n***	**%**
Manilkara huberi (Ducke) Standl.	9,038	13.0
Carapa guianensis Aubl.	4,465	6.4
Pouteria bilocularis (H.J.P.Winkl.) Baehni	4,156	6.0
Lecythis jarana var. latifolia (Ducke) A.C. Sm	2,119	3.0
Sclerolobium melanocarpum Ducke	1,948	2.8
Couratari spp	1,548	2.2
Pouteria cladantha Sandwith	1,218	1.7
Vatairea guianensis Aubl.	1,214	1.7
Chamaecrista scleroxylon (Ducke) H.S. Irwin & Barneby	1,174	1.7
Manilkara sp	1,114	1.6
Couratari guianensis Aubl.	894	1.3
Piptadenia spp	702	1.0
Trattinnickia rhoifolia Willd	673	1.0
Pseudopiptadenia psilostachya (DC.) G.P.Lewis & M.P.Lima	554	0.8
Mezilaurus itauba (Meisn.) Taub. ex Mez	542	0.8
*Minquartia guianensis*Aubl.	460	0.7
Virola spp	457	0.7
Tetragastris altissima Aubl.(Swart)	426	0.6
Apuleia leiocarpa (Vogel) J.F.Macbr.	255	0.4
Hymenea spp	242	0.3
Total	33,199	47.7

Table 4. Distribution of trees according to the dbh classes in the 18 plots of the 3 APU.

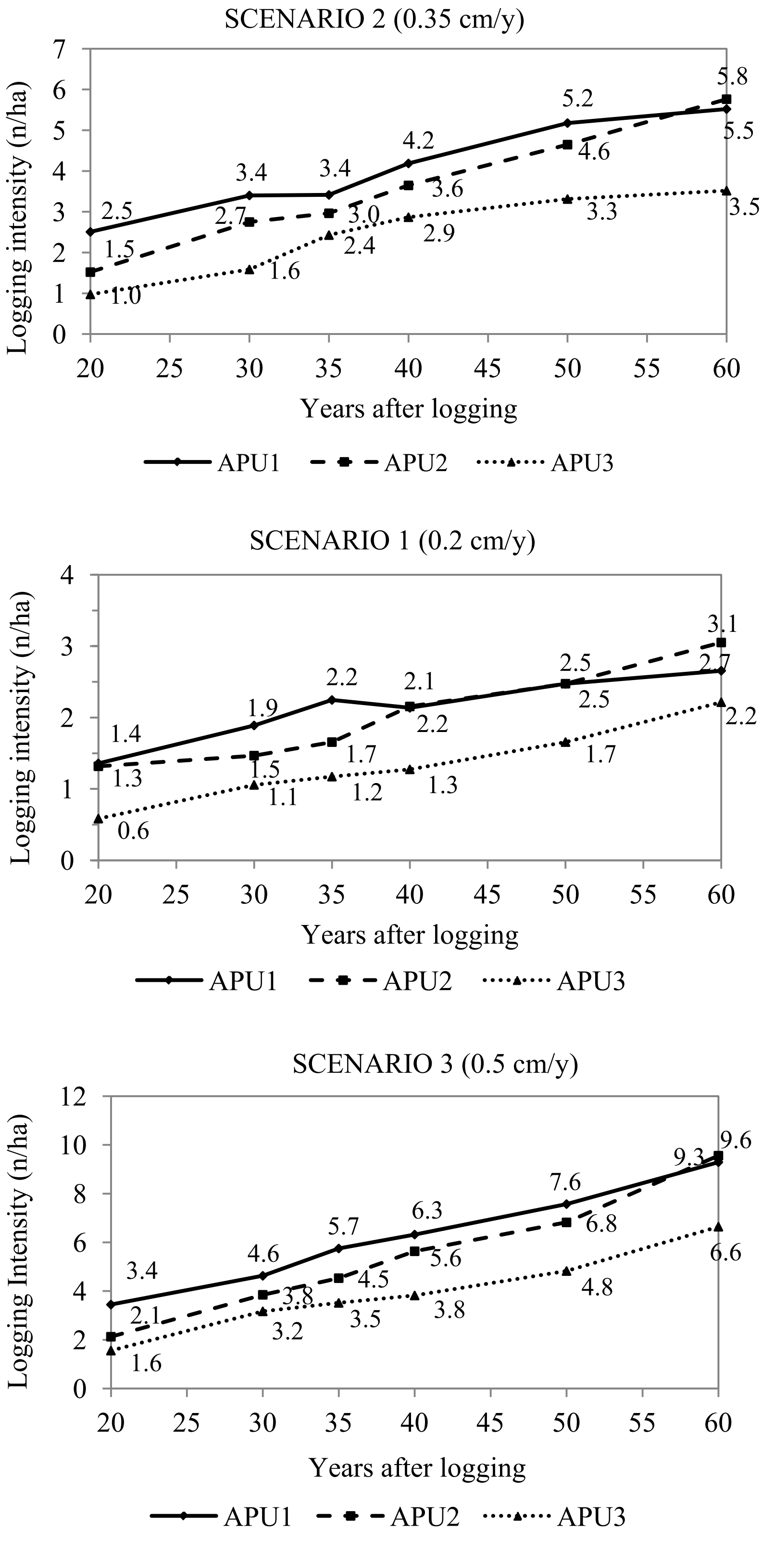
	Dbh Classes (cm)								**Mean density**	**Mean basal**
	10–20	**20–30**	**30–40**	**40–50**	**50–60**	**60–70**	**≥70**	**Total**	**n/ha (SD)**	**Area m²/ha (SD)**
APU 1 (N)	1829	445	191	115	61	22	42	2705	451 (53.8)	22.7 (5.3)
APU 2 (N)	1840	577	232	113	53	31	40	2886	481 (24.2)	25.7 (2.9)
APU 3 (N)	1840	431	176	82	42	31	32	2634	439 (69.3)	19.2 (2.9)
Mean (n/ha)	306	81	33	17	9	5	6	457		
SD	46	17	9	5	4	2	2	53		

The comparison of tree distribution according to dbh classes suggested a significantly lower density of large trees (dbh ≥ 70 cm) in APU 3 than in the other APUs, which explains the lower mean basal area in the APU 3 forest stand (Table 4, x^2 =36.23, df = 12, p < 0.001).

In the three scenarios, estimated timber stock recovery after logging in APUs 1 and 2 was similar whereas it was always lower in APU 3 (Figure 2). In the most optimistic scenario with a 0.5 cm year^{-1} annual diameter increment, the highest timber harvesting intensity 35 years after logging was in APU 1 with an estimated intensity of about 6 trees ha^{-1} and an estimated harvested volume of 18 m^3 ha^{-1} (means estimated on the total of 11,855 harvestable trees inventoried in the three APUs). In the other less optimistic scenarios, the logging intensity ranged from 1 to 2 trees ha^{-1} (3–6 m^3 ha^{-1}) in scenario 1

(0.2 cm year growth rate) and from to 2 to 3 trees ha^{-1} (7–10 m^3 ha^{-1}) in scenario 2 (0.35 cm year $^{-1}$ growth rate, Figure 2).

Figure 2. Recovery rates of timber stocks according to the three diameter growth rate scenarios Logging intensity = number of potentially harvestable trees.



3.2. Carapa Guinanensis Seed Production

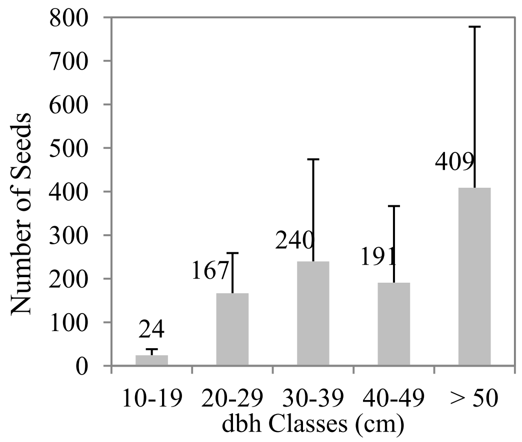
With a total population of 4465 trees and an average density of 1.4 individuals/ha before logging, *Carapa guianensis* was the second most abundant species in the pre-logging forest inventories conducted in the four APUs. However, these figures should be interpreted with caution since the minimum inventory diameter (dbh) of inventory *Carapa guianensis* was 20 cm, *vs.* 45 cm for the other timber species. The density of *Carapa guianensis* was the lowest in APU 1 with 0.7 trees/ha *vs.* 1.1 to 1.3 trees/ha in the other APUs. The abundance of *Carapa guianensis* also varied considerably from 0 to 199 trees depending on the unit concerned. Major variations like these have to be taken into account when planning the harvest, because they will also affect oil production, which depends directly on the density of *Carapa guianensis* trees in the farm land units.

During the 10 week fruit production monitoring period (7 March to 16 May 2009), the highest seed production was recorded in early March (Table 5). Among the 100 trees monitored, 66 trees produced a total of 17,141 seeds. The total weight of the seeds collected was 481 kg, with 384 kg of sound seeds and 97 kg (20% of total weight) of damaged seeds that were unsuitable for oil production (Table 5). The mean production was 5.8 kg of sound seeds per tree, but actual seed production varied from 0.2 to 51.5 kg. The minimum diameter of productive *Carapa guianensis* trees observed during this survey was 17 cm. Although there was no significant difference in seed production between dbh classes (ANOVA, $F = 1.68$, $p = 0.15$, $gl = 5$) and no significant correlation between seed production and dbh ($R^2 = 0.05$, $p = 0.06$, $df = 64$) trees with dbh 30–40 and 50–60 cm produced the most seeds with respectively 240 and 456 seeds per tree, *i.e.*, 6 and 10 kg respectively (Figure 3). Trees with dbh ≥ 30 cm represented 69% of productive individuals.

Table 5. Fruit counts of 100 trees of *Carapa guianensis* monitored in 2009.

Fruit Count	Dates	Seeds (n)	Healthy Seeds (kg)	Damaged Seeds (kg)
1	7–16 March 2009	13,891	316.8	77.7
2	21–22 March 2009	1,280	31.4	5.3
3	30–31 March 2009	1,396	32.0	8.1
4	7–8 April 2009	194	1.7	1.6
5	24–25 April 2009	309	1.7	4.1
6	16–18 May 2009	71	0.3	0.6
Total		17,141	384	97

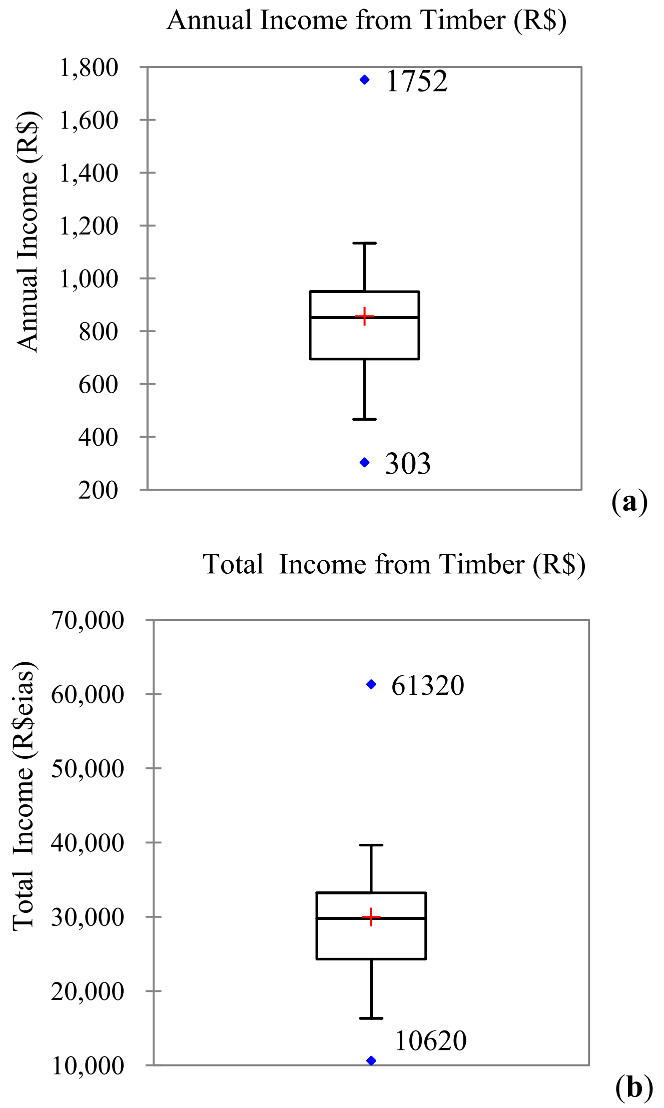
Figure 3. Mean production of seeds of Carapa according to dbh classes.



3.3. Profits from Timber Harvesting, Andiroba Oil Production and Agriculture

Mean annual income and total income from timber production calculated for APUs 2 and 3 were R$856 (US$468) and R$29,977 (US$16,380) respectively (Figure 4). Incomes varied considerably depending on the abundance of timber species in the forest reserve of each farm unit, from R$303 to R$1,752 annual income and from R$10,620 to 61,320 (US$5,800 to 33,510) total income (Figure 4). Considering that the mean surface of the forest reserve was 67 ha, the mean annual income per hectare of forest was therefore R$13 ha^{-1} (US$7.1).

Figure 4. Mean, minimum and maximum of annual (**a**) and total incomes (**b**) from timber harvesting.



Andiroba oil production during a period of high fruit production (*i.e.*, when 66% of the adults trees are productive), was estimated at 13,750 kg or 393 kg/farm. During a period of low fruit production (only 10% of adult trees producing fruits), seed production would drop to 2083 kg and the production of oil during low fruit production period would not be not economically profitable in any of the four scenarios as all the mean daily incomes would be less than R$20 or even negative (Figure 5a). The highest daily incomes were obtained in scenario 1(R$80 L^{-1} of oil) although the value was twice lower than the usual daily wage of an agricultural worker (Figure 5a). The other scenarios were not economically viable as daily incomes were all negative (Figure 5a). During the high fruit production period, the highest incomes were obtained in scenarios 1 and 2 (no significant difference in the means, Tukey's test, $p > 0.05$) with R$65 and R$61 day^{-1} or about three times the basic daily wage (Figure 5a). Scenario 4 was the only economically inviable scenario with a daily wage of only R$1 (Figure 5a). In scenarios 1, 2, and 3 economic viability also depended on the minimum number of adult *Carapa guinanensis* trees on each farm, which was 15 trees in scenario 1, 18 in scenario 2 and 62 in scenario 3 (Figure 5b). Mean annual family income in scenarios 1, 2, 3 and 4 was respectively R$1,985 (US$1,530), R$1,853 (US$1,010), R$849 (US$464) and R$117 (US$ 64) (Figure 5c). Mean annual income per hectare was R$30 ha^{-1} $year^{-1}$ (US$16 ha^{-1} $year^{-1}$), R$28 ha^{-1} $year^{-1}$ (US$15 ha^{-1} $year^{-1}$), R$13 ha^{-1} $year^{-1}$ (US$7 ha^{-1} $year^{-1}$) and R$2 ha^{-1} $year^{-1}$ (US$1 ha^{-1} $year^{-1}$) respectively in scenarios 1, 2, 3, and 4.

Estimated annual income from agriculture (Table 6) ranged from R$3,000 (US$1640) in the basic family system (type 1) to R$15,000 (US8197) in the agrarian system based on intensive black pepper production (type 4). The type 1 system corresponds to the one with the largest forest reserve area (92 ha). However, the intensive pepper production system undoubtedly has one negative aspect which is its high dependency on a single source of income, making it vulnerable to price fluctuations. The most diversified agrarian systems are types 3 and 5 which generate an estimated annual income ranging from R$6,000 (US$3278) to R$10,000 (US$5464, Table 6) for a forest reserve area of around 75 ha. Finally, the mean annual income per ha for the six different types of agrarian systems was R$633 ha^{-1} $year^{-1}$ with significant variations (R$163 ha^{-1} $year^{-1}$ for type 6a to R$1,875 ha^{-1} $year^{-1}$ for type 4, Table 6).

Figure 5. Incomes from *andiroba* oil production; (**a**) Daily incomes of the four scenarios in low fruit production period and during high fruit production; (**b**) relation between number of adult tree in the permanent forest reserve in each farm and daily incomes generated; (**c**) annual incomes in the four scenarios during a masting fruit period.

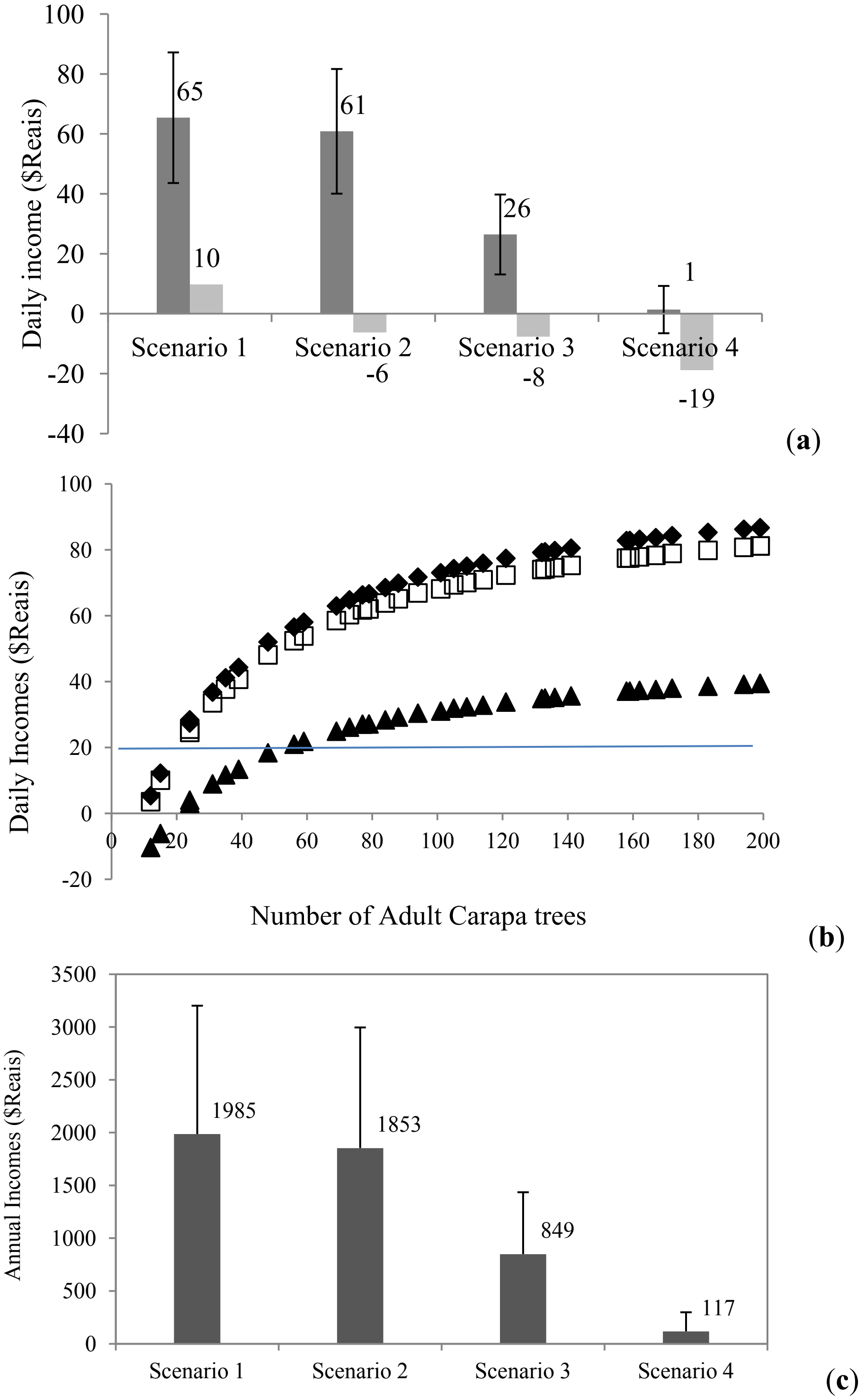


Table 6. Main types of agrarian production systems in the study area and mean annual incomes from agriculture and forest management.

		Main characteristics of the deforested area of the Farm Unit (há)							Incomes ($R)	
	n	**Farm Area**	**Annual Crops + Garden house**	**Pepper Area**	**Pasture**	**Secondary forest**	**Total deforested area**	**Forest reserve**	**Annual Incomes ($R)**	**Annual Income ($R/ha)**
Annual Incomes from Agriculture										
1. Familiar system with annual crop plant production farms for self-consuming in which the incomes are completed by selling labor to others farms	8	100	1.0	-	-	2.5	3.50	96.50	3,000	857
2. (1) + Production of Manioc for selling. and no incomes from labor selling outside the farm	14	100	2.5	-	-	10.0	12.50	87.50	8,250	660
3a. (2) + Production of pepper plantation without fusariosis	11	100	2.5	0.70	-	7.5	10.70	89.30	9,750	911
3b. (2) + Production of pepper plantation with fusariosis	13	100	2.5	0.25	12	10.0	24.75	75.25	6,038	244
4. Intensive pepper production with exclusively external labor	1	100	0.0	6.00	-	2.0	8.00	92.00	15,000	1 875
5a. (2) + extensive cattle ranching	9	100	2.5	0.40	10	9.0	21.90	78.10	6,600	301
5b. (2) + intensive cattle ranching	8	100	2.5	0.40	15	5.0	22.90	77.10	10,000	436
6a. Familiar system based on extensive cattle ranching	6	100	0.5	-	45	5.0	50.50	49.50	8,244	163
6b. Familiar system based on intensive cattle ranching	2	100	0.5	-	40	5.0	46.00	54.00	11,319	249
Means			**1.61**	**0.87**	**13.58**	**6.22**	**22.28**	**77.72**	**8,689**	**633**
Annual Incomes from Forest										
Mean annual Income from Timber	-	-	-	-	-	-	34	66	856	13
Mean annual Income from Andiroba (Scenario 1)	-	-	-	-	-	-	34	66	1,985	30
Mean annual Income from Andiroba (Scenario 2)	-	-	-	-	-	-	34	66	1853	28
Mean annual Income from Andiroba (Scenario 3)	-	-	-	-	-	-	34	66	849	13
Mean annual Income from Andiroba (Scenario 4)	-	-	-	-	-	-	34	66	117	2
Highest income from Forest	-	-	-	-	-	-	34	66	**2,841**	**43**

4. Discussion

The mean logging intensity in the study area ranged from 13 to 16 m^3 ha^{-1}. The timber recovery simulations indicated that for the next harvest in 35 years, the expected timber volume will range from 3 to 18 m^3 ha^{-1}. Harvesting a similar volume of timber in 35 years to that extracted in 2008–2009 would require maintaining high growth rates of the remaining potential crop trees as simulated in scenarios 2 (0.35 cm $year^{-1}$) or 3 (0.5 cm $year^{-1}$). However, post-logging growth rates reported in the region are relatively modest (0.2 cm $year^{-1}$, [21]) and only post logging silvicultural treatment would be capable of maintaining growth rates of potential crop trees in the range of 0.3–0.5 as simulated in scenarios 2 and 3. Without any silvicultural intervention, or an increase in the rotation cycle to at least 60 years, the volume harvested at the next rotation is likely to be much lower than that harvested during the first logging operations. Long-term data on post logging forest dynamics are still needed to provide more accurate estimation of timber yield.

Because of the high variability of timber density in the forest, the income generated by logging varied considerably from one farm forest reserve to another. The mean annual income from logging remained modest compared to the income from agriculture, although it did represent a complementary income of about 10% of annual income from agriculture (R$856 *vs.* R$8,669). On a per hectare basis, the mean annual income from timber sales was even lower compared to agricultural income (R$13 ha^{-1} $year^{-1}$ *vs.* R$633 ha^{-1} $year^{-1}$, US$7 to US$346 ha^{-1} $year^{-1}$, Table 6). However, it is important to point out that the one shot logging income received by each farmer represents a significant amount of money, from R$10,620 to R$61,320 (US$5,800 to US$33,508). This represents 3 to 20 times the annual income generated by the type 1 agrarian system. The price of R$30 m^{-3} (US$16) paid by the MAFLOPS logging company could be considered low compared to the sales price at the sawmill (mean price of round wood in Pará state = US$118 per m^3, [34]). However, in the partnership agreement between MAFLOPS and the farmers, the entire cost of drawing up and executing the forest management plan—including transport of the timber to the sawmill—is carried by the logging company. MAFLOPS is also responsible for the maintenance of the main access roads to the settlement, which legally speaking, is the responsibility of the government.

Considering a rotation cycle of 35 years and the low productivity of timber (less than 1 m^3/ha/year), the incomes generated by timber harvesting mainly depend on the size of the forest area harvested each year. It is clear that 67 ha of forest reserve area harvested at 35-year intervals cannot generate a high income. Community forests covering several thousand ha managed for timber harvest, like in the Tapajos National Forest located near the study area, indeed generate much higher annual incomes, between US$4,742 and US$5,347 $year^{-1}$ [35]. Moreover, in the region neighboring the Trans-amazon Highway road, Drigo *et al.* [7] reported that annual incomes generated by logging carried by a cooperative of farmers generated an annual economic benefit of US$1,921 per farmer. Although, this is much higher than the annual income calculated in the present study (R$856), the investment costs (*i.e.*, inventory costs; preparation of the forest management plans, annual operational plans; hiring of a forest engineer) were not taken into account as these costs were covered by a government program to promote community forest management [7]. Although communities are generally poorly informed about these costs, Drigo *et al.* [7] estimated them to exceed US$100,000 while Medina and Pokorny [36] estimated that the start-up costs of eight Brazilian Amazonian community forest enterprises ranged from US$22,400 to 348,000 (not adjusted for inflation). These investment costs were associated with the laborious administrative procedures required for the approval of the forest management plan by the State authorities, which usually takes two years. Such administrative costs are therefore the main limiting factors for community and family forest management in the Brazilian Amazon [5–7,36]. In these conditions, partnerships between logging companies and farmers are an alternative way for farmers to receive income from their forest without having to bear the prohibitive investment costs of drawing up forest management plans on their own. However, in practice, the partnerships between logging companies and farmers are generally informal (no legal agreements) and in most cases, favor the companies which usually pay very low prices for standing trees (e.g., R$10, Sablayrolles *et al.* [6], Menton *et al.* [8]. The partnership conditions between MAFLOPS and the farmers in the study areas are more profitable for the farmers than those described with informal logging companies, but are certainly not the most frequent type of partnership in the region.

In our study, the economic viability of the production of *andiroba* oil depended on three main factors. First the availability of the fruits, as *Carapa guianensis* is known for its irregular fruit production from year to year [29]. During a poor fruit production period, oil production will not generate a profit even under the scenario with the highest sales price of R$80. Second, according to our simulations, the minimum price to cover production costs is R$25 L^{-1}, and prices of R$50 or 80 would ensure higher profits. Third, the abundance of adult *Carapa guianensis* trees varies considerably among the permanent forest reserves of the farms and tree density will play a major role in the economic viability of oil production. For a sales price of R$50 to 80, the minimum number of adult trees in a forest reserve required to ensure economic sustainability was 15 and 18 trees respectively but increased to 62 trees for a sales price of R$25 (Figure 5b).

According to our estimates, the highest mean annual incomes generated by the permanent forest reserve of a farm would be R$2,841 (R$856 from timber and R$1,985 from *andiroba* oil production with a sales price of R$80, US$1,552), which are close to those generated by type 1 basic agricultural production system (R$3,000 or US$1,640) but five times lower than those generated by the intensive pepper production system (type 4). The maximum annual income from the forest is insignificant if calculated with respect to the mean area of the forest reserve (R$43/ha, US$24) and compared to that of the basic agriculture production system (R$857, US$476). Moreover, during periods of low fruit production, oil production is not economically viable and no income will be generated. Depending on the frequency of low fruit production years, the mean annual income for a period of several years) might be two or three times lower than that estimated in our study. This is the main limitation of this study, as we were unable to continue monitoring both timber reconstitution and *andiroba* fruit production over a period of several years.

Finally, the direct economic benefits from multiple forest use are well below less tangible regional and international benefits associated with the ecosystem regulation services of Amazonian forests. *i.e.*, under a scenario that compensates for avoided degradation, the possible economic value of carbon stocks lost in logging operations is higher than the price paid to farmers for timber [37]; secondly, and possibly more relevant, disturbance of the regulation of regional rainfall regimes caused by forest loss [38], may result in water scarcity in the future and hence in important economic losses that are not taken into account when considering the economic value of multiple forest use at the present time.

Current instruments for transforming regional and worldwide benefits from tropical forests into local economic benefits are not sufficient to fill this gap. The conceptual underpinnings of multiple-use forest management (MFM) for timber and non-timber values in tropical forests were laid down almost 20 years ago [15]. Since then, only a few MUFM systems have been implemented in the tropics, the most cited examples being those implemented in Guatemala and Mexico [14,16]. If multiple use management in tropical forests is recognized to be the preferred alternative, in practice, so far, it has remained an elusive goal and is largely ignored as a forest management alternative by stakeholders of the forestry sector.

5. Conclusions

Although, the present study is not representative of multiple use forest management systems in all regions, it is one of the few case studies to assess the economic performance of a multiple-use forest management system in a small farmers' settlement, and thus provides important information on the potential and the limitation of such systems.

In this study, the mean annual economic benefits from multiple forest use are the same as the least productive farm production system, but only equivalent to 25% of the annual income generated by the most productive system. These figures reveal the limits of multiple forest use when compared to income generated by agriculture. Nevertheless, although income generated by logging may be considered low when calculated on an annual basis and compared to income generated by agriculture, the cash payment after logging represent a significant amount of cash that could be used to implement more intensive and productive cropping systems such as planting pepper. Establishing 1 ha of black pepper in the region was estimated to cost R$2,796 (US$1,528) [39]. The income from the forest could therefore be used to increase the income from agriculture through a shift to high value crops such as pepper. Other possible investments could also be establishing permanent fields for highly productive annual crops using conservation agriculture techniques, which also require high investment (R$3,000 ha^{-1} for 1 ha of rice or corn) but would result in a significant increase in crop productivity (from 4 to 5 T ha^{-1}) in comparison with the traditional crop production system (less than 1 T ha^{-1}, Sist, *et al.* [40]).

While until recently, large farms were estimated to be responsible for 75% of the deforestation *vs.* 25% for small landholders [41], analysis of recent satellite images showed that deforestation in smaller land units has increased significantly in the last few years [42]. The cause of this new trend might be a higher proportion of deforestation by small farmers who are having difficulty adapting their own practices to the new laws against deforestation [11]. If this is the case, there is an urgent need to find alternatives to the traditional form use of land by small farmers, based on periodic clearing of forest land. The income generated by forest management might be part of the solution to enable small farmers to invest in these new alternatives. Nevertheless, the shift in current agriculture practices towards more sustainable conservation agriculture techniques will also require technical and legal support from the State to help small farmers implement alternatives whose aim is to integrate forest management in sustainable agricultural production systems.

Finally the Brazilian forest still poorly take into consideration the condition of small farmers or communities (low investment capacity, poor knowledge of forestry techniques, and poor connections with timber markets) and legislation is undoubtedly more in favor of the mechanized intensive selective logging practiced by forest companies than local small scale forestry. It is therefore crucial to revise current legislation in order to take the specific conditions of small scale forestry carried out by small farmers and forest communities into account.

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Author Contributions

All authors contributed to the conceptual development and methodology for the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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