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Harvesting Criteria Application as a Technical and Financial Alternative for Management of Degraded Tropical Forests: A Case Study from Brazilian Amazon

Marco A. Siviero [1], Ademir R. Ruschel [2], Jorge A. G. Yared [1], Osmar J. R. de Aguiar [3], Paulo C. G. Pereira [4,5], Sabrina B. Vieira [1] and Agust Sales [1,5,*]

1 Grupo Arboris, Department of Research and Innovation, Dom Eliseu 68633-000, PA, Brazil; marco.siviero@grupoarboris.com.br (M.A.S.); jagyared@gmail.com (J.A.G.Y.); sabrina.benmuyal@grupoarboris.com.br (S.B.V.)

2 Embrapa Amazônia Oriental, Eastern Amazon Brazilian Agricultural Research Corporation P.O. Box 48, Belém 66095-100, PA, Brazil; ademir.ruschel@embrapa.br

3 Universidade do Estado do Pará, Center of Natural Sciences and Technology, Paragominas 66095-015, PA, Brazil; o.aguiarromeiro@gmail.com

4 Universidade Federal Rural da Amazônia, Department of Forest Engineering Campus Paragominas, Paragominas 68625-970, PA, Brazil; paulo.pereira@ufra.edu.br

5 Universidade Federal de Viçosa, Department of Forest Engineering, Viçosa 36570-000, MG, Brazil

* Correspondence: agust.sales@ufv.br

Received: 1 July 2020; Accepted: 5 September 2020; Published: 27 September 2020

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Abstract: This article addresses a case study on the application of criteria for harvesting, aiming at restoration and profitability in a degraded tropical forest in the Amazon. The objective is to provide technical and economic information to promote a truly sustainable silvicultural management system in forests with this profile and turn them into a desirable financial asset for conservation and social development. In the forest census, 85.907 trees ha^{-1} (100.8566 m^3 ha^{-1}) were inventoried with diameter at breast height (*dbh*) ≥ 25 cm, belonging to 106 commercial species. When applying the harvest criteria, 19.923 trees ha^{-1} (29.99 m^3 ha^{-1}), referring to 53 species, were destined for harvest. Some trees were selected by more than one criterion, totalizing 17.985 trees ha^{-1} by density, 1.831 trees ha^{-1} by compromised health, 0.212 trees ha^{-1} by maximum *dbh*, 18.933 trees ha^{-1} by minimum *dbh*, 1.385 trees ha^{-1} by tree stem (quality 3), and 0.080 trees ha^{-1} by species conservation. In all scenarios, the application of criteria for harvesting proved to be profitable with excellent cost–benefit ratios. The selection of trees with a minimum cutting diameter of 25 cm in shorter cycles tends to allow the promotion of new commercial species. The set of actions presented has the potential to favor the maintenance of biodiversity and expansion of low-density populations, health and the potential increment of the forest productivity. In addition, it is more feasible for the supply of forest products in a shorter time than provided for in Brazilian regulations; however, they must respect the specificities of the species and also of the site.

Keywords: forest economics; forest harvest; harvest diameter; management of natural forests

1. Introduction

The management of natural forests seeks to conserve forest resources and to perpetuate forest production with sustainable feedstock for industry [1–3]. However, discussions show the confrontation and difficulties in establishing rational parameters that enable environmental, social, and economic interests in the use of natural forests [4–6]. Studies in the region show mainly the ecological character of management through floristic composition, diversity of tree species, and growth dynamics, encouraging managers to justify the management of species outside the standards prescribed in the regulations that guide such activity [7–10]. In this context, it has been a challenge to reconcile economic interests with the maintenance of natural forests [11,12].

Through the last decades, nascent knowledge about the renewable potential of forest resources and the deforestation increase in the Amazon have encouraged Brazilian authorities to take preventive measures. In Brazil, several initiatives were established to conserve the Amazon rainforest: (a) creation of a legal reserve area for the sustainable use of 50% of the area covered with native vegetation on the property [12] and later changed to 80% [13]; (b) establishment of the minimum diameter cutting rule (MDC) for harvesting in natural forests, first MDC ≥ 45 cm, afterward MDC ≥ 50 cm; (c) gap of 25 to 35 years between harvests [14,15]; and (d) Law on Environmental Crimes, nº 9605 of 1998 [16].

The Brazilian Forest Code defines the sustainable forest management in a broad way, while the specific rules establish homogeneous and rigid criteria for the management of all types of forests [13–15]. In this aspect, forests are managed as if they were similar or in the same stage of development or anthropization. However, forests in the Amazon have a diversity of 6727 tree species [17], with different floristic composition, diametric structure, growth, life cycle, and adaptation [5–25].

Intensely anthropized forests are a type of vegetation that corresponds to approximately 4.5 million hectares in the Amazon, according to the monitoring of the DEGRAD Project from 2006 to 2016 [26]. If managed rationally, those forests could present perennial sources to supply human needs, considering that forest resources, especially wood, are renewable goods [27]. However, the current management rules limit forestry activity. Rules encourage producers to join agribusiness, converting their forest areas into areas intended for agriculture or animal husbandry [28,29]. These restrictions increase the number of areas with agricultural and animal production, since the legal and technical difficulties in conducting the productive restoration of degraded forests discourage producers from investing.

In this context, Brazilian regulations must supplement and promote the management of different types of forest formations and not impose limiting measures to prevent those forests from being rationally used. The adoption of a technically adequate silvicultural management system can significantly contribute to forest management, respecting the ecosystem's sustaining mechanisms and considering cumulative or alternative use of multiple species [13,30].

Research institutions and forestry companies concerned with the maintenance of natural forests began to invest in research that sought to make conservation and production aspects viable. Recently, advances have been made in the knowledge of anthropized forests with the use of new species, the technology for small-scale wood processing, the enrichment of forest clearings that had been intensively exploited, with fast-growing species, and the conduction of regeneration species that are interesting to the market [21–35]. Studies with this focus aim to enable ecological, productive, and economic management. However, there is still no management proposal that makes forests' productive restoration environmentally and financially feasible.

There is no doubt about the importance of studying sustainable means of production for tropical forests, especially for the Amazon rainforest. This article addresses a case study on the application of criteria for harvesting, aiming at environmental restoration and profitability in a degraded tropical forest in the Amazon. The objective is to provide technical and economic information to promote a truly sustainable silvicultural management system in forests with this profile and turn them into a desirable financial asset for conservation.

2. Material and methods

2.1. Study Area

Shet Farm, managed by Grupo Arboris, is located in the municipality of Dom Eliseu, state of Pará, Brazil (altitude 320 m, 4°30′48″ S and 47°39′36″ W). The forest management is carried out in the Legal Reserve area (535.6 ha), subdivided into seven working units (UT) (Figure 1). This study is part of the SubBosque Project, registered by the Innovation Network of the logging forest production chain to promote the sustainable development of the State of Pará-SubBosque Forest Biomass Network (Embrapa Project SEG Code 02.10.00.001.00.02).

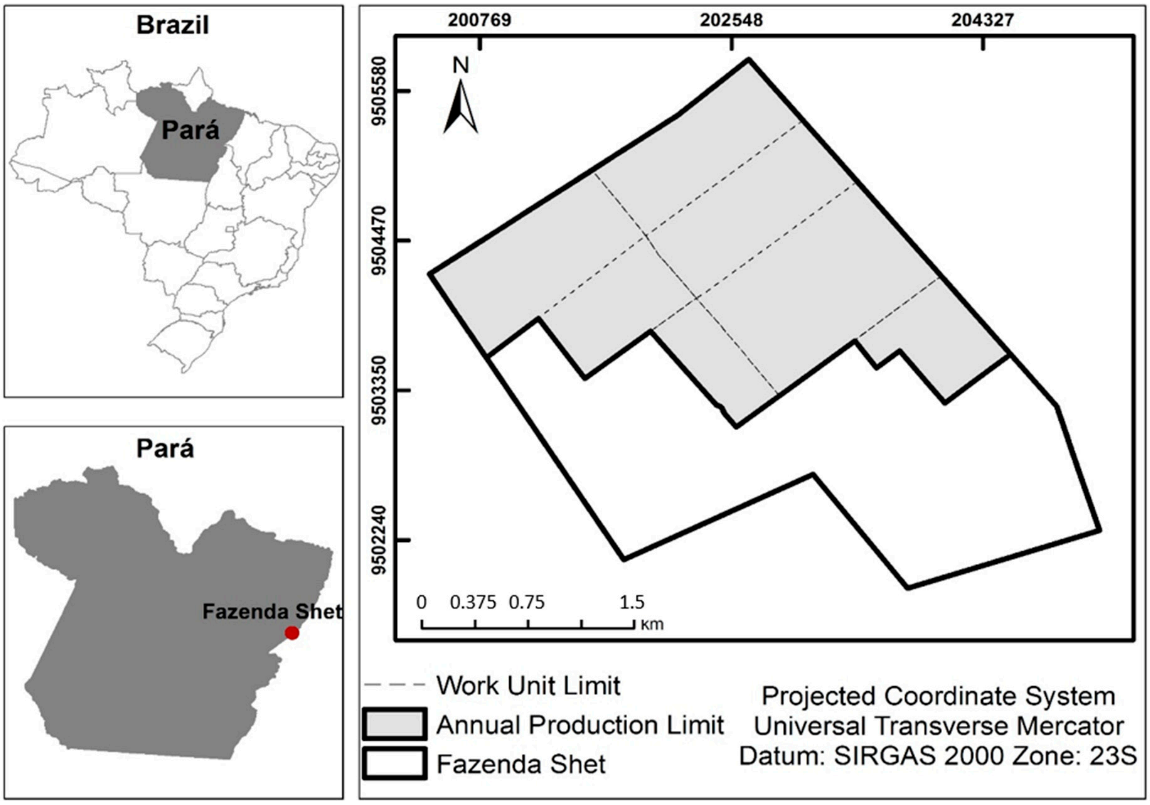

Figure 1. Location and description of Shet Farm, Dom Eliseu, Pará, Brazil.

The climate in the region is Aw (Köpen). Tropical climate with summer rains and average annual rainfall of 2500 mm [36,37]. The average annual temperature is 25 °C [38]. The vegetation type of the municipality is dense submontane ombrophylous forest with emerging canopy [39]. The predominant soils are dystrophic yellow latosol and dystrophic red-yellow argisol [40].

Shet Farm is represented by a degraded natural forest, which is a characteristic of the region of the deforestation arc in the Amazon [41]. Such forest was degraded due to illegal logging activity that took place between the 70 s and 90 s, with no information on the volume of extracted wood. The first legal logging activity in the area occurred in 1993 and 1994, allowed by the Brazilian forestry authorities, with an average harvest volume of 65 m^3 ha^{-1}. The current regulation that prescribes a maximum harvest of 30 m^3 ha^{-1} for the Amazon rainforest began only in 2006 [14]. Enrichment planting was carried out sowing paricá (*Schizolobium parahyba var. amazonicum*) in the clearings formed by logging activity between 1993 and 1994 [33].

A forest inventory was carried out in 2008, in which all trees with the diameter at breast height (*dbh*, the diameter at 1.3 m in height) ≥ 25 cm were evaluated. The methodology proposed by [42] was used to perform the forest census. The following procedures were performed: botanical identification and vines cut off; attachment of a numbered label at the base of the tree trunk; *dbh* measurement; visual estimate of commercial height; classification regarding shaft quality (shaft 1—straight and cylindrical shaft; shaft 2—slightly tortuous and/or ribbed; shaft 3—crooked, strongly ribbed or forked); and health (rot, senescence, broken, dead, and/or fallen tree top).

The census quantified 46,010 trees and 106 species divided into three market value groups that were defined by the company. For the groups 1, 2, and 3, 13, 41, and 52 species were included, respectively. The trees were classified as "for harvest" or "remaining" (next harvest). For harvesting resulted in a total of 10,671 trees of 53 species, with 13 m average height, 37 cm average *dbh*, 16,067.53 m^3 volume, and production for harvest of 29.99 m^3 ha^{-1} (Table 1).

Table 1. Species (commom and scientific name) listed by market value group, forest management area (535.6 ha) at Shet Farm, Dom Eliseu, Pará, Brazil.

Group 1
Angelim-pedra (*Hymenolobium petraeum* Ducke); cedro (*Cedrela odorata* L.); copaíba (*Copaifera* Ducke); cumaru (*Dipteryx odorata* (Aubl.) Willd.); freijó-cinza (*Cordia goeldiana* Huber); ipê-amarelo (*Handrohanthus serratifolius* (Vahl) S. Grose); jatobá (*Hymenaea courbaril* L.); jatobá-curuba (*Hymenaea parvifolia* Huber); louro-canela (*Nectandra* sp.); maçaranduba (*Manilkara elata* (Allemão ex Miq.) Monach.); muiracatiara (*Astronium lecointei* Ducke); roxinho (*Peltogyne lecointei* Ducke); and tatajuba (*Bagassa guianensis* Aubl.).
Group 2
Amapá (*Brosimum guianense* (Aubl.) Huber); amarelão (*Apuleia leiocarpa* (Vogel) J. F. Macbr.); amescla/breu (*Trattinnickia burseraefolia* Mart. Willd.); amescläo (*Trattinnickia rhoifolia* Willd.); amesclinha (*Protium altissimum* (Aubl.)) Marchand); angico/timborana (*Pseudopiptadenia suaveolens* (Miq.) J. W. Grimes); caju (*Anacardium giganteum* W. Hancock ex Engl.); caneleiro (*Cenostigma tocantinum* Ducke); casca seca (*Licania* sp. Aubl.); catuaba (*Lacmellea aculeata* (Ducke) Monach.); cedrorana (*Vochysia maxima* Ducke); coco-pau (*Coupeia robusta* Huber); cupiúba (*Goupia glabra* Aubl.); axixá/envira-quiabo (*Sterculia pruriens* (Aubl.) K. Schum.); envira/envira-preta (*Guatteria punctata* (Aubl.) R. A. Howard); escorrega-macaco (*Albizia pedicellaris* (DC.) L. Rico); estopeiro/tauari (*Couratari* sp. Aubl.); farinha-seca (*Ampelocera edentula* Kuhlm.); faveira (*Parkia multijuga* Benth.); goiabão (*Pouteria bilocularis* (H. K. A. Winkl.) Baehni); inharé (*Helicostylis pedunculata* Benoist); jarana (*Lecythis lurida* (Miers) S.A. Mori); louro-pimenta (*Ocotea* sp.); louro-vermelho (*Sextonia rubra* (Mez) van der Werff); mandiocão/morototó (*Didymopanax morototoni* (Aubl.) Decne. & Planch.); marupá (*Simarouba amara* Aubl.); orelha-de-macaco (*Enterolobium schomburgkii* (Benth.) Benth.); paricá (*Schizolobium parahyba* var. *amazonicum* (Huber ex Ducke) Barneby); pau-santo (*Zollernia paraensis* Huber); pequiá (*Caryocar vilosum* (Aubl.) Pers.); pequiarana (*Caryocar glabrum* (Aubl.) Pers.); quina (*Geissospermum sericeum* Miers); quina-rosa (*Quiina amazonica* A.C.Sm.); sapucaia (*Lecythis pisonis* Cambess.); seringarana (*Ecclinusa guianensis* Eyma); sumaúma (*Ceiba pentandra* (L.) Gaertn.); tanibuca (*Terminalia tanibouca* Rich.); itaúba (*Mezilaurus itauba* (Meisn.) Taub. ex Mez); tauari (*Couratari* ssp./*Eschweilera coriacea* (DC.) S. A. Mori) and uxi (*Endopleura uchi* (Huber) Cuatrec.).
Group 3
Amarelinho (*Neoraputia paraensis* (Ducke) Emmerich ex Kallunki); andirobarana (*Guarea kunthiana* A. Juss.); ata (*Annona* sp.); atraca (*Ficus* sp.); baço-de-boi (*Myrocarpus venezuelensis* Rudd); bicuíba/ucuúba-da-terra-firme (*Virola michelii* Heckel); Buranju (*Neea floribunda* Poepp. & Endl.); Cacau (*Theobroma speciosa* Willd. ex Spreng.); canafístula (*Senna multijuga* (Rich.) H. S. Irwin & Barneby); capa-bode (*Bauhinia acreana* Harms.); conduru (*Cynometra bauhiniifolia* Benth.); cravinho/goiabarana (*Myrcia paivae* O.Berg); embaúba (*Cecropia distachya* Huber./*C. sciadophylla* Mart./*C. palmata* Willd.; *Pourouma guianensis* Aubl.); freijó-branco (*Cordia alliodora* (Ruiz & Pav.) Cham.); Gabiroba (*Campomanesia grandiflora* (Aubl.) Sagot); gema-de-ovo (*Amphiodon effusus HuberPoecilanthe*); goiabinha (*Eugenia lambertiana* DC.); inajarana (*Quararibea guianensis* Aubl.); ingá (*Inga* spp.; *Inga alba* (Sw.) Willd.; jaca-braba (*Abarema campestres* (Spruce ex Benth.) Barneby & J. W. Grimes); jambo/muúba (*Bellucia grossularioides* (L.) Triana); jiboião/matamatá-preto (*Eschweilera grandiflora* (Aubl.) Sandwith); jurema (*Senna polyphylla* (Jacq.) H. S. Irwin & Barneby); juruparana (*Gustavia augusta* L.); limãozinho (*Zanthoxylum rhoifolia* Lam/*Z. ekmanii* (Urb.) Alain); mangaba/abiu-mangabarana (*Micropholis guyanensis* (A. DC.) *Pierre*); mangue (*Buchenavia capitata* (Vahl) Eichler); maria-preta (*Ziziphus cinnamomum* Triana & Planch.); matamata/matamata-jibóia (*Eschweilera ovata* (Cambess.) Mart. ex Miers); mirindiba (*Glycydendron amazonicum* Ducke); moreira (*Maclura tinctoria* (L.) D. Don ex Steud.); mutamba (*Guazuma umifolia* Lam.); pele de sapo (*Pausandra trianae* (Müll.Arg.) Baill.); pitomba (*Talisia* sp.); seringueira (*Hevea brasiliensis* (Willd. ex A Juss) Mull. Arg.); tamburil (*Enterolobium maximum* Ducke); taxi/taxi-branco (*Tachigali vulgaris* L. G. Silva & H. C. Lima/*Tachigali glauca* Tul.) and tuturubá/abiurana (*Pouteria guianensis Aubl./Pouteria venosa* subsp. amazonica T. D. Penn)

2.2. Harvesting Criteria

According to Brazilian regulations for harvesting in natural forests, only trees with $dbh \geq 50$ cm can be harvested [14]. To support this research, an authorization for wood extraction was issued by the Pará State Department of Environment and Sustainability (SEMAS-PA) to harvest trees with $dbh \geq 25$ cm.

The harvesting criteria were established based on the harvest history of the area, considering trees' silvicultural conditions and the ecological behavior of the species. The criteria were applied together or separately to select the trees. With these parameters, the following criteria were defined for the harvest, in this order:

Density: tree harvest of species with higher density in the management area, aiming at the conservation of low-density species and the maintenance of biodiversity. The density was obtained using the equation [43]:

$$Da = \frac{n_i}{A} \quad (1)$$

where *Da* absolute density; n_i = number of inventoried trees of the *i*-th species; and *A* = total sampled area, in hectare.

Health: harvest of trees identified with rot, senescence, broken top, signs of disease, or death were selected for harvest. Traditionally, trees with compromised health are not selected for harvest. However, the permanence of these trees influences negatively the quality of the future forest as they are more susceptible to pests and diseases, facilitating their proliferation. Furthermore, trees in these conditions use growth resources (space, light, water, and nutrients) that could be made available for healthy and productive trees. In general, trees with compromised health have a reduced life cycle.

Maximum *dbh* (>100 cm): harvesting trees with *dbh* > 100 cm. This criterion aims to increase the population of trees with smaller diameters. The harvest of trees with larger diameters helps to make the future industrial plant suitable for a larger number of trees of smaller diameters compatible.

Minimum *dbh* (≥25 and <50 cm): harvesting trees with *dbh* (≥25 and <50 cm) below the one provided in Brazilian regulations was performed. It includes species that, due to biological characteristics, do not reach the minimum *dbh* recommended by law in the industrial production process.

Tree stem: harvesting trees with tree stem type 3 for the maintenance of trees with tree stem types 1 and 2.

Conservation: all inventoried trees of low-density species (≤0.15 tree ha^{-1}) were maintained for seed production, natural regeneration, and species diversity maintainance. On the other hand, the species *A. lecointei*, *C. odorata*, *C. goeldiana*, *Copaifera* sp., *H. courbaril*, *H. petraeum*, *H. serratifolius*, and *M. elata* that had been pressured in previous harvests, regardless of density, were then selected as remaining. However, the trees of these species classified by the aforementioned criteria (health, shape shaft, and maximum *dbh*) were destined for harvest.

2.3. Cost–Benefit and Sensitivity Analysis

Net present value (*NPV*) was used to estimate profitability of criteria for harvesting in degraded forests. *NPV* is a tool to calculate profitability of projects through discounted cash flow analysis [44]:

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

where B_t is the revenues for the sale of standing wood in year *t*, C_t is the total cost in year *t*, *r* is the discount rate per year, *t* is the year when revenue or cost occurs, and *n* is the time demanded for revenues. Only *NPV*s larger than zero indicate profitability of the investment [45]. The profitability of the sale of standing wood was calculated based on the 13 years of forest growth, after the last logging at Shet farm.

Cash flow was based on field worksheets provided by the Arboris Group, with a total cost of USD 37.82 ha^{-1}, which is the sum of the annual cost plus the costs of forest census, planning for harvest, and management. The revenues considered for the sale of standing wood is the result of the volume of wood multiplied by the price determined by the business group for the inventoried species, according to the market value group (1, 2, and 3). Based on the values of costs and revenues, a cash flow was created using current values (Table 2).

Table 2. Current values of forest management activity. Production for harvest and sales prices of standing timber, market value group, and cash flow for Shet Farm, Dom Eliseu, Pará, Brazil.

Production for Harvest (m^3 ha^{-1})	Market Value Group						Cash Flow (USD ha^{-1})		
	Production (m^3 ha^{-1})			Price (USD m^{-3})			Cost	Revenue	Balance
	1	2	3	1	2	3			
29.99	0.46	19.77	9.77	43.04	17.39	14.58	37.82	506.00	468.18

A nominal interest rate of 7% per year was used to estimate profitability. This is the interest rate on the capital loan considered by Banco do Brasil's Commercial Forest Planting Program (PROPFLORA) and other banks accredited by the National Bank for Economic and Social Development (BNDES) for investing and producing forests.

Scenarios with different interest rates were constructed through a sensitivity analysis to project the profitability of the commercialization of trees authorized for harvest. In addition to the basic rate of 7%, other scenarios were built with interest rates of 4% and 10% per year. These scenarios aim to encompass, through interest rates, possible economic fluctuations in wood-based products and forest production inputs/operations and, consequently, in the cost of production, wood selling price and interest rates, and to project how they can affect the *NPV* if they occur.

3. Results

3.1. Technical Analysis

In the forest census, 85.907 trees ha^{-1} (100.8566 m^3 ha^{-1}) were inventoried with *dbh* ≥ 25 cm, belonging to 106 species. When applying the harvest criteria, 19.923 trees ha^{-1} (29.99 m^3 ha^{-1}), referring to 53 species, were destined for harvest. Some trees were selected by more than one criterion, totalizing 17.985 trees ha^{-1} by density, 1.831 trees ha^{-1} by compromised health, 0.212 trees ha^{-1} by maximum *dbh*, 18.933 trees ha^{-1} by minimum *dbh*, 1.385 trees ha^{-1} by tree stem (quality 3), and 0.080 trees ha^{-1} by species conservation (Figure 2).

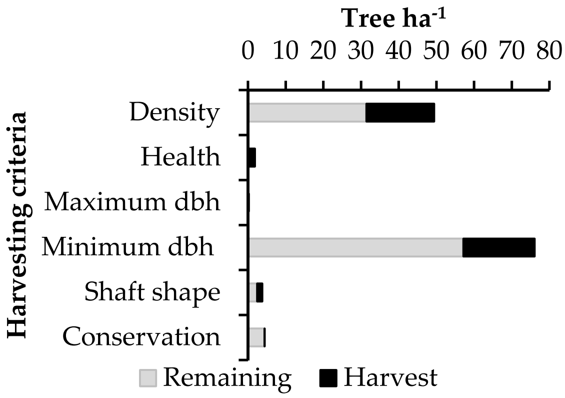

Figure 2. Trees selected for harvest and remaining trees (RM), forest management area (535.6 ha) at Shet Farm, in Dom Eliseu, Pará, Brazil.

Among the inventoried population, 57.50% (49.401 trees ha^{-1}) are *S. parahyba* var. *amazonicum*, genus *Cecropia* (*C. distachya*, *C. sciadophylla*, *C. palmata*), *C. aliodora*, *H. pedunculata*, *Inga* spp., *P. guianensis*, *S. pruriens*, *T. burseraefolia*, *Talisia* sp., and *Z. ekmanii*. These species contributed 90.26% of trees (17.985 trees ha^{-1}) and 80.29% of volume (24.0863 m^3 ha^{-1}) of the harvest. *S. parahyba* var. *amazonicum* (12.881 trees ha^{-1}) and genus *Cecropia* (12.705 trees ha^{-1}) were the species with the highest tree density (29.78% of trees) and the highest harvested volume (58.30%).

The trees classified by the health criterion represented 2.16% (1.854 trees ha^{-1}) of the total inventoried, totalizing 48 species and 1.4032 m^3 ha^{-1}. Of this total, 98.79% (1.832 trees ha^{-1}) were destined for harvest totalizing 1.3943 m^3 ha^{-1} (99.37% m^3 ha^{-1}). The species that had compromised health were more frequently genus of *Cecropia*, *Inga* spp., *T. burseraefolia*, and *P. guianensis*, representing 67.18% of the population destined for harvest by this criterion.

The population inventoried with *dbh* > 100 cm was 0.269 trees ha^{-1} (0.31%), 28 species, and a volume of 3.6182 m^3 ha^{-1}. According to the maximum *dbh* criterion, 0.213 trees ha^{-1} (79.17%) of 20 species with a volume of 2.9250 m^3 ha^{-1} (80.84%) were destined for harvest. The species *C. tocantinum*, *P. suaveolens* and *T. burseraefolia*, contributed 64.04% of the trees destined for harvest by the maximum *dbh* criterion.

Among the inventoried population, 76.387 trees ha^{-1} (88.92%) belong to 104 species and were present in the *dbh* classes between 25 and 55 cm. When the minimum *dbh* criterion (≥25 and <55 cm) was applied, 17.657 trees ha^{-1} (21.7044 m^3 ha^{-1}), distributed in 47 species, were destined for harvest. In the middle of the species with the highest frequency of trees destined for harvest by the minimum *dbh* criterion are genus *Cecropia*, *Inga* spp., *P. guianensis*, *S. parahyba* var. *amazonicum*, *S. pruriens*, *T. burseraefolia*, and *Z. ekmanii*, representing 89.77% (16.882 trees ha^{-1}).

In the forest census, 4.671 trees ha^{-1} (6.0073 m^3 ha^{-1}) with a tree stem type quality 3 were verified and allocated in 66 species, which corresponded to 5.44%. Among them, 29.66% (1.385 trees ha^{-1}) were destined for harvest, referring to 2.5297 m^3 ha^{-1} of 26 species. The species with the highest frequency of trees destined for harvest using the tree stem quality 3 criterion were genus *Cecropia*, *C. tocantinum*, *E. ovata*, *G. sericeum*, *Inga* spp., *P. guianensis*, *S. parahyba* var. *amazonicum*, and *T. burseraefolia*, with 1.142 trees ha^{-1} (2.1830 m^3 ha^{-1}).

The conservation criterion inventoried 4.221 trees ha^{-1} that correspond to 4.91% (7.5167 m^3 ha^{-1}) and belong to 13 species classified as having density below 0.15 trees ha^{-1} and pressed in the previous logging. Of these trees, 4.141 trees ha^{-1} (7.3532 m^3 ha^{-1}) were set as remainings and only 0.080 trees ha^{-1} were harvested.

3.2. Cost–Benefit and Sensitivity Analysis

Cost–benefit analysis indicates the application of the harvest criteria in a lucrative activity, proving that this forest management system is financially viable under the nominal interest rate of 6% per year, since their *NPV*s were higher than zero in all simulations (Figure 3).

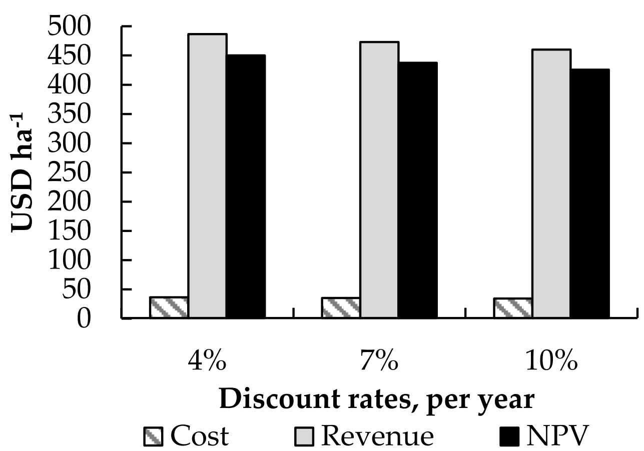

Figure 3. Cash flow and net present value (*NPV*) (USD ha^{-1}) with discount rates, from 4% to 10% per year, for the forest management activity submitted to harvest criteria at Shet Farm, in Dom Eliseu, Pará, Brazil.

Maintenance cost of the area is relatively low in the period of forest growth, with 95% of the costs associated with the activities of the year in which the forest census was carried out to sale of standing wood. This fact positively disfavors the other feasible activities for the area which, according to Brazilian regulations, would need at least two more decades to carry out standing wood sale activities.

Scenarios with interest rates below and above the rate of 7% per year showed positive *NPV* in all simulations. It shows that with a fluctuation in the discount rate between 4% and 10% there is no probability of obtaining an *NPV* below USD 425.62 ha^{-1}. This fact weighs in favor of forest owners who have invested in these forest profiles in recent decades but still could not economically enjoy the wood products of the respective forests.

4. Discussion

4.1. Technical Analysis

It is known that harvesting intervention in intensely pressured forests is one of the factors that influences the composition of future species in the forest, without compromising species diversity, mainly promoting the abundance of pioneer species, with no significant negative effect on shade-tolerant species [3,46,47]. In this case, the criteria defined for harvesting involve a rational management hypothesis aimed at maintaining the abundance of species in the forest, from the conservation of species and the use of trees with compromised health, senescents, and promoting species of greater and lower value in the forest.

In order to issue a logging authorization in natural forests in the Amazon, Brazilian authorities require trees with *dbh* ≥ 50 cm to be selected for harvest, directing the use of trees of larger diameter and species of high commercial value. However, this management pressures a reduced number of species in successive harvesting events, reducing the density and dominance of these species and compromising the perpetuation of forest production and abundance [14,47–49].

Some species do not reach the minimum diameter determined by Brazilian regulations (*dbh* > 50 cm) due to their own natural characteristics. These species are included in the forest productive chain by the destination for logging trees with *dbh* ≥ 25 cm and with a high population density [14,15,21]. One example is the *Cecropia* that is part of the plywood panel production chain at Adeco Indústria e Comércio de Compensados Ltd.a. industry located in Dom Eliseu-PA, Brazil [50]. The *Cecropia* is highlighted for being an important species in the recovery of the forest [51] and traditional medicine as well [52]. Other species such as *Manilkara elata, Swietenia macrophylla*, and *Dipteryx odorata* need more time to develop and become economically and ecologically productive [8,10,53–55].

Species submitted to enrichment planting in clearings and *S. parahyba* var. *amazonicum* (from this study) tend to form high density at the site [33]. Therefore, the result of forest clearing with *S. parahyba* var. *amazonicum* added to the natural regeneration of *Cecropia* genus specimens, both pioneers with short life cycle, promoted the restructuring and productive viability of the forest in approximately 10 years [21,56–58]. Consequently, it is suggested that these populations are preferably used for harvesting, supposing the maintenance of remaining trees of low-density species and favor the diversity of the forest. Researches carried out with the planting of *C. odorata*, *C. goeldiana*, *H. serratifolius*, *M. itauba*, and *H. courbaril* in clearings identified a relatively slower development [59,60]. It takes more time for the recovery process of forest productivity. However, such technique has potential for use in other species that have regeneration difficulties or in cases where density is intended to increase.

The health level of the trees is defined as one of the main causes of tree mortality [61]. Although this loss generaly does not have economic value, it is only evaluated as a priority when there is an importance of nutrient cycling [62]. It excludes the hypothesis that these trees are precursors of diseases that, biologically, could be transmitted to their descendants [63].

In this study, harvesting trees with compromised health is potential alternative to eliminate hosts of pests and diseases and to make available a greater amount of resources (e.g., space, light, water, and nutrients). Is is known that pests and diseases can lead to changes in the composition, structure, functions, and productivity of forests [64–66]. This criterion represented a relatively low percentage in relation to the total population inventoried (2.16%; 1.854 trees ha^{-1}). However, 98.79% of these trees with compromised health were destined for harvest and used in the industry.

The Amazon wealth is characterized by the rarity of species [67], and knowledge about the density per species to define the degree of their conservation is limited [68]. The minimum population density (>0.15 trees ha^{-1}) defined in this study takes into account the stages of plant development [69] so that the richness, diversity, and productivity of multiple species are maintained. The conservation of low-density species and those defined as being widely pressured in previous harvests was applied to favor natural regeneration and to expand the population in future harvests, according to the concept proposed of population control. The same could be applied to the tree stem criterion, which indicates that priority should be given to harvesting trees with tree stem quality 3 and senescent in the forest, seeking to improve the quality of the forest based on the concept of population genetics that defines matrix trees to generate descendants with better quality.

4.2. Cost-Benefit and Sensitivity Analysis

Successful the application of criteria for harvesting in this study confirms the results from other experiments [24–29]. The authors suggest the economic efficiency and ecological potential of applying harvesting criteria to degraded tropical forests, which presents itself as a potential silvicultural alternative for the management of the tropical forest.

The use of silvicultural practices aiming profitability at short, medium and long term is one of the factors that makes it possible to make the management of tropical forests truly sustainable for maintaining wealth and productivity. This study demonstrates the application of technical and economic tools that aim to increase the health and productivity of these forest profiles, contribute significantly to breake paradigms and encourage effective practices of sustainable management of intensively exploited tropical forests.

Applying the criteria for harvesting makes it possible to have financial profitability from the potential conservation techniques of species and the use of trees with compromised health, senescents, and promoting species of greater and lower value in the forest. Furthermore, the application of these criteria for harvesting tends to promote continuous forest production, which is an essential factor for this type of forest to become desirable for conservation.

It is suggested that tree harvesting in Amazon forests that are considered intensively exploited should be treated as silvicultural interventions aiming to maintain biodiversity and timber productivity. Remaining trees could be benefitted from the low canopy height (20 m) of the degraded forest in Fazenda Shet. Lower canopy heights contribute for a larger illumination reaching the forest floor [27]. Dealing with the forest as an environmentally and financially productive structure throughout the interventions process is a promising purpose to awaken the people's desire and motivation to care for and to maintain this standing forest profile.

As a viable silvicultural alternative, the application of criteria for harvesting can be applied in tropical forests under risk of land use changes [29]. Such treatment can provide a high timber production while the treated forest maintains its environmental services. This is particularly important in the arc of deforestation region [21,48], in the Brazilian Amazon, where the experiment was developed. The arc of deforestation, a 500,000 km^2 area in south and southeast Amazon, presents high levels of forest losses and degradation due to decades of uncontrolled logging. Its landscapes are formed by a mosaic of lands covered by crop fields, pastures, and degraded forests.

At this moment, it is necessary to comment on the management of natural forests in the Brazilian Amazon and forests that have been intensively explored in the past. Financial returns, however, are not the only benefit of the application of criteria for harvesting in degraded tropical forests. Fazenda Shet typically represents private areas with degraded forests in the arc of deforestation. It is not part of a public protected area (conservation unit) but a private area under significant deforestation risks due to high pressures of land use changes to more financially competitive activities such as agriculture and livestock.

Under this scenario, the application of criteria for harvesting with a minimum cutting diameter of 25 cm permits shorter cycles (13 years in this experiment) and has the potential to promote degraded tropical forests in a more competitive land use in opposition to the long harvesting cycles allowed in the Brazilian Amazon (30–35 years). In a shorter cutting cycle, based on an assortment of planted species and/or less commercially known species, but which are abundant in the diameter classes ≥ 25 cm, as well as trees of compromised health, of low-quality tree stem and/or for presenting biological characteristics that make them suitable for harvest, depending on the *dbh* ≥ 25 cm, makes the harvest more profitable. However, specific legal regulations addressed to the management of degraded natural forests are necessary to guarantee their conservation and economic viability.

5. Conclusions

The case study indicated that the application of criteria for harvesting trees with a minimum cutting diameter of 25 cm in degraded tropical forests it's a lucrative activity with potential conservationist and that proposes to make a more competitive land use in opposition to the long harvesting cycles allowed in the Brazilian Amazon, mainly, for private forests that have been heavily exploited in the past.

The selection of trees with a minimum cut diameter of 25 cm in shorter cycles is proposed, based on the assumption of promoting new commercial species, diversifying the income of forest owners and reducing pressure on species that have been the most pressured in the past.

In all scenarios, the application of criteria for harvesting presented excellent cost-benefit ratios, being little sensitive to discount rates.

The set of actions presented has potential for favors the maintenance of biodiversity and expansion of low-density populations and health of forest. In addition, it is more feasible for the supply of forest products in a shorter time than the provided for in Brazilian regulations.

Degraded tropical forests similar to this case study tend to be able to be subjected to silvicultural interventions in shorter cycles than those recommended by Brazilian regulations, respecting the specificities of the species and also of the location, as long as the harvest is carried out in enriched clearings, regeneration natural of species with high tree density, considering the health conditions and species suitable for harvesting due to biological characteristics.

With the recommendation of potential forest management strategies in the Amazon, it is expected to motivate in a practical way the maintenance of the forest standing, making it a sustainable financial asset from an environmental, social and economic point of view.

Author Contributions: Conceptualization, M.A.S., J.A.G.Y., O.J.R.d.A. and A.R.R.; methodology, M.A.S., J.A.G.Y., A.R.R., P.C.G.P.; analysis, M.A.S., J.A.G.Y., A.R.R., S.B.V. and A.S.; resources, S.B.V. and A.S.; data curation P.C.G.P., S.B.V. and A.S.; writing—original draft preparation M.A.S., S.B.V. and A.S.; writing—review and editing, S.B.V. and A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: To the project "Innovation network of the timber forest production chain to promote the sustainable development of the State of Pará, Brazil-Rede Biomassa Florestal", also called "Sub-Bosque" project (2009–2014).

Conflicts of Interest: The authors declare no conflict of interest.

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