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Silvicultural Management System Applied to Logged Forests in the Brazilian Amazon: A Case Study of Adaptation of Techniques to Increase the Yield and Diversity of Species Forestry

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Abstract: The existence of degraded forests is common in the Eastern Amazon. The maintenance of these forests standing and the recovery of their productivity play an important role in the conservation of biodiversity, storage and carbon sequestration. However, the management techniques currently employed are designed for natural forests in the first harvest cycle or lightly explored and do not apply adequately to forests that have gone through several harvest cycles. Therefore, adaptations and the establishment of new management criteria that take into account other characteristics of these types of forests are necessary to ensure their sustainability. The objective of this study was to propose a silvicultural management system that has the potential to recover and perpetuate the productivity of an intensively logged tropical forest. A forest census was carried out on 535.6 ha for trees with dbh $\geq$ 25 cm. With these data, the following two treatments were designed: (1) criteria: the BDq method was applied from B = 9.8 m^2 ha^{-1}, D = 100 cm and q = 2. The criteria for standing wood commercialization were, in this order, first, Health; second, Tree Stem; third, Tree Density and fourth, dbh $\geq$ 105 cm. (2) Control: the planning was in accordance with Brazilian regulations. For the cost–benefit and sensitivity analysis, the Net Present Value (NPV) was used and a projection of $\pm$20% was made in the commercial price of standing wood. In the criteria treatment, a higher number of trees and species destined for the commercialization of standing wood was verified in relation to the control treatment, showing a greater diversity of species. In the criteria treatment, NPV was positive and superior to the control treatment in all scenarios. The proposed silvicultural management system with an object of an explored and enriched forest, with criteria for harvesting trees with a minimum cut diameter of 25 cm, proved to be viable to generate economic returns and with conservationist potential for the continuous supply of forest products and maintaining biodiversity.

Keywords: BDq method; Eastern Amazon; degraded tropical forest; forest restoration; forest economy; logging selection criteria; sustainable forest management

1. Introduction

Procedures for forest management in the Brazilian Amazon have not been regulated based on technical parameters appropriated to all types of forests. There are also questions that normative instructions, government policies and forest management are the main barriers to make the management effective, efficient and sustainable [1–6].

It is estimated that 4.8% (4.5 million hectares) of natural forests classified as degraded, that is, forests in which successive logging cycles have occurred, are in the Legal Amazon [7]. These forests have a high richness of tree species with a diversified floristic composition, with potential for biodiversity conservation. A promising aspect is that, in recent decades, research in the area of forest restoration has been intensified for the profile of exploited or degraded forest, as an attempt to encourage the use of techniques that can keep the forest standing [8–10].

A forest restoration and management system proved to be viable to generate economic returns with continuous supply of wood products [11,12] and potential for the maintenance of the diversity of species forestry [13,14] as well contribute to mitigating the effects of climate change [15].

One of the key elements for forest restoration and natural forest management is understanding the structure of natural forests, especially the use of indicators such as floristic composition and diametric structure [3,16,17]. The diversity of species and their distribution in different classes of diameters are important factors, among many others, that provide stability to ecosystems [18]. The "J-inverted" shape, diametric distribution or negative exponential distribution for uneven-aged forests, indicates that populations of a forest naturally recompose themselves through the balance between mortality and entrance of individuals [19,20]. However, in order to maintain the forest's balanced diametric structure, it is necessary to apply management techniques to lead it to a "balanced" distribution [21,22].

The diametric distribution models that estimate growth and production provide support for forest planning, making it possible to identify the trees that make up the forest by diameter classes and predict forest production [18,23,24]. They also determine the interventions in the forest in a way to guarantee the ecological and economic sustainability of the stands [25].

The advance in management techniques in uneven-aged forests has led to the development of the BDq (B = remaining basal area, D = maximum diameter and q = De Liocourt constant) method of selection [19]. This method was also used in forests in Brazil [20,26,27] to determine the balanced harvest intensity in the diametric classes [28]. This method is conditioned to the values of the remaining basal area, the maximum intended diameter, the number of individuals per class of diameter per hectare and the choice of species to be harvested [29]. Associated with the balanced distribution model, the application of post-harvest silvicultural treatments, such as conduction of regeneration, thinning and enrichment planting, has been an alternative to recover the forest structure as well as the populations of species of interest [11,12,30–35].

The consolidation of new technical parameters is important to make forest management effectively sustainable from an environmental, social and economic point of view [36,37]. This case study deals with the use of the BDq Method and ecological and economic criteria for tree selection for planning the harvest and commercialization of standing wood in an intensively logged tropical forest.

The objective of this case study is to provide technical and economic information to promote a sustainable silvicultural management system for the commercialization of wood in an intensely logged tropical forest and make it desirable for environmental protection and conservation as a perpetual financial asset, with the maintenance of biodiversity and expansion of populations of low-density species and the quality of the forest.

2. Materials and Methods

2.1. Study Area

The study was conducted in the forest management area (535.6 ha) of the Fazenda Shet farm, located in the municipality of Dom Eliseu, State of Pará, Brazil (altitude, 320 m; 4°30′48″ S and 47°39′36″ W) (Figure 1), owned by the Arboris Group®.

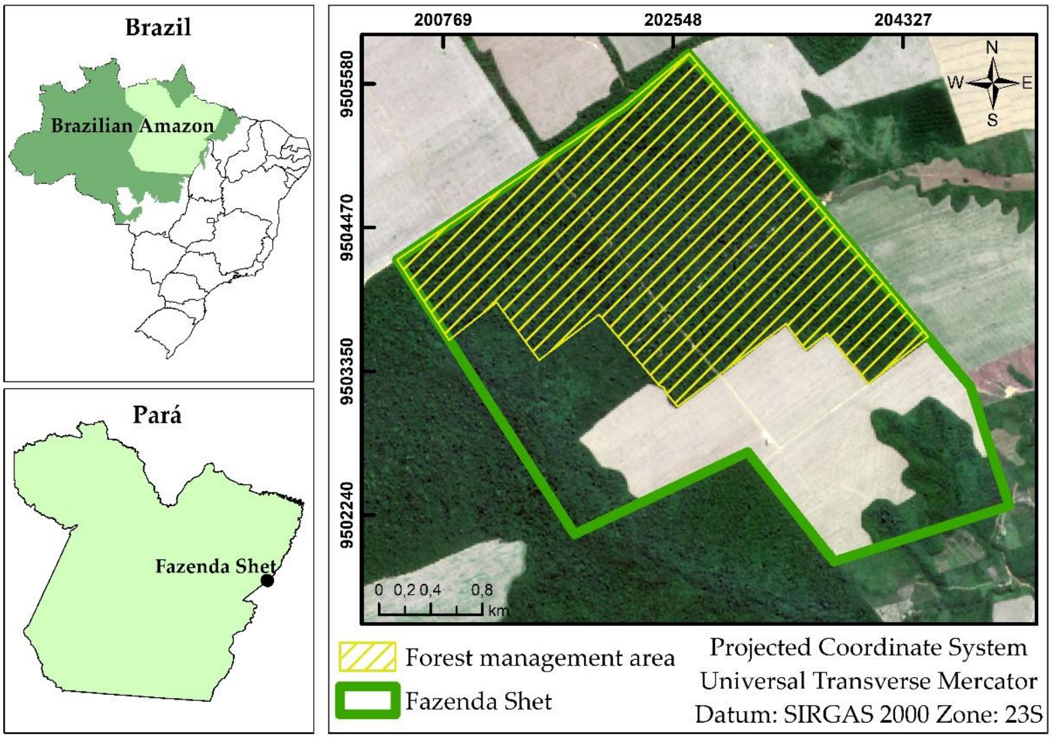

Figure 1. Forest management area of Fazenda Shet, Dom Eliseu, State of Pará, Brazil.

The region's climate is Aw (Köpen), tropical with summer rains, with an average annual rainfall of 2500 mm [38,39]. The average annual temperature is 25 °C. The municipality's vegetation type is Dense Ombrophilous Submontane Emerging Canopy Forest [40]. The predominant soils are dystrophic Yellow Latosol and dystrophic Red–Yellow Argisol [41].

The forest management area of Fazenda Shet is represented by an exploited natural forest characteristic of the region of the arch of deforestation in the Amazon [42]. This forest underwent successive forest exploitation processes that took place between the 1970s and the 1990s, and the volume of wood extracted is unknown. After the establishment of legal regulations for management, the first logging in the area, permitted by environmental agencies, occurred in 1993 and 1994. The average harvest volume was 65 m^3 ha^{-1}. The current regulation that prescribes a maximum harvest of 30 m^3 ha^{-1} for the Brazilian Amazon only began in 2006 [6]. In the clearings formed by logging, enrichment planting with direct seeding of *Schizolobium parahyba* var. *amazonicum* was performed by [11].

2.2. Forest Census

A forest census was carried out in 2008, considering the methodology presented in Technical Guidelines for Exploration of Reduced Impact in Forest Operations of Terra Firme in the Brazilian Amazon [43] for all trees with a dbh (diameter at 1.3 m high) ≥25 cm. On that occasion, the following procedures were performed: botanical identification procedures, cutting vines, fixing a numbered label at the base of the trunk, measuring the dbh, visual estimate of the commercial height, classification of the quality of the tree stem (tree stem 1—straight and cylindrical tree stem; tree stem 2—slightly tortuous and/or corrugated; tree stem 3—crooked, strongly corrugated or forked) and sanity (rot, senescence, broken, dead and/or fallen canopy).

The species were divided into three groups of market value. For groups 1, 2 and 3, 13, 41 and 52 species are included, respectively, in which the species in group 1 represent the highest economic value, followed by the species in group 2 and the species in group 3 representing the lowest economic value (Table 1 and Supplementary Materials).

Table 1. Species (popular and scientific name) classified by market value group, forest management area of Fazenda Shet (535.6 ha), Dom Eliseu, State of 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.); amesclão (*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).

Based on the forest census data of forest management area (535.6 ha) of Fazenda Shet, the following two scenarios in harvest planning were designed for the same area of the case study: (1) criteria treatment: trees with a dbh $\geq$ 25 cm, quantifying 46,010 trees and 106 species; and (2) control treatment: trees with a dbh $\geq$ 40 cm, accounting for 13,638 trees and 91 species.

2.3. Criteria Treatment

BDq method: to plan the wood harvest with the aim of maintaining a balanced structure of the forest, we performed the BDq method of selection [19], which was first used in Brazil in the Atlantic forest [26]. The diametric structure was characterized by the distribution of the number of trees, the basal area and the volume, per hectare and by diameter class. To perform this analysis, trees with a dbh $\geq$ 25 cm were grouped according to classes of diameter, previously fixing the class width of 10 cm.

The remaining basal area (B = 9.8 m^2 ha^{-1}) was obtained through the forest census; a maximum desirable diameter was established (D = 100 cm, amplitude of $\pm$5 cm) because generally trees with a dbh > 105 cm have already fulfilled their reproductive role [12] and reached the culmination (asymptote) growth, presenting an increase in volume relatively lower than that trees of predecessor diameter class [44]. Trees with diameters above 100 cm may eventually remain in the area, if they are rare species or if they have very dense crowns, since they can promote large clearings in their fall. The quotient (q = 2) of Liocourt was adjusted in order to minimize the diameter classes with deficits and to allocate to commercialization a larger number of standing trees of a specific diameter class in relation to the successor diameter class.

From the BDq parameters, coefficients β_0 and β_1 were calculated using the following equations:

$$\beta_1 = \frac{Ln\ (q)}{X_i - X_{i+1}}\ \beta_0 = Ln.\frac{40000.B}{\pi.\sum_{i=1}^{n} dbh_i^2\ .e^{\beta_1.dbh_i}} \tag{1}$$

The parameters were included in the function for the calculation of the remaining frequencies, thus the classes with surplus or deficit in number of trees were defined using the following equation:

$$Y = e^{\beta_0+\beta_1.X_i} + e_i \tag{2}$$

where Y = the estimated number of trees per diameter class per hectare; X = the diameter class center; e = the base of the Neperian logarithm; e_i = random error and β_0 and β_1 = function parameters.

The number of trees destined for commercialization of standing wood (harvest) within each dbh class was obtained by subtracting the number of trees in the "forest" by the number of "remaining" trees [20]. In this way, balancing curves of the forest were generated with the number of trees, per hectare, observed (forest), estimated by the BDq method (remaining) and destined for commercialization of standing wood (harvest) by dbh class center.

Criteria for commercialization of standing wood: considering the number of trees by diameter class center, with surplus or destined for commercialization of standing wood (harvest) using the BDq method, a selection was made, considering the silvicultural conditions and the tree density by species, in the following order:

- 1st, Health: trees identified with rot, senescence, broken crown, signs of disease or that were dead were selected for sale of standing wood.

Traditionally, trees with compromised health are not selected for harvest. However, the permanence of these trees causes negative influences on 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 to healthy and productive trees. In general, trees with compromised health have a reduced life cycle. Branches of different sizes and leaves remain in the forest, which allows for the survival of other living organisms that have a habitat or feed on this type of material.

- 2nd, Tree Stem: trees with quality of tree stem 2 and 3 were selected for commercialization of standing wood, aiming at maintaining trees with quality tree stem 1;
- 3rd, Density: trees of the 15 species with the higher tree density values located in the management area were selected to be commercialized as standing wood. This

procedure aims to conserve low density species and to maintain biodiversity. The density was obtained using the following equation [45]:

$$Da = \frac{n_i}{A} \tag{3}$$

where Da = Absolute density; ni = the number of inventoried trees of the i-th species and A = total area sampled, in hectares.

- 4th, dbh > 105 cm: trees with a dbh > 105 cm were selected to be commercialized as standing wood. This criterion aimed at reducing the number of senescent trees and increasing the population of trees with smaller diameters. The current harvest of trees with larger diameters aims to make the future industrial plant compatible, which will be adequate for a larger number of trees with smaller diameters.
- 5th, abundance: prioritized the selection of the most abundant species. These species have characteristics of pioneers, fast growing, with greater ease of propagation and were less pressured in previous harvests.

2.4. Control Treatment

Harvest planning in control treatment was carried out in the same forest management area (535.6 ha) of Fazenda Shet that was used for the criteria treatment. The difference is that the control treatment was conducted according to the following Brazilian regulations [2,6,46]:

- Minimum interval of 12 years from the last logging;
- Maximum harvest (m^3 ha^{-1}) determined by multiplying the constant "0.86 m^3 ha^{-1}", which is the average annual increase in volume of the portfolio of commercial species, by the number of years that have elapsed since the last logging [6];
- Forest census for all trees with a dbh $\geq$ 40 cm, from which trees with dbh $\geq$ 50 and $\leq$200 cm were destined for the commercialization of standing wood;
- Minimum maintenance of 3 trees per species, per 100 hectares (or 0.03 trees ha^{-1}) with a dbh $\geq$ 50 cm;
- Exclusion of prohibited species or of those with harvesting restriction;
- Selection of trees with tree stem form quality 1 and 2 for commercialization of standing timber.

2.5. Cost–Benefit and Sensitivity Analysis

The Net Present Value (NPV) was the indicator used to estimate the financial viability of applying the BDq method and criteria for commercialization of standing wood in forests explored in the Amazon (i.e., the criteria treatment), and the control treatment as well. The NPV is a tool to calculate the profitability of projects through the analysis of discounted cash flow [47].

$$\text{NPV} = \sum_{t=0}^{n} \frac{B_t}{(1+r)^t} - \frac{C_t}{(1+r)^t} \tag{4}$$

where t is the year when revenue or cost occurs, B_t is the income from the commercialization of standing wood in the year t, C_t is the total cost in the year t, r is the discount rate per year and n is the time demanded for incomes. Only an NPV greater than zero indicates a return on investment [48]. The profitability of standing timber sale was calculated based on the 13 years of forest growth, after the last logging at Fazenda Shet. This period was defined as a function of monitoring the productivity of the site, carried out in permanent sample plots considering the growth of the species planted in the enrichment of clearings, of species with a short life cycle that regenerated and the abundance of other species in the area, making an assortment of 30 m^3 ha^{-1} harvest, which is the maximum production allowed for harvesting according to Brazilian regulations [2,6,46].

The cash flow was based on field spreadsheets provided by the Arboris Group. Costs totaled USD 29.70 ha^{-1} for criteria treatment and USD 23.31 ha^{-1} for control, resulting from the sum of the annual cost, forest census and administration.

The incomes were calculated from the volumes of each tree destined for the commercialization of standing wood from the criteria and control treatments. The calculated volumes were multiplied by the price determined by the business group for the inventoried species, according to the market value group: 1 (USD 183.76 m^{-3}), 2 (USD 74.25 m^{-3}) and 3 (USD 62.25 m^{-3}).

Profitability per hectare (NPV ha^{-1}) was calculated based on a yearly nominal interest of 7%. This is the current interest rate on the capital loan adopted by the *Banco do Brasil* Commercial Forest Planting Program (PROPFLORA) and by other banks accredited by the National Bank for Economic and Social Development (BNDES) for forest investment and production.

Different price scenarios for the wood commercialization were built through a sensitivity analysis to project the profitability of the commercialization of standing trees. In addition to the wood commercialization values established for the groups of the species 1, 2 and 3, two other scenarios were built varying from −20% to +20% on the wood commercialization price.

3. Results

3.1. Criteria and Control Treatment

BDq method: the dbh class centers with surpluses and deficits in the number of trees ha^{-1} in relation to the adjusted balanced curve (remaining curve) are shown in Figure 2. By means of balancing, the commercialization of trees in the surplus classes (harvest curve) until they reach the desired remaining number and the maintenance of the trees in the deficit classes was proposed. In the dbh class centers of 30, 40 and 50 cm, there were surpluses of 10.414, 6.985 and 0.732 trees ha^{-1}, respectively, totaling 18.131 trees ha^{-1}, which were destined for the commercialization of standing wood. For the other dbh class centers, deficits ranging from 0.134 to 1.231 ha^{-1} were found.

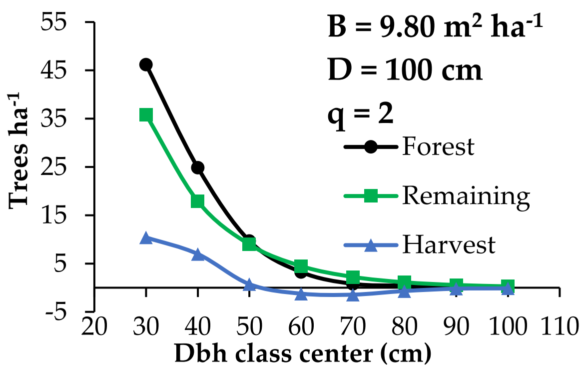

Figure 2. Balancing curves of the forest with the number of trees, per hectare, observed (forest), estimated using the BDq method (remaining) and destined for the commercialization of standing wood (harvest) by dbh class center, management area of the Fazenda Shet, Dom Eliseu, State of Pará, Brazil.

In the criteria treatment's forest census, 85.907 trees ha^{-1} with a dbh $\geq$ 25 cm were inventoried, corresponding to 106 species (535.6 ha). Of the inventoried population, 29.78% are trees of the species *S. parahyba* var. *amazonicum* (12.880 trees ha^{-1}) and *C. obtusa* (12.705 trees ha^{-1}). When applying the BDq method and the criteria for the commercialization of standing wood, 18.332 trees ha^{-1} were selected, referring to 77 species (535.6 ha). Some trees were selected by more than one criterion, totaling 1.752 trees ha^{-1} for compromised health, 10.951 trees ha^{-1} by tree stem (quality two and three), 16.173 trees ha^{-1} by tree density and 0.224 trees ha^{-1} per dbh > 105 cm.

Concerning the population destined for the commercialization of standing wood in the criteria treatment, *S. parahyba* var. *amazonicum* and *C. obtusa* contributed with 6.614 trees ha^{-1}, the largest number of trees being selected for harvest by the density criterion. In addition to these species, *Inga* sp., *J. spinosa*, *T. burseraefolia*, *P. densiflora*, *P. guianensis*, *C. tocantinum*, *P. effusa*, *S. parviflora*, *S. pruriens*, *Z. rhoifolium*, *G. sericeum*, *C. aliodora* and *Nectandra* sp. had trees selected for standing wood commercialization by the density criterion. The sum of the trees of these species corresponded to 16.173 trees ha^{-1}, corresponding to the 15 species with the highest tree density.

The trees selected by the health criterion represented 1.752 trees ha^{-1}, with 44 verified species (535.6 ha). The species with the highest frequency of trees with compromised health destined for the sale of standing wood were *C. obstusa, Inga* sp., *T. burseraefolia* and *P. guianensis*, adding up to 1.205 trees ha^{-1}. Regarding the tree stem form criterion (quality two and three), 10.951 trees ha^{-1} of 74 species (535.6 ha) were destined to be commercialized as standing timber. The species selected by the tree stem criterion with the highest frequency of trees were *J. spinosa*, *Inga* sp., *T. burseraefolia* and *C. obstusa*, totaling 5.804 trees ha^{-1}.

Considering the dbh criterion >105 cm, 0.224 trees ha^{-1} of 26 species (535.6 ha) were destined for the commercialization of standing wood. The species most frequently found in trees with a dbh >105 cm were *C. tocantinum*, *P. suaveolens*, *G. sericeum* and *T. burseraefolia*, totaling 0.127 trees ha^{-1}.

In the control treatment, 25.463 trees ha^{-1} were inventoried, which presented a dbh $\geq$40 cm and belonged to 91 species. Of the inventoried population, 27.79% were trees of the species *S. parahyba* var. *amazonicum* (3.462 trees ha^{-1}) and *N. paraensis* (3.615 trees ha^{-1}). Following Brazilian regulations, 2.112 trees ha^{-1} were selected for the commercialization of standing wood, which refer to 41 species (535.6 ha).

Trees and species destined for the sale of standing wood by the dbh class center and market value group for the criteria and control treatments are shown in Figure 3. In the criteria treatment, a higher quantity of trees ha^{-1} and species destined for the commercialization of wood was verified in relation to the control treatment, with the largest quantity present in the dbh class centers of 30, 40 and 50 cm (Figure 3a).

3.2. Cost–Benefit and Sensitivity Analysis

The treatments (criteria and control) were profitable for the commercialization of standing wood under the nominal interest rate of 7% per year, since its NPVs were greater than zero in all scenarios (Figure 4a). The differences, however, were in favor of criteria treatment in all scenarios. The scenarios with a variation of ±20% for the commercialization price of standing wood showed that the criteria treatment is more profitable than conducting this forest profile based on the technical guidelines contained in the Brazilian regulations (i.e., the control treatment).

The scenarios indicated an NPV variation from 156.27 to USD 263.84 ha^{-1} in the criteria treatment and 124.80 to USD 198.74 ha^{-1} in the control treatment, under the nominal interest rate of 7% per year. In the criteria treatment, total production (m^3 ha^{-1}) was found to be 44% higher than the control treatment, with higher production observed in market value groups two and three (Figure 4b).

For the control treatment, the highest production was found in the market value group one, indicating the preference that is generally destined for the species with the greatest economic value. However, the highest trade demand for the use of a reduced number of species, even though they have greater commercial value, does not guarantee greater profitability as shown in Figure 4b, besides the fact that loss in species diversity may occur due to high selective logging pressure on certain and few species.

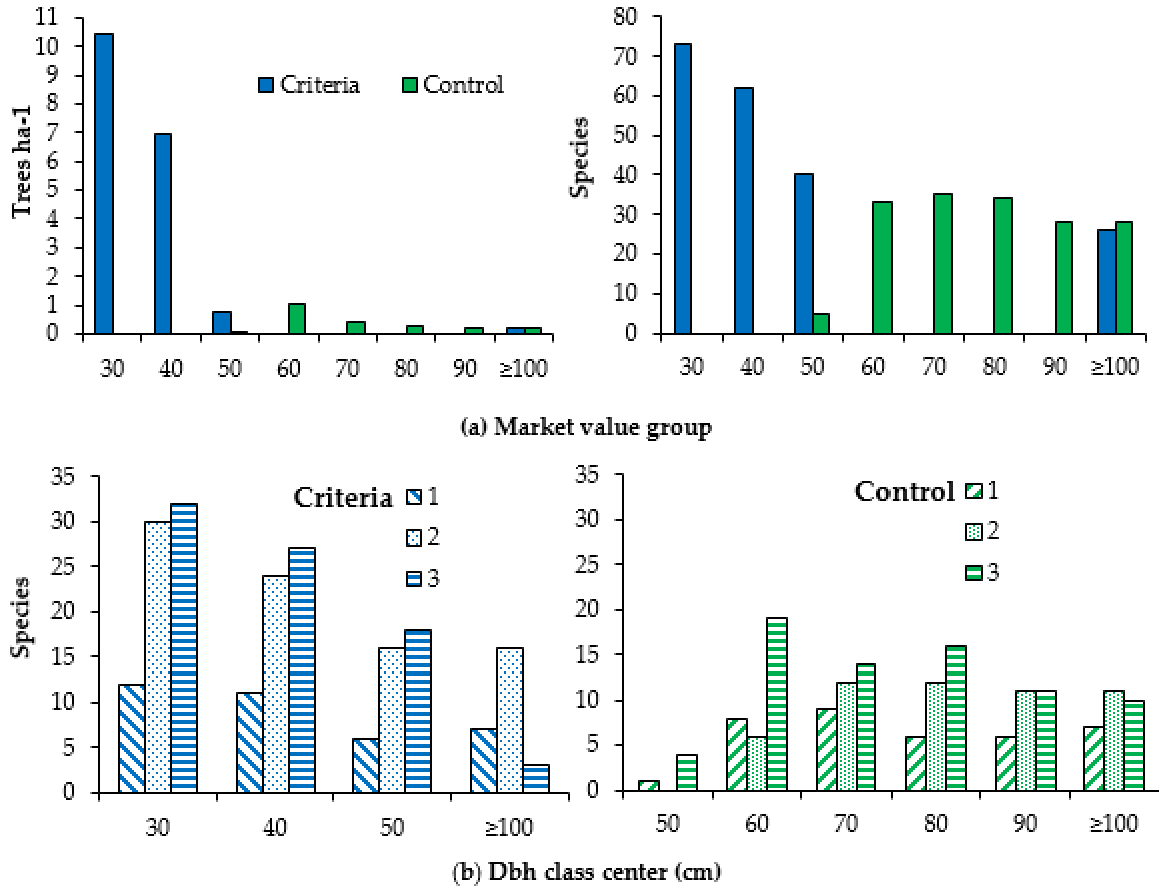

Figure 3. Trees and species destined for the sale of standing wood by the market value group (**a**) and dbh class center (**b**) for the criteria and control treatments, forest management area of Fazenda Shet, Dom Eliseu, State of Pará, Brazil.

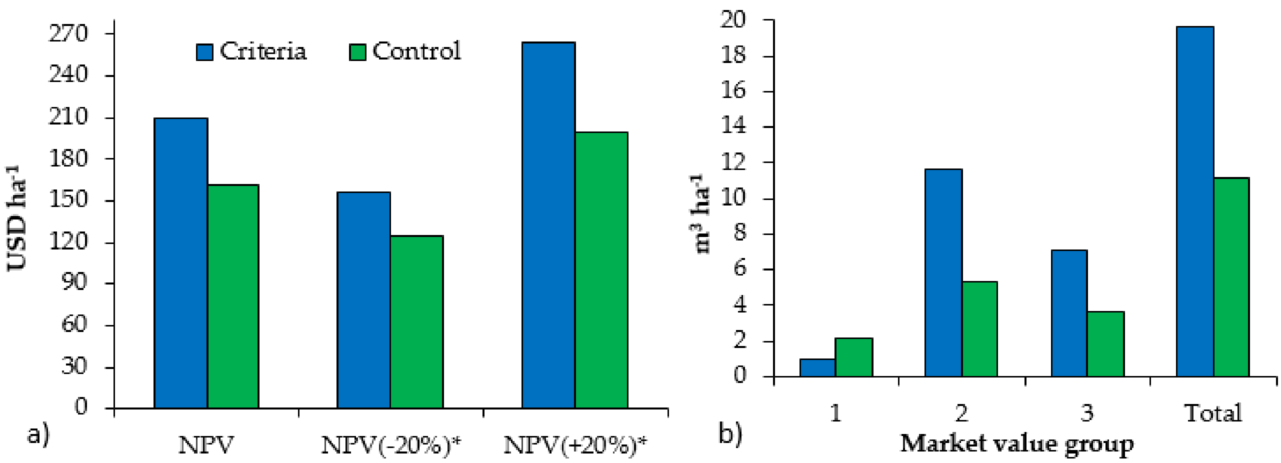

Figure 4. Financial indicators (NPV ha^{-1}) (**a**) and production (m^3 ha^{-1}) by the market value group of species destined for the commercialization of standing wood (**b**) for the criteria and control treatments, forest management area of Fazenda Shet, Dom Eliseu, State of Pará, Brazil. * NPV result of the projection of ±20% in the commercialization price of standing wood.

4. Discussion

4.1. Criteria and Control Treatment

In exploited natural forests, similar to the one present in this study, it is common to have an imbalance in relation to the abundance or lack of trees in certain centers of diameter classes, reflecting the result in general of human action [19,27,49].

However, it is observed that the studied forest maintains its structure in the inverted-J form, although it may change slightly after harvesting and decrease the abundance of species. Additionally, it presents a sufficient tree stock to be recovered, as shown in other studies [11,44]. Considering the minimum dbh of 25 cm and the regulation of the remaining stock of trees, the application of the BDq method in this forest profile demonstrates a trend in improving the future stock of wood with greater commercial attractiveness, which should promote greater industry sustainability in the short, medium and long terms [12].

Our findings demonstrate that there is greater diversity and possibilities in the choice of species, as an advantageous result of the application of the BDq method, just as of the criteria for the commercialization of standing wood in these dbh class centers, an alternative that would not be possible when following the Brazilian regulations for this forest profile. This fact is confirmed by the number of species per market value group verified according to the criteria treatment (Figure 3b), which shows a higher number of species selected for the commercialization of standing wood, distributed in dbh class centers, in relation to the control treatment.

The application of the BDq method and the criteria for the commercialization of standing wood could be seen as a silvicultural treatment of thinning, in which the selected trees (all trees with a dbh $\geq$25 cm) from the enrichment planting and from natural regeneration are commercialized. For instance, at Fazenda Shet, there was a high trees stock of various species not included in the first line of commercialization (those with a dbh $\geq$25 cm) that could serve as an assortment for the harvest and generate revenue in successive intermediate periods of the harvest cycle. Therefore, with forest growth monitoring, it is possible to identify the peculiarities of each species for proper management. Fast-growing species could be commercialized in shorter periods of time, while slower-growing species would be part of a longer-term crop assortment. Therefore, silvicultural systems that take into account the management by species or group of species with similar characteristics are an option potentially applicable to the reality of small, medium and large areas of forest management.

The authorization for logging in Amazon natural forests is subject to regulations for harvesting trees with a dbh $\geq$50 cm. With this regulation, trees of larger diameters and high commercial value are prioritized, establishing greater pressure under a reduced number of species after consecutive harvests. This fact compromises the richness of the forest and the perpetuation of timber productivity [6,13,50,51].

The commercialization of trees with a dbh $\geq$25 cm will make possible the inclusion of new species in the market that do not reach a dbh $\geq$50 cm due to biological characteristics, as they would be excluded according to Brazilian regulations. These species are represented by a high density of trees in the forest in this studied region, as is the example of *C. obtusa* [52]. On the other hand, species from enrichment sowing in clearings, such as the species *S. parahyba* var. *amazonicum* in this study, also present a high tree density [11].

In addition to this, it is preferable to allocate species with high tree abundance for commercialization, with the objective of favoring the maintenance of biodiversity and the regeneration of low abundance species that, in some cases, have been widely pressured in previous logging.

Enrichment sowing in a clearing with *S. parahyba* var. *amazonicum* is a consolidated practice in the areas of the studied company. This practice has made it possible to accelerate the recovery of the wood stock in a shorter time than indicated by Brazilian regulations [6,11,34].

The application of the BDq method and the definition of criteria for the commercialization of standing wood imply rational management aimed at maintaining the richness of species in the forest, based on the conservation of species and the use of trees with compromised health and senescent, promoting the species of greater and lowest value in the forest. Still, the application of these criteria for harvesting promotes continuous forest production, as this is an essential factor for this type of forest to become a desirable asset for conservation.

It is worth mentioning that, in general, the mortality rate in forest ecosystems is influenced by the health of the trees [53]. The mortality rate of trees for health reasons has been wrongly treated with little environmental and economic relevance. Although the importance of compromised health trees for nutrient cycling has been questioned, the presence of these trees in the forest promotes the function of hosts and precursors of pests and diseases, in addition to the poor reproductive quality [54].

The use of silvicultural practices aiming at profitability in the short, medium and long term tends to make the management of tropical forests truly sustainable in order to maintain wealth and productivity. This study demonstrates the application of technical and economic tools with the potential to increase the health and productivity of these forest profiles, contributing significantly to breaking paradigms and encouraging effective sustainable management practices of tropical forests exploited in recent decades.

Trees destined for the commercialization of standing wood by the health criterion represent a relatively low percentage. However, harvesting trees with compromised health is an efficient and profitable method to eliminate host trees for pests and diseases, and to make more growth resources available (space, light, water and nutrients) for the remaining healthy and productive trees [12]. Harvesting interventions in exploited forests are one of the factors that influence the composition of future species in the forest, mainly promoting the abundance of pioneer species, with no significant negative effect on shade-tolerant species [55].

In a certain way, the management of natural forests for wood production is significantly questioned regarding the impact on species composition and richness [14,56], the provision and maintenance of ecosystem services [57], the frequency of silvicultural harvest and post-harvest operations [11,13] and the economic viability [12]. However, research on management in forests that were exploited in the past and that take into account the harvest criteria [58], techniques of harvest optimization and forest densification [11,33] and management compatible with the behavior of each species [59] has revealed great potential for the recovery and rational use of forests.

4.2. Cost–Benefit and Sensitivity Analysis

As a financially viable alternative, the application of the BDq method and the definition of standing wood commercialization criteria have the potential to be applied in exploited tropical forests. This fact is highly promising to keep the forest stand; otherwise, there are serious risks of converting land use to other economic activities [60,61]. This silvicultural management system tends to provide high wood production, while the treated forest maintains its environmental services.

The results found in this study become even more important considering that this region is in the Brazilian Amazon's arc of deforestation [62–64]. In this region, there is great demographic pressure and strong demand for land use in order to develop agricultural and livestock activities.

The deforestation arc is an area of 50 million hectares located in the south and southeast regions of the Amazon and it has high rates of forest degradation due to decades of disorganized and illegal exploitation. The arc's landscapes are composed of a mosaic of lands submitted to agricultural and forestry crops, pastures and exploited forests [65,66].

Financial returns, however, are not the only benefit of applying the BDq method and criteria for the commercialization of standing timber in forests exploited in the Amazon. Fazenda Shet is not part of a public protected area (conservation unit), but of a private area under significant risk of suppression in the face of pressure on alternative land use.

This pressure is due to the advantages of changing the forest cover of the property for land use in more financially competitive activities, such as agriculture and livestock. In this context, the silvicultural management system adopted is considered promising to promote more financially competitive activities in exploited tropical forests in relation to agriculture and livestock.

At this moment, it is necessary to comment on the management of natural forests in the Brazilian Amazon and forests exploited in the past. The forest regulation, according to the current rules, considers a maximum harvest of up to 30 m^3 ha^{-1} in cutting cycles of up to 35 years and a minimum diameter of 50 cm. Within a conservative view, these technical procedures are acceptable for the management of unexploited dense natural forests. However, for the management of already exploited forests or other forest types whenever associated with clearings enrichment, forest regulation should have other criteria that could be similar to the principles of planted forests management such as the use of thinning.

Species that are more commercially known and that have suffered greater pressure due to exploitation, such as *H. courbaril*, *M. huberi* and others with a low growth rate [7], should be harvested with diameters over 50 cm and in cycles of 60 years or more. Intermediate release thinning should occur to reduce competition between trees of different species and improve cash flow, increasing revenues and making management more economically attractive. It is worth mentioning that specific regulations directed to the management of exploited tropical forests are necessary to guarantee their conservation, as well as their productive perpetuity and economic viability.

Finally, it is noteworthy that the identification of a viable solution for the use of degraded forests in eastern Pará is of great importance before they are replaced by other alternatives for using the tarra that are more economically viable. A relevant aspect of our findings in this case study is that there is the possibility of keeping this forest standing productively, through sustainable management and offering wood to local industries. In addition, these forests play an important role in carbon retention in plant biomass and sequestration by faster tree growth, contributing to the mitigation of the effects of climate change.

5. Conclusions

The proposed silvicultural management system has as an object an exploited forest in the Amazon and criteria for harvesting trees with a minimum cut diameter of 25 cm. This management system proved to be viable to generate economic returns, with conservation potential for the continuous supply of forest products and maintenance of the diversity of species forestry. The proposed management system requires normative adjustments in the current legislation for these types of forests, in relation to cutting cycles and technical criteria for harvest planning.

The selection of trees, mainly from market value groups two and three, with a minimum cut diameter of 25 cm in shorter cycles has the potential to promote new commercial species, diversify the income of forest owners and reduce the pressure on more pressed species in the past.

The application of harvesting criteria resulted in positive cost–benefit ratios, being superior to the control treatment in all scenarios.

The set of actions presented is promising to favor the maintenance of biodiversity and expand populations of low density species and the quality of the forest. Besides that, it is more viable for the supply of forest products in a shorter period than that provided for in Brazilian regulations, favoring the viability and the economic sustainability of management.

Exploited tropical forests similar to the one of this study tend to be susceptible to silvicultural interventions in shorter cycles, as long as they are verified to the specificities of each species, as well as the location of the forest and industry. Harvesting must be carried out in areas that are enriched and have a natural regeneration of species with a high tree density, considering the appropriate health conditions of the trees and the biological characteristics of the species.

With the recommendation of solid forest management strategies in the exploited tropical forests worldwide, 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.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/d13110509/s1. Table S1: Species (scientific name and common name) listed by market value group of criteria treatments in the forest census and trees selected for harvest and remaining trees with a dbh ≥25 cm. forest management area (535.6 ha) at Shet Farm. Dom Eliseu. Pará. Brazil. Table S2: Species (scientific name and common name) listed by market value group of control treatments in the forest census and trees selected for harvest and remaining trees with a dbh ≥25 cm. forest management area (535.6 ha) at Shet Farm. Dom Eliseu. Pará. Brazil. Table S3: Species (scientific name and common name) listed description by market value group in the forest at Shet Farm. Dom Eliseu. Pará. Brazil.

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