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Forest Management with Reduced-Impact Logging in Amazonia: Estimated Aboveground Volume and Carbon in Commercial Tree Species in Managed Forest in Brazil's State of Acre

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Abstract: Tropical forest management has both positive and negative effects on climate change, and quantifying these effects is important both to avoid or minimize negative impacts and to reward net positive effects. This study contributes to this effort by estimating the aboveground volume and carbon present in commercial tree species in a managed forest in the forest harvest stage in Brazil's state of Acre. A total of 12,794 trees of commercial species were measured. Trees were categorized and quantified as: "harvested trees" ("harvest or cut"), which were felled in the harvest stage, and "remaining trees" ("future cutting," "trees in permanent protection areas or APPs," "seed trees," "rare trees" and "trees protected by law") that remained standing in the forest post-harvest. Aboveground volume and carbon stocks of the 81 commercial species (diameter at breast height [DBH] $\geq$ 10 cm) totaled 79.19 m^3 ha^{-1} and 21.54 MgC ha^{-1}, respectively. The category "harvested trees" represents 44.48% and "remaining trees" 55.49% of the aboveground volume stocks. In the managed area, the category "harvested trees" is felled; this is composed of the commercial bole that is removed (19.25 m^3 ha^{-1} and 5.32 MgC ha^{-1}) and the stump and crown that remain in the forest as decomposing organic material (15.97 m^3 ha^{-1} and 4.41 MgC ha^{-1}). We can infer that the 21.54 MgC ha^{-1} carbon stock of standing commercial trees (DBH $\geq$ 10 cm) represents 13.20% of the total aboveground carbon in the managed area. The commercial boles removed directly from the forest represent 3.26% of the total aboveground carbon, and the stumps and crowns of the harvested trees represent the loss of an additional 2.70%. For sustainability of the management system in terms of carbon balance, growth in the 35-year management cycle must be sufficient to replace not only these amounts (0.27 MgC ha^{-1} $year^{-1}$) but also losses to collateral damage and to additional loggingrelated effects from increased vulnerability to forest fires. Financial viability of future management cycles will depend on replenishment of commercial trees of harvestable size (DBH ≥ 50 cm).

Keywords: forest disturbance; forest harvest; climate change mitigation; forest carbon stock; tropical forest

1. Introduction

Tropical forest management stimulates the growth of the forest and sequestration of carbon in biomass [1,2], and commercial trees (diameter at breast height [DBH] ≥ 50 cm) contribute a large part of a forest's biomass and carbon storage [3–5]. Management has both positive and negative effects on greenhouse gas emissions [6]. On the positive side, management has a substantial benefit if the alternative would be deforestation. It also can store carbon in long-lived wood products while the forest recovers its carbon stock through regrowth, thus reducing the load of carbon dioxide in the atmosphere (although carbon stored in wood products will decline continuously as the products decay). On the negative side, the biomass and carbon stocks of the managed forest are reduced as compared to the original forest, and, with the exception of the carbon in long-lived wood products, most of this reduction is a contribution to carbon emissions. Emissions come from decomposition of wood products, sawmill waste and the stumps, crowns and roots of harvested trees, as well as the unharvested trees that are killed or damaged in logging operations. Additional emissions can come from forest fires, which are more likely to occur in logged forests [7,8]. The carbon emissions and uptakes resulting from forest management occur over an extended period of years, and their timing and the value attributed to time are key determinants of the positive or negative effect attributed to forest management [6,9]. Large emissions occur in the first years after logging, while accumulation of carbon in long-lived wood products is slow [6]. All of the carbon stocks and flows affected by forest management need to be quantified in order to properly account for their effect on global change and to allow any net positive benefits to be rewarded through payments for environmental services, such as carbon credits for projects under REDD+ (reducing emissions from deforestation and forest degradation) (e.g., Brazil, MMA, 2016 [10]).

In the Amazon forest, the estimated capacity for timber production is defined by the available merchantable volume ($m^3\ ha^{-1}$) [11]. Brazil requires management projects to conduct a "100% inventory" of the merchantable volume in the forest management unit, with the 100% inventory defined as the measuring and mapping of all individuals of commercial species, considering a minimum diameter at breast height (DBH) of 50 cm. The trees selected for cutting must be identified based on the criteria provided by Brazilian regulations, a minimum diameter at breast height (DBH) of 50 cm [11]. The maximum permitted cutting intensity is 30 $m^3\ ha^{-1}$, and low-impact harvest techniques must be incorporated in the plans in order to minimize impacts [1,12–17].

The commercial bole (the trunk from the point of the cut to the first significant branch) is the main component of the trees used for the production of sawn wood. The stump and the crown are left in the management system and gradually emit CO_2 until they completely decompose. Information about the carbon stocks of commercial trees and how they are partitioned among the components (bole, stump and crown) is essential for the formulation of strategies to mitigate climate change in this activity. Despite initiatives by environmental agencies to regulate wood production and despite the efforts of researchers in this area, there is still little information available about the carbon stock in commercial trees in areas under forest management in Brazil, including those in southwestern Amazonia (e.g., Goodman et al. [2]; Romero [18]).

In this context, the main objective of the present study was to estimate the above-ground volume, biomass and carbon stocks of commercial species in areas under forest management in order to obtain information on the stocks of the different categories ("harvested trees" and "remaining trees") in the "sustainable forest management plan" (PMFS), in addition to the carbon removed and remaining in the managed forest, and their respective stock distributions by tree compartment in an annual production unit. We consider how these results apply to recommendations on forest management in the Amazon, on the sustainability of the management system and on mitigating climate change.

2. Materials and Methods

2.1. Study Area

The present study was carried out in Fazenda Antimary I and II (9°23′43′′ S and 67°58′50′′ W), located in the municipality (county) of Porto Acre, Acre state, Brazil. The vegetation of the study area consists primarily of the forest types "open forest with bamboo," "open forest with palms" and "dense forest" [19–21].

The climate of the region is type Am (tropical monsoon climate) according to the Köppen classification [22], with an annual mean temperature of 24.5 °C [23] and annual mean rainfall ranging from 1750 to 2250 mm [24]. The rainy season begins in October and ends in April or May, with the largest accumulation of precipitation in the first quarter of the year. The dry season extends from June to September, when forest harvest activities begin [23].

The soils in the study area are classified as two types of Ultisol: "red loamy sand" and "red yellow latosol" [21]. The predominant topography is flat, with a slope of ~5% and only rarely exceeding 10% [24]. The elevation is 220–300 m above mean sea level [19].

The study area is under forest management using the reduced-impact procedures of Modeflora [21]. The study area encompasses a total of 1253 ha (Figure 1) and is designated as Annual Production Unit (APU) 002. A 100% forest inventory of commercial tree species was carried out in May 2015 and was approved in 2016 by the Institute of the Environment of Acre (IMAC) [21].

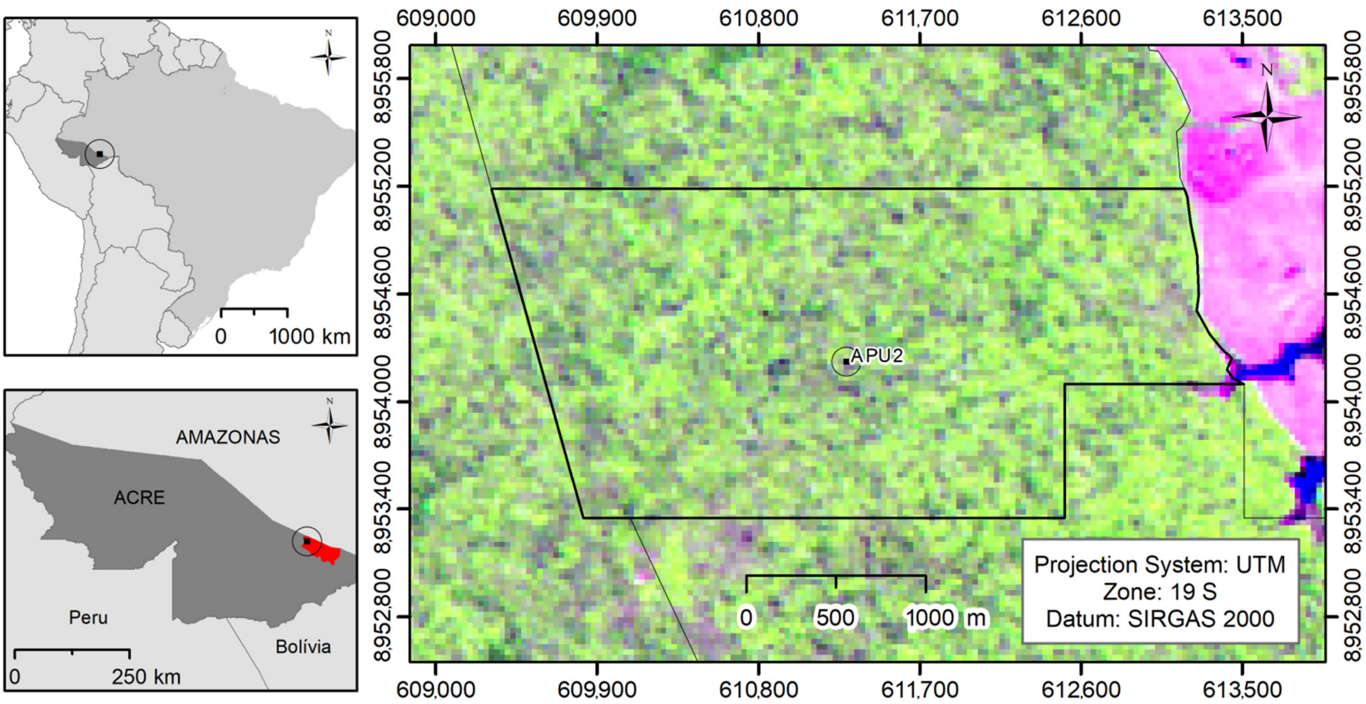

Figure 1. Location of the study area in Fazenda Antimary I and II in the municipality of Porto Acre, Acre state, Brazil, in a 1253-ha annual production unit (OLI/Landsat 8, composition 654 in RGB).

2.2. Forest Inventory and Categories of Commercial Trees

The data used in this study were provided by the company responsible for forest management. The criteria for selecting the individuals harvested for the study were those which met the criteria for felling according to the Brazilian regulations for forest management [11,25,26]. Diameter at breast height (DBH) and commercial height (HC) were measured for all individuals of commercial value with DBH ≥ 10 cm. DBH was measured 1.30 m above the ground or just above any buttresses.

The commercial trees in the database were separated into categories in accordance with the criteria defining classes in the 100% forest inventories (Table 1) required by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) (Standard No. 2 of 26 April 2007) [26]. "Commercial trees" refers to trees of commercial species with DBH ≥ 10 cm measured in the managed area as described in the "sustainable forest management plan" (PMFS) [11,26] (Supplementary Materials Table S1). These are divided into two categories, "remaining trees" and "harvested trees", where trees authorized for harvesting and marketing are called "harvested trees" [11,25,26] and "remaining trees" have the purpose of maintaining the ecosystem and are used for the conservation of commercial species. Commercial trees in the category "remaining trees" comprise the classes: "protected by law", "trees in permanent protection areas (APPs)", "rare trees" (where DBH ≥ 10 cm), "seed trees" (where DBH ≥ 30 cm) and "future cut" (10 cm ≤ DBH < 50 cm) (Table 1). Note that trees with DBH ≥ 50 cm that are in the "trees in APPs", "rare trees" and "seed trees" classes cannot be cut, and these trees remain standing as a way of maintaining biodiversity and conserving suppressed commercial species. "APPs" are areas of permanent preservation that are required to be maintained along watercourses. Trees in the "future cut" category (10 cm ≤ DBH < 50 cm) are those that can be cut when they reach the minimum DBH of 50 cm.

Table 1. Category and description of the criteria defining the classes established for cutting and maintenance of trees (IBAMA Standard No. 2 of 26 April 2007) [26]).

Category	Criterion	Class
Remaining trees	This category includes trees of species protected by law (DBH ≥ 10 cm) and trees located in areas of permanent preservation (APPs) that are inventoried (DBH ≥ 30 cm).	Trees in APPs
		Protected by law or prohibited from cutting
	Seed trees, trees below the minimum cutting diameter, rare species and trees of commercial species that do not meet the selection criteria for felling (DBH ≥ 30 cm).	Seed trees ("*matrizes*")
		Rare trees Future cutting
Harvested trees	Trees that can be cut with DBH ≥ 50 cm by species and stem quality class.	Harvested or cut

2.3. Estimation of Volume, Biomass and Carbon of Commercial Trees in Areas under Forest Management

We estimated volume (m^3 ha^{-1}), biomass (Mg ha^{-1}) and carbon stocks (MgC ha^{-1}) in the different tree components in three steps, namely, pre-harvest, harvest and post-harvest, known as "stages of logging." The "pre-harvest" stage of logging is defined as the stage when commercial trees with DBH ≥ 10 cm are measured, including all standing trees in the categories "remaining trees" and "harvested trees" (Table 1 and Figure 1). The "harvest stage" is defined as the phase when commercial trees with DBH ≥ 50 cm are measured. The productive capacity of the "harvested trees" category was estimated in the 1253-ha management area. Finally, the "post-harvest" stage is defined as the difference between the pre-harvest and the harvest stages, and this category encompasses the "remaining trees" (trees of commercial species with DBH ≥ 10 cm, including trees in APPs, rare trees, seed trees and trees protected by law). We estimated the volume, biomass and carbon stocks of standing commercial trees (pre-harvest; Figure 2, step 2). The merchantable volumes (VC; m^3) of the inventoried trees were estimated using an equation developed by Romero et al. [27] specifically for the study area: VC = 0.0003313 $DBH^{1.761}$ $HC^{0.800}$, where DBH = diameter at breast height (cm) and HC = commercial height (m) (the length of the commercial bole from the 30-cm stump cut to the first significant branch). This equation has a root mean square error (RMSE) of 1.634 m^3 and a mean absolute deviation (MAD) of 1.066 m^3. To estimate the tree crown volume (VCo; m^3), we used an expansion factor following Goodman et al. [3], who found that, on average, 44% of the aboveground biomass of trees in southwest Amazonia is comprised of branches, leaves and fruits and the rest (56%) is comprised of the stem (the trunk from the ground to the first significant branch). We obtained the total volume of each tree by summing the volumes of the stem and the crown. Subsequently, the volumes of all inventoried trees were summed and the mean volume per hectare was calculated. The aboveground biomasses of the stems and crowns were obtained by multiplying the volume of each component by the basic density of the wood (oven-dry weight divided by saturated volume) [28]. Where available, the values for basic wood density (oven-dry weight divided by saturated volume) obtained by Romero [18] were used for the species harvested in the study area. In cases where a species-specific value for basic wood density was not available, the arithmetic mean for the genus was used. The carbon stock in each tree component was determined by multiplying the biomass of each component by 0.49 (with standard deviation $\pm$ 0.05), which is the average carbon content obtained for harvested trees in the study area [27]. Subsequently, the total biomass and carbon stocks for the individuals were summed and divided by the area to obtain biomass and carbon stock per hectare. In the case of the "harvested trees" class, the volume of the stump (VTo; m^3) was estimated assuming a cylinder 0.3 m in height [29]: $VTo = 0.3\,\pi\,(DBH/200)^2$. The values for the stump were discounted from the standing volume, biomass and carbon of harvested commercial trees. This information determines what is retained in the management system (crown and stump) and what is removed (commercial bole) (Figure 2).

2.4. Percentage of Commercial Trees and Growth Rate

To obtain the contribution percentages of the "remaining trees" and "harvested trees" categories, information on aboveground volume, biomass and carbon per hectare (DBH $\geq$ 10 cm) was used according to studies reported in the southwestern portion of the Brazilian Amazon. Previous studies by Salimon et al. [20], Brown et al. [30,31], D'Oliveira et al. [32], Brazil, SFB [33] and Souza et al. [34] provide values of aboveground volume, biomass and carbon stock per hectare (DBH $\geq$ 10 cm). These values were summed and divided by the number of previous studies, thus obtaining the arithmetic mean for each variable (Table 2). For those studies that did not estimate carbon per hectare, carbon was calculated from the biomass values multiplied by the carbon content for "dense" and "semi-open" ombrophylous forest (49%) [18,27]. The values in Table 2 allowed extrapolation to calculate the percentage that the commercial trees represent, on average, in one hectare. At the same time, it was possible to calculate the percentage leaving the management system in the harvested commercial boles.

Table 2. Volume and carbon inferred from previous studies in the southwestern portion of the Brazilian Amazon for trees of all species with DBH $\geq$ 10 cm.

Variable	Mean	References
Volume	330.60 $\pm$ 21.28 m^3 ha^{-1}	Brazil, SFB, 2014 (≈315.45 m^{-3} ha^{-1}) [33]; Souza et al., 2012 (345.65 m^{-3} ha^{-1}) [34]
Carbon	163.23 $\pm$ 34.57 MgC ha^{-1}	Brown et al., 1995 (≈139.65 MgC ha^{-1}) [30], 2009 (≈213 MgC ha^{-1}) [31]; D'Oliveira et al., 2012 (≈113.53 MgC ha^{-1}) [32]; Salimon et al., 2011(≈157.78 MgC ha^{-1}) [20]; Souza et al., 2012 (≈181.01 MgC ha^{-1}) [34]; Brazil, SFB, 2014 (≈174.4 MgC ha^{-1}) [33]

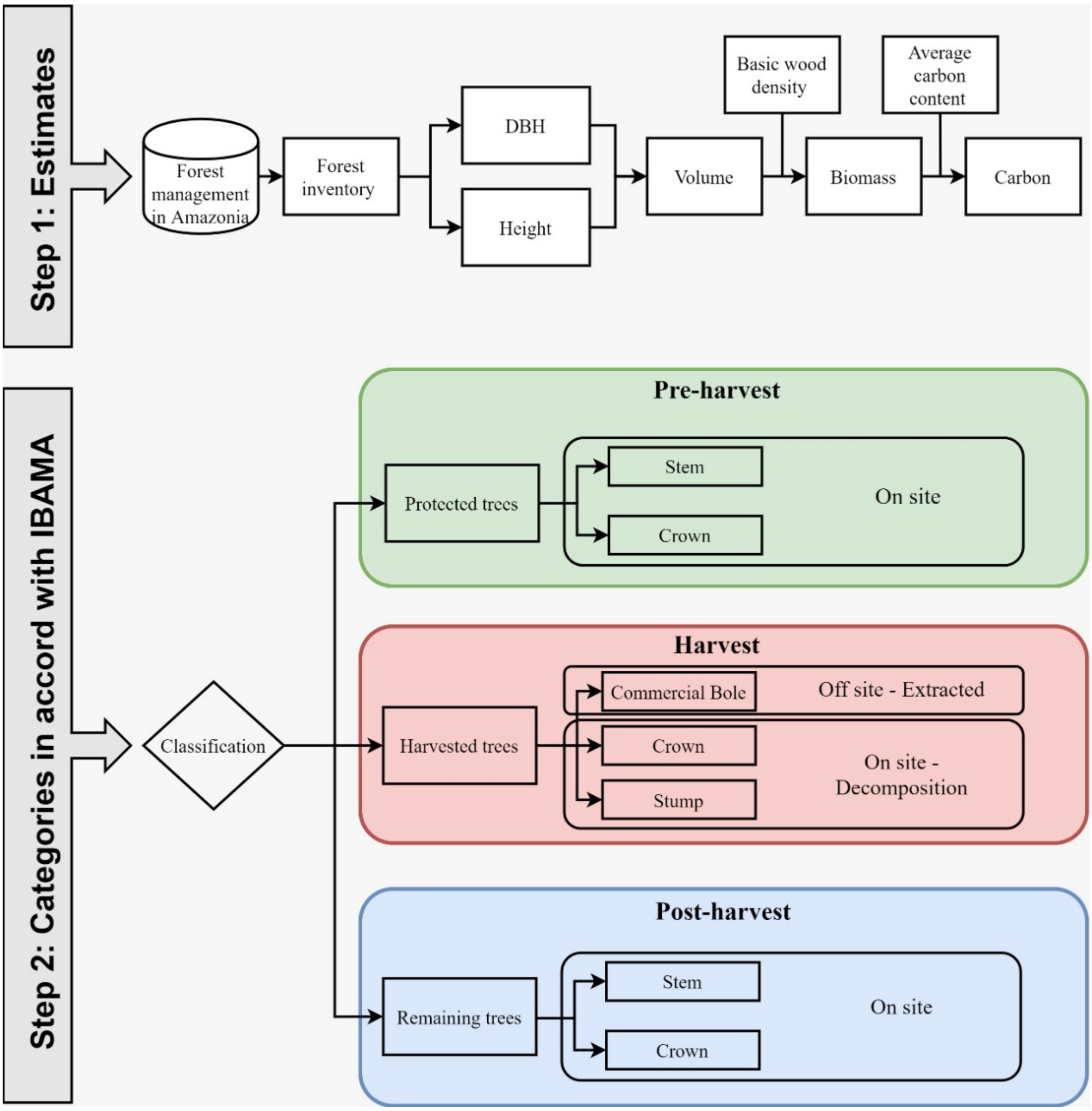

Figure 2. Methodological flowchart with the steps for pre- and post-harvest volume, biomass and carbon of managed forest in Brazil's state of Acre. Stem = trunk from the ground to the first significant branch. Commercial bole = trunk from the stump cut to the first significant branch. The stumps in this management system are 30 cm in height.

To replace the volume and carbon of harvested trees in the management system, the growth rates for volume and carbon were calculated by dividing the amounts removed per hectare of the commercial trees by 35 (the number of years in the harvest cycle) [11,26]. Note that, in addition to replacing the stocks removed in harvested trees, the amounts lost from the system in trees inadvertently killed or damaged in the logging operation or by other disturbances must also be replaced.

3. Results

In the study area, we found 12,794 trees of commercial species with DBH ≥ 10 cm distributed among 22 families, 68 genera and 81 species. The density was 10.21 trees ha^{-1}, with DBH ranging from 10 to 248 cm. The basic wood density for the species ranged from

0.288 to 0.825 g cm^{-3}. The commercial height (height to the first significant branch) ranged from 4 to 29 m (Figure 3).

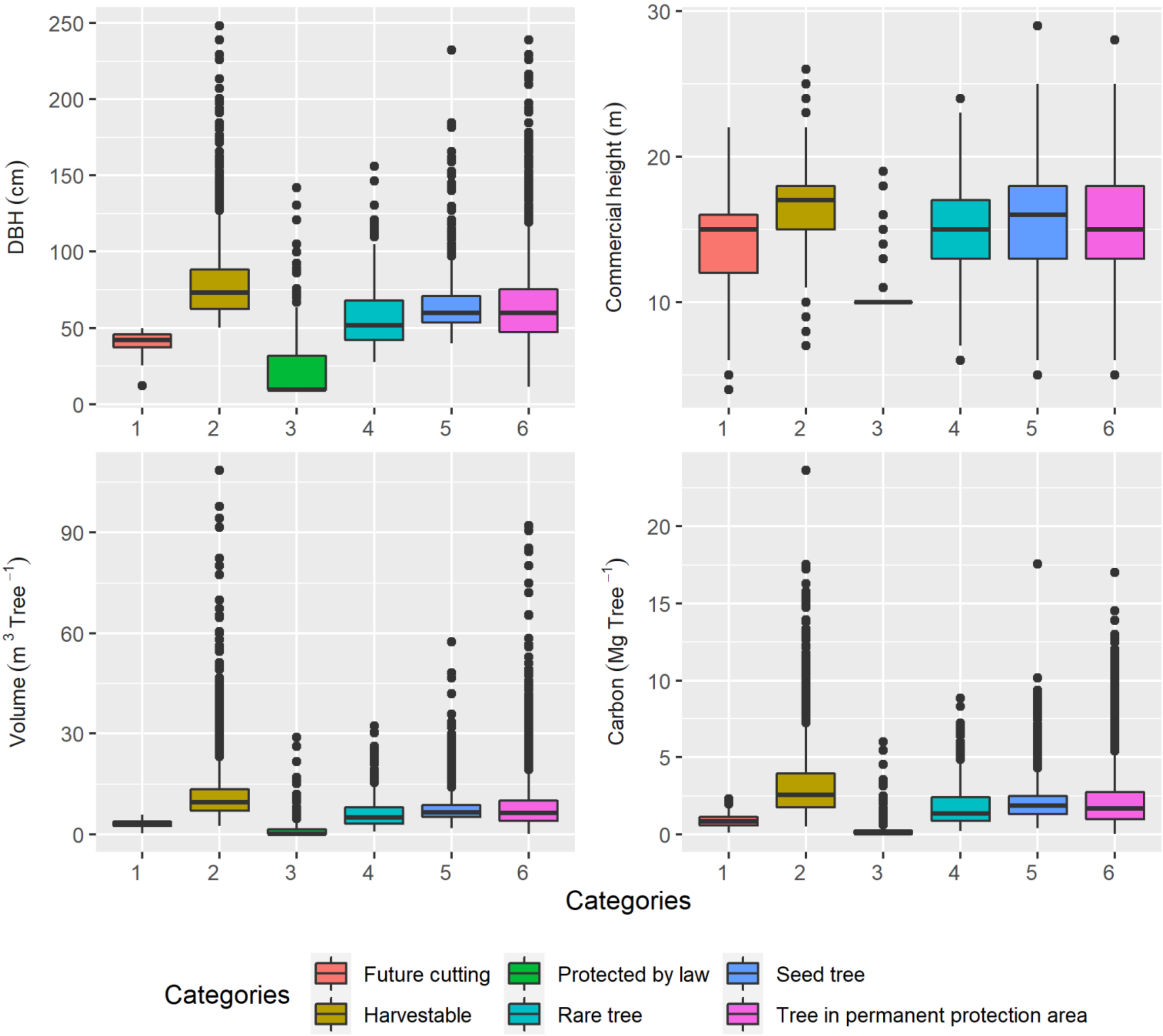

Figure 3. Distribution of dendrometric variables for each tree category in a managed forest in Brazil's state of Acre. Boxes outline interquartile range, and vertical lines extend to 1.5× interquartile range, with outliers individually marked. Note that volume and carbon values include stumps and crowns.

3.1. Estimated Aboveground Volume and Carbon in Trees of Commercial Species by Category and Class for Felling and Maintenance

The volume in trees of commercial species (DBH $\geq$ 10 cm) in the 1253-ha area totaled 79.16 m^3 ha^{-1}; aboveground and carbon totaled 21.54 MgC ha^{-1} (pre-harvest stage; standing trees). Of these totals, 35.22 m^3 ha^{-1} of the volume and 9.72 MgC ha^{-1} of the carbon were in the "harvestable trees" category (harvest stage; felled tree), i.e., with DBH $\geq$ 50 cm. The difference between the pre-harvest and harvest stages provides values for stocks in standing trees in the post-harvest stage: 43.94 m^3 ha^{-1} (55.49%) of the volume and 11.82 MgC ha^{-1} (54.87%) of the carbon in the categories "remaining trees". These categories represent the trees with DBH $\geq$ 10 cm left standing in the forest (post-harvest stage). The volume in the different categories ranged from 0.64 to 35.22 m^3 ha^{-1} and carbon ranged from 0.15 to 9.72 MgC ha^{-1} (Table 3).

Table 3. Aboveground volume and carbon of commercial trees by category and class for felling and maintenance of the 81 species measured in an area of 1253 ha in the state of Acre, Brazil.

Category	Class	N	DBH (cm)	DA	V	rV	C	rC
Remaining trees	Trees in areas of permanent preservation (APPs)	3219	11.46–238.73	2.57	21.88	27.63	5.74	26.65
	Protected by law	767	10.00–141.97	0.61	0.64	0.81	0.15	0.70
	Seed trees	1872	39.79–232.37	1.49	11.71	14.79	3.25	15.09
	Rare trees	615	27.69–155.97	0.49	3.00	3.79	0.83	3.85
	Future cutting	2588	12.10–49.97	2.07	6.57	8.30	1.85	8.59
Subtotal					43.94	55.49	11.82	54.87
Harvested trees	Harvested or cut	3733	50.29–248.28	2.98	35.22	44.48	9.72	45.13
Subtotal						44.48		45.13
Total		12,794	10.00–248.28	10.21	79.19	100.00	21.54	100.00

Number of trees sampled by species per class (N), number of individuals per hectare (DA; n ha^{-1}), volume (V; m^3 ha^{-1}) and carbon (C; MgC ha^{-1}). These values include the crown and the first 30 cm of the trunk that corresponds to the stump if harvested. The relative percentages refer to the percentage of the total stock (the column total) that is represented by each class: rV = relative percentage of volume for each class (%), and rC = relative percentage of carbon for each class (%).

3.2. Estimated Aboveground Volume and Carbon in the Category Harvested Trees

Of the 81 commercial species measured in all categories, only 44 (Supplementary Material, Table S2) were in the category "harvested trees" (DBH $\geq$ 50 cm) (Table 1). Their volume totaled 35.22 m^3 ha^{-1}, and aboveground carbon totaled 9.73 MgC ha^{-1}. The species with the lowest volume was *Martiodendron elatum* (Ducke) Gleason, with volume totaling 0.0048 m^3 ha^{-1}, and the species with the highest was *Ceiba pentandra* (L.) Gaertn., with volume totaling 0.0339 m^3 ha^{-1}. For carbon, the species with the lowest stock was *Clarisia* Ruiz & Pav., with 0.0012 MgC ha^{-1}, and the species with the highest was *Micropholis* (Griseb.) Pierre, with 0.0070 MgC ha^{-1} (Supplementary Materials Table S2).

Estimates for the Commercial Bole, Crown and Stump in the "Harvested Trees" Category

When the trees to be harvested (DBH $\geq$ 50 cm) are separated into their tree components, the commercial bole (the trunk from the 30-cm stump cut to the first significant branch), stump and crown determine the volume, biomass and carbon retained and removed in the management system (Table 4). On a per-hectare basis, the commercial bole had volume and carbon of 19.25 m^3 ha^{-1} and 5.32 MgC ha^{-1}, respectively. Under a 35-year cutting cycle, the growth rate to replenish harvested stem volume, biomass and carbon by growth of trees of commercial species with DBH $\geq$ 10 cm should be 0.55 m^3 ha^{-1} $year^{-1}$ and 0.15 MgC ha^{-1} $year^{-1}$, respectively. The crowns and stumps together had volume and carbon stocks of 15.97 m^3 ha^{-1} and 4.41 MgC ha^{-1}. To replenish the volume and carbon that will be lost from decay of the crowns and stumps that are left in the forest, the growth rates need to be 0.45 m^3 ha^{-1} $year^{-1}$ and 0.12 MgC ha^{-1} $year^{-1}$, respectively, and the growth rate needed to replace carbon present the tree biomass as a whole (commercial boles, stumps and crowns) would be 0.27 MgC ha^{-1} $year^{-1}$. Note that sustainability also requires additional growth to replace stocks lost to collateral damage during logging and from other disturbances, including forest fires (which are made more likely by logging).

Table 4. Volume and carbon stock in the commercial boles, crowns and stumps of trees of commercial species (DBH ≥ 50 cm) harvested in 1253 ha.

Tree Part	Volume			Carbon		
	m^3	$m^3\ ha^{-1}$	$m^3\ ha^{-1}\ year^{-1}$	MgC	$MgC\ ha^{-1}$	$MgC\ ha^{-1}\ year^{-1}$
Commercial bole *	24,122.95	19.25 *	0.55	6662.35	5.32 *	0.15
Crown	19,417.33	15.50	0.44	5360.51	4.28	0.12
Stump	590.01	0.47	0.01	160.10	0.13	0.00
Total	44,130.29	35.22	1.00	12,182.96	9.73	0.27

* "Commercial bole" (ET) refers to the harvested portion of the trunk (from the 30-cm stump cut to the first significant branch).

3.3. Percentage of Volume and Carbon of Commercial Trees in Relation to Previous Studies in the Southwestern Brazilian Amazon

The total aboveground live volume per hectare (DBH ≥ 10 cm), including all trees and not only commercial species, averaged 330.6 $m^3\ ha^{-1}$ (Table 5) based on other studies in the southwestern portion of Brazil's Amazon region. Assuming this represents the volume at the study site, it can be inferred that the volume of the species studied represented 23.95% (79.19 $m^3\ ha^{-1}$; Table 3) of the total in the forest (trees of all species with DBH ≥ 10 cm). Of this total, only 5.82% (19.25 $m^3\ ha^{-1}$; Table 4) left the system in the harvested commercial boles (Table 5).

Table 5. Volume stock of all species for the study area extrapolated from the literature, commercial species as a percentage of the volume of all species and volume of the commercial boles (harvested trunks) as a percentage of the volume of all species.

Scheme 3	VTE ($m^3\ ha^{-1}$) (DBH ≥ 10 cm)	V ($m^3\ ha^{-1}$) (DBH ≥ 10 cm)	VTS (%) (DBH ≥ 10 cm)	ET ($m^3\ ha^{-1}$) (DBH ≥ 50 cm)	VTT (%) (DBH ≥ 50 cm)
Brazil, SFB (2014) [33]	315.55	79.19	25.10	19.25	6.10
Souza et al. (2012) [34]	345.65		22.91		5.57
Mean	330.60	79.19	23.95	19.25	5.82

Where: VTE = volume stock of all species from previous studies in the southwestern portion of the Brazilian Amazon (DBH ≥ 10 cm); VTS = percentage of total volume (DBH ≥ 10 cm) (V = 79.19 $m^3\ ha^{-1}$; Table 3) of commercial species in relation to *VTE* (V × 100%/*VTE*); VTT = percentage of the volume of commercial bole (DBH ≥ 50 cm) (ET = 19.25 $m^3\ ha^{-1}$; Table 4) of the commercial species in relation to *VTE* (ET × 100%/*VTE*); ET = commercial bole; V = total volume.

Aboveground carbon stored in the forest was estimated to be 163.23 $MgC\ ha^{-1}$ (trees of all species with DBH ≥ 10 cm) (CTE; Table 6), implying that the trees under study (21.54 $MgC\ ha^{-1}$; C, Table 3) represented 13.20% of this total and the carbon taken from the forest in the harvested commercial boles (5.32 $MgC\ ha^{-1}$; Table 4) represented only 3.26% (Table 6).

Table 6. Carbon stock for the forest, including trees of all species in the study area extrapolated from the literature, and for the commercial boles of harvested trees that are removed from the management system.

Study	CTE ($MgC\ ha^{-1}$) (DBH ≥ 10 cm)	C ($MgC\ ha^{-1}$) (DBH ≥ 10 cm)	CTS (%) (DBH ≥ 10 cm)	ET ($MgC\ ha^{-1}$) (DBH ≥ 50 cm)	CTT (%) (DBH ≥ 50 cm)
Brazil, SFB (2014) [33]	174.4	21.54	12.35	5.32	3.05
Brown et al. (1995) [30]	139.65		15.42		3.81
Brown et al. (2009) [31]	213		10.11		2.50
Souza et al. (2012) [34]	181.01		11.90		2.94
Salimon et al. (2011) [20]	157.78		13.65		3.37
D'Oliveira et al. (2012) [32]	113.53		18.97		4.69
Mean	163.23	21.54	13.20	5.32	3.26

Where: CTE = carbon stock of all species (DBH ≥ 10 cm) based on previous studies in the southwestern portion of the Brazilian Amazon; CTS = percentage of total carbon stock (C = 21.54 $MgC\ ha^{-1}$; Table 3) of commercial species (DBH ≥ 10 cm) in relation to *CTE* (C × 100%/*CTE*); CTT = percentage of the carbon stock in harvested commercial boles (DBH ≥ 50 cm) (ET = 5.32 $Mg\ ha^{-1}$; Table 4) of the commercial species in relation to *CTE* (ET × 100%/*CTE*); C = carbon stock; ET = commercial bole.

4. Discussion

In Brazil, IBAMA Standard No. 2 of 26 April 2007 establishes criteria for the selection of commercial trees for cutting and maintenance in areas under forest management, in addition to the volume stocks that can be removed from the managed areas [26]. However, little is known about the stocks of commercial trees that remain standing. In the management system, we found that more than 50% of the trees were in the category "remaining trees" (Table 3; Supplementary Material, Table S3; data in terms of biomass are given in Tables S4–S7). The "remaining trees" category stored volume (43.94 m^3 ha^{-1}) and carbon (11.82 MgC ha^{-1}), and these trees remove carbon dioxide from the atmosphere over the course of the 35-year felling cycle [11]. In the case of protected trees in this category, such as those in areas of permanent preservation (APPs), seed trees and trees protected by law (or prohibited from felling), carbon dioxide removal will occur continuously so long as they are metabolically active. However, the natural mortality of Amazon tree biomass would neutralize most of this gross uptake; biomass mortality in eastern Amazonia has been estimated at 3.6% $year^{-1}$ [17]. It should be noted that within the category "remaining trees," the class "future cutting," when reaching the minimum cutting diameters (DBH $\geq$ 50 cm), moves to the class "harvested or cut," contributing to the stocks for future production (commercial trees that could be felled in a second management cycle).

The cutting intensity in the managed area refers to the commercial bole (19.25 m^3 ha^{-1}; 0.55 m^3 ha^{-1} $year^{-1}$), which represents 5.82% the volume of logs obtained in the study area. The commercial boles of the felled trees (DBH $\geq$ 50 cm) are removed from the managed area, and this component therefore defines the productive capacity of the management unit. The stump and crown (4.69%) remain in the forest as necromass (dead biomass), decomposing and emitting CO_2 for a certain period of time. Estimates of this necromass are only rarely included in studies of forest management (e.g., Numazawa et al., 2020) [35]. In the context of climate change, we can infer that the 21.54 MgC ha^{-1} carbon stock of standing commercial trees (DBH $\geq$ 10 cm) is responsible for 13.20% of the total aboveground carbon in managed areas. The commercial bole is responsible for 3.26% (5.32 MgC ha^{-1}) of the carbon removed directly from the forest in the harvested trunks for the production of wood. Of this total, 53.2% remains stocking carbon in the form of timber products, and the remaining 46.8% (waste) is reused for burning as a source of electricity (replacing fossil fuels) and for firewood, building fences or other forms of use that emit into the atmosphere over different time scales [5]. The stump and crown are responsible for 2.70% (4.41 MgC ha^{-1}) of the loss of carbon stock in managed areas. Of carbon in the stump and crown, 76% is emitted to the atmosphere and the remaining 24% stays in the ecosystem [36]. Information on these quantities is valuable for estimates of the role of forest management in global climate change.

The harvest intensities in our study were much higher than those reported for Amazonian forests outside of Brazil [2,37]. The harvest intensity in our study area was within the range of intensities reported for forests in the Brazilian Amazon (15 to 30 m^3 ha^{-1} and 4.04 MgC ha^{-1}) [33,38,39]. Our values allow us to infer that the growth rate that would be needed to replenish volume (0.55 m^3 ha^{-1} $year^{-1}$) and carbon (0.15 MgC ha^{-1} $year^{-1}$) exports from harvest is within the maximum allowable limit (0.86 m^3 ha^{-1} $year^{-1}$) established by Brazilian regulations for a 35-year cycle [11,40]. In order for growth of this stock in commercial species (DBH $\geq$ 10 cm) to replace the 19.25 m^3 ha^{-1} that was removed in harvested boles, bole volume in the remaining trees of commercial species must accumulate, on average, at 2.79% of the initial stock per year over the 35-year management cycle. This is close to the rate of approximately 3% $year^{-1}$ at which tropical trees can grow [41]. However, the present study does not include measurements of growth rates, and we therefore cannot determine whether the trees will grow at the rate needed to recuperate stocks over the course of a 35-year management cycle. Some studies indicate recovery of volume or biomass of trees $\geq$ 10 cm DBH in comparable management systems. In the CELOS system in Suriname with harvest intensities of 15 and 23 m^3 ha^{-1}, there was an 80% probability of this recovery after 32 years of observation [42]. In Pará state in the eastern portion of Brazilian Amazonia, Numazawa et al. [35] used a global process-based model to simulate growth in 13 logged areas (average harvesting intensity = 26.9 m^3 ha^{-1}) and concluded that they could recover harvested stocks in a 30-year cycle, although at levels below those in unlogged forests. Note that these studies refer to stocks in trees with DBH $\geq$ 10 cm, which are not the same as trees that will be of harvestable size in the next management cycle.

Although Brazilian regulations are based on a rate of increase in the volume of trees of commercial species with DBH $\geq$ 10 cm, what is relevant to the financial viability of the next management cycle is instead the increase in volume in those trees that will have DBH $\geq$ 50 cm within the next 35 years. For example, in Suriname after selective logging without special treatments, commercial species increase in diameter at 4 mm $year^{-1}$ [43]. At this rate, diameter increase would total 14 cm in 35 years, and only trees presently with DBH $\geq$ 36 cm would be harvestable in the next management cycle. In addition, even if harvest intensities greater than the allowed 30 m^3 ha^{-1} maximum might still guarantee this growth rate, they would jeopardize the biodiversity of species in the areas under management [40,42].

Harvesting in our study area was conducted with reduced-impact logging, which has limited negative impacts on the environment and on the continuity of biological diversity [1,12–16,40,44]. All Amazonian management operations need to incorporate reduced-impact logging procedures if they are to minimize harvesting impacts and satisfy society's demand for low-impact end products. Low-impact forest management creates openings in the forest canopy that allow entry of sunlight [15,17,45,46], and the removal of trees both by harvesting and in the openings of log decks, roads and skid trails favors the regeneration of light-dependent species.

The values we report are relevant to silvicultural treatments such as techniques for natural regeneration, commercial species enrichment, species composition structuring and management of forest gaps; these treatments are important for the maintenance of commercial species and growth rates after harvest [42,47–50]. Post-harvest silvicultural treatments are needed to conserve the forest and its natural regeneration, since the application of post-harvest silvicultural treatments will favor the enrichment and continuity of species composition. Monitoring the harvested forests allows application of treatments to increase the rate of growth and the recruitment of new individuals [50–53]. These treatments would increase carbon stocks in forest biomass [42,46,52,53].

Currently, post-harvest silvicultural treatments in southwestern Amazonia do not occur, even though they may be required by the POA (Annual Operational Plan). This is because these treatments are not mandatory, and their economic return may be considered questionable. In addition, most entrepreneurs do not take responsibility for maintaining the forest under the same conditions in terms of benefits for future generations. The government should adopt regulations that encourage entrepreneurs to carry out silvicultural treatments that favor natural regeneration and the continuity of benefits generated by forests.

5. Conclusions

The productive capacity of the managed area (volume and carbon) depends on the "harvested trees" category and on the cutting intensity applied in the forest management plan for wood production. Our study found that the commercial bole removed from the forest represents a small part of the total aboveground forest stock of volume and carbon in trees with DBH $\geq$ 10 cm, including non-commercial species. However, uncertainties exist, especially considering the paucity of regionally relevant information on the growth rates of commercially important species. The carbon stocks and flows estimated in the present paper represent one of the multiple effects of forest management that need to be quantified in order to assess the impacts and benefits of this important land use in Amazonia.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f12040481/s1, Table S1: Means and ranges of DBH for commercial trees by species and class measured in the 100% forest inventory of 1253 ha; Table S2: Basic wood density, and estimated aboveground volume biomass and carbon (stump, commercial bole and crown) of trees (DBH $\geq$ 50 cm) harvested in 1253 ha; Table S3: Numbers of individuals measured in the 100% inventory by class and diameter range in a 1253-ha forest-management area in Acre; Table S4: Biomass inferred from previous studies in the southwestern portion of the Brazilian Amazon for trees of all species with DBH $\geq$ 10 cm; Table S5: Aboveground biomass of commercial trees by category and class for felling and maintenance of the 81 species measured in an area of 1253 ha in the state of Acre, Brazil; Table S6: Biomass stock in the commercial boles, crowns and stumps of trees of commercial species (DBH $\geq$ 50 cm) harvested in 1253 ha; Table S7: Biomass stock for forest in the study area extrapolated from the literature and for the trunks of harvested trees that are removed from the management system.

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