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Stocks of Carbon in Logs and Timber Products from Forest Management in the Southwestern Amazon

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Abstract: Amazon forest management plans have a variety of effects on carbon emissions, both positive and negative. All of these effects need to be quantified to assess the role of this land use in climate change. Here, we contribute to this effort by evaluating the carbon stocks in logs and timber products from an area under forest management in the southeastern portion of Acre State, Brazil. One hundred and thirty-six trees of 12 species had DBH ranging from 50.9 cm to 149.9 cm. Basic wood density ranged from 0.3 cm^{-3} to 0.8 g cm^{-3} with an average of 0.6 g cm^{-3}. The logs had a total volume of 925.2 m^3, biomass of 564 Mg, and carbon stock of 484.2 MgC. The average volumetric yield coefficient (VYC) was 52.3% and the carbon yield coefficient (CYC) was 53.2% for logs of the 12 species. The sawn-wood products had a total volume of 484.2 m^3, biomass of 302.6 Mg, and carbon stock of 149.9 MgC. Contributions of the different species to the total carbon stored in sawn-wood products ranged from 2.2% to 21.0%. Means and standard deviations for carbon transferred to sawn-wood products per-species from the 1252.8-ha harvested area ranged from 0.4 ± 1.1 MgC to 2.9 ± 0.4 MgC, with the largest percentages of the total carbon stored in wood products being from *Dipteryx odorata* (21.0%), *Apuleia leiocarpa* (18.7%), and *Eschweilera grandiflora* (11.7%). A total of 44,783 pieces of sawn lumber (such as rafters, planks, boards, battens, beams, and small beams) was obtained from logs derived from these trees. Lumber production was highest for boards (54.6% of volume, 47.4% of carbon) and lowest for small beams (1.9% of volume, 2.3% of carbon). The conversion factor for transforming log volume into carbon stored in sawn-wood products was 16.2%. Our results also show that species that retain low amounts of carbon should be allowed to remain in the forest, thereby avoiding low sawmill yield (and consequent generation of waste) and allowing these trees to continue fulfilling environmental functions.

Keywords: carbon yield coefficient; volumetric yield coefficient; wood sawing; climate change; sawmill; forest management

1. Introduction

Climate change is no longer a distant threat but rather a problem that is already knocking at our door and affecting biodiversity and the human economy on a global scale [1]. Deforestation is one of the major drivers contributing to climate change [2]. However, developing countries often fail to reconcile development with environmental preservation, believing that this can affect their economic growth [3].

Many people are dependent on forest resources for their subsistence [4–6]. Wood is an important natural resource that is used for pulp, energy, and sawmill products [7–9]. The advisability of removing wood from the Amazonian forest and the effectiveness of controls on logging have been questioned in recent decades due to illegal logging and deforestation [10–13]. This situation has caused global concern and stimulated the creation of regulatory guidelines, monitoring, controls, and new approaches to forest resource management [14–16].

One method of limiting damage from logging is low-impact forest management (LIM), a process that aims to reduce costs and waste [14,17,18] and minimize impacts on the forest [19,20], increase the growth rates of trees (and consequently the supply of wood [14,19,21]), and enhance socio-economic and environmental development [15,22,23]. However, there are challenges to be overcome in maintaining species biodiversity while extracting timber [24].

Brazil's legislation establishes permissions, obligations, and restrictions for the removal of wood from the forest, which can be done under approved "sustainable forest-management plans" (PMFSes) [25,26]. For this, the proponent must provide an estimate of the volume of the stems of commercial trees in the forest to be managed and conduct a "100% survey" that identifies and maps all trees with a diameter greater than 50.0 cm at breast height (DBH: measured 1.30 m above of the ground or just above any buttresses), 50.0 cm being the minimum cut diameter (DMC—Brazilian acronym). The harvesting process must also follow the legislation established for PMFSes. For projects using machinery for logging, the initial cutting cycle must be 25–35 years in length and the cutting intensity cannot surpass 30 m^3 ha^{-1} [25]. In addition, a logging authorization (AUTEX) is required from the government body that approves the beginning of harvesting in each annual production unit (UPA); this document specifies the maximum volume per species allowed for harvesting. The managers must present annual operating plans (POAs) specifying the maximum volume to be harvested each year; alteration of land use is only permitted in 20.0% of the area, after discounting the areas of permanent protection (APPs) required by Brazil's Forest Code [25,26]. The restrictions are intended to ensure the protection and sustainability of the forest by not allowing significant changes in the horizontal and vertical structures of the forest and by not allowing the removal of all individuals of any given species. The forest-management plans have the objectives of minimizing harvest and post-harvest impacts, providing society with low-impact end products, and, theoretically, providing a sustainable source of income to the local community [15,19].

Brazilian legislation on forest management does not require estimates of carbon stocks [27]. Management activities can be regulated to maintain economic benefits, to minimize environmental damage, and to allow accurate carbon accounting. Forest management can potentially help reduce concentrations of greenhouse gases by retaining carbon stocks in the final sawmill products. Other factors that need to be taken into account to better assess the net effects of management include the rate of deterioration of product stocks, the quantities of unused parts of harvested trees (sawmill waste and tree crowns, stumps and roots), collateral damage to unharvested trees, and forest mortality, including that from the fires that have increased the probability of occurring in partially harvested forests [28,29]. The value attributed to time in carbon accounting is critical in the balance of benefits and costs to climate from forest management and its wood products. Forest management in the Brazilian Amazon is less aggressive than deforestation for large-scale agriculture, such as the expansion of monocultures for the production of biofuels [30].

In forest management in the Amazon, the log is the tree component harvested and removed from the management system [18,27]. The final sawn-wood products are obtained from logs in sawmills for primary preparation [31–33]. Primary products (such as planks, beams, and rafters) and their subsequent use to manufacture furniture or for construction of structures (e.g., floor covering, roof structures, and windows frames) [18] generate employment and income in the production chain and also provides a carbon stock service [34] by maintaining carbon in products with life expectancies of decades to hundreds of years [35]. The volumetric yield (percentage of a log that is transformed into useful sawn wood) of commercial timber species in the Amazon is still low (41.1% on average), while waste production is high [31,33]. It is important to pursue higher volumetric yields because of the importance of timber products in carbon storage and their contribution to mitigating climate change [18,28].

Obtaining final sawn-wood products generates waste that is often burned as an energy source. Burning this waste to replace fossil fuels in thermal power plants is common in Brazil's Amazon region and returns CO_2 to the atmosphere [18,33,36,37]. If the biomass comes from a sustainably managed forest, the CO_2 released will be reabsorbed as the harvested plots regrow. Electricity generation from biomass from sustainable sources causes lower net CO_2 emission than does generation from fossil fuels [37].

The carbon stock in timber products obtained from logs from managed forests is related to time and permanence [38,39]. Wood stores carbon throughout the life of products, over a period of years [39–42]. In this way, they contribute to mitigate climate change over the period [43–45]. However, after their useful life, they are usually either buried in landfills or burned, emitting CO_2, thus affecting the emissions balance. However, these emissions from decomposition of discarded wood products occur in smaller quantities over time until they become neutral [18,39,45,46]. In addition, wood products can replace the use of more greenhouse-intensive products that require large amounts of energy in production and that are derived from raw materials, such as iron or aluminum, that also have impacts on emissions [47]. Accordingly, the information we present here is relevant both for the economics of logging in Amazonia and for efforts to reduce CO_2 emissions from this process by increasing the carbon stock from the forest that is held in the final manufactured products. If the net effect of forest management is positive for climate change mitigation, then the carbon benefit may provide both a means of reducing the impact of deforestation in the Amazon and a source of income for the local population. The objective of the present study is to quantify the carbon stock transferred to timber products from logs removed from an area under forest management in Brazil's state of Acre.

2. Materials and Methods

2.1. Study Area for Log Harvesting and Processing

The study was conducted in Acre State, in the southwestern portion of the Brazilian Amazon, in a harvested area that is 95% "dense ombrophilous forest" and 5% "open bamboo forest" [48]. The management area is located in the Antimary I and II ranches (Figure 1). The present study was done in Annual Production Unit No. 2 (UPA 2), which has an area of 1252.8 ha [49].

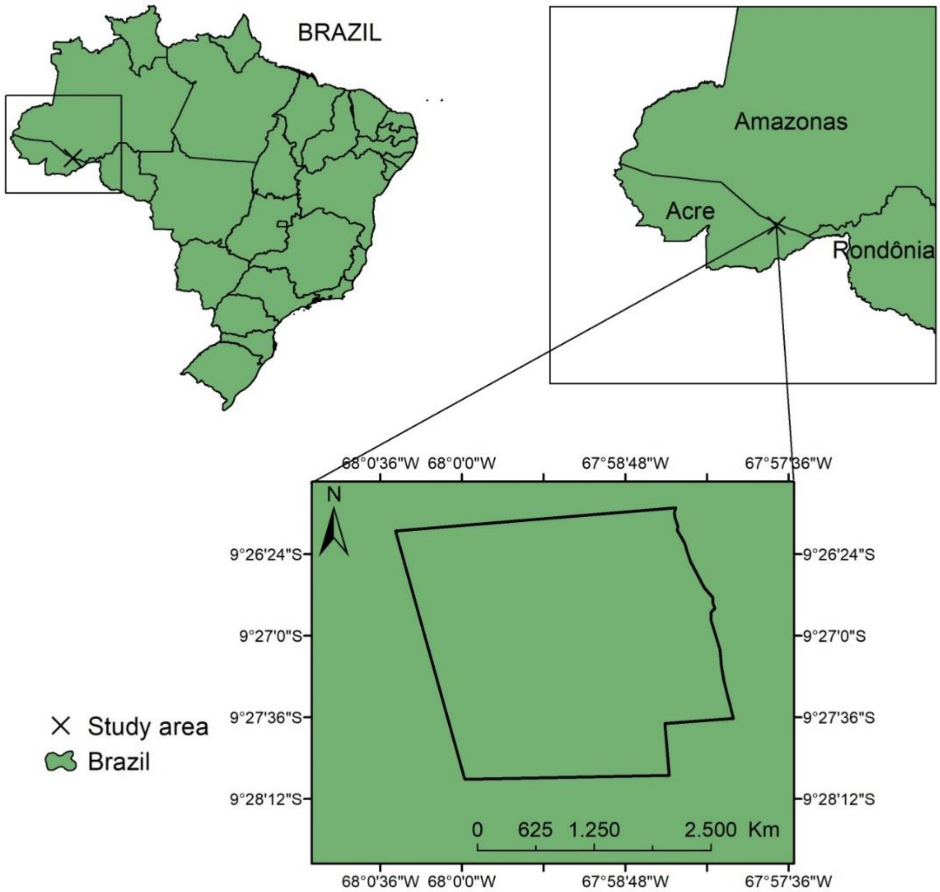

Figure 1. Location of the study area in the southwestern Amazon, in the municipality of Porto Acre, Acre, Brazil.

Logs were harvested by the Fox Madeiras sawmill in the municipality (county) of Rio Branco, which is located on the edge of Highway AC-10 at km 28, 44 km from the harvested area. Fox Madeiras conducts logging under a "sustainable forest management plan" that uses reduced-impact logging techniques. The Fox Madeiras sawmill consists of three yards totaling 8 ha to store logs from the management areas. The sawmill has two main sheds: the first has equipment such as a vertical band saw, and the second has a simultaneous split saw. Logs are transported to the sawmill in company trucks, sorted by species, and arranged randomly (in terms of diameter and length) in the storage yards for mechanical processing in the production sheds. This produces, on average, 50 m^3 per day. The boards, planks, beams, small beams, rafters, and other products produced are stored in designated final-product areas in the main warehouse.

2.2. Sample Selection, Harvesting, and Data Analysis

The volume, biomass, and carbon levels were obtained for the 12 species with the highest coverage values in the study area (57.8% of the total basal area of individuals of commercial species with a diameter at breast height (DBH) ≥ 50 cm). This was calculated from data provided by the company from its 100% forest inventory data in which all trees of commercial species in this size range were measured. The number of individuals sampled was determined according to the sample size (n) for a population considered to be infinite using the formula $n = \frac{t^2 * CV^2}{(E\%)^2}$, where n = number of individuals sampled; t = tabulated value of Student's t-statistic at 5% significance with n-degrees of freedom; CV = coefficient of variation; and E% = required accuracy (10%). The number of individuals sampled per species was proportional to the relative density (individuals with DBH ≥ 50 cm ha^{-1}) of the species in question [27,50]. Log volume (with bark) (V_l) values for the selected species were determined by the Smalian method, measuring the diameter along the stem at heights of 0.0 m, 0.3 m, and 1.0 m above the stump cut and every 2.0 m thereafter [50,51].

After obtaining the volume of the logs (with bark) (V_l), the logs were sawn to generate sawn-wood products (planks of different widths, rafters, battens, boards, beams, and small beams). The products were measured using a measuring tape, and the measurements were entered in a standardized field form where the quantities of the products (pieces) were noted together with their dimensions: thickness (T), width (W), and length (L) [52]. Products were categorized following Resolution no. 474 of 6 April 2016 of the Ministry of the Environmental [53] (Table 1). The volume of lumber (Vlum; [54,55]) was obtained based on the thickness (T; cm), width (W; cm), and length (L; m) of each piece using the formula $V_{lum} = \sum(W \times T \times L)$.

Table 1. Classification of sawn wood as defined by Resolution no. 474 of 6 April 2016 [53].

Name (Brazilian Equivalent)	Thickness (cm)	Width (cm)
Block, square, or fillet (*Bloco, quadrado*, or *filé*)	>12.0	>12.0
Wide plank (*Pranchão*)	>7.0	>20.0
Plank (*Prancha*)	4.0–7.0	>20.0
Beam (*Viga*)	≥4.0	11.0–20.0
Small beam (*Vigota*)	4.0–11.0	8.0–10.9
Rafter (*Caibro*)	4.0–8.0	4.0–7.9
Board (*Tábua*)	1.0–3.0	>10.0
Batten (*Sarrafa*)	2.0–3.9	2.0–10.0
Clapboard (*Ripa*)	<2.0	≤10.0

The volumetric yield coefficient (VYC; %) of sawn wood was calculated from the relationship between the volume of pieces of sawn wood (V_{sw}; m^3) and the log (V_l; m^3) by the formula $YC = \left(\frac{V_l}{V_{sw}}\right) \times 100$. The carbon yield coefficient (CYC; %) of the volume of the log was obtained with the formula $CY = \left(\frac{C_{sw}}{C_t}\right) \times 100$, where C_{sw} = carbon stock in sawn wood (MgC), and C_t = carbon stock in the log (MgC). VYC and CYC were calculated for each species from the arithmetic mean of CRV and CRC obtained for each log [53–55].

2.3. Determination of the Carbon Stock in Commercial Species in Logs (with Bark) and Timber Products

It was necessary to obtain fundamental information on biomass and carbon content in order to calculate the carbon stock in the trunk and in the wood products of the 12 species (136 felled trees), [27,32]. Biomass was calculated by multiplying the trunk volume (with bark) by the basic density of the wood (with bark), using the formula: $B_l = V_l \times \overline{d}_{bc}$, where: B_l = stem biomass of the sampled trees with bark (Mg), V_l = log volume with bark (m^3), and $\overline{d}_{bc}$= mean basic density of wood with bark (g cm^{-3}) [34,56].

For this, it was necessary to obtain the basic density of the wood (with bark) that was calculated in the laboratory from wood discs collected at the lower end of each log segment. For those trees with DBH > 80 cm, a disk was removed at 0 m and then at intervals every 4.3 m until the total length of the commercial log was reached. For trees from 50 cm to 79.9 cm DBH, collections were made at 0 m and thereafter every 8 m until the total length of the commercial log was reached [27,34]. The 8-m log length allowed these logs to be used for sawn-wood products. The 307 wood disks collected in the field were taken to the laboratory, where we cut a wedge from each disk. The wedge represents the disk from the bark to the center of the disc, with the volume of each portion of the wedge being proportional to the volume of that portion of the full disc. The wedges were submerged in water for 21 days, and the saturated volume was obtained by the immersion method [27]. These samples were then dried in a forced-air oven at 103 ± 2 °C until weight stabilization was reached [21]. Basic wood density was determined as the ratio of dry weight (g) to saturated volume (cm^3). A density value for each individual tree was obtained as the arithmetic mean of the densities of the log segments from that individual, and a species mean was calculated as the average of the means for the individual trees [21,57]. We categorized the species by type of wood: species with $\overline{d}_{bc} < 0.5$ cm^3 were classified as "low density" ("*madeiras moles*"), and species with $\overline{d}_{bc} \geq 0.5$ cm^3 were classified as "high density" ("*madeiras duras*") [34].

The basic wood density of the trunk (with bark) was used to estimate biomass and carbon in sawn-wood products (Vlum × $\overline{d}_{bc}$]. The bark was included in the density estimates because biomass and carbon were estimated with this component. The bark contributes to the emissions generated by the waste but not to the carbon stocks in the wood products. The inclusion of bark in the conversion factor makes the carbon estimates for wood products slightly overestimated, but the effect of bark on the density of logs 50 cm or more in diameter is small. Data for trunks of 47 tree species in the Tapajós National Forest in Pará indicate that 4.5% of the volume is bark and that including this component lowers the wood density of commercial stems by 0.93% [58] because the wood products (pieces) must not have any damage (holes and imperfections) if they are later to be sold. A number of studies, such as ABNT (1997) [59], Baker et al. (2004) [60], Chave et al. (2004) [61], Nogueira et al. (2005) [62], and Siliprandi et al. (2016) [63], have shown that it is better to work with samples from the same species (samples by wedges) that are collected in the same study area than to use data from other studies that, although they may have used similar methods, were done at different locations. This makes our methodology suitable for the study.

This method was chosen with the aim of reducing uncertainties in the 12 studied species, since using data from other parts of the Amazon can cause underestimates or overestimates of wood density due to biogeographical variation within any given species [59–62]. Also, an alternative method using rectangular wood samples (NBR 7190) [59], which is commonly used to determine the basic density of wood in products, does not always fully describe the vertical and radial variation, unlike the complete method (samples by wedges) [62]. Therefore, the biomasses of the commercial logs (with bark) and the sawn-wood products were obtained by multiplying the basic wood density by the volume of the log and of the products.

The carbon stocks in the log and in the sawn wood were calculated using the methodology of Romero et al. (2020) [27], who also worked in the same area and with the same species. The carbon stocks were calculated by multiplying the biomass values by the mean carbon content of 0.49 with standard deviation 0.05 [27].

2.4. Factor for Converting Carbon Stocks in Logs to Stocks in Sawn Wood

To obtain the factor (in %) that transforms data on log volume into carbon stored in wood products, the carbon present in the sawn wood (Csw; MgC) was divided by the volume of the log with bark (V_l; m^3) and multiplied by 100 using the formula $F_c = \frac{C_{sw}}{V_l} \times 100$.

3. Results

The present study sampled a total of 136 individuals of 12 commercially valuable tree species, these being among the most commonly harvested in the Amazon region, namely, *Albizia niopoides*, *Apuleia leiocarpa*, *Castilla ulei*, *Cedrela odorata*, *Ceiba pentandra*, *Copaifera multijuga*, *Dipteryx odorata*, *Eschweilera bracteosa*, *Eschweilera grandiflora*, *Handroanthus serratifolius*, *Hura crepitans*, and *Hymenaea courbaril*. DBH of the sampled trees ranged from 50.9 cm to 149.9 cm. Wood density for the trees ranged from 0.3 cm^{-3} to 0.8 g cm^{-3}, with an arithmetic mean of 0.6 g cm^{-3} and a mean weighted by volume of 0.6 g cm^{-3} (Table 2).

The logs removed from the forest had a total volume of 925.2 m^3, biomass of 564 Mg, and carbon stock of 484.2 MgC. The volume per species varied between 25.5 m^3 to 162.7 m^3, with mean ± standard error of 77.1 ± 0.39 m^3; biomasses varied between 13.6 to 97.7 Mg (47 ± 0.1 Mg). and carbon stocks ranged from 6.7 MgC to 51.3 MgC (23.5 ± 0.1 MgC). The sawn-wood products had a total volume of 484.2 m^3, biomass of 302.6 Mg, and carbon stock of 149.9 MgC. The volume of sawn-wood products varied from 10.6 to 79.8 m^3 (40.3 ± 0.2 m^3); the biomass varied between 6.7 to 63.5 Mg (25.2 ± 0.1 Mg), and carbon ranged from 3.3 MgC to 31.5 MgC (12.4 ± 0.1 MgC). The values per hectare are shown in Table 2.

Table 2. Scientific name, number of trees sampled per species (N), diameter range (diameter at breast height—DBH), mean basic density of wood with bark ($\bar{d}_{bc}$) in g cm^{-3}, volume (V) in m^3 per 1000 ha biomass (B) in kg ha^{-1}, and carbon (C) in kgC ha^{-1} of products and of commercial logs for the twelve species in a 1252.8 ha area harvested in a forest-management area in the state of Acre, Brazil.

Scientific Name	N	DBH Range (cm)	$\bar{d}_{bc}$ (g cm^{-3})	$\bar{d}_{bc}$ Category	Commercial Logs			Sawn-Wood Products		
					V per 1000 ha (m^3)	B per ha (kg)	C per ha (kgC)	V per 1000 ha (m^3)	B per ha (kg)	C per ha (kgC)
Albizia niopoides	7	54.8–79.3	0.6	High	20.4	12.9	6.4	8.5	5.4	2.7
Apuleia leiocarpa	13	64.3–130.5	0.8	High	101.0	77.0	38.2	59.3	45.2	22.4
Castillaulei	37	56.7–121	0.4	Low	129.9	52.9	26.2	58.9	24.3	12.0
Cedrela odorata	8	57.3–118.1	0.4	Low	25.5	10.9	5.4	12.5	5.4	2.6
Ceiba pentandra	4	100–149.9	0.3	Low	59.3	17.3	8.1	30.6	9.0	4.4
Copaifera multijuga	6	78.9–136.9	0.5	High	50.8	26.4	13.1	25.0	13.3	6.6
Dipteryx odorata	11	70–124	0.8	High	97.2	77.9	40.9	63.8	50.7	25.1
Eschweilera bracteosa	15	54.1–95.5	0.6	High	52.4	34.2	16.9	26.3	17.1	8.5
Eschweilera grandiflora	13	55.4–111.4	0.7	High	79.6	58.4	28.9	38.3	28.2	14.0
Handroanthus serratifolius	8	50.9–78	0.8	High	22.9	18.8	9.3	12.4	10.1	5.0
Hura crepitans	6	74.9–121	0.4	Low	31.6	11.6	5.7	15.6	5.7	2.8
Hymenaea courbaril	8	66.21–120.1	0.8	High	67.9	51.8	25.7	35.6	27.2	13.5
Grand Total	136	50.9–149.9			738.5	450.2	224.9	386.5	241.5	119.7
Mean ± standard error			0.6		61.5 ± 0.3	37.5 ± 0.1	18.7 ± 0.1	32.2 ± 0.2	20.1 ± 0.1	10.0 ± 0.1

Figure 2 presents the carbon stored in the logs of the 12 commercial species and its relationship to basic wood density. Wood density $(\overline{d}_{bc})$ and DBH were the determinant variables for estimating biomass. The sizes of the dots in Figure 2 are proportional to DBH. Figure 2 shows that "low-density" species ($\overline{d}_{bc} < 0.5$ g cm^{-3} generally had the smallest mean diameters and lowest amounts of carbon storage in their logs. However, *Ceiba pentandra* has a mean diameter of >100 cm but has low $\overline{d}_{bc}$ (0.3 g cm^{-3}; Table 2). Wood density was a determining factor in carbon storage regardless of diameter, as in the case of *Ceiba pentandra*. "High-density" species ($\overline{d}_{bc} > 0.5$ g cm^{-3}) store the greatest amounts of carbon in their logs (Table 2).

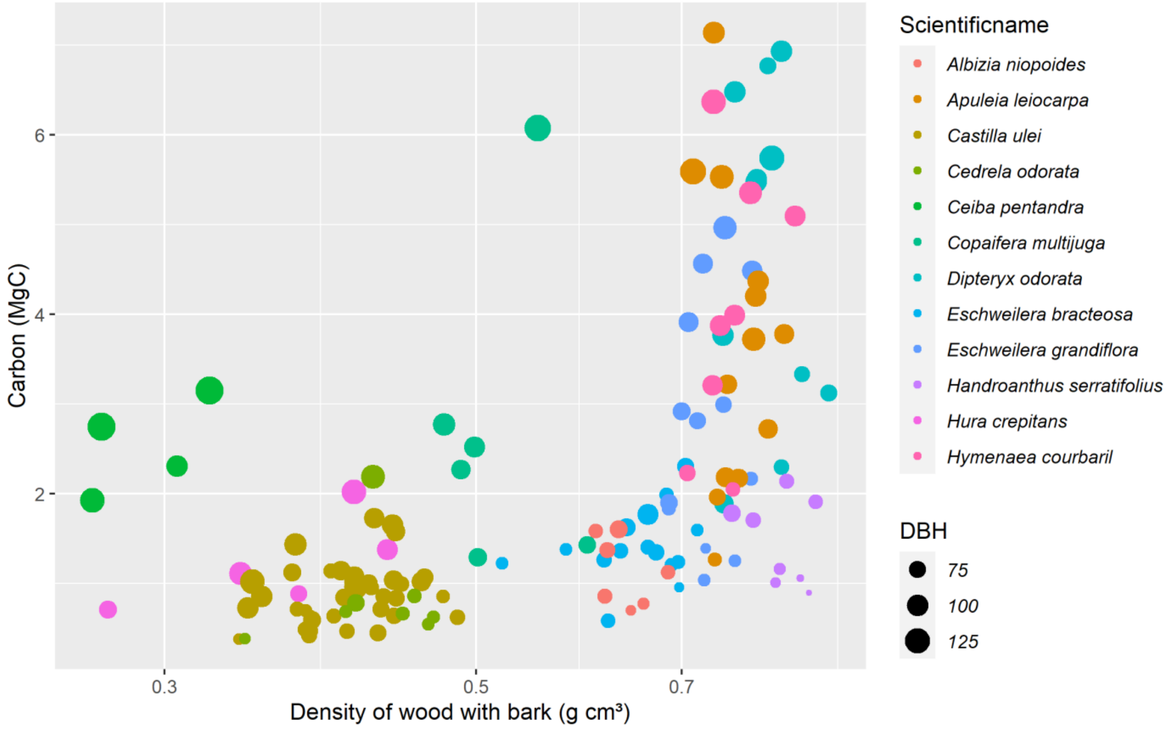

Figure 2. Relationship between carbon stock in a 1252.8-ha harvested area and wood density (g cm^{-3}). The size of the dots is proportional to the DBH of the individual trees, and the colors indicate the species. The points in the graph correspond to the 136 individual trees sampled.

3.1. Volume and Carbon Yield of Commercial Logs

The mean volumetric yield coefficient (VYC) (percentage of the volume of a harvested log that is converted to sawn wood) was, on average, 52.3%, ranging from 41.6% to 65.6% depending on the species (Table 3). The mean carbon yield coefficient (CYC) was 53.2%, ranging from 41.6% to 61.4% for the different species (Table 3 and Figure 3). The species that had the greatest yields in terms of volume (VYC = 65.6%) and carbon (CYC = 61.4%) was *Dipteryx odorata* (Table 3 and Figure 3). The fact that wood of this species has high durability and resistance generates market demand, which may motivate taking care to obtain the maximum possible yield from these logs.

Table 3. Log volume (LV) and product volume (PV) in cubic meters (m^3), volumetric yield coefficient (VYC) as a percentage; log carbon (LC) and carbon stored in sawn-wood products (PC) in megagrams of carbon (MgC); and carbon yield coefficient (CYC) as a percentage for 12 species in a 1252.8-ha area harvested in a forest-management area in the state of Acre, Brazil.

Scientific Name	Volume			Carbon		
	LV (m^3)	PV (m^3)	VYC (%)	LC (MgC)	PC (MgC)	CYC (%)
Albizia niopoides	25.5	10.6	41.6	8.0	3.3	41.6
Apuleia leiocarpa	126.6	74.3	58.6	47.9	28.1	58.7
Castilla ulei	162.8	73.7	45.3	32.9	15.1	45.9
Cedrela odorata	31.9	15.7	49.0	6.7	3.3	49.3
Ceiba pentandra	74.3	38.3	51.6	10.1	5.6	54.8
Copaifera multijuga	63.6	31.3	49.1	16.4	8.3	50.6
Dipteryx odorata	121.8	80.0	65.6	51.3	31.5	61.4
Eschweilera bracteosa	65.6	33.0	50.2	21.2	10.6	49.9
Eschweilera grandiflora	99.7	48.0	48.1	36.2	17.5	48.4
Handroanthus serratifolius	28.7	15.5	53.9	11.7	6.3	54.0
Hura crepitans	39.5	20.0	49.5	7.2	3.5	49.1
Hymenaea courbaril	85.0	44.6	52.4	32.2	16.9	52.5
Grand Total	925.2	484.2	52.3	281.8	149.9	53.2

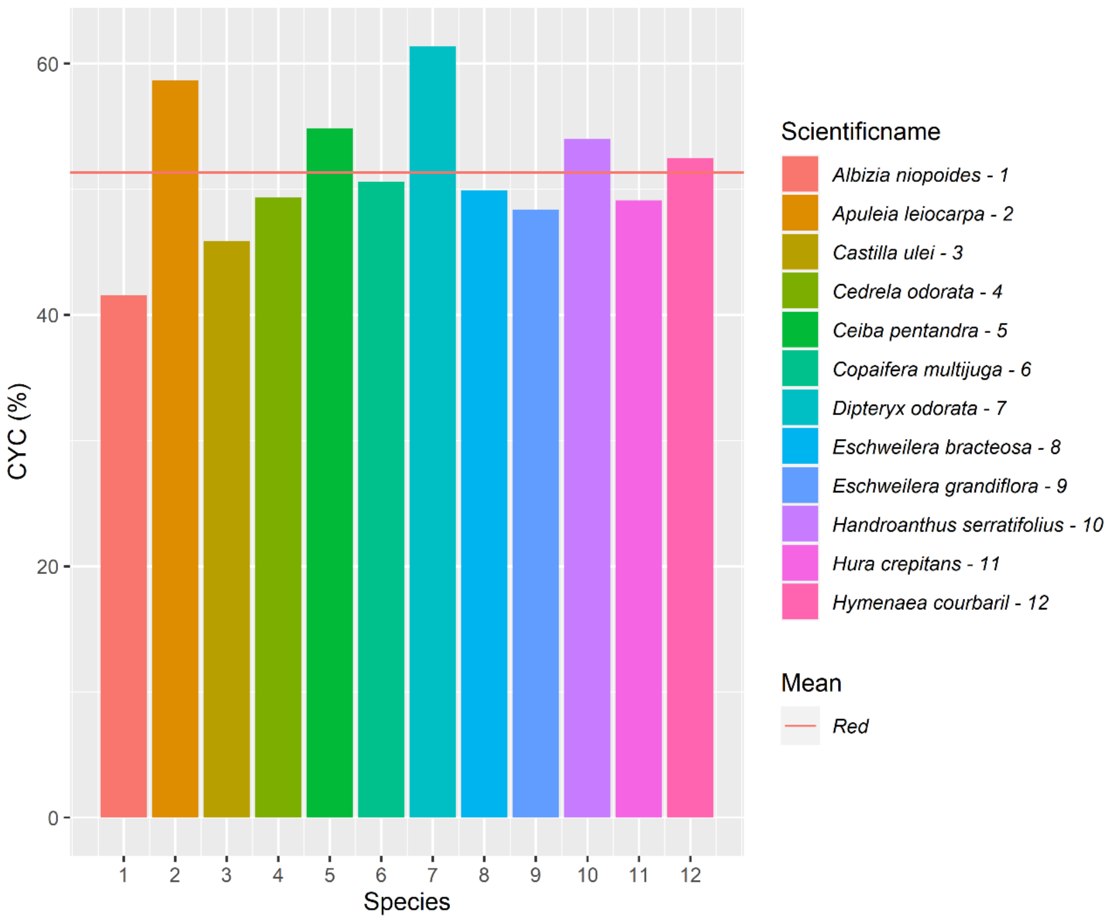

Figure 3. Carbon yield coefficient (CYC; %) on the y-axis and the number for each tree species on the *x*-axis (given in the legend, together with the colors that correspond to the different species).

The results revealed that the average final carbon stock per harvested tree in sawn-wood products from the different species ranged from 0.4 ± 0.1 MgC to 2.9 ± 0.4 MgC, with the highest percentages of the total wood-product carbon stock being for *Dipteryx odorata* (21.0%), *Apuleia leiocarpa* (18.7%), and *Eschweilera grandiflora* (11.7%) (Table 4).

Table 4. Number of trees sampled per species (N), total carbon stored in sawn-wood products by species (PC, in MgC), mean ± standard error of the mean for carbon per harvested tree (M, in MgC), and percentage of carbon (%) for 12 tree species in a 1252.8-ha area harvested in a forest-management area in the state of Acre, Brazil.

Scientific Name	*N*	PC (MgC)	M (MgC)	(%)
Albizia niopoides	7	3.3	0.5 ± 0.1	2.2
Apuleia leiocarpa	13	28.1	2.2 ± 0.3	18.7
Castilla ulei	37	15.1	0.4 ± 0.1	10.0
Cedrela odorata	8	3.3	0.4 ± 0.1	2.2
Ceiba pentandra	4	5.6	1.4 ± 0.2	3.7
Copaifera multijuga	6	8.3	1.4 ± 0.3	5.5
Dipteryx odorata	11	31.5	2.9 ± 0.4	21.0
Eschweilera bracteosa	15	10.6	0.7 ± 0.1	7.1
Eschweilera grandiflora	13	17.5	1.4 ± 0.2	11.7
Handranthus serratifolius	8	6.3	0.8 ± 0.1	4.2
Hura crepitans	6	3.5	0.6 ± 0.1	2.4
Hymenaea courbaril	8	16.9	2.1 ± 0.3	11.3
Grand Total	136	149.9	1.1 ±0.1	100

3.2. Finished Products

A total of 44,783 pieces of sawn lumber were produced from the logs removed from the 1252.8-ha harvested area (Table 5). The volume of the different products ranged from 9.1 ± 0.1 to 264.2 ± 3.1 × 10^{-3} m^3, and the carbon stored in the products ranged from 3.4 ± 0.1 to 71.1 ± 9.0 × 10^{-3} Mg. The highest values for volumetric yield (54.6%) and for carbon stored in the products (47.4%) were found in boards (*tábuas*) (Table 5).

Table 5. Number of pieces (N), volume of sawn wood by type of product (V, in m^3), and carbon stored in sawn wood by product type (C, in MgC) (mean ± standard error of the mean) for commercial sawn-wood end products from 12 species in a 1252.8-ha area harvested in a forest-management area in the state of Acre, Brazil.

Product	*N*	V (m^3)	%	C (MgC)	%
Rafter (*Caibro*)	12,665	119.2 ± 2.9 × 10^{-3}	24.6	43.7 ± 1.3× 10^{-2}	29.2
Plank (*Prancha*)	367	24.3 ± 9.2 × 10^{-3}	5.0	7.4 ± 1.3 × 10^{-2}	4.9
Batten (*Sarrafo*)	11,798	46.1 ± 8.0 × 10^{-3}	9.5	16.1 ± 4.8 × 10^{-2}	10.7
Board (*Tábua*)	18,613	264.2 ± 3.1 × 10^{-3}	54.6	71.1 ± 9.0 × 10^{-2}	47.4
Beam (*Viga*)	796	21.4 ± 12.4 × 10^{-3}	4.4	8.2 ± 3.4 × 10^{-2}	5.5
Small beam (*Vigota*)	544	9.1 ± 8.1 × 10^{-3}	1.9	3.5 ± 2.8 × 10^{-2}	2.3
Overall total	44,783	484.2 ± 1.6 × 10^{-3}	100	149.9 ± 5.6 × 10^{-2}	100

The carbon stock in products was highest for products from logs in the 95-cm diameter class, which constituted 28.7% of the total sawn-wood products produced by the sawmill (Table 6). This class had the highest percentage because it has both large trees and a high number of individuals.

Table 6. Carbon (MgC) distribution by diameter class (cm) in sawmill-derived products from logs in a 1252.8-ha area harvested in a forest-management area in the state of Acre, Brazil.

Product	Diameter-Class Center (cm) and Carbon (MgC)										
	55 cm	**65 cm**	**75 cm**	**85 cm**	**95 cm**	**105 cm**	**115 cm**	**125 cm**	**135 cm**	**145 cm**	**Total**
Rafter (*Caibro*)	2.8	4.3	8.5	2.8	11.5	4.4	3.6	2.9	3.0		43.7
Plank (*Prancha*)	0.8	1.0	0.2	0.2	4.3		0.8				7.4
Batten (*Sarrafo*)	1.4	1.6	4.0	1.5	4.8	1.1	0.5	0.7	0.5	0.1	16.1
Board (*Tábua*)	3.2	7.5	14.7	10.6	18.2	3.3	2.3	5.4	2.8	3.2	71.1
Beam (*Viga*)	0.2	0.3	0.7	1.7	3.7		1.6				8.2
Small beam (*Vigota*)		0.1	0.9	0.3	0.6	1.3	0.2	0.1			3.5
Overall total	8.4	14.7	29.0	17.1	43.0	10.1	9.0	9.1	6.2	3.3	149.9
%	5.6	9.8	19.3	11.4	28.7	6.8	6.0	6.1	4.1	2.2	100.0

The total log volume was 925.2 m^3, with mean ± standard error of 77.1 ± 0.4. The factor (percentage) that transforms the volume of a log into carbon stored in sawn-wood products was 16.2% (Table 7). This indicates that for each cubic meter of wood in logs extracted from the forest, 0.162 MgC is stored in sawn-wood products.

Table 7. Conversion factor (%) for converting log volume (m^3) to carbon (MgC) stored in sawn-wood products (mean ± standard error of the mean) for the 12 tree species sampled in a 1252.8-ha area harvested in a forest-management area in the state of Acre, Brazil.

Scientific Name	Log Volume (m^3)	Sawn-Wood Carbon (MgC)	Conversion Factor (%)
Albizia niopoides	25.5 ± 0.5	$3.3 \pm 6.0 \times 10^{-2}$	13.0
Apuleia leiocarpa	126.6 ± 1.3	$28.1 \pm 1.4 \times 10^{-2}$	22.2
Castillaulei	162.8 ± 0.3	$15.1 \pm 3.1 \times 10^{-2}$	9.3
Cedrela odorata	31.9 ± 0.9	$3.3 \pm 1.2 \times 10^{-2}$	10.4
Ceibapentandra	74.3 ± 1.6	$5.6 \pm 9.5 \times 10^{-2}$	7.5
Copaiferamultijuga	63.6 ± 2.6	$8.3 \pm 2.0 \times 10^{-2}$	13.0
Dipteryxodorata	121.8 ± 1.3	$31.5 \pm 1.6 \times 10^{-2}$	25.9
Eschweilerabracteosa	65.6 ± 0.3	$10.6 \pm 5.0 \times 10^{-2}$	16.2
Eschweilera grandiflora	99.7 ± 1.0	$17.5 \pm 1.1 \times 10^{-2}$	17.6
Handroanthusserratifolius	28.7 ± 0.4	$6.3 \pm 7.2 \times 10^{-2}$	22.0
Huracrepitans	39.5 ± 0.7	$3.5 \pm 8.6 \times 10^{-2}$	9.0
Hymenaea courbaril	85.1 ± 1.4	$16.9 \pm 1.4 \times 10^{-2}$	19.9
Overall mean	77.1 ± 0.4	$12.5 \pm 5.7 \times 10^{-2}$	16.2

4. Discussion

The carbon stored in tree-derived products varies with basic wood density and carbon content and such tree attributes as diameter and height [64–67]. Importantly, some genera among the industry-preferred species, such as *Eschweilera*, are hyper-dominant in the Amazon rainforest [68], which may be an important factor for management and harvest.

In the current study, estimates of volume, biomass, and carbon stocks are affected by variations in the minimum DBH in a forest-management system in Brazil and by the basic wood density. Generally, species with the highest carbon storage had the highest wood densities (Figure 2 and Table 2). These species are desired for their resistance and durability, and the sawing process minimizes the generation of sawdust and other residues [34]. Wood density was a determining factor in the storage of biomass and carbon in the log and, consequently, in wood products [60,62]. This information allowed us to evaluate the most common commercial species and how they contribute individually to the carbon stock and to the supply of durable wood products that do not emit CO_2 for a long time [34]. In addition, this information can contribute to discussions on forest harvesting and on the minimization of greenhouse gas emissions from wood products obtained from tropical forest management [27,34].

The volumetric yield coefficient (VYC; 52.3%, Table 3) for logs lies within the value range that has been estimated for Brazil's Amazonian states of Pará, Rondônia, and Amazonas (41.0% to 59.7%) [32,33].

However, our VYC value is higher than the 45% value used since December 2016 [54] for this conversion by federal authorities in determining whether sawn-wood volumes are consistent with approved harvests from management plans. The previous value used for this was the 35% value given in CONAMA Resolution 474 of 6 April 2016 [53], and prior to that it was 45% [52]. If the official conversion factor is unrealistically low, it offers a means of "laundering" illegally harvested wood.

The volume yield in the sawmill can be affected by compounds in the wood such as terpenoids, acidic resins, and phenolic substances, which are present in some species and can affect the operation of sawmill equipment [36,67,69] and cause variations in the ease with which logs can be cut, as well as in the yield of each processed log. The carbon yield coefficient (CYC) of the log, the VYC, and the basic wood density were key factors in determining the low carbon storage in the low wood-density species, as was also observed by Nogueira et al. [62], Chave et al. [61], and Goodman et al. [57]. The unused percentage of the log volume (100.0% − 52.3% VYC = 47.7%) and carbon (100% − 53.2% CYC = 46.8%) represents sawmill waste that returns to the atmosphere as CO_2. Not all of this carbon represents a net emission because waste can be burned as an electricity source, replacing fossil fuels [31,37]. At the sawmill we studied, people living close to the sawmill use the residues for building fences and other structures and for firewood for domestic cooking and for bakeries and brick kilns [34].

Products derived from high-density species ("*madeiras duras*") store more carbon than do those derived from low-density species ("*madeiras moles*") [62,64,65], indicating the importance of prioritizing the former from the standpoint of carbon storage (assuming that product recovery for the two types is equal). As a consequence, we recommend that low-density species be left in the forest, both because this avoids their large contribution to sawmill waste and because their remaining in the forest helps fulfill environmental functions such as water and nutrient cycling. In addition, areas under management should be enriched with species that store large amounts of carbon, such as *Dipteryx odorata*, *Apuleia leiocarpa*, *Handroanthus serratifolius*, *Eschweilera bracteosa*, *Eschweilera grandiflora*, *Hymenaea courbaril*, and *Cedrela odorata*. This would result in post-harvest processes that help maintain ecological diversity [19] and would contribute to providing wood products under harvest cycles of 30–35 years [18,24].

The high values for the boards and the low values for the small beams (Table 5) are influenced by the DBH, shape of the trunk, basic density of the wood, and number (N) of pieces and their dimensions (width, thickness, and length) [55,64,65]. However, the production of beams is important in the market. The beams are derived from high-density wood (*Dipteryx odorata*, *Apuleia leiocarpa*), these being species that sequester more carbon [64]. On the other hand, the largest stocks of carbon in products (rafters, battens, boards, planks, beams, and small beams) are found in the largest diameter classes [65]. In our study, the largest carbon stocks were found in the classes with centers 95 cm or above (Table 6). However, carbon stocks were lower in the class with centers >105 cm DBH, which is explained by the fact that there are fewer individuals in the upper classes.

Carbon storage in tropical forests maintains carbon dioxide out of the atmosphere and mitigates climate change [16,70]. Forest management with low-impact harvesting techniques allows the conservation of most of the forest carbon stock and its diversity through selective extraction and taking advantage of non-wood products [19,71–74]. This offers social, economic, and environmental benefits [72]. If the alternative is deforestation, forest management is clearly preferable for climate [28]. Forest management also makes a positive contribution to climate mitigation through flows of forest carbon to pools in long-lived wood products. The carbon stocks in sawn-wood pools quantified in this paper will be reduced by the losses that occur [18,19,34] when this wood is transformed into houses, furniture, and other end products [39,40]. Storage of carbon in wood products is limited by the useful life of the wood, which is related to the treatment of time and permanence in accounting for global-warming mitigation benefits [38,39] remaining constant over time [75]. Wood products store carbon over years and emit carbon at the end of their useful life, which is affected by the final decomposition of wood [39–42]. After the products' lifetimes have ended, they are usually burned or buried in landfills, emitting greenhouse gases and affecting the balance of emissions in progressively smaller quantities over time until the effect becomes neutral [18,39,45,46]. Therefore, forest management affects the carbon storage and environmental quality of its products [18,76].

Much of the wood presently harvested in Brazilian Amazonia does not come from forest management; instead, it comes either from illegal logging or from areas that are being deforested for agriculture and ranching (e.g., Brancalion et al. (2018) [13], Ferrante and Fearnside (2018) [30], Uhl and Buschabacher (1985) [77] Regardless of its origin, the carbon in harvested logs is being transferred to wood products that will maintain it out of the atmosphere for a given period of time. The lifespans of the different products, and the value attributed to time, will determine this transfer's net contribution to mitigating global warming. In addition to the delayed emission of carbon from forest products, forest management emits carbon immediately in the sawmill waste quantified in this paper. Other emissions include decay of the stumps and crowns of harvested trees [28]. To these must be added the decay of trees killed from collateral damage in logging operations and the decay of the roots of trees killed both by harvesting and by collateral damage [28]. Over a period of years, forest regeneration recovers a part of the lost carbon stock, but carbon remains in the atmosphere, causing global warming during the recovery period. If the forest carbon stock stabilizes over successive management cycles, the accumulation of carbon in forest products can eventually pay back the carbon "debt" that results from the equilibrium carbon stock in the forest being lower than that in the unlogged forest, thus producing a future climate benefit. Again, the value attributed to time determines the magnitude and the sign of the effect of forest management on climate.

Selective logging increases the probability of Amazonian forest fires (e.g., Uhl and Bushbacher (1985) [77], Nepstad et al. (1999) [78], Berenguer et al. (2014) [79]). This is due to the deadwood left in the forest from logging and from collateral damage, together with the opening of gaps in the forest canopy that allow sunlight and wind to dry combustible material on the forest floor [34,77]. Extreme events made more frequent by climate change are already increasing the occurrence and scale of forest fires in Amazonia, including Acre [80]. The first fire that occurs in an area initiates a positive-feedback process, where dead wood from trees killed by the fire and the opening of holes in the canopy make the forest more vulnerable to a sequence of subsequent fires that can destroy the forest completely [79,81,82]. The carbon consequences of the increased probability of forest fires in logged forests, including those with reduced-impact logging practices, must also be taken into account in assessing the overall role of forest management in climate change.

Forest management in Amazonia is in its initial stages, where unlogged forest is being incorporated into management systems, which makes the implications for climate different from what would apply to the continuation of a management system that has been in place for multiple harvest cycles and has reached an equilibrium state. Many of the carbon-accumulation processes associated with forest management are slow, such as the accumulation of carbon stocks in long-lived product pools and the recovery of forest biomass after logging [28]. This makes the importance of time (expressed, for example, through a discount rate for carbon) a critical factor in calculations of climatic benefits [28,72,83]. The carbon benefit of forest management depends heavily on the long-term sustainability of the management systems. This depends on maintaining a continuous flow of revenue that renders this investment option profitable as compared to competing opportunities. In addition to revenues from the sale of wood, new revenues can be added to forest management, such as payments for environmental services. For this to occur, solutions must be found for the economic rationale that leads to abandoning potentially sustainable forest-management systems once the first harvest cycle has been completed [29,84–87]. Tapping the value of the environmental services of the forest has been proposed as a solution to this problem [85,88,89].

Providing benefits over time requires that the forest-management system be sustained in practice (not just that it be theoretically sustainable in technical terms), and this requires that the system provide a continuous income stream that is sufficient to make it commercially attractive throughout the harvest cycle [29]. This is frequently not the case because a loophole in Brazil's forestry regulations allows harvesting an entire management area in the first few years of the harvest cycle ([90], Article 5, Paragraph 1; [91], Article 3.3, Paragraph 5, thus implying a long period without an income source to support the management system and a strong motive for the areas to be sold once harvesting is complete, thus, in practice, making the areas subject to deforestation [92].

Forest management must go beyond simple carbon-stock considerations, especially since, even in managed areas with legally permitted harvest intensities, the impacts of logging on biodiversity and ecosystem services have been found to be extensive [93,94]. It should be noted that Amazonia has already reached its tolerable deforestation limit, making development alternatives that maintain standing forests an urgent priority [95]. Current development policies, which encourage the expansion of monocultures in the Amazon region, may result in the collapse of vital ecosystem services such as the export of water vapor from Amazonia to southern and southeastern Brazil by the winds known as ''flying rivers" (e.g.,Arraut et al. (2012) [96], Zemp et al. (2014) [97]). This has the potential to drastically affect the country's agriculture and the supply of water to major cities like São Paulo [98]. The potential role of Amazonian forest management in averting deforestation, therefore, merits special attention.

The present paper presents data on the transfer of carbon from harvested logs to wood products, which is only one of the many factors that must be quantified in order to assess the effect, either positive or negative, of Amazonian forest management on global climate. A complete analysis must include emissions from sawmill waste; decay of wood products; unharvested portions of trees such as branches, stumps, and roots; collateral damage to the forest from harvesting operations, log decks, trails, and access roads; and the increased probability of forest fires in logged forest. These analyses must also consider realistic scenarios for future land use both for a scenario with the project and for a scenario without the project. The scenario with the project cannot simply assume that management will be sustainable and that it will continue until the end of the agreed harvest cycle, much less that it will continue indefinitely. The rate of carbon recovery in the harvested forest must be estimated, as well as the recovery of harvestable stocks of commercial species that are expected to sustain future harvest cycles. The timing of all carbon flows between the atmosphere and the forest and the stocks of wood products must be estimated, and their value to climate calculated based on the value attributed to time for carbon accounting must also be calculated. The value attributed to time is an ethical and political decision rather than a scientific one [84].

Although calculating the effect of forest management on climate is beyond the scope of this paper, the data we provide here contributes a part of the information needed for that evaluation, whether or not forest management is judged to be a benefit for climate. If forest management has a net benefit for climate, having reliable estimates for carbon transfer to wood products will be part of the suite of estimates needed to underpin rewarding these benefits, thus motivating more sustainable use of the forest.

5. Conclusions

Final sawn-wood products depend on density, diameter, and number of individuals per tree species, with less carbon being stored in lighter woods than in denser ones. When operating in the context of climate change, forest management should harvest tree species with high-density wood, as their products store more carbon for longer periods. However, caution should be exercised in the management and harvesting of species that store the most carbon so as not to make the forest homogeneous and thereby cause the loss of biodiversity and ecosystem services in managed areas. In this regard, further studies are recommended to improve knowledge of the tolerable carrying capacity of the Amazon ecosystem for logging in managed areas. Low-carbon trees should be retained in the forest, as this avoids emissions from the large quantities of waste they produce due to their low yields in the sawmill and because they perform important environmental functions if left in the forest. The carbon stored in long-lived timber products can contribute to maintaining carbon dioxide out of the atmosphere. However, this is only one of an array of factors that must be evaluated to assess the net effect of Amazonian forest management on the global climate.

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