Article

# Volume, Biomass, and Carbon Estimates for Commercial Tree Species in a Managed Forest: A Case Study in the Bolivian Amazon

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**Abstract:** Tropical forest management has a potential role in forest conservation if it is sustainable. This study of a forest under management in Bolivian Amazonia strongly suggests that the management project is not sustainable and that no potential changes in management would be likely to make it so. In a 216.41 ha harvested area, 278 commercial trees from 10 families, 15 genera, and 15 species were measured. The density of commercial species with diameter at breast height (DBH) ≥ 50 cm was 1.28 trees $ha^{-1}$, and the harvestable commercial volume was 12.40 $m^3$ $ha^{-1}$. Due to market restrictions, the actual amounts harvested were much lower: 96 trees were harvested with commercial boles totaling 2.7 $m^3$ $ha^{-1}$. Of the total impact on biomass and carbon (above- and belowground), the logs removed from the area represented only 13.4%, while 86.6% was from losses in the forest as follows: 14.5% from the stumps, crowns, and roots of harvested trees (DBH ≥ 50 cm) plus 72.1% from the trees (DBH ≥ 10 cm) in the forest lost to roads, log landings, and skid tracks and the gap openings caused by felling the harvested trees. The estimated expenses exceeded the gross revenue of the management company (USD 519.15 $ha^{-1}$), a fact confirmed by the company's subsequent bankruptcy. The project's low harvest intensity reduces the environmental impact per hectare but increases the impact per cubic meter of wood harvested because producing a given volume of wood requires disturbing a larger area and because more kilometers of access roads and skid tracks have to be installed to extract a given volume of wood. Because many costs are fixed regardless of harvest intensity, small harvest volume can render such projects financially unfeasible, increasing the likelihood that they will be abandoned and not provide long-term "sustainable" forest protection. However, this does not mean that higher harvest intensity results in sustainability,

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as other constraints apply to high-intensity projects. We conclude that conservation alternatives to maintain the forest would be more beneficial than management for timber.

**Keywords:** climate change; $CO_2$ emission; forest harvest; global warming; logging residues; logging; tropical forest

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## 1. Introduction

Almost half of Bolivia's 110-million-hectare area is covered by subtropical and tropical forests that have a role in the global carbon cycle [1,2]. The possible role of carbon stocks in areas under forest management in maintaining global climate and biodiversity is a subject of high research interest [3–6]. Estimates of biomass and carbon stocks in the three main tropical forests (Latin America, central Africa, and Southeast Asia) vary in both quantity and spatial distribution [5–7] due to differences in the extent and the species composition of the forests [7–10]. Variations in carbon estimates arise from sampling that is based on a limited number of individual trees [10,11], differences in tree height-to-diameter relationships [12], forest structure [13], and species characteristics [14,15].

The Amazon forest stores 230–260 Pg C (1 Pg = $10^{15}$ g = 1 Gigaton), or 40%–60% of the carbon contained in the world's terrestrial vegetation [5,15–17], but carbon stock in areas under forest management is still uncertain. Few studies have been performed on the carbon stored in logs and wood products [4–6]. After trees are felled, crowns and stumps are left in the forest, where they decompose and emit carbon dioxide over time [6,7,18]. Other factors add to this loss of forest biomass and to the consequent $CO_2$ emissions, such as forest fires that degrade the Amazon forest and its natural functions [19]. Deforestation and the increase in the frequency of prolonged droughts have contributed to the high recurrence of forest fires in the Amazon [19].

Managed areas in Bolivian Amazonia are harvested through selective logging [5,19,20]. This can affect the relationships between individuals of different species (interspecific ecological relationships). A study in Bolivia by Soriano et al. [21] found that selective logging of tree species that coexist with *Bertholletia* (Brazil nut) can positively affect *Bertholletia* populations, providing a special case in forest management. Pioneer species, such as *Schizolobium amazonicum*, can benefit from soil disturbance by skidders [21], similar to natural regeneration in the gaps formed by harvesting trees in managed areas [22].

Bolivia's Forest Law nº 1700/1996 made it mandatory for management plans to include the monitoring and control of harvesting and post-harvest activities [23–25]. In accordance with Article 27 of this law and its regulations under Supreme Decree No. 24,453, a management plan is required for all types of forest use, including concessions, authorizations, and clearing permits. Protection areas and other uses are to be delimited in the management plan, and only the resources that are the subject of the management plan can be used [26]. Every forest management plan has a 20-year cutting cycle, with the managed area divided into 20 annual production units (APUs) that serve as the basis for the yearly forest operating plans (POAFs). The location of the APU is chosen each year in this operating plan. An APU to be logged can be subdivided into two compartments if they are separated (not contiguous) and up to three compartments if they are contiguous [26]. Although Bolivia's mandatory management plans are intended to conserve forests, there is little investment in post-harvest silvicultural treatments [27,28]. Studies on the loss of volume, biomass, and carbon from the suppression of vegetation for roads, log landings, skid tracks, and gap openings in the managed areas in Bolivia and Brazil are few [29,30].

Bolivia and other tropical countries need to develop policies to reduce greenhouse gas emissions from forest management [20,21,31] and to ensure the conservation of the biodiversity of managed species [32]. Reconciling logging with the provision of other ecosystem services is a challenge for forest managers and policymakers [33]. Formulating mitigation policies in managed areas requires the quantification of tree stocks and the stock of carbon removed. Estimates are needed of the emissions generated by the harvest and from the subsequent decomposition of branches, leaves, and stumps left in the area.

Bolivia, along with other nations, is urged to develop effective policies to reduce greenhouse gas emissions from forest management [32,34,35]. These policies must also guarantee the conservation of the biodiversity of managed species. Although carbon market mechanisms are seen as critical for achieving climate objectives [36], Bolivia expresses caution regarding these mechanisms and the commodification of environmental functions [37].

In Bolivia, studies on above- and belowground biomass are limited [38] compared with other countries such as Brazil [39,40]. Dauber et al. [38] carried out a comprehensive analysis of data from 600,000 trees from 74 forest inventories in four Bolivian ecoregions and estimated biomass using the equations of Brown et al. [41]. The results showed average aboveground biomass (DBH > 10 cm) ranging from 97 Mg ha$^{-1}$ (Mg = Megagrams, or metric tons) in the Chiquitano–Amazonian transition zone to 171 Mg ha$^{-1}$ in the Amazon, with a carbon stock ranging from 49 to 86 Mg C ha$^{-1}$.

Little is known about biomass and carbon in managed areas, especially in the northern part of the Bolivian Amazon. This includes the state of Pando, with 63,827 km$^2$ of forests, both flooded and unflooded [42]. Trees with a DBH above 50 cm are measured in forest management projects, and these large trees make a disproportionate contribution to biomass and carbon [43,44]. Carbon dioxide is emitted from vegetation lost in the construction of log landings, skid tracks, and access roads at the harvest stage [6,29].

In an area under forest management in the northern Bolivian Amazon, the present study estimates the volume, biomass, and carbon that is removed in the commercial boles (the trunk from the stump cut to the first significant branch) and that is lost in the crowns, stumps, and roots of the harvested trees and the forest lost to collateral damage and management infrastructure. This study also examines the management system's prospects for financial and biological sustainability.

## 2. Materials and Methods

### 2.1. Study Area

This study was conducted in a 216.41 ha production unit known as "Compartment 2" located in the El Lago community in the northern portion of the Bolivian Amazon (11°30′5.01″ S, 68°34′48.12″ W) in the municipality of Filadelfia, Manuripi Province, Pando Department, Bolivia (Figure 1) [44]. The El Lago community, to which the production unit belongs, is a registered social organization (Filadelfia municipality registration no. 17/97; Pando department registration no. 08/98) composed of peasant families that share a common territory. The community has a General Forest Management Plan (PGMF) approved in 2006 by the Authority for Surveillance and Social Control of Forest and Land (ABT) [44]. A forest inventory was performed in 2011 in the annual production unit (APU) evaluated in this study. The management plan for the study area is based on a 20-year cutting cycle with an APU of 568.54 ha to be harvested each year. In 2012, the 2011 APU was harvested and partitioned into two compartments (1 and 2) [44]. This study was carried out in Compartment 2, with 216.41 ha. Forest harvest occurred in 2012 and 2013. The El Lago community has the prerogative of selecting a company or entity to be responsible for the use of the community's forest resources. Through an agreement, the community grants permission to either a public or private entity to prepare and use resources through the Annual Forestry Operational Plan (POAF), which must be presented to the Forestry and Territorial Authority (ABT) through a contract. The Industria Maderera Arce (IMAR) company was selected by the community to be responsible for the POAF for Compartment 2 [44,45]. This process ensures that the entity assumes the responsibility for carrying out adequate management of the POAF area, focusing on the "sustainable" extraction of timber resources and the protection of soil, fauna, and vegetation [45,46]. Silvicultural practices are adopted to cut lianas (woody vines) on trees to be felled, and precautions are taken when opening clearings to avoid the loss of trees identified for future harvesting [47–50]. The practices include guidance to facilitate natural regeneration [46,49,51], requiring that the cut to fell the trees be made near ground level, which both leaves a smaller stump and helps prevent the saw operator from tripping while fleeing when the tree falls [49–51].

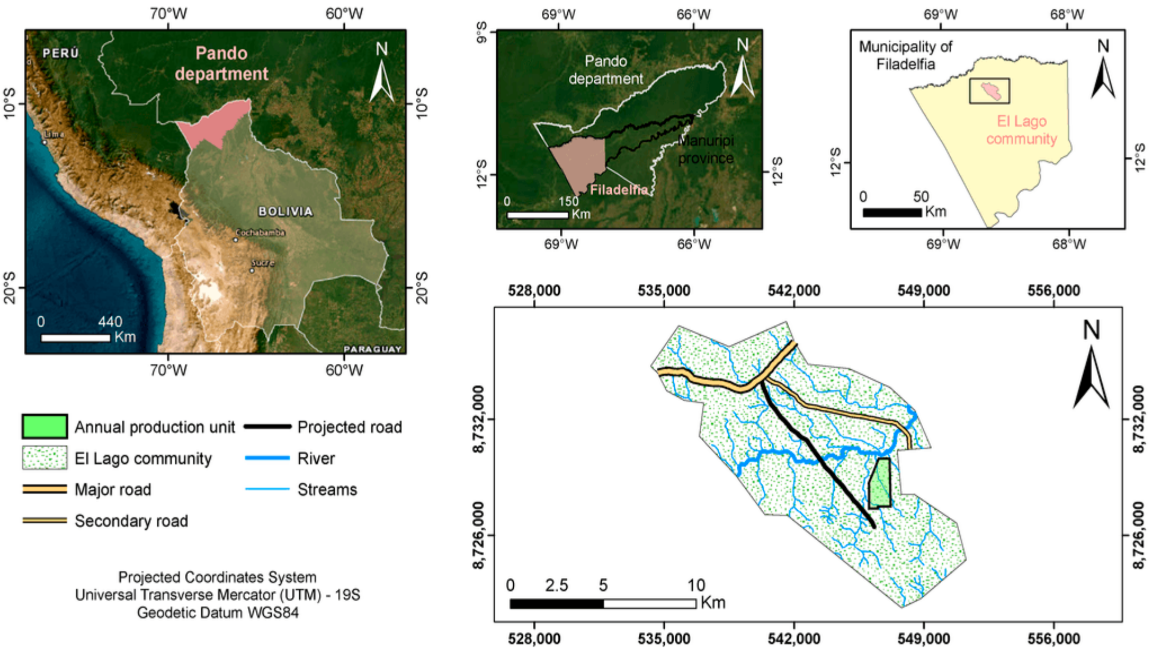

**Figure 1.** Location of the study area highlighting the 216.41 ha production unit (Compartment 2).

The vegetation in the study area is classified as dense *tierra firme* (unflooded upland) forest [45,52,53] with a predominance of dense forest with palms [53,54]. The region's climate is Aw under the Köppen–Geiger classification [55] with a mean temperature of 24.7 °C and annual precipitation ranging from 1454 to 2000 mm [37]. The rainy season is from October to May, with the highest rainfall in the October–December period. The soils in the study area are Acrisols and Luvisols [45,53]. The predominant topography is flat, with a slope of approximately 5% and an altitude between 150 and 220 m above mean sea level [44,54]. Forest harvesting occurs during the dry season, from June to September [54].

### 2.2. Measurement of Dendrometric Variables and the Ecological Importance of the Species

Dendrometric variables, such as diameter at breast height (DBH) $\geq$ 50 cm measured 1.30 m above the ground or just above any buttresses (in accord with technical standard 248/98 [25]) and commercial height (CH; m), were obtained from the forest inventory of the El Lago community. The height of the stumps was measured as a function of the characteristics of the commercial bole; the height of the stump is 30 cm in the case of trees with a cylindrical commercial shape, while the height can reach 50 cm when the tree has buttresses [46]. The order of ecological importance of the species was determined for commercial trees with DBH $\geq$ 50 cm, and the absolute and relative phytosociological parameters of the horizontal structure were considered by applying the cover value estimator of the ith species (CVEi. %) [55], where: $\text{CVEi (\%)} = \text{RDens} + \text{RDomi}/2$, RDensi = relative density of the ith species (%) and RDomi = relative dominance of the ith species (%).

### 2.3. Estimated Volume, Biomass, and Carbon of Harvested Trees

The harvested logs are processed industrially for sawn or laminated wood. Only the commercial bole exits the management system, while the crowns and stumps stay in the forest and decay. Bolivian legislation requires the application of a "species safety factor" [26,45,46], whereby a maximum of 80% of individuals (DBH ≥ 50 cm) of any given species can be removed from the area, leaving the remainder for seed production and reproduction (Table 1). Scientific names and families (Table 1) were based on the National Forestry Inventory and Forestry Resources Control Program of Bolivia [25,26,46], the Missouri Botanical Garden [56], and REFLORA [57].

**Table 1.** Safety factor applied to commercial species, separated into harvested trees and remaining trees in the 216.41 ha study area.

| Family | Species | Minimum DBH | Total Trees | Trees Eligible for Harvest | Remaining Trees |
|---|---|---|---|---|---|
| Lecythidaceae | *Couratari macrosperma* A.C.Sm. | 50 | 71 | 56 (78.9%) | 15 (21.1%) |
| Fabaceae | *Apuleia leiocarpa* (Vogel) J.F.Macbr. | 50 | 37 | 29 (78.4%) | 8 (21.6%) |
| Meliaceae | *Cedrela odorata* L. | 60 | 33 | 26 (78.8%) | 7 (21.2%) |
| Moraceae | *Clarisia racemosa* Ruiz and Pav. | 50 | 19 | 15 (79.0%) | 4 (21.0%) |
| Fabaceae | *Dipteryx odorata* (Aubl.) Forsyth f. | 50 | 15 | 11 (73.3%) | 4 (26.7%) |
| Apocynaceae | *Aspidosperma macrocarpon* Mart. and Zucc. | 50 | 17 | 13 (76.5%) | 4 (23.5%) |
| Fabaceae | *Amburana cearensis* (Allemão) A.C.Sm. | 50 | 15 | 12 (80.0%) | 3 (20.0%) |
| Apocynaceae | *Aspidosperma australe* Müll. Arg. | 50 | 16 | 12 (75.0%) | 4 (25.0%) |
| Fabaceae | *Enterolobium contortisiliquum* (Vell.) Morong | 50 | 11 | 8 (72.7%) | 3 (27.3%) |
| Fabaceae | *Hymenaea courbaril* L | 50 | 13 | 10 (76.9%) | 3 (23.1%) |
| Sapotaceae | *Manilkara bidentata* (A.DC.) A. Chev. | 50 | 12 | 9 (75.0%) | 3 (25.0%) |
| Betulaceae | *Alnus acuminata* Kunth | 50 | 10 | 6 (60.0%) | 4 (40.0%) |
| Bignoniaceae | *Tabebuia chrysantha* (Jacq.) G. Nicholson | 50 | 4 | 3 (75.0%) | 1 (25.0%) |
| Olacaceae | *Heisteria spruceana* Engl. | 50 | 3 | 1 (33.3%) | 2 (66.7%) |
| Anacardiaceae | *Tapirira guianensis* Aubl. | 50 | 2 | 1 (50.0%) | 1 (50.0%) |
| | Total | - | 278 | 212 | 66 |

Calculations were performed individually for each tree to obtain estimates of volume, biomass, and carbon for the commercial boles, crowns, and stumps. The commercial volume (CV), or the volume of the commercial bole ($m^3$), was obtained with an allometric equation (Equation (1)) developed for the same forest type (dense ombrophilous forest) at a location 300 km to the north in Brazil's state of Acre [58] as follows:

$$\mathrm{CV} = -8.23250 + 1.74399 \times \mathrm{DBH} + 0.87702 \times \mathrm{CH} \tag{1}$$

where CV = commercial volume ($m^3$); DBH = diameter at breast height with bark measured 1.30 m above the ground or just above any buttresses (cm); and CH = commercial height (m).

Stump volume (StuV) per tree was calculated with Equation (2) [6]:

$$\mathrm{StuV} = 0.30 \text{ or } 0.50\ (\frac{\mathrm{DBH}}{200})^2 \times \pi \tag{2}$$

where StuV = stump volume ($m^3$), 0.30 = stump height (m) for trees without buttresses, 0.50 = stump height (m) for trees with buttresses; DBH = diameter at breast height with bark measured 1.30 m above the ground or just above any buttresses (cm).

Crown volume (CroV) was calculated with Equation (3) based on the relationship between the crown volume (0.44) and total bole volume (0.56) [4,6]:

$$\mathrm{CroV} = \left(\frac{0.44}{0.56}\right) \times (\mathrm{CV} + \mathrm{StuV}) \tag{3}$$

where CroV = crown volume (m$^3$) and 0.44/0.56 = the ratio of crown volume to total bole volume. Total bole volume (m$^3$) is the sum of commercial volume (CV) and stump volume (StuV).

Subsequently, the biomass of each harvested tree was obtained by multiplying the volume of each part of the tree by the basic wood density (WD; g cm$^{-3}$) for the species (Table 1). The basic wood density (WD; g cm$^{-3}$) of each species was obtained from the studies by Romero et al. [58] and Zanne et al. [59] (Table 2). Basic wood density is oven-dried weight divided by saturated volume. Carbon was determined by multiplying the biomass of each tree component by the mean carbon content (0.49) [58].

**Table 2.** Species with measured individuals (DBH ≥ 50 cm) in the 216.41 ha study area (Compartment 2) and values for basic wood density (WD; g cm$^{-3}$) used to obtain the biomasses of the harvested trees.

| Scientific Name | Family | N | Wood Density (g cm$^{-3}$) |
|---|---|---|---|
| *Couratari macrosperma* A.C.Sm. | Lecythidaceae | 71 | 0.73 |
| *Apuleia leiocarpa* (Vogel) J.F.Macbr. | Fabaceae | 37 | 0.77 |
| *Cedrela odorata* L. | Meliaceae | 33 | 0.43 |
| *Clarisia racemosa* Ruiz and Pav. | Moraceae | 19 | 0.41 |
| *Dipteryx odorata* (Aubl.) Forsyth f. | Fabaceae | 15 | 0.80 |
| *Aspidosperma macrocarpon* Mart. and Zucc. | Apocynaceae | 17 | 0.71 |
| *Amburana cearensis* (Allemão) A.C. Sm. | Fabaceae | 15 | 0.52 |
| *Aspidosperma australe* Müll. Arg. | Apocynaceae | 16 | 0.74 |
| *Enterolobium contortisiliquum* (Vell.) Morong | Fabaceae | 11 | 0.40 |
| *Hymenaea courbaril* L | Fabaceae | 13 | 0.76 |
| *Manilkara bidentata* (A.DC.) A. Chev. | Sapotaceae | 12 | 0.87 |
| *Alnus acuminata* Kunth | Betulaceae | 10 | 0.39 |
| *Tabebuia chrysantha* (Jacq.) G. Nicholson | Bignoniaceae | 4 | 0.78 |
| *Heisteria spruceana* Engl. | Olacaceae | 3 | 0.73 |
| *Tapirira guianensis* Aubl. | Anacardiaceae | 2 | 0.46 |
| Total | | 278 | 0.63 |

### 2.4. Estimated Volume, Biomass, and Carbon in the 96 Harvested Trees and the Commercial Value of the Sawn Wood (Final Product)

During harvesting, not all the species that are officially considered appropriate for wood production [25,28] are harvested in practice due to a series of economic factors [28]. For example, the company managing the area we studied had the skidders, trucks, and other machinery necessary for forest intervention, but the cost of operating them could only be justified for harvesting the most-valuable species. Therefore, like most companies in the region, only the species with a guaranteed market were removed, leaving the others standing even if they were considered to be of "commercial value" in the management plan. In the whole of Compartment 2, the "harvestable" category consisted of 212 trees (80% of the individuals of each species with commercial value and DBH ≥ 50 cm), but only 96 of these trees were felled [26,44]. We estimated the quantities of volume, biomass, and carbon in the 96 felled trees.

The harvested boles were measured at the log landings [44]. The volume of each section of the bole was obtained using the Smalian method (Equation (4)) [60].

$$A = \left(\frac{SA_1 + SA_2}{2}\right) * L \tag{4}$$

where Vs = volume of a section of the commercial bole (m$^3$), $SA_1$ and $SA_2$ = cross-sectional areas with bark, obtained at the two ends of the section (m$^2$), and $L$ = length of the section (m) [60]. The total volume of each commercial bole was determined by summing the volumes of its sections.

Bole biomass was obtained by multiplying the bole volume by the basic wood density for each tree (Table 2). To obtain the carbon stored in each commercial bole, the biomass was multiplied by the carbon content of 0.49 (proportion of the dry weight that is carbon) [58]. The biomass and carbon from the crown and stump of each tree were obtained using the same procedures described in Section 2.3. The aboveground volume, biomass, and carbon of the 96 trees were obtained by summing the stocks in the bole, crown, and stump [58].

The commercial values of the boles of the 96 trees were calculated by multiplying the volume of wood in the boles harvested ($m^3$) by the price per cubic meter of wood. Subsequently, we converted the values of the 96 trees into quantities per hectare. To calculate the commercial value of sawn wood ($m^3s$) from the 96 logs, we used a volumetric yield of 46.7% during the sawing process, which is a value from a survey of 11 sawmills in Paragominas, Pará, Brazil [61]. To estimate the total volume of sawn wood ($m^3s$) for each species, we multiplied the volume of logs by the volumetric yield. The unit of measurement for sawn wood in Bolivia is the board foot (1 $m^3s$ = 423.78 board feet). Prices are based on interviews conducted by one of the authors (SISV) in sawmills in Cobija in March 2024. Bolivian currency (Bolivianos) was converted to USD considering the exchange rate at that time (USD 1 = BOB 6.96).

### 2.5. Above- and Belowground Volume, Biomass, and Carbon Removed and Lost in the Managed Area

Two scenarios were used to estimate the volume, biomass, and carbon above- and belowground (Figure 2). The first scenario tracks the fate of the total stocks of volume, biomass, and carbon of the 96 harvested trees. This scenario, called "MA" (for "management area") includes the sum of the stocks of each component (boles, crowns, stumps, and roots) to estimate the total volume, biomass, and carbon per tree. In the case of root estimates, we used the conversion factor determined by Nogueira et al. [39], where 20.57% of the tree is root biomass.

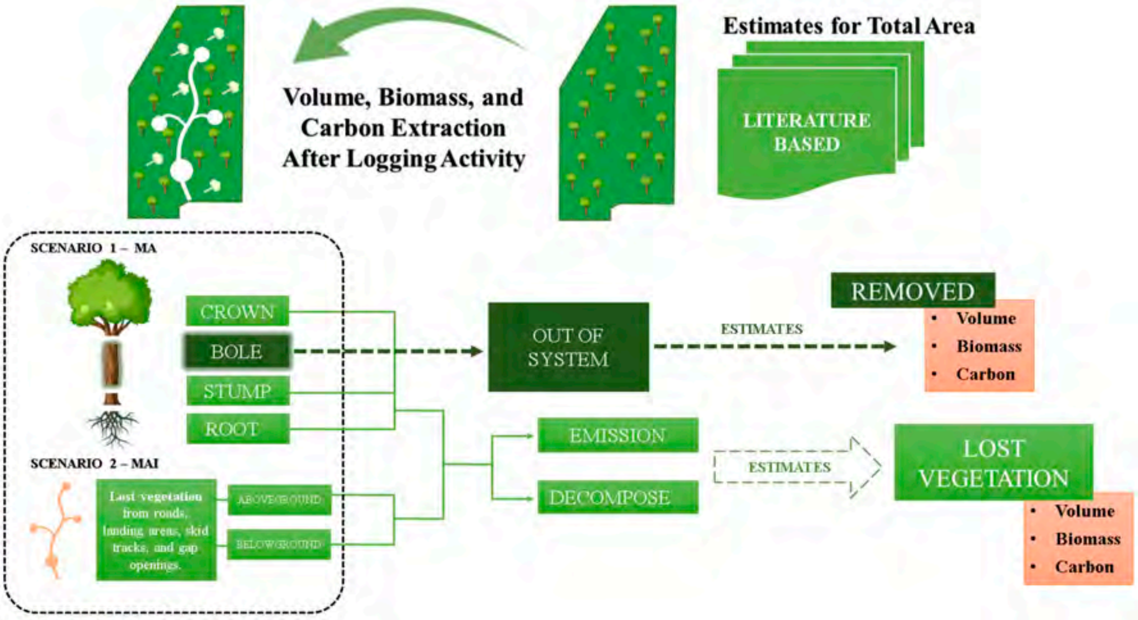

**Figure 2.** Flowchart of volume, biomass, and carbon calculations for an area under forest management in Bolivian Amazonia.

The second scenario accounts for forest lost in the construction of roads, log landings, and skid tracks. This scenario is called "MAI" (for "management area infrastructure") (Figure 2). The area opened for roads was calculated considering its length and width in meters, which were later transformed into values per hectare and percentages [62,63]. The areas of the log landings and gap openings formed as a result of felling the harvested trees were obtained by marking the waypoints in the coordinate system of the global positioning system (GPS) WGS 84-UTM Zone 19, Lambert equal-area projection, generating the areas of the polygons in square meters. Information on the areas of the log landings was used in the planar coordinate matrix method with the Gauss formula: $A = \frac{1}{2}\left|\sum_{i=1}^{n-1} x_i\, y_{i+1} + x_n y_1 - \sum_{i=1}^{n-1} x_i\, y_{i+1} - x_n y_1\right|$, where $A$ = polygon area; $n$ = the number vertices (and sides) of the polygon; and ($x_i$, $y_i$), $i$ = 1, 2, …, $n$ vertices. This equation is a matrix representing the X and Y coordinates in a plane through which the abscissa of the first vertex is multiplied by the ordinate of the second and so forth until the abscissa of the last vertex is multiplied by the ordinate of the first vertex [63].

The area calculated for skid tracks (Figure 3) illustrates the trajectory of wood extraction according to the distance from the main road or from a log landing [28,63]. Trees located up to 50 m from a log landing were dragged directly to the landing. More distant trees were dragged to the nearest skid track, or (depending on the distance from the main road) they were dragged onto the road and then taken to a log landing.

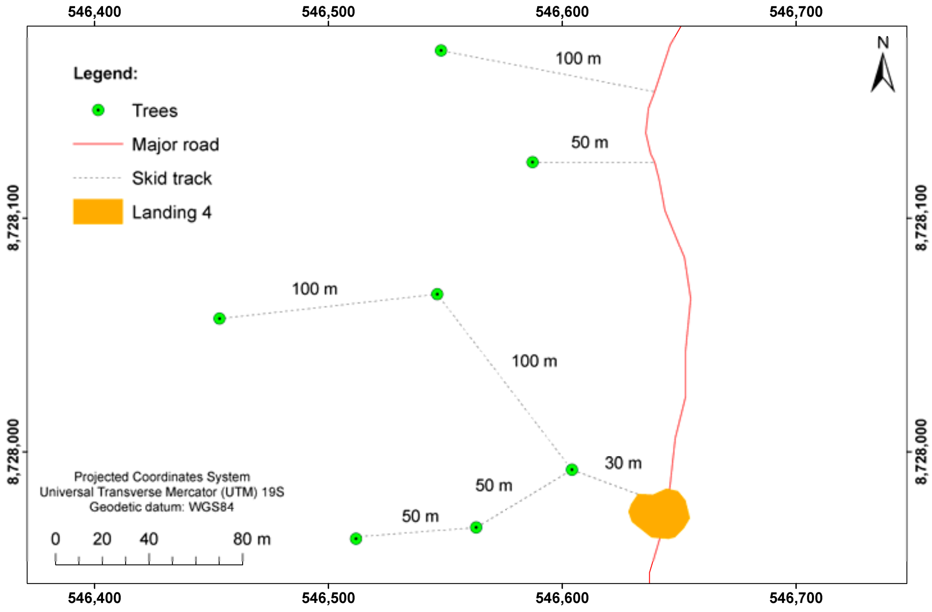

**Figure 3.** Trajectory of skid tracks for tree extraction according to their distances from the main road or from a log landing.

After obtaining the size of the open areas (roads, log landings, skid tracks, and gap openings = MAI), the vegetation lost in Scenario 2 was estimated using information on average aboveground biomass (318.9 Mg ha$^{-1}$) and total live biomass above- and belowground (384.5 Mg ha$^{-1}$) for stocks in trees with DBH ≥ 10 cm in dense lowland forest obtained by Nogueira et al. [39] as the average in Acre, Brazil, which is adjacent to Pando, Bolivia (the study area is 48 km from border with Acre). We emphasize that the information used corresponds to the type of forest that occurs in our study area. The biomass obtained by Nogueira et al. [39] allowed for the generation of volume and carbon values. Consequently, the biomass value was multiplied by the conversion factor of 0.49, determined by Romero et al. [58] (Table 3), to obtain carbon stocks. The values for losses in the MIA were obtained by multiplying the areas by the per-hectare stock of each variable (volume, biomass, and carbon).

**Table 3.** Volume and carbon inferred from studies by Nogueira et al. [39] and Romero et al. [58] for dense lowland rain forests (including trees of all species with DBH ≥ 10 cm).

| Reference | Estimated Variable | Estimated Values |
|---|---|---|
| Nogueira et al. [39] (aboveground biomass ≈ 318.9 Mg ha$^{-1}$; below + aboveground, ≈384.5 Mg ha$^{-1}$) | $\text{Volume} = \frac{\text{Biomass (Mg ha}^{-1})}{\text{Density (g cm}^{-3})}$ | 506.19 m$^3$ ha$^{-1}$ (aboveground) |
| | | 610.32 m$^3$ ha$^{-1}$ (below + aboveground) |
| Romero et al. [58] (0.49; refers to the average carbon proportion in the biomass) | Carbon = biomass × 0.49 | 156.26 Mg ha$^{-1}$ (aboveground) |
| | | 188.41 Mg ha$^{-1}$ (below + aboveground) |

## 3. Results

### 3.1. Aboveground Stocks in Commercial Trees

In total, 278 standing trees were measured (DBH ≥ 50 cm). These trees had an average density of 1.28 individuals per hectare and represented 15 commercial species from 15 genera in 10 families. *Couratari macrosperma*, in the family Lecythidaceae, was the species with the highest coverage value (percentage of the total basal area) (26.75%) (Table 4). The aboveground volume (including stumps and crowns) of these 15 commercial species (DBH ≥ 50 cm), including seed trees, averaged 11.8 ± 4.80 m$^3$ per tree (mean ± standard deviation), and the total volume in the 216.41 ha area was 3269 m$^3$, or 15.11 m$^3$ ha$^{-1}$, which represented an aboveground biomass totaling 2198.26 Mg or 10.12 Mg ha$^{-1}$, and an average aboveground carbon stock totaling 1072.74 MgC or 4.96 MgC ha$^{-1}$ (Table 5).

**Table 4.** Species in decreasing order of importance in terms of coverage value (CovV%) or the percentage of the total basal area of 15 commercial species with DBH ≥ 50 cm; absolute and relative phytosociological parameters of horizontal structure by species.

| Scientific Name | N | ADens | RDens% | ADom | RDom% | CovV% |
|---|---|---|---|---|---|---|
| *Couratari macrosperma* | 71 | 0.33 | 25.54 | 0.19 | 27.75 | 26.65 |
| *Apuleia leiocarpa* | 37 | 0.17 | 13.31 | 0.10 | 15.01 | 14.16 |
| *Cedrela odorata* | 33 | 0.15 | 11.87 | 0.07 | 9.98 | 10.93 |
| *Clarisia racemosa* | 15 | 0.07 | 5.40 | 0.05 | 7.49 | 6.44 |
| *Dipteryx odorata* | 19 | 0.09 | 6.83 | 0.04 | 6.05 | 6.44 |
| *Aspidosperma macrocarpon* | 17 | 0.08 | 6.12 | 0.04 | 6.51 | 6.31 |
| *Amburana cearensis* | 15 | 0.07 | 5.40 | 0.03 | 4.39 | 4.89 |
| *Aspidosperma australe* | 16 | 0.07 | 5.76 | 0.02 | 3.57 | 4.66 |
| *Enterolobium contortisiliquum* | 11 | 0.05 | 3.96 | 0.03 | 4.84 | 4.40 |
| *Hymenaea courbaril* | 13 | 0.06 | 4.68 | 0.03 | 3.82 | 4.25 |
| *Manilkara bidentata* | 12 | 0.06 | 4.32 | 0.02 | 3.29 | 3.80 |
| *Alnus acuminata* | 10 | 0.05 | 3.60 | 0.03 | 3.80 | 3.70 |
| *Tabebuia chrysantha* | 4 | 0.02 | 1.44 | 0.01 | 2.06 | 1.75 |
| *Heisteria spruceana* | 3 | 0.01 | 1.08 | 0.01 | 0.90 | 0.99 |
| *Tapirira guianensis* | 2 | 0.01 | 0.72 | 0.00 | 0.55 | 0.63 |
| Total | 278 | 1.28 | 100 | 0.688 | 100 | 100 |

Where N = number of individuals (including seed trees) with DBH ≥ 50 cm in 216.41 ha; ADens = absolute density (ind ha$^{-1}$); RDens = relative density in %; RDom = relative dominance in %; Adom = absolute dominance in m$^2$ ha$^{-1}$; CovV% = coverage value in %.

### 3.2. Estimates of Aboveground Volume, Biomass, and Carbon of 96 Trees Harvested by Tree Component and Revenue from Commercial Boles

The commercial boles of the 96 felled trees had a total volume of 583.43 m$^3$ (2.70 m$^3$ ha$^{-1}$), biomass of 371.42 Mg (1.72 Mg ha$^{-1}$), and carbon stock of 182 MgC (0.84 MgC ha$^{-1}$). The commercial values of the harvested trees sold (roundwood) are presented in Table 6. The total gross revenue to the management company per hectare harvested (net of a small royalty of USD 35.74 to the El Lago community) is USD 554.89.

**Table 5.** Aboveground volume, biomass, and carbon stocks by tree component in commercial boles, crowns, and stumps of 278 harvestable trees in 216.41 ha.

| | | | | **Volume** | | | | | **Biomass** | | | | | **Carbon** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Scientific Name** | **N** | **DBH** | **h** | **$m^3$** | **$\bar{x}$** | **SD ±** | **$m^3$ $ha^{-1}$** | **%** | **Mg** | **$\bar{x}$** | **SD ±** | **Mg $ha^{-1}$** | **%** | **MgC** | **$\bar{x}$** | **SD ±** | **MgC $ha^{-1}$** | **%** |
| *Alnus acuminata* | 10 | 84.1 | 14.7 | 118.3 | 11.8 | 2.8 | 0.55 | 3.62 | 45.70 | 4.57 | 1.1 | 0.21 | 2.09 | 22.39 | 2.24 | 0.5 | 0.10 | 2.09 |
| *Amburana cearensis* | 15 | 73.5 | 14.5 | 140.5 | 9.4 | 3.2 | 0.65 | 4.30 | 73.61 | 4.91 | 1.7 | 0.34 | 3.36 | 36.07 | 2.40 | 0.8 | 0.17 | 3.36 |
| *Apuleia leiocarpa* | 37 | 86.1 | 14.6 | 461.1 | 12.5 | 5.1 | 2.13 | 14.11 | 353.31 | 9.55 | 3.9 | 1.63 | 16.14 | 173.12 | 4.68 | 1.9 | 0.80 | 16.14 |
| *Aspidosperma australe* | 16 | 64.8 | 15.4 | 124.2 | 7.8 | 1.5 | 0.57 | 3.80 | 91.99 | 5.75 | 1.1 | 0.43 | 4.20 | 45.08 | 2.82 | 0.5 | 0.21 | 4.20 |
| *Aspidosperma macrocarpon* | 17 | 84.2 | 14.8 | 203.7 | 12.0 | 3.6 | 0.94 | 6.23 | 144.63 | 8.51 | 2.5 | 0.67 | 6.61 | 70.87 | 4.17 | 1.2 | 0.33 | 6.61 |
| *Cedrela odorata* | 33 | 74.6 | 11.9 | 273.5 | 8.3 | 3.6 | 1.26 | 8.37 | 116.31 | 3.52 | 1.5 | 0.54 | 5.31 | 56.99 | 1.73 | 0.8 | 0.26 | 5.31 |
| *Clarisia racemosa* | 19 | 77.1 | 11.9 | 163.5 | 8.6 | 2.7 | 0.76 | 5.00 | 66.52 | 3.50 | 1.1 | 0.31 | 3.04 | 32.60 | 1.72 | 0.5 | 0.15 | 3.04 |
| *Couratari macrosperma* | 71 | 85.1 | 18.9 | 1074.5 | 15.1 | 4.7 | 4.96 | 32.87 | 786.02 | 11.07 | 3.4 | 3.63 | 35.90 | 385.15 | 5.42 | 1.7 | 1.78 | 35.90 |
| *Dipteryx odorata* | 15 | 95.7 | 15.1 | 231.6 | 15.4 | 5.2 | 1.07 | 7.08 | 186.18 | 12.41 | 4.2 | 0.86 | 8.50 | 91.23 | 6.08 | 2.1 | 0.42 | 8.50 |
| *Enterolobium contortisiliquum* | 11 | 89.5 | 12.5 | 127.9 | 11.6 | 4.6 | 0.59 | 3.91 | 50.81 | 4.62 | 1.8 | 0.23 | 2.32 | 24.90 | 2.26 | 0.9 | 0.12 | 2.32 |
| *Heisteria spruceana* | 3 | 75.3 | 15 | 29.5 | 9.8 | 0.6 | 0.14 | 0.90 | 21.50 | 7.17 | 0.4 | 0.10 | 0.98 | 10.54 | 3.51 | 0.2 | 0.05 | 0.98 |
| *Hymenaea courbaril* | 13 | 74.2 | 15.2 | 127.4 | 9.8 | 2 | 0.59 | 3.90 | 96.75 | 7.44 | 1.6 | 0.45 | 4.42 | 47.41 | 3.65 | 0.8 | 0.22 | 4.42 |
| *Manilkara bidentata* | 12 | 71.6 | 15.1 | 109.5 | 9.1 | 2.1 | 0.51 | 3.35 | 95.70 | 7.97 | 1.8 | 0.44 | 4.37 | 46.89 | 3.91 | 0.9 | 0.22 | 4.37 |
| *Tabebuia chrysantha* | 4 | 97.8 | 16.3 | 67.9 | 17.0 | 5.4 | 0.31 | 2.08 | 52.92 | 13.23 | 4.2 | 0.24 | 2.42 | 25.93 | 6.48 | 2.1 | 0.12 | 2.42 |
| *Tapirira guianensis* | 2 | 72 | 13 | 16.0 | 8.0 | 0.2 | 0.07 | 0.49 | 7.32 | 3.66 | 0.1 | 0.03 | 0.33 | 3.58 | 1.79 | 0.0 | 0.02 | 0.33 |
| Total | 278 | 81.2 | 15.3 | 3269.00 | 11.8 | 4.80 | 15.11 | 100 | 2189.26 | 7.88 | 4.1 | 10.12 | 100 | 1072.74 | 3.86 | 2.0 | 4.96 | 100 |

N = number of trees; DBH = diameter at breast height; h = commercial height; $m^3$, Mg and MgC = total volume, biomass, and carbon in 216.41 ha; $\bar{x}$ = mean per tree; SD = standard deviation; % = percent of the total for all 15 species.

**Table 6.** Calculation of gross revenue per hectare to the management company from the sale of sawn wood from the 216.41 ha harvested area.

| Scientific Name | Number of Trees Harvested | Roundwood Volume Harvested | | Sawn Wood | | | | Royalty Paid to El Lago Community | | | Gross Revenue to Management Company (Net of Royalty) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total Volume (m$^3$) | Volume per ha (m$^3$ ha$^{-1}$) | Total Volume (m$^3$) | Price (USD Board foot$^{-1}$) | Price (USD m$^{-3}$) | Total Value (USD) | Royalty Rate (USD m$^{-3}$ Roundwood) | Royalty per ha (USD ha$^{-1}$) | Total Royalty (USD) | Total Revenue (USD) | Revenue per ha (USD ha$^{-1}$) |
| *Couratari macrosperma* | 7 | 78.02 | 0.36 | 36.44 | 0.57 | 241.55 | 8801.04 | 8 | 2.88 | 624.17 | 8176.87 | 37.78 |
| *Apuleia leiocarpa* | 16 | 102.01 | 0.47 | 47.64 | 1.00 | 423.78 | 20,188.13 | 10 | 4.71 | 1020.09 | 19,168.04 | 88.57 |
| *Cedrela odorata* | 22 | 79.95 | 0.37 | 37.34 | 1.44 | 610.24 | 22,784.22 | 30 | 11.08 | 2398.61 | 20,385.61 | 94.20 |
| *Clarisia racemosa* | 5 | 29.88 | 0.14 | 13.95 | 0.72 | 305.12 | 4257.61 | 8 | 1.10 | 239.04 | 4018.57 | 18.57 |
| *Dipteryx odorata* | 3 | 34.65 | 0.16 | 16.18 | 1.10 | 466.15 | 7543.09 | 10 | 1.60 | 346.51 | 7196.58 | 33.25 |
| *Aspidosperma macrocarpon* | 10 | 74.51 | 0.34 | 34.80 | 0.80 | 339.02 | 11,796.63 | 8 | 2.75 | 596.05 | 11,200.58 | 51.76 |
| *Amburana cearensis* | 8 | 43.83 | 0.2 | 20.47 | 1.36 | 576.34 | 11,796.78 | 25 | 5.06 | 1095.84 | 10,700.94 | 49.45 |
| *Aspidosperma australe* | 6 | 21.51 | 0.10 | 10.05 | 0.57 | 241.55 | 2426.43 | 8 | 0.80 | 172.07 | 2254.36 | 10.42 |
| *Enterolobium contortisiliquum* | 2 | 12.59 | 0.06 | 5.88 | 0.57 | 241.55 | 1420.21 | 8 | 0.47 | 100.74 | 1319.47 | 6.10 |
| *Hymenaea courbaril* | 1 | 6.33 | 0.03 | 2.96 | 0.72 | 305.12 | 901.96 | 8 | 0.23 | 50.65 | 851.31 | 3.93 |
| *Manilkara bidentata* | 6 | 21.88 | 0.10 | 10.22 | 0.80 | 339.02 | 3464.10 | 8 | 0.81 | 175.06 | 3289.04 | 15.20 |
| *Alnus acuminata* | 6 | 45.16 | 0.21 | 21.09 | 0.57 | 241.55 | 5094.27 | 8 | 1.67 | 361.28 | 4732.99 | 21.87 |
| *Tabebuia chrysantha* | 2 | 24.21 | 0.11 | 11.31 | 3.80 | 1610.35 | 18,206.72 | 20 | 2.24 | 484.19 | 17,722.53 | 81.89 |
| *Heisteria spruceana* | 1 | 3.90 | 0.02 | 1.82 | 0.90 | 381.40 | 694.64 | 8 | 0.14 | 31.22 | 663.42 | 3.07 |
| *Tapirira guianensis* | 1 | 4.98 | 0.02 | 2.33 | 0.72 | 305.12 | 709.60 | 8 | 0.18 | 39.88 | 669.72 | 3.09 |
| Total | 96 | 583.43 | 2.70 | 272.45 | | | 120,085.44 | | 35.74 | 7735.42 | 112,350.04 | 519.15 |

The crowns and stumps represented 2.24 m$^3$ ha$^{-1}$ of volume, 1.25 Mg ha$^{-1}$ of biomass, and 0.61 MgC ha$^{-1}$ of carbon. Table 7 shows the volume that was removed from the forest (commercial bole) and that decomposed on site (crown and stump).

**Table 7.** Volume, biomass, and carbon stocks by tree component in commercial boles, crowns, and stumps of 96 felled trees in 216.41 ha.

| **Tree Component** | **Volume** | | **Biomass** | | **Carbon** | |
|---|---|---|---|---|---|---|
| | **m$^3$** | **m$^3$ ha$^{-1}$** | **Mg** | **Mg ha$^{-1}$** | **MgC** | **MgC ha$^{-1}$** |
| Commercial bole * | 583.43 | 2.70 | 371.42 | 1.72 | 182 | 0.84 |
| Stump | 15.36 | 0.07 | 8.52 | 0.04 | 4.18 | 0.02 |
| Crown | 470.48 | 2.17 | 261.11 | 1.21 | 127.95 | 0.59 |
| Total | 1069.26 | 4.94 | 641.06 | 2.96 | 314.12 | 1.45 |

* "Commercial bole" refers to the portion of the trunk between the point of cut and the first significant branch.

### 3.3. Estimates of Infrastructure Areas and Loss of Aboveground Vegetation

A total of 5.19 ha was opened for roads, log landings, skid tracks, and gap openings (MAI), or 2.40% of the 246.41 ha study area. The loss of aboveground vegetation in the 5.19 ha area represents a volume of 2629.15 m$^3$, a biomass of 1656.37 Mg, and a carbon stock of 811.62 MgC (Table 8). When belowground stocks are included, the values increase, resulting in losses of forest lost to infrastructure (MAI) totaling 3169.99 m$^3$ of volume, 1997.09 Mg of biomass, and 978.58 Mg of carbon.

**Table 8.** Forest lost to management infrastructure (roads, log landings, gap openings, and skid tracks) (trees ≥ 10 cm DBH in 216.41 ha).

| **Use (MAI)** | **Area Occupied** | | | **Aboveground Forest Stocks Lost** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | **Volume** | | **Biomass** | | **Carbon** | |
| | **ha** | **FA** | **MI** | **m$^3$** | **m$^3$ ha$^{-1}$** | **Mg** | **Mg ha$^{-1}$** | **MgC** | **MgC ha$^{-1}$** |
| Roads | 0.986 | 18.99 | 0.46 | 499.10 | 2.31 | 314.44 | 1.45 | 154.07 | 0.71 |
| Log landings | 0.165 | 3.18 | 0.08 | 83.52 | 0.39 | 52.62 | 0.24 | 25.78 | 0.12 |
| Gap openings * | 1.160 | 22.33 | 0.54 | 587.18 | 2.71 | 369.92 | 1.71 | 181.26 | 0.84 |
| Skid tracks | 2.883 | 55.51 | 1.33 | 1459.35 | 6.74 | 919.39 | 4.25 | 450.50 | 2.09 |
| Total | 5.194 | 100.00 | 2.40 | 2629.15 | 12.15 | 1656.37 | 7.65 | 811.62 | 3.76 |

Where: FA = area occupied in percent of the felled area; MI = area occupied in percent of the managed area; MAI = managed area infrastructure. * Values for gap openings include the harvested trees.

### 3.4. Total Stocks (Above- and Belowground) of Forest Removed or Lost in the Management Area

The total vegetation removed or lost in the management area had a total volume of 4459.22 m$^3$ or 20.61 m$^3$ ha$^{-1}$, biomass of 2770.01 Mg or 12.80 Mg ha$^{-1}$, and carbon of 1357.32 MgC or 6.27 MgC ha$^{-1}$. These values are the sum of Scenario 1 (MA; commercial bole, stumps, crowns, and roots) and Scenario 2 (MAI; total vegetation lost to roads, log landings, gap openings, and skid tracks) (Figure 1; Table 9).

In Scenario 1 (MA), the stocks and percentages lost from the harvested trees (crowns, stumps, and roots) totaled 15.8% of the volume and 14.5% of the biomass and carbon. Commercial boles removed from the management area represented only 13.1% of the total reduction in volume, biomass, and carbon and 13.4% of the total vegetation removed or lost. In Scenario 2 (MAI), the vegetation lost totaled 71.1% of the volume and 72.1% of the biomass and carbon of the vegetation impacted by MAI. The total forest stocks (above- and belowground) lost or removed in the management area are presented in Table 9. In terms of biomass and carbon, MAI represented 86.6% and removals represented 13.4%.

**Table 9.** Total forest stocks (above- and belowground) lost or removed in the management area (216.41 ha).

| Vegetation | Volume | | | Biomass | | | Carbon | | |
|---|---|---|---|---|---|---|---|---|---|
| | $m^3$ | $m^3$ ha$^{-1}$ | % | Mg | Mg ha$^{-1}$ | % | MgC | MgC ha$^{-1}$ | % |
| Lost (stumps + crowns + roots; Scenario 1, MA) | 705.80 | 3.26 | 15,8 | 401.49 | 1.86 | 14.5 | 196.75 | 0.91 | 14,5 |
| Removed (commercial bole; Scenario 1, MA) | 583.43 | 2.70 | 13.1 | 371.42 | 1.72 | 13.4 | 182 | 0.84 | 13.4 |
| Lost (Scenario 2, MAI) | 3169.99 | 14.65 | 71.1 | 1997.09 | 9.23 | 72.1 | 978.58 | 5.82 | 72.1 |
| Total | 4459.22 | 20.61 | 100 | 2770.01 | 12.80 | 100 | 1357.32 | 6.27 | 100 |

## 4. Discussion

### *4.1. Comparison with Other Management Systems*

The number of large commercial individuals of each species in the study area and, consequently, the density of large trees per hectare (1.28 trees ha$^{-1}$), are low when compared with areas that have been studied in Brazilian Amazonia. *Couratari macrosperma* is the predominant commercial tree species in the area, and other species in the area are similar to those reported by Soriano et al. [21] and Guariguata et al. [31] in studies carried out in the northern Bolivian Amazon. The lower density of commercial trees in Bolivia as compared with Brazil can be explained by the fact that in the northern Bolivian Amazon, the "basket" of species in the Bolivian market [25] is effectively limited to five species. The most sought-after species are "cedro" (*Cedrela odorata*), "mara" (*Swietenia macrophylla*), and "roble" (*Amburana cearensis*), together with some species with very hard wood, such as "almendrilho negro" (*Dipteryx odorata*) and "almendrilo amarillo" (*Apuleia leiocarpa*). This selection means that forest inventories are focused on searching for areas with these species and quantifying their stocks in order to have a secure market in the sale of wood. In most forest inventory reports from Bolivia, the number of species used is between 12 and 20, according to the National Institute of Statistics of Bolivia (INE) [64]. In the present study, 15 species were sold, whereas in Brazilian Amazonia, the species are more diverse, with the number of commercial species identified ranging from 44 to 81 [6], meaning that the number of individuals will be greater regardless of the minimum diameter for inclusion in the inventories.

All harvested individuals in Bolivian forest management must have DBH $\geq$ 50 cm. The number of species, number of trees, and diameter significantly impact the volume stocks of commercial boles. The volume stock harvested in the present study (2.7 $m^3$ ha$^{-1}$) was smaller than those observed in the Peruvian Amazon, which range between 2.9 and 8.1 $m^3$ ha$^{-1}$ [22], and much smaller than those in the Brazilian Amazon, where stocks range from 15 to 30 $m^3$ ha$^{-1}$ [6]. These differences are attributed to the demand for the five species that are sought after in the Bolivian market [64]. Although 15 species were harvested in the management project we studied in Bolivia, the pressure on the most preferred five species (Table 6) is strong as their price is greater per cubic meter; for example, *Cedrela odorata* sells for USD 466.24 $m^{-3}$, a price much higher than for other species (such as *Tapirira guianensi*s, at USD 243.59 $m^{-3}$; Table 6). The pressure on the most valuable species could compromise their regeneration in future management cycles [28,65,66]. In summary, variation in stocks indicates significant differences in forest management practices and ecological characteristics among areas that have been studied in different Amazonian countries. Caution is needed when making direct comparisons of volumes per hectare, both those permitted and those actually harvested, considering the diversity of criteria, legislation, and measurement methodologies adopted in the different countries [6.30,68,69].

Timber infrastructure impacted 5.19 ha or 2.40% of the managed area we studied, a substantially lower percentage as compared with other countries, especially Brazil [30], where a greater volume is harvested per hectare (15 to 30 $m^3$ ha$^{-1}$), and consequently, there is a greater need for management infrastructure. As compared with projects in Brazil with higher harvesting intensities, the management system we studied in Bolivia implies a greater loss of forest biomass per unit volume of harvested timber due to infrastructure and collateral damage caused by tree extraction (Table 8) [67,68]. Greater damage per unit of wood extracted when harvest intensity is low has been shown in a study of a forest management project in Bolivia's Beni department [69,70]. Collateral damage is substantial, despite required reduced-impact logging practices, as shown in a forest management project in Bolivia's Santa Cruz department, where "On average, 44 trees were damaged for every tree extracted including 22 trees killed or severely damaged, 6 of them commercial species" [71]. Differences in forest management planning and logistics [23] arise from differences in legislation, location, management areas, and investment.

Although the percentage of the area impacted by infrastructure appears to be low (2.4%), the volume, biomass, and carbon lost to infrastructure in this area totaled 72.1% of the total biomass and carbon lost or removed in the management project (Table 9). This significant loss of biomass and carbon highlights the challenge of minimizing environmental impact in forest management [65,72]. A contradiction arises in forest management, where the loss to infrastructure (72.1%) exceeds that of the wood actually harvested (13.4%), increasing emissions and operational costs without guaranteeing economic return [71]. Many management costs are fixed, such as road construction and licensing, making the cost per cubic meter higher at low harvest intensities [72,73]. This can make a project economically unviable without subsidies, increasing the risk of abandonment and failing to provide long-term sustainable forest protection.

The sustainability of the managed area is unlikely, even when complying with legal standards (technical standard 248/98). The 20-year cutting cycle is questionable because the tree species would be unable to restore their stocks in such a short time [68]. Sist et al. [68] calculated that, to be sustainable, forest management in Amazonia would need to have a 60-year cycle with a harvest of 10 $m^3$ $ha^{-1}$ $cycle^{-1}$ (0.17 $m^3$ $ha^{-1}$ $year^{-1}$) and would have to have an initial volume that is 90% commercially valuable species. Except for the low harvest intensity (0.14 $m^3$ $ha^{-1}$ $year^{-1}$ in the system we studied), the Bolivian system is far from these minimum requirements for sustainability.

In an analysis of the financial viability of forest management in northern Bolivia under the current Bolivian regulations, Bojanic and Bulte [73] concluded that that "many firms will not be able to earn 'normal profits' under the new regime", although they could still be marginally profitable. These authors assumed that the permitted amounts of timber would be harvested and sold, whereas in the case we studied, the actual harvest was only a fraction of these amounts, implying an even less favorable financial balance. Bojanic and Bulte [73] calculated that "the net present value per hectare is depressed to such low levels that forests are unlikely to earn competitive rates of return, so that future conversion or misuse of forestlands may be feared". This is also our fear. This suggests that it would be more beneficial to leave the trees standing to continue fulfilling their biological functions within the forest ecosystem and promote conservation alternatives for this type of forest.

### *4.2. The Significance and Challenges of the Bolivian Management System*

Our study provides information needed for the consideration of questions surrounding tropical forest management as a means of maintaining forests and as a means of avoiding carbon emissions. Forest management projects throughout the tropics vary widely in their intensity of harvesting, and the one we studied, with the harvesting of 2.70 $m^3$ $ha^{-1}$ $cycle^{-1}$ (0.14 $m^3$ $ha^{-1}$ $year^{-1}$) (Tables 6, 8 and 9), is one of the lowest. Some management systems in Brazil have low harvest intensities, such as a community management system with intensities as low as 4.82 $m^3$ $ha^{-1}$ [74], but most Brazilian projects harvest on the order of 30 $m^3$ $ha^{-1}$ (e.g., [75]), and, prior to Brazil's 1997 regulations on forest management, some projects harvested as much as 50 $m^3$ $ha^{-1}$ [76]. At the other end of the spectrum, in Southeast Asia, where the percentage of the trees that are commercially valuable is much higher than in Amazonia, a management system harvested an average of 86.9 $m^3$ $ha^{-1}$, and some areas were harvested at up to 247 $m^3$ $ha^{-1}$ [77].

However, the relationship between harvesting intensity and profitability to impact is not simple (Tables 7 and 9). While low harvesting intensity can mean that larger areas will be managed to supply the market for tropical timber, high intensity can also lead to expanding the area under forest management. If high-intensity forest exploitation is very profitable, at least in the short term, then the normal economic logic will lead to more investment and expansion of this activity, thus affecting a larger area. The argument that it would be better to have high-intensity exploitation in a small area rather than low-intensity exploitation over a large area is based on the false assumption that with higher intensity, the companies would be satisfied with their revenues and would refrain from further expansion, thus having a "land sparing" effect. This is not the way that market economies work, and the likely result would be high-intensity exploitation over the largest possible area. It should be remembered that the potential global market for tropical timber is essentially infinite from the perspective of a country like Bolivia, and the extent to which forest management can expand will not be limited by market saturation. The projected sequence of exhausting Southeast Asian timber stocks, followed by Africa, and finally Amazonia ([78], p. 98) is now playing out, although more slowly than originally expected. We believe that there is no way that Amazon forest management can harvest at sustainable levels and supply global demand for tropical timber [79].

Many studies have shown that logging increases the vulnerability of tropical forests to the entry of fires and increases the destructiveness of fires when they occur (e.g., [19,80,81]). Southwestern Amazonia is particularly prone to forest fires under its current (already altered) climate [82], and Pando department has experienced large-scale forest fires during extreme droughts [83,84]. The climatic phenomenon that caused major droughts and widespread forest fires in southwestern Amazonia in 2005 and 2010 is expected to increase greatly in frequency under projected climate change [85]. Fire is virtually never anticipated in forest management plans and can make their assumption of long-term sustainability fictitious. The extent to which the probability of fire reduces the climatic benefits of forest management needs to be quantified under different present and projected climate regimes, and with different logging intensities.

In our study, the value obtained for sawn wood per harvested hectare was USD 554.89, or USD 519.15 after deducting the royalty (Table 6). We lack data on the company's costs for forest management and for sawmill operation. A rough idea can be gained from costs in Brazil. In a study with data from 20 sawmills in Acre in 2008, Silva [86] calculated the total costs of logs delivered to sawmills (including transport) and of milling for logs coming from different distances (at 25 km intervals) from a sawmill. Interpolating between these values and correcting for U.S. inflation to 2024 (based on the U.S. consumer price index: https://www.usinflationcalculator.com/ (accessed on 22 March 2024)), the total cost in 2024 dollars would be USD 526.35 $m^{-3}$ of sawn wood at the 48 km distance for the Bolivian management project we studied, or USD 662.65 $ha^{-1}$ at the 2.7 $m^3$ $ha^{-1}$ harvest intensity for commercial boles in the Bolivian project.

Many factors would make costs in Acre different from those in our area; for example, a factor lowering costs per $m^3$ compared with Acre relative to Bolivia is the higher logging intensity (12.34 $m^3$ $ha^{-1}$). Factors increasing the cost in Brazil relative to the Bolivian case include higher government taxes and higher labor costs. Despite the differences, the cost per $m^3$ in Acre implying a cost of USD 662.65 $ha^{-1}$ at the harvest intensity in Bolivia, or 28% higher than the gross return per hectare in the Bolivian case (USD 519.15 $ha^{-1}$), suggests a lack of financial viability. An older study in the Brazilian state of Pará in 1989 [61] (prior to a requirement for a forest survey and management plan and for reduced-impact logging measures) indicated an average cost of USD 522.86 $ha^{-1}$ in 2024 USD at the Bolivian harvest intensity, or 1% higher than the gross return in Bolivia, providing an additional indication that the Bolivian management project was not financially viable.

The harvest we studied was part of the first management cycle in this forest, and subsequent management cycles would be even less viable because the first cycle has the benefit of harvesting the large trees that have been growing for centuries at no cost to the manager, whereas in future cycles, all or most of the harvested trees will be those that have grown past the 50 cm DBH minimum size during the 20-year cycle, and most will be only slightly larger than this diameter. To be financially viable, these amounts must cover operational costs in all phases of forestry exploitation (pre-harvest, harvest, and post-harvest). This leads us to conclude that such revenue would be difficult to cover all these steps without compromising the company's financial viability, which could lead to its closure.

The bankruptcy and closing of the company managing the area we studied, even under the favorable economic conditions of the first management cycle as compared with subsequent cycles, confirms this conclusion. We note that the existence of other companies with management plans that continue to produce in the region without going bankrupt does not necessarily mean that the management plans as authorized are viable, since the practices of illegally harvesting more than the quantities permitted in the management areas and of harvesting illegally outside of the management areas are common in Bolivia [87].

Our study shows that vegetation loss significantly exceeds the volume harvested in the Bolivian management system. This finding makes us reflect on the need to reorient forest management practices in the north of the Amazon, aiming for a sustainable and economically viable approach. A key question in assessing forest management's environmental benefit (or lack thereof) is what the baseline would be if no management were taking place. If the alternative would be conversion to pasture or agriculture, management is clearly better, whereas if it is maintaining an undisturbed forest, management implies a negative impact. In Bolivia, an example of dealing with this quandary is provided by the leakage agreements associated with the Noel Kempff Climate Action project in the Santa Cruz department [88,89].

## 5. Conclusions

Volume, biomass, and carbon stocks are relatively low in a forest management system in Bolivian Amazonia that follows the country's legal requirements (technical standard 248/98). However, despite low harvesting intensity and a small percentage of the management area lost to timber infrastructure, the harvested species cannot be expected to regenerate in a 20-year cycle. Less than half of the legally permitted quantity was harvested due to a lack of access to markets for all but the most valuable commercial species. The questionable economic return of the management system also makes the long-term sustainability of the system very unlikely.

The low harvesting intensity in the management system in the study area implies a greater loss of forest biomass due to infrastructure and collateral damage from tree extraction. Preserving the standing species would be more beneficial, safeguarding their biological functions and promoting conservation alternatives for this type of forest.

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## References

1. Pacheco, P.; Ormachea, E.; Cronkleton, P.; Albornoz, M.A.; Paye, L. *Trayectorias y Tendencias de la Economía Forestal Extractiva en el Norte Amazónico de Bolivia*; Centro para la Investigación Forestal Internacional (CIFOR), Centro de Estudios para el Desarrollo Laboral y Agrario (CEDLA), Iniciativa de Derechos y Recursos (RRI): La Paz, Bolivia, 2009; 52p. Available online: https://bit.ly/3lzhcx5 (accessed on 24 March 2024).
2. Broadbent, E.N.; Asner, G.P.; Peña-Claros, M.; Palace, M.; Soriano, M. Spatial partitioning of biomass and diversity in a lowland Bolivian forest: Linking field and remote sensing measurements. *For. Ecol. Manag.* **2008**, *255*, 2602–2616. https://doi.org/10.1016/j.foreco.2008.01.044.
3. Comunidad de Práctica Sobre Financiamiento Florestal (COP-FF). *Diagnóstico de Mecanismos Financieros para el Manejo Sostenible y la Conservación de los Bosques en Bolivia, Hacia una Estrategia Nacional*; Proyecto FAO/UICN/HOLANDA (LNV-DK)/CCAD GCP/INT/953/NET: "Estrategias y Mecanismos Financieros para el Uso Sostenible y la Conservación de Bosques" Fase 1: América Latina; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2006; 107p.
4. Goodman, R.C.; Phillips, O.L.; Baker, T.R. The importance of crown dimensions to improve tropical tree biomass estimates. *Ecol. Appl.* **2014**, *24*, 680–698. https://doi.org/10.1890/13-0070.1.
5. Saatchi, S.S.; Harris, N.L.; Brown, S.; Lefsky, M.; Mitchard, E.T.; Salas, W.; Zutta, B.R.; Buermann, W.; Lewis, S.L.; Hagen, S.; et al. A benchmark map of forest carbon stocks in tropical regions across three continents. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 9899–9904. https://doi.org/10.1073/pnas.1019576108.
6. Romero, F.M.B.; Jacovine, L.A.; Torres, C.M.; Ribeiro, S.C.; de Morais Junior, V.T.; Da Rocha, S.J.; Romero, R.A.B.; Gaspar, R.D.; Velasquez, S.I.; Staudhammer, C.L.; et al. 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. *Forests* **2021**, *12*, 481. https://doi.org/10.3390/f12040481.
7. Chave, J.; Andalo, C.; Brown, S.; Cairns, M.A.; Chambers, J.Q.; Eamus, D.; Fölster, H.; Fromard, F.; Higuchi, N.; Kira, T.; et al. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* **2005**, *145*, 87–99. https://doi.org/10.1007/s 00442-005-0100-x.
8. Lewis, S.L. Tropical forests and the changing earth system. *Philos. Trans. R. Soc. Biol. Sci.* **2006**, *361*, 195–210. https://doi.org/10.1098/rstb.2005.1711.
9. Keeling, H.C.; Phillips, O.L. The global relationship between forest productivity and biomass. *Glob. Ecol. Biogeogr.* **2007**, *16*, 618–631. https://doi.org/10.1111/j.1466-8238.2007.00314.x.
10. Sullivan, M.J.P.; Talbot, J.; Lewis, S.L.; Phillips, O.L.; Qie, L.; Begne, S.K.; Chave, J.; Cuni-Sanchez, A.; Hubau, W.; Lopez-Gonzalez, G.; et al. Diversity and carbon storage across the tropical forest biome. *Sci. Rep.* **2017**, *7*, 39102. https://doi.org/10.1038/srep39102.
11. Houghton, R.A.; Hall, F.; Goetz, S.J. Importance of biomass in the global carbon cycle. *J. Geophys. Res.-Biogeosci.* **2009**, *114*, G00E03. https://doi.org/10.1029/2009JG000935.
12. Basuki, T.M.; Van Laake, P.E.; Skidmore, A.K.; Hussin, Y.A. Allometric equations for estimating the aboveground biomass in tropical lowland Dipterocarp forests. *For. Ecol. Manag.* **2009**, *257*, 1684–1694. https://doi.org/10.1016/j.foreco.2009.01.027.
13. Aiba, S.I.; Kohyama, T. Tree species stratification in relation to allometry and demography in a warm-temperate rain forest. *J. Ecol.* **1996**, *84*, 207–218. https://doi.org/10.2307/2261356.
14. Banin, L.; Feldpausch, T.R.; Phillips, O.L.; Baker, T.R.; Lloyd, J.; Affum-Baffoe, K.; Arets, E.J.M.M.; Berry, N.J.; Bradford, M.; Brienen, R.J.W.; et al. What controls tropical forest architecture? Testing environmental, structural and floristic drivers. *Glob. Ecol. Biogeogr.* **2012**, *21*, 1179–1190. https://doi.org/10.1111/j.1466-8238.2012.00778.x.
15. Baker, T.R.; Phillips, O.L.; Malhi, Y.; Almeida, S.; Arroyo, L.; Di Fiore, A.; Erwin, T.; Killen, T.J.; Laurance, S.G.; Laurance, W.F.; et al. Variation in wood density determines spatial patterns in Amazonian forest biomass. *Glob. Change Biol.* **2004**, *10*, 545–562. https://doi.org/10.1111/j.1365-2486.2004.00751.x.
16. Barbier, N.; Couteron, P.; Proisy, C.; Malhi, Y.; Gastellu-Etchegorry, J. The variation of apparent crown size and canopy heterogeneity across lowland Amazonian forests. *Glob. Ecol. Biogeogr.* **2009**, *19*, 72–84. https://doi.org/10.1111/j.1466-8238.2009.00493.x.
17. Baccini, A.G.S.J.; Goetz, S.J.; Walker, W.S.; Laporte, N.T.; Sun, M.; Sulla-Menashe, D.; Hackler, J.; Beck, P.S.A.; Dubayah, R.; Friendl, M.A.; et al. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat. Clim. Change* **2012**, *2*, 182–185. https://doi.org/10.1038/nclimate1354.
18. Chambers, J.Q.; Schimel, J.P.; Nobre, A.D. Respiration from coarse wood litter in central Amazon forests. *Biogeochemistry* **2001**, *52*, 115–131. https://doi.org/10.1023/A:1006473530673.
19. Barni, P.E.; Rego, A.C.M.; Silva, F.C.F.; Lopes, R.A.S.; Xaud, H.A.M.; Xaud, M.R.; Barbosa, R.I.; Fearnside, P.M. Logging Amazon forest increased the severity and spread of fires during the 2015–2016 El Niño. *For. Ecol. Manag.* **2021**, *500*, 119652. https://doi.org/10.1016/j.foreco.2021.119652.

20. Piponiot, C.; Rutishauser, E.; Derroire, G.; E Putz, F.; Sist, P.; West, T.A.P.; Descroix, L.; Guedes, M.C.; Coronado, E.N.H.; Kanashiro, M.; et al. Optimal strategies for ecosystem services provision in Amazonian production forests. *Environ. Res. Lett.* **2019**, *14*, 124090. https://doi.org/10.1088/1748-9326/ab5eb1.
21. Soriano, M.; Kainer, K.A.; Staudhammer, C.L.; Soriano, E. Implementing multiple forest management in Brazil nut-rich community forests: Effects of logging on natural regeneration and forest disturbance. *For. Ecol. Manag.* **2012**, *268*, 92–102. https://doi.org/10.1016/j.foreco.2011.05.010.
22. Goodman, R.C.; Aramburu, M.H.; Gopalakrishna, T.; Putz, F.E.; Gutiérrez, N.; Alvarez, J.L.M.; Amuchastegui, N.A.; Ellis, P.W. Carbon emissions and potential emissions reductions from low-intensity selective logging in southwestern Amazonia. *For. Ecol. Manag.* **2019**, *439*, 18–27. https://doi.org/10.1016/j.foreco.2019.02.037.
23. Fredericksen, T.S.; Pariona, W. Effect of skidder disturbance on commercial tree regeneration in logging gaps in a Bolivian tropical forest. *For. Ecol. Manag.* **2002**, *171*, 223–230. https://doi.org/10.1016/S0378-1127(01)00767-8.
24. Fredericksen, T.S.; Mostacedo, B. Regeneration of sawtimber species following selective logging in a Bolivian tropical forest. *For. Ecol. Manag.* **2000**, *131*, 47–55. https://doi.org/10.1016/S0378-1127(99)00199-1.
25. Bolivia. Ley Forestal Boliviana n° 1700 del 12 julio de 1996, La Paz, Bolivia. 1996. Available online: https://www.bivica.org/file/view/id/3717 (accessed on 30 December 2023).
26. Ministerio de Desarrollo Sostenible y Planificación (MDSP). *Normas Técnicas para la Elaboración de Instrumentos de Manejo Forestal (Inventarios, Planes de Manejo, Planes Operativos, Mapas) en Propiedades Privadas o Concesiones con Superficies Mayores a 200 Hectáreas: Resolución Ministerial n. 248/98*; MDSP: La Paz, Bolivia, 1998. Available online: https://bit.ly/2ZSrYqn (accessed on 24 March 2024).
27. Ministerio de Medio Ambiente y Agua (MMAA). *Resolución Ministerial n. 182. Norma Técnica para la Elaboración de Planes de Manejo Integral de los Bosques para el Departamento de Pando*; MMAA: La Paz, Bolivia, 2016; 14p. Available online: https://bit.ly/3doWDyA (accessed on 24 March 2024).
28. Fredericksen, T.S. Logging and conservation of tropical forests in Bolivia. *Int. For. Rev.* **2000**, *2*, 271–278. Available online: https://www.jstor.org/stable/42609324 (accessed on 24 March 2024).
29. Romero, F.M. Impacto da Abertura de Estradas e Pátios na Exploração Florestal: Um Estudo de Caso na Amazônia Boliviana. Master's Thesis, Universidade Federal do Acre (UFAC), Rio Branco, Brazil, 2014.
30. Silva, J.L. Danos Florestais e Estimativa do Estoque de Carbono em Áreas de Manejo Florestal sob Concessão Pública: Floresta Nacional do Jamari—RO, Brasil. Master's Thesis, Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Brazil, 2014.
31. Guariguata, M.R.; Licona, J.C.; Mostacedo, B.; Cronkleton, P. Damage to Brazil nut trees (*Bertholletia excelsa*) during selective timber harvesting in Northern Bolivia. *For. Ecol. Manag.* **2009**, *258*, 788–793. https://doi.org/10.1016/j.foreco.2009.05.022.
32. Submission of the Plurinational State of Bolivia. 2021. Available online: https://unfccc.int/sites/default/files/resource/GLOBAL%20STOCKTAKE%20Bolivia.pdf (accessed on 24 March 2024).
33. Piponiot, C.; Rödig, E.; E Putz, F.; Rutishauser, E.; Sist, P.; Ascarrunz, N.; Blanc, L.; Derroire, G.; Descroix, L.; Guedes, M.C.; et al. Can timber provision from Amazonian production forests be sustainable? *Environ. Res. Lett.* **2019**, *14*, 064014. https://doi.org/10.1088/1748-9326/ab195e.
34. *Contribución Nacionalmente Determinada del Estado Plurinacional de Bolivia 2021–2030*; Autoridad Plurinacional de la Madre Tierra (Ministerio de Medio Ambiente y Agua): La Paz, Bolivia, 2022.
35. United Nations Framework Convention on Climate Change (UNFCCC). FAN Bolivia, RFN, ISA: Raising Voices from the Amazon: Voluntary Carbon Market Challenges and Solutions. 2023. Available online: https://unfccc.int/event/fan-bolivia-rfn-isa-raising-voices-from-the-amazon-voluntary-carbon-market-challenges-and-solutions (accessed on 24 March 2024).
36. United Nations Framework Convention on Climate Change (UNFCCC). *Project 2510: Carbon Sequestration through Reforestation in the Bolivian Tropics by Smallholders of "The Federación de Comunidades Agropecuarias de Rurrenabaque (FECAR)"*; UNFCCC: La Paz, Bolivia, 2009.
37. Plurinational State of Bolivia Speech at GST Plenary. 6 June 2023. Available online: https://unfccc.int/sites/default/files/resource/Bolivian%20GST%20speech.pdf (accessed on 24 March 2024).
38. Dauber, E.; Terán, J.; Guzmán, R. Estimaciones de biomasa y carbono en bosques naturales de Bolivia. *Rev. For. Iberoam.* **1992**, *1*, 1–10. Available online: https://www.yumpu.com/es/document/view/14521764/estimaciones-de-biomasa-y-carbono-en-bosques-naturales-de-bolivia (accessed on 24 March 2024).
39. Nogueira, E.M.; Fearnside, P.M.; Nelson, B.W.; Barbosa, R.I.; Keizer, E.W.H. Estimates of forest biomass in the Brazilian Amazon: New allometric equations and adjustments to biomass from wood-volume inventories. *For. Ecol. Manag.* **2008**, *256*, 1853–1857. https://doi.org/10.1016/j.foreco.2008.07.022.
40. Chen, N.; Tsendbazar, N.E.; Suarez, D.R.; Silva-Junior, C.H.; Verbesselt, J.; Herold, M. Revealing the spatial variation in biomass uptake rates of Brazil's secondary forests. *ISPRS J. Photogramm. Remote Sens.* **2024**, *208*, 233–244. https://doi.org/10.1016/j.isprsjprs.2023.12.013.
41. Brown, S.; Gillespie, A.J.R.; Lugo, A.E. Biomass estimation methods for tropical forests with applications to forest inventory data. *For. Sci.* **1989**, *35*, 881–902. https://doi.org/10.1093/forestscience/35.4.881.
42. City-Facts. Pando Department. 2024. Available online: https://www.city-facts.com/pando/population (accessed on 24 March 2024).
43. Lutz, J.A.; Furniss, T.J.; Johnson, D.J.; Davies, S.J.; Allen, D.; Alonso, A.; Anderson-Teixeira, K.J.; Andrade, A.; Baltzer, J.; Becker, K.M.L.; et al. Global importance of large-diameter trees. *Glob. Ecol. Biogeogr.* **2018**, *27*, 849–864. https://doi.org/10.1111/geb.12747.

44. Velasquez, S.I.S. *Plan Operativo Anual Forestal de la Comunidad Campesina "El Lago"*; Industria Maderera Arce (IMAR): Cobija, Bolivia, 2012; 14p. Available online: https://bit.ly/3GbXEGO (accessed on 24 March 2024).
45. *Zonificación Agroecologica y Socioeconomica y Perfil Ambiental del Departamento de Pando*; Projecto de Zonificación Agro-Ecológico y Establecimiento de una Base de Datos y Red de Sistema de Información Geográfica en Bolivia (ZONISIG); República de Bolivia, DHV Consulturas–ITC; Cooperación del Gobierno de los Países Bajos; ZONISIG: La Paz, Bolivia, 1997; 109p. Available online: https://bit.ly/3Ea9eRo (accessed on 24 March 2024).
46. Ministerio de Asuntos Campesinos y Agropecuarios (MACA). *Proyecto Inventario Forestal Nacional y Programa de Control de los Recursos Forestales de Bolivia PD 17/99 Rev. 3 (F) "INFOBOL", Ejecutado por el Ministerio de Asuntos Campesinos y Agropecuarios "MACA" y la Organización Internacional de las Maderas Tropicales "OIMT", Especies Forestales Reportadas en los Bosques Tropicales de Bolivia*; MACA: La Paz, Bolivia, 2004; 67p. Available online: https://bit.ly/3EoWAit (accessed on 24 March 2024).
47. Ferreira, M.V.S. Avaliação Econômica do Manejo Florestal em Floresta de Terra Firme na Amazônia Brasileira com Aplicação de Silvicultura Pós-Colheita. Master's Thesis, Universidade Federal Rural da Amazônia, Belém, Brazil, 2012. Available online: https://bit.ly/3EodLAD (accessed on 24 March 2024).
48. Espada, A.L.V.; Pires, I.P.; Lentini, M.A.W.; Bittencourt, P.R.G. *Manejo Florestal e Exploração de Impacto Reduzido em Florestas Naturais de Produção da Amazônia*; Informativo Técnico 1; Fundação Floresta Tropical (FFT): Belém, Brazil, 2013; 31p. Available online: https://bit.ly/3onzzqz (accessed on29 March 2024).
49. FFT (Fundação Floresta Tropical). *Manual de Procedimentos Técnicos para Condução de Manejo Florestal e Exploração de Impacto Reduzido (Versão 4.0)*; FFT: Belém, Brazil, 2002; 86p. Available online: https://bit.ly/3Gf7GHm (accessed on 24 March 2024).
50. Putz, F.E.; Sist, P.; Fredericksen, T.; Dykstra, D. Reduced-impact logging: Challenges and opportunities. *For. Ecol. Manag.* **2008**, *256*, 1427–1433. https://doi.org/10.1016/j.foreco.2008.03.036.
51. Mostacedo, B.; Fredericksen, T.S. *Regeneración y Silvicultura de Bosques Tropicales en Bolivia*; Proyecto de Manejo Forestal Sostenible (BOLFOR): Santa Cruz, Bolivia, 2001; 224p. Available online: https://bit.ly/3Do3suU (accessed on 24 March 2024).
52. Mostacedo, B.; Balcazar, J.; Montero, J.C. Tipos de bosque, diversidad y composición florística en la Amazonia sudoeste de Bolivia. *Ecol. Boliv.* **2006**, *41*, 99–116. Available online: http://www.scielo.org.bo/scielo.php?script=sci_arttext&pid=S1605-25282006001000002 (accessed on 24 March 2024).
53. Pizango, C.G.H.; Coronado, E.N.H.; del Águila-Pasquel, J.; Llampazo, G.F.; de Jong, J.; Oroche, C.J.C.; Huaymacari, J.M.R.; Carver, S.J.; Torres, D.d.C.; Draper, F.C.; et al. Sustainable palm fruit harvesting as a pathway to conserve Amazon peatland forests. *Nat. Sustain.* **2022**, *5*, 479–487.
54. Köppen, G.W.; Geiger, R. *Das Geographische System der Klimate*; Handbuch der Klimatalogie; Verlag von GebrüderBorntl'aeger: Berlin, Germany, 1936.
55. Moro, M.F.; Martins, F.R. Métodos de levantamento do componente arbóreo-arbustivo. In *Fitossociologia no Brasil, Métodos e Estudos de Caso*; Felfili, J.M., Eisenlohr, P.V., d'Melo, M.M.d'R.F., d'Andrade, L.A., Neto, J.A.A.M., Eds.; Universidade Federal de Viçosa: Viçosa, Brazil, 2011; pp. 174–212.
56. Missouri Botanical Gardens Tropics. 2019. Available online: http://www.tropicos.org (accessed on 14 January 2024).
57. REFLORA. *Flora do Brasil 2020 em Construção*; Jardim Botânico do Rio de Janeiro: Rio de Janeiro, Brazil, 2021. Available online: http://floradobrasil.jbrj.gov.br/ (accessed on 14 January 2024).
58. Romero, F.M.; Jacovine, L.A.; Ribeiro, S.C.; Torres, C.M.; Silva, L.F.; Gaspar, R.D.; Rocha, S.J.; Staudhammer, C.L.; Fearnside, P.M. Allometric equations for volume, biomass, and carbon in commercial stems harvested in a managed forest in the southwestern Amazon: A case study. *Forests* **2020**, *11*, 874. https://doi.org/10.3390/f11080874.
59. Zanne, A.E.; Lopez-Gonzalez, G.; Coomes, D.A.; Ilic, J.; Jansen, S.; Lewis, S.; Miller, R.B.; Swenson, N.G.; Wiemann, M.C.; Chave, J. Data from: Towards a worldwide wood economics spectrum [Dataset]. *Dryad* **2009**. https://doi.org/10.5061/dryad.234
60. Husch, B.; Beers, T.W.; Kershaw, J.A. *Forest Mensuration*; John Wiley & Sons: Hoboken, NJ, USA, 2003.
61. Verissimo, A.; Barreto, P.; Mattos, M.M.; Tarifa, R.; Uhl, C. Logging impacts and prospects for sustainable forest management in an old Amazonian frontier: The case of Paragominas. *For. Ecol. Manag.* **1992**, *55*, 169–199. https://doi.org/10.1016/0378-1127(92)90099-U.
62. Fredericksen, T.S.; Mostacedo, B.; Justiniano, J.; Ledezma, J. Seedtree retention considerations for uneven-aged management in Bolivian tropical forests. *J. Trop. For. Sci.* **2001**, *13*, 352–363. Available online: https://www.jstor.org/stable/43582306 (accessed on 24 March 2024).
63. Contreras, F.; Cordero, W.; Fredericksen, T.S. *Evaluación del Aprovechamiento Forestal*; Proyecto de Manejo Forestal Sostenible (BOLFOR): Santa Cruz, Bolivia, 2001; 46p. Available online: https://pdf.usaid.gov/pdf_docs/pnacw361.pdf (accessed on 24 March 2024).
64. Instituto Nacional de Estadística (INE). Cuadros Estadísticos; Bolivia—Volumen de Madera Extraída, Según Departamento 2006–2022. Available online: https://www.ine.gob.bo/index.php/medio-ambiente/recursos-forestales-cuadros-estadisticos/ (accessed on 14 January 2024).
65. Sist, P.; Ferreira, F.N. Sustainability of reduced-impact logging in the Eastern Amazon. *For. Ecol. Manag.* **2007**, *243*, 199–209. https://doi.org/10.1016/j.foreco.2007.02.014.
66. Gregory, R.; Kozak, R.; Peterson St-Laurent, G.; Nawaz, S.; Satterfield, T.; Hagerman, S. Under pressure: Conservation choices and the threat of species extinction. *Clim. Change* **2021,** *166*, 2. https://doi.org/10.1007/s10584-021-03102-3.

67. de Avila, A.L.; Schwartz, G.; Ruschel, A.R.; Lopes, J.C.; Silva, J.N.M.; Carvalho, J.O.P.; Dormann, C.F.; Mazzei, L.; Soares, M.H.M.; Bauhus, J. Recruitment, growth and recovery of commercial tree species over 30 years following logging and thinning in a tropical rain forest. *For. Ecol. Manag.* **2017**, *385*, 225–235. https://doi.org/10.1016/j.foreco.2016.11.039.
68. Sist, P.; Piponiot, C.; Kanashiro, M.; Pena-Claros, M.; Putz, F.E.; Schulze, M.; Verissimo, A.; Vidal, E. Sustainability of Brazilian forest concessions. *For. Ecol. Manag.* **2021**, *496*, 119440. https://doi.org/10.1016/j.foreco.2021.119440.
69. Gullison, R.E.; Hardner, J.J. The effects of road design and harvest intensity on forest damage caused by selective logging: Empirical results and a simulation model from the Bosque Chimanes, Bolivia. *For. Ecol. Manag.* **1993**, *59*, 1–14. https://doi.org/10.1016/0378-1127(93)90067-W.
70. Howard, A.F.; Rice, R.E.; Gullison, R.E. Simulated financial returns and selected environmental impacts from four alternative silvicultural prescriptions applied in the neotropics: A case study of the Chimanes Forest, Bolivia. *For. Ecol. Manag.* **1996**, *89*, 43–57. https://doi.org/10.1016/S0378-1127(96)03867-4.
71. Jackson, S.M.; Fredericksen, T.S.; Malcolm, J.R. Area disturbed and residual stand damage following logging in a Bolivian tropical forest. *For. Ecol. Manag.* **2002**, *166*, 271–283. https://doi.org/10.1016/S0378-1127(01)00681-8.
72. Medjibe, V.P.; Putz, F.E. Cost comparisons of reduced-impact and conventional logging in the tropics. *J. For. Econ.* **2012**, *18*, 242–256. https://doi.org/10.1016/j.jfe.2012.05.001.
73. Bojanic, A.; Bulte, E.H. Financial viability of natural forest management in Bolivia: Environmental regulation and the dissipation and distribution of profits. *For. Policy Econ.* **2002**, *4*, 239–250. https://doi.org/10.1016/S1389-9341(02)00003-5.
74. Vianna, A.L.M.; Fearnside, P.M. Impact of community forest management on biomass carbon stocks in the Uatumã Sustainable Development Reserve, Amazonas, Brazil. *J. Sustain. For.* **2014**, *33*, 127–151. https://doi.org/10.1080/10549811.2013.836717.
75. Gerwing, J.; Vidal, E. *Degradação de Florestas Pela Exploração Madeireira e Fogo na Amazônia (Série Amazônia N°20)*; Instituto do Homem e Meio Ambiente da Amazônia (Imazon): Belém, Brazil, 2002; 26p. Available online: https://imazon.org.br/degradacao-de-florestas-pela-exploracao-madeireira-e-fogo-na-amazonia-oriental-brasileira-no-20/ (accessed on 24 March 2024).
76. Uhl, C.; Kauffman, J.B. Deforestation effects on fire susceptibility and the potential response of tree species to fire in the rainforest of the eastern Amazon. *Ecology* **1990**, *71*, 437–449. https://doi.org/10.2307/1940299.
77. Sist, P.; Nolan, T.; Bertault, J.-G.; Dykstra, D. Harvesting intensity versus sustainability in Indonesia. *For. Ecol. Manag.* **1998**, *108*, 251–260. https://doi.org/10.1016/S0378-1127(98)00228-X.
78. Grainger, A. Modeling the impact of alternative afforestation strategies to reduce carbon dioxide emissions. In Proceedings of the Conference on Tropical Forestry Response Options to Global Climate Change, São Paulo, Brazil, 9–11 January 1990; pp. 95–104.
79. Piponiot, C.; Rödig, E.; Putz, F.E.; Rutishauser, E.; Sis, P.; Ascarrunz, N.; Blanc, L.; Derroire, G.; Descroix, L.; Guedes, M.C.; et al. Compliance with reduced-impact harvesting guidelines by timber enterprises in the terra firme forests of the Brazilian Amazon. *Int. For. Rev.* **2005**, *7*, 9–20. https://doi.org/10.1505/ifor.7.1.9.64158.
80. Nepstad, D.C.; Alencar, A.; Nobre, C.A.; Lima, E.; Lefebvre, P.; Schlesinger, P.; Potter, C.; Moutinho, P.; Mendoza, E.; Cochrane, M.; et al. Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* **1999**, *398*, 505–508. https://doi.org/10.1038/19066.
81. Berenguer, E.; Ferreira, J.; Gardner, T.A.; Aragão, L.E.O.C.; de Camargo, P.B.; Cerri, C.E.; Durigan, M.; de Oliveira Junior, R.C.; Vieira, I.C.G.; Barlow, J. A large-scale field assessment of carbon stocks in human-modified tropical forests. *Glob. Change Biol.* **2014**, *20*, 3713–3726. https://doi.org/10.1111/gcb12627.
82. da Silva, S.S.; de Oliveira, I.S.; Morello, T.F.; Anderson, L.O.; Karlokoski, A.; Brando, P.M.; de Melo, A.W.F.; da Costa, J.G.; Souza, F.S.C.; de Souza, I.S.; et al. Burning in southwestern Brazilian Amazonia, 2016–2019. *J. Environ. Manag.* **2021**, *286*, 112189. https://doi.org/10.1016/j.jenvman.2021.112189.
83. Pueyo, S.; Graça, P.M.L.A.; Barbosa, R.I.; Cots, R.; Cardona, E.; Fearnside, P.M. Testing for criticality in ecosystem dynamics: The case of Amazonian rainforest and savanna fire. *Ecol. Lett.* **2010**, *13*, 793–802. https://doi.org/10.1111/j.1461-0248.2010.01497.x.
84. Torrelles, R.C.; Pons, E.C.; Brown, I.F. *Análisis de la Superficie Afectada por Fuego en el Departamento de Pando el año 2005 a Partir de la Clasificación de Imágenes del Satélite CBERS*; Anais XIII Simpósio Brasileiro de Sensoriamento Remoto; INPE: São José dos Campos, Brazil, 2007; pp. 835–842. Available online: http://marte.sid.inpe.br/col/dpi.inpe.br/sbsr@80/2006/11.15.10.08/doc/835-842.pdf (accessed on 24 March 2024).
85. Cox, P.M.; Harris, P.P.; Huntingford, C.; Betts, R.A.; Collins, M.; Jones, C.D.; Jupp, T.E.; Marengo, J.A.; Nobre, C.A. Increasing risk of Amazonian drought due to decreasing aerosol pollution. *Nature* **2008**, *453*, 212–215. https://doi.org/10.1038/nature06960.
86. Silva, Z.A.G.P.G. Economic aspects of the demand for commercial forest land in the state of Acre, Brazil. *For. Policy Econ.* **2022**, *138*, 102704. https://doi.org/10.1016/j.forpol.2022.102704.
87. Gutierrez-Velez, V.H.; MacDicken, K. Quantifying the direct social and governmental costs of illegal logging in the Bolivian, Brazilian, and Peruvian Amazon. *For. Policy Econ.* **2008**, *10*, 248–256. https://doi.org/10.1016/j.forpol.2007.10.007.

88. Brown, S.; Burnham, M.; Delaney, M.; Vaca, R.; Powell, M.; Moreno, A. Issues and challenges for forest-based carbon-offset projects: A case study of the Noel Kempff Climate Action Project in Bolivia. *Mitig. Adapt. Strateg. Glob. Change* **2000**, *5*, 99–121. https://doi.org/10.1023/A:1009620903231.
89. Brown, S.; Hall, M.; Andrasko, K.; Ruiz, F.; Marzoli, W.; Guerrero, G.; Masera, O.; Dushku, A.; DeJong, B.; Cornell, J. Baselines for land-use change in the tropics: Application to avoided deforestation projects. *Mitig. Adapt. Strateg. Glob. Change* **2007**, *12*, 1001–1026. https://doi.org/10.1007/s11027-006-9062-5.