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Forest Degradation in the Southwest Brazilian Amazon: Impact on Tree Species of Economic Interest and Traditional Use

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Citation: Costa, J.G.; Fearnside, P.M.; Oliveira, I.; Anderson, L.O.; de Aragão, L.E.O.e.C.; Almeida, M.R.N.; Clemente, F.S.; Nascimento, E.d.S.; Souza, G.d.C.; Karlokoski, A.; et al. Forest Degradation in the Southwest Brazilian Amazon: Impact on Tree Species of Economic Interest and Traditional Use. *Fire* **2023**, *6*, 234. https://doi.org/10.3390/fire6060234

Academic Editors: Emerson Monteiro Vieira and Isabel B. Schmidt

Received: 9 March 2023
Revised: 16 May 2023
Accepted: 17 May 2023
Published: 13 June 2023

Abstract: Amazonian biodiversity has been used for generations by human populations, especially by Indigenous peoples and traditional communities in their cultural, social and economic practices. However, forest degradation, driven by forest fires, has threatened the maintenance of these resources. This study examined the effects of recent forest fires on species with timber, non-timber and multiple-use potential in Brazil's state of Acre. Forest inventories in five forest types were analyzed, identifying species with timber, non-timber and multiple-use potential based on a review of existing scientific articles, books and studies in the technical literature. The indicators of the effect of forest fires on species density were based on the mean and standard deviation of tree density and absolute abundance. We found that 25% of the tree individuals have potential for use by humans, 12.6% for timber, 10.7% non-timber and 1.4% have multiple-use potential. With the negative impact of fire, the reduction in timber, non-timber and multiple-use potential can range from 2 to 100%, depending on the vegetation type and especially on the recurrence of fire. However, even in forests that are degraded by fire, species that are useful to humans can be maintained to a certain degree and contribute to other environmental services, thus they must be preserved.

Keywords: forest fire; timber trees; non-timber trees; multiple-use trees

1. Introduction

The Amazon, which represents almost 50% of the remaining humid tropical forests, is one of the most important hot spots of natural resources and biological diversity on the planet [1,2]. Amazonian biodiversity, including that of plant communities, has been used for generations by human populations, especially by Indigenous communities in their traditional cultural, social and economic practices [3,4]. In the Amazon rainforest, 84% of individual trees and palms have been shown to be useful for daily human life or for commercial purposes [5].

Despite its biological importance and use for human life, the Amazon rainforest has been continuously deforested and degraded through fragmentation and forest fires, reducing the abundance of forest products used by humans [6–8]. Among the types of forest degradation processes, forest fires have been occurring on a large scale in the Brazilian Amazon and are increasingly frequent due to the synergy between human actions and extreme droughts [9,10]. In recent decades, large forest fires have affected the Amazon forests, causing reductions in biomass and tree density and changes in floristic composition [11–14]. Fire- and drought-induced changes in Amazon forests, aggravated by human activities and by the synergistic effects between these factors, can reduce conservation value by up to 54% in Amazonian forests, which contain species that are rare and more susceptible to environmental changes and are likely to become locally extinct [9,13–17].

In Acre in the extreme southwest of the Brazilian Amazon, forest fires have already affected more than 500,000 ha of forests over the last 30 years, causing significant socioeconomic and environmental damage, including impacting tree species used by humans [18–21]. The increase in forest fires compromises Amazonian biodiversity, including species with high value to humans for timber and non-timber forest products, because few forest species are able to tolerate thermal stress, with most being poorly adapted to burning events [4]. Oliveira et al. [22] estimated that forest fires in the Brazilian Amazon cause economic losses of USD 39 $\pm$ 2 ha/year in the wood sector.

Timber products are those used for pulp, charcoal, civil construction, furniture and boats; however, some species are used only for one objective depending on timber characteristics (e.g., for construction [5,23]). Examples of non-timber forest products are resins, fruits, oils, seeds, roots, bark and fibers [24,25]. Multipurpose species are those that are used in more than one use category, such as construction, food or medicinal uses [5]. These species are of fundamental importance to those who live in the interior of the forest areas or far from urban centers, where the products are essential for subsistence, medicines and materials for house construction and other uses. Therefore, it is necessary to conserve trees and palms in standing forests as a resource for both diverse basic needs security and cultural and spiritual values [5,26,27].

Plant communities in Acre have high conservation value in the Amazon context due to their high floristic composition and functional diversity, presenting many contrasts, transitions, rarities and endemisms. This makes Acre particularly rich in plant economic resources, such as fruits, nuts, medicinal plants, wood and natural rubber [28,29]. The state of Acre has high potential for timber and non-timber forest products and stands out among Amazonian states for its extractive value chains, in addition to having the largest area of native bamboo forest in South America [19,30]. However, disturbance caused by human activities through slash-and-burn practices, agriculture and logging severely impacts these forest patches, their functions and products [8,9,15].

Our aim in this study is to analyze the effects of recent forest fires on species with timber, non-timber and multiple-use potential in five types of vegetation in Brazil's state of Acre. Our specific questions are (1) Does the type of forest influence the loss of timber, non-timber and multiple-use species when subjected to forest fire? (2) Do the time after the fire and the existence recurrence affect the loss of timber, non-timber and multiple-use forest species?

2. Materials and Methods

2.1. Study Area

This study was carried out in the state of Acre, located in the extreme southwest of the Brazilian Amazon. The state of Acre has international borders with Peru and Bolivia, and national borders with the Brazilian states of Amazonas and Rondônia [30]. Five vegetation types were selected, distributed among the municipalities (counties) of Mâncio Lima, Cruzeiro do Sul, Manoel Urbano, Rio Branco and Sena Madureira, which were affected by forest fires in the years 2005, 2010 and 2016. Forest inventories were carried out within these areas (Table 1 and Figure 1).

Table 1. Description of the study area indicating the vegetation type, frequency of forest fire and year of occurrence, number of plots, size of plot and location.

Vegetation Type/Acronym	Frequency of Forest Fire and Year of Occurrence	Inventory Year/Years Post First Fire and Last Fire	Number of Plots /Sizes	Location
Forested Campinarana FC	Unburned	2019	10/ 50 × 50 m	Mâncio Lima, Acre −7.5623°, −72.9805°
	Burned once: 2010	2019/9 years		Mâncio Lima, Acre −7.5760°, −73.0004°
Treed Campinarana TC	Unburned	2019	10/ 50 × 50 m	Mâncio Lima and Cruzeiro do Sul, Acre −7.4804°, −72.8711°/ −7.4281°, −72.9504°
	Burned three times: 2010, 2016 and 2018	2019/9 years–2 years		Mâncio Lima, Acre −7.5548°, −72.9937°
Open Forest with dominant bamboo OFDB	Unburned	2016	10/ 100 × 50 m	Manoel Urbano, Acre −8.7018°, −69.668087°
	Burned once: 2005	2019/14 years		Manoel Urbano, Acre −8.7128°, −69.6768°
Open Forest with Bamboo and Palms OFBP	Unburned	2016/0 years	18/100 × 50 m	Rio Branco, Acre −9.9234°, −68.3559°
	Burned once: 2005	2016/9 years		Rio Branco, Acre −9.9046°, −68.1376°
	Burned twice: 2005 and 2010	2016/9 years–6 years		Rio Branco, Acre −9.9010°, −67.975009°
Open Forest with Palms OFP	Unburned	2020/10 years	10/ 100 × 50 m	Sena Madureira, Acre −10.1136°, −69.2211°
	Burned once: 2010	2020/10 years		Sena Madureira, Acre −10.1296°, −69.2601°

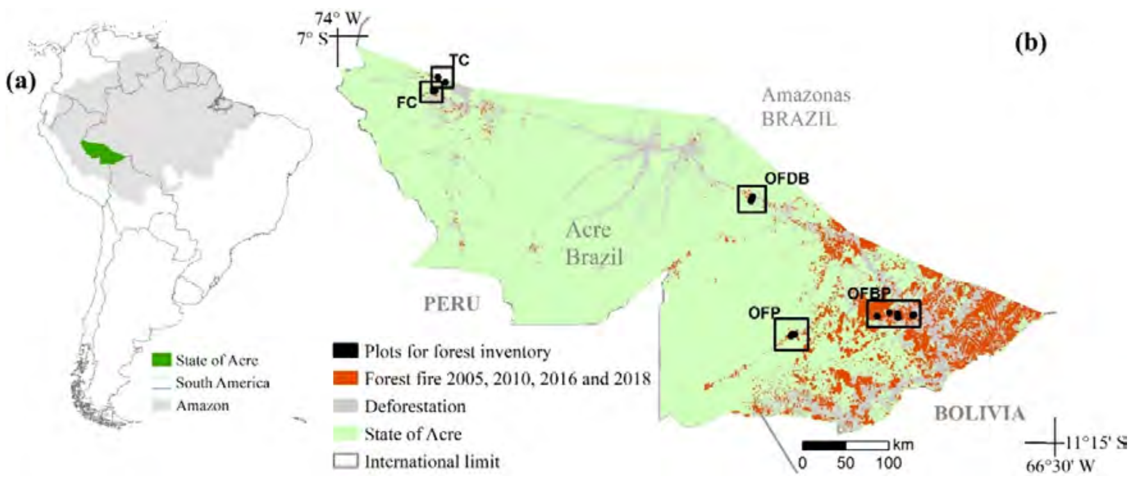

Figure 1. Location of the study area, state of Acre in the context of South America and the Amazon (**a**) and spatial distribution of forest inventory plots (**b**).

2.1.1. Campinarana

Campinaranas are non-forest vegetation types on oligotrophic white-sand soils in the Amazon, which are also frequently associated with flooding. Campinaranas occur in various parts of the Amazon, and in the state of Acre the largest patches are in the extreme north of the municipalities of Cruzeiro do Sul and Mâncio Lima [30,31]. This vegetation grows on white sand in small patches; it is ecologically unique in function, has a peculiar floristic composition, adaptations to nutritionally poor soil and to a seasonal water regime and generally has low floristic richness and high endemism [29,32–34].

In Acre, this formation represents 0.04% (66 km^2) of the vegetation and still remains without any type of protection [30]. The fragility of this ecosystem to human disturbances makes this vegetation one of the most threatened in the Amazon [29–32]. The different vegetation communities of campinaranas in the state of Acre have a specialized character and peculiar compositions that are distinct from the white-sand vegetation in other parts of the Amazon [30].

Forested Campinarana

The forested campinarana occurs along watercourses and has the densest and tallest vegetation and the greatest canopy coverage, being the subgroup among the campinaranas that most resembles a forest. Trees are 15 to 20 m in height with a diameter at breast height (DBH) of 30–45 cm. The vegetation is characterized by the presence of tree species such as *Trattinnickia burserifolia*, *Couma* sp. and some palms such as *Oenocarpus bataua* and *Mauritia flexuosa*, in addition to the presence of emergent trees up to 30 m in height, including *Ocotea gracilis* and *Allantoma decandra*. It is dominated by *Lepidocaryum tenue* and, in addition to the presence of emergent trees up to 30 m in height, including *Cinnamomum* sp., forested campinarana has tree species found in adjacent forests that are not on white sand. In forested campinarana, the thickness of the fine root layer reaches 50 cm, below which Quartzarenic Neosols, Entisols and Spodosols predominate. These locations have tropical climate with high humidity and high levels of rainfall [30,32,34].

Treed Campinarana

Treed campinarana occurs in patches interspersed among dense forest and shrub vegetation communities. It has a canopy height of 7 m and emergent trees up to 15 m in height. In well-drained areas, it has a canopy at 10 m and emergent trees up to 35 m. Its trees have DBH of 15–20 cm. The layer of roots and litter in treed campinarana is little more than 20 cm in thickness; the soil is deep and poorly drained and is classified as Quartzarenic Neosol. This vegetation has an understory with low height and sometimes has an open canopy. It is characterized by the predominance of tree species such as *Dendropanax* sp., *Palicourea grandifolia*, *Vismia macrophylla* and *Remijia* spp. [29,30].

2.1.2. Bamboo-Dominated Open Forest

Bamboo-dominated open forest occupies 10% of the area of the state of Acre. It presents a concentration of bamboo culms in the understory, dominating the vegetation. Climbing bamboo often reaches the canopy, dominating the vegetation. The understory is dense, with small trees, few palms and most of the arboreal individuals have DBH of approximately 20 cm. The dominant soil is Eutrophic red argisol (Alfisol). Patches of open and dense forest with a lower concentration of bamboos and a greater number of tree individuals may also occur [30,34].

2.1.3. Open Forest with Bamboo and Palms

Open forest with bamboo and palms occurs in almost every part of Acre, covering about 25% of the state's area. It is well represented in the tabular interfluves. This vegetation presents a mixture of plant groups, among which bamboo and palms such as *Astrocarium murumuru*, *Phytelephas macrocarpas*, *Attalea* sp. and *Oenocarpus bataua* can be found in similar proportions in the understory; however, they may be interspersed with small patches of dense forest. The arboreal individuals in this vegetation type have DBH of approximately 40 cm. The predominant soil in this vegetation type is Dystrophic and Eutrophic Red-Yellow Argisol [30].

2.1.4. Open Forest with Palms

Open Forest with palms has an open canopy with the presence of palms such as *Euterpe precatoria*, *Socratea exorrhiza, Phytelephas macrocarpa* and *Oenocarpus bataua*, and a higher density of lianas may also occur. It presents a high abundance of tree individuals with a DBH of approximately 20 cm. This vegetation is generally found in areas close to the floodplains of rivers with high flow in the flood season. The predominant soil type is Haplic Cambisol (Inceptisol). The state of Acre has 4516 km^2 of this soil type, or 2.75% of the state [30].

2.2. Forest Inventory

To carry out the forest inventory, 58 sample plots were allocated, distributed in five selected types of vegetation, with and without the impact of fire (Table 1). In the inventoried areas, all live trees with DBH $\geq$ 10 cm were measured and tagged. Each living individual was identified in loco at the family, genus and/or species level by a parabotanist with more than 20 years of experience in Amazonian forests, without collecting botanical material. The plots in the areas before and after fire events are not the same because the funding for carrying out the field work was obtained after the fire events. The present study, therefore, is not a controlled forest fire experiment where the same plots are measured before and after the fire impact. However, our plots considered regional representativeness between forest types and anthropogenic forest fires associated with extreme droughts.

The plots in the campinarana vegetation measured 50 $\times$ 50 m, and in open forests they measured 100 $\times$ 50 m. The choice of plot size was defined based on a review of the literature, logistics and field cost. The campinarana vegetation has a higher tree density, with inventories carried out in 0.25 ha plots [35,36], while for open and dense forests, plots varied in size from 0.25 to 0.5 ha [19,37].

2.3. Characterization of Species by Timber, Non-Timber and Multiple-Use Potential

The categorization of species by timber, non-timber and multiple-use potential (species included in more than one use category) was carried out with the aim of understanding the impacts of forest fires on forest resources, considering the socio-environmental impacts for the local populations that depend on these species in their daily and economic activities. The classification was established based on a review of existing scientific articles, books and technical literature, such as the *First Catalog of the Flora of Acre* [28]; *Illustrated Guide and Leaf Architecture Manual for Timber Species of the Western Amazon* [38]; *Flora of Reserva Ducke: Identification Guide for Vascular Plants of a Terra-Firme Forest in Central Amazonia* [39]; and the List of Forest Species of the Brazilian Forestry Service [40].

The classification of the species in the categories of use was based on the human use of the species. For timber species, the economic value was considered, as well as the traditional use (firewood, stakes, fence posts, charcoal, construction and boats) [5,23]. Species of non-timber uses were classified based on use for food (fruit, heart-of-palm and seeds), crafts (fibers and seeds), rural construction (use of the stipe and leaves of some palm trees) and medicinal use (bark, leaves, roots and essential oils) [25]. Multiple-use species were classified based on traditional and economic use, a single species used for food, construction and medicinal uses.

The scientific names and families were initially based on identification by the parabotanist with more than 20 years of experience in Amazonian flora (Antônio José Barretos dos Santos) and were later confirmed based on the Brazilian national list of algae, fungi and plants from *Flora e Funga do Brasil* and also through The Plant List website. Based on the literature, we listed the species with timber, non-timber and multiple-use potential (Supplementary Material, Table S1). Pioneer species with potential use for humans were also listed (Supplementary Material, Table S2).

2.4. Data Analyses

To compare the density of species with timber, non-timber and multiple-use potential between forests not impacted by fire and those impacted by fire, we calculated the mean and standard deviation of tree density (number of individual trees per plot) and absolute abundance of species (total number of individuals per hectare) in all plots, for unburned forest, burned forest and in other vegetation types.

For the analyses, we considered the plots as replicas and the unburned and burned forest areas as treatments, using the mean values of the plots for each type of vegetation. For averaging tests on each vegetation type between unburned areas and burned areas, we analyzed the normality of the data using the Shapiro–Wilk test. Due to the lack of normality in the data, the non-parametric Kruskal–Wallis method and the Dunn post hoc test were used for testing significant differences.

To diagnose the effect of vegetation type (VF), time after the first fire event (TAF) and fire recurrence (FR) on loss of species for timber (TP), non-timber products (NTP) and multiple-use potential (MUP), we fit Generalized Linear Mixed Models (GLMMs) in the R software environment [41] by applying functions from the "Lme4" package. For this, we included the forest types as a random effect and the variables "time after the first fire event" and "fire recurrence" as fixed effects using the Poisson distribution. To select the most appropriate equation for the tested data set, we followed the following steps: (i) Define the base model including all fixed-effect variables and the random-effect variable. (ii) Verify the absence or existence of interaction between the fixed-effect variables and between the fixed- and random-effect variables. (iii) Check the individual effect of each fixed-effect variable. For each paired comparison in the equation selection steps, we used the ANOVA test; in cases with p-value < 0.05, we adopted the more complex model. To confirm the adoption of the best model, we also used the values of AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) to verify the goodness-of-fit of the models [41] (Supplementary Material, Table S3). The selected model was subjected to an effectiveness diagnosis using the "DHARMa" package in R [42].

3. Results

In the 58 sampled plots distributed across the five vegetation types, 13,290 individuals were registered, of which 25% had potential for use by humans: 1672 individuals or 12.6% with timber potential, 1427 individuals or 10.7% with non-timber potential and 191 individuals or 1.4% with multiple-use potential (Table 2). With the impact of fire, the reduction in the density of individuals with timber, non-timber and multiple-use potential ranged from 2 to 100%, depending on the recurrence of fire and type of vegetation. In the open forest with palms, the total number of trees increased by 35% and the total number of species increased by 5% after the fire impact, due to the growth of pioneer species.

Table 2. Density and standard deviation of living individuals in the five vegetation types in the state of Acre. Timber potential (TP); non-timber potential (NTP); multiple-use potential (MUP). Means followed by "ns" do not differ statistically. Significance levels are * for $p < 0.05$ and ** for $p < 0.01$. Significance was determined by the Kruskal–Wallis test applied between unburned and burned areas for each vegetation type. FC = forested campinarana, TC = treed campinarana, OFDB = open forest with dominant bamboo, OFBP = open forest with bamboo and palms, OFP = open forest with palms. UB = unburned, B′ = forest fire once, B″ = forest fire twice, B‴ = forest fire three times.

Number of Individuals Measured in the Plots		Total	TP	NTP	MUP
		13,290	**1672**	**1427**	**191**
Area		individuals ha^{-1} ± standard deviation			
FC	UB	599 ± 103 ^{ns}	70 ± 25 ^{ns}	67 ± 58 **	-
	B′	680 ± 54 ^{ns}	53 ± 18 ^{ns}	5 ± 5 **	-

Table 2. *Cont.*

Number of Individuals Measured in the Plots		Total	TP	NTP	MUP
		13,290	**1672**	**1427**	**191**
TC	UB	710 ± 124 **	85 ± 74 **	39 ± 36 **	-
	B‴′	10 ± 10 **	00 ± 00 **	00 ± 00 **	-
OFDB	UB	423 ± 50 ns	84 ±15 **	88 ± 22 ns	10 ± 6 ns
	B′	389 ± 34 ns	39 ± 0 **	87 ± 15 ns	7 ± 4 ns
OFBP	UB	518 ± 129 **	66 ±57 **	61 ± 14 *	20 ± 5 **
	B′	360 ± 164 **	40 ± 15 **	33 ± 14 *	10 ± 10 **
	B″	221 ± 106 **	31 ±14 **	17 ± 10 *	7 ± 8 **
OFP	UB	486 ± 61 **	188 ±15 **	109 ± 48 ns	12 ± 6 ns
	B′	658 ± 60 **	96 ± 34 **	117 ± 35 ns	10 ± 6 ns
Area		total number species in all plots per area			
FC	UB	188	24	7	-
	B′	145	19	4	-
TC	UB	171	13	4	-
	B‴′	7	0	0	-
OFDB	UB	179	31	24	5
	B′	164	28	19	5
OFBP	UB	272	44	20	8
	B′	179	39	16	7
	B″	152	33	19	4
OFP	UB	176	35	18	5
	B′	185	36	26	7

The effect of vegetation types (VT), time after the first fire (TAF) as well as fire recurrence (FR) on the number of individuals with timber (TP), non-timber (NTP) and multiple-use potential (MUP) lost, were fit in Mixed Generalized Linear Models (GLMMs). The average statistically best adjusted GLMM for species with timber potential was the equation $\log(\text{TP}) = 4.51 - 0.31(\text{TAF}) - 2.37(\text{FR}) + 0.46(\text{FR} \times \text{TAF}) + \varepsilon$. The equation shows that in the case of the density of species with timber potential, the independent variables time after the first fire (TAF) and fire recurrence (FR) have a direct and interactive effect on the reduction in species density (Figure 2; Supplementary Material Table S3). In addition, the vegetation types have an interactive effect with fire recurrence and were used as a modulating factor in the adjustment of the equation.

For the density of species with non-timber potential (NPT), the best adjusted-average GLMM had the following equation: $\log(\text{NTP}) = 2.63 - 1.28(\text{FR}) + \varepsilon$. The equation shows that only the independent variable fire recurrence (FR) had a significant effect on the decrease in the density of species with non-timber potential (NTP), there was also a significant interaction between FR and forest type (VT). Although we have two vegetation types, open forest with dominant bamboo and open forest with palm tree, the distribution follows the trend of decreasing NPT density with increasing FR. The GLMM analysis resulted in the equation $\log(\text{MUP}) = 2.63 - 0.49(\text{FR}) + \varepsilon$ for the density of multiple-use species (MUP). As for the density of species with non-timber potential (NTP), there was no significant effect of time after the first fire (TAF) on MUP, with a significant effect of RF, as well as its interaction with the type of forest.

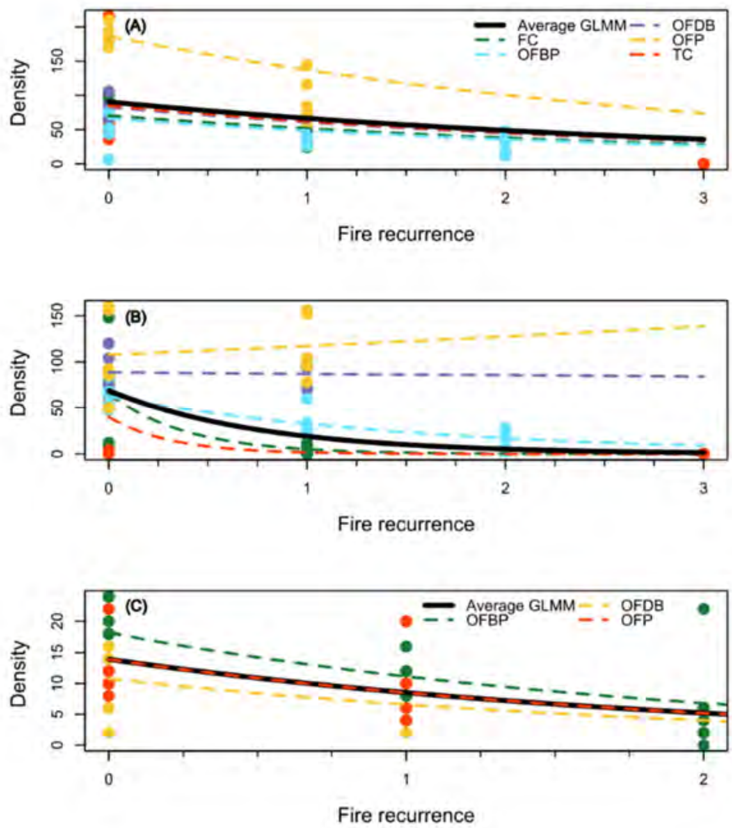

Figure 2. Analysis of the predictive factors of the dependent variables for Generalized Mixed Linear Models (GLMMs): (**A**) density of species with logging potential, (**B**) density of species with non-timber potential and (**C**) density of species of multiple uses. The solid black line indicates the representative GLMM for the entire dataset that includes all evaluated vegetation types. The colored and dashed lines are individual GLMMs for each assessed vegetation type. FC = forested campinarana, TC = treed campinarana, OFDB = open forest with dominant bamboo, OFBP = open forest with bamboo and palms, OFP = open forest with palms.

3.1. Forested Campinarana

The density of individuals with timber potential in the unburned area in the forested campinarana vegetation type was 70 ± 25 individuals ha^{-1} (24 species). With the impact of fire in 2010, there was a 23% reduction in the density of individuals (53 ± 18 individuals ha^{-1}, 19 species; Figure 3). The density of individuals with non-timber potential in the area without fire was 67 ± 58 individuals ha^{-1} (seven species). Fire, however, caused a reduction of 93% in the density of these individuals (5 ± 5 individuals ha^{-1}, four species).

The unburned area had 24 timber species and 7 species classified as non-timber uses. In the burned area, the numbers of species in these categories were 19 and 4, respectively. The most abundant species with timber potential in the unburned area was *Brosimum rubescens* (amapá-doce), representing 21% of the individuals. The wood of this species is widely used in the furniture sector and in the construction of high-quality musical instruments. In the area of burned forest in 2010, the most abundant species were *Eschweilera coriacea* (matamatá), *Laetia procera* (pau-jacaré) and *Tapirira guianensis* (pau-pombo), each representing 17% of the individuals classified as pioneer species.

For species with non-timber potential, the palm species *Oenocarpus bataua* (patauá) was the most abundant, both in the unburned area and in the burned area. The reduction of 43% for this species was estimated after the fire impact.

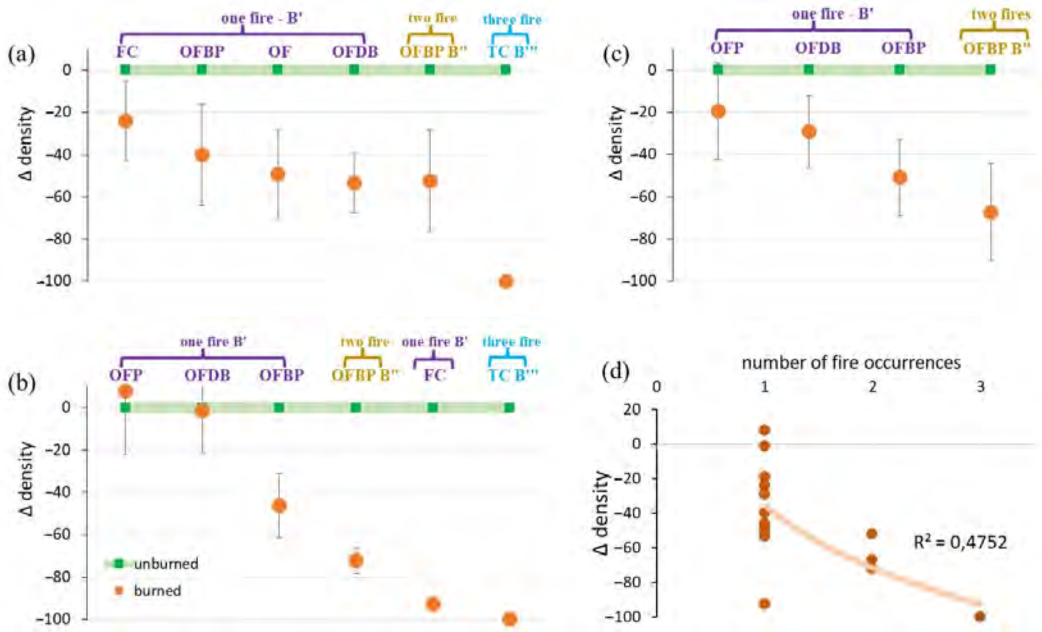

Figure 3. Average percentage difference (Δ) in tree density for individuals (% ± standard deviation) with timber (**a**), non-timber (**b**) and multiple-use potential (**c**) between each burned plot and the unburned mean values and (**d**) reduction in all species by the number of fire occurrences. FC = forested campinarana, TC = treed campinarana, OFDB = open forest with dominant bamboo, OFBP = open forest with bamboo and palms, OFP = open forest with palms. UB = unburned, B′ = forest fire once, B′′ = forest fire twice, B′′′ = forest fire three times.

3.2. Treed Campinarana

In the treed campinarana, 710 ± 124 trees ha^{-1} were recorded in the unburned area. The density of individuals with timber potential in the unburned area was 85 ± 74 individuals ha^{-1}. In the area impacted by fire (forest fire in 2010-2016-2018), individuals with timber potential were absent (0 trees ha^{-1}), a reduction of 100% (Figure 3). None of the sampled individuals were classified in the timber or non-timber potential use category (Table 2).

Individuals with timber or non-timber potential were found only in the unburned area. The most abundant species with timber potential was *Sextonia rubra* (louro-vermelho). The most abundant non-timber potential species was the palm *Oenocarpus bataua* (patauá), a species with high commercial and food security importance in the Amazon [43].

3.3. Bamboo-Dominated Open Forest

In open forest with dominant bamboo, the average density of individuals was 423 ± 50 trees ha^{-1}. There was a 54% reduction in the number of potential timber individuals, comparing unburned with burned plots. The mean density of potential non-timber and multiple-use individuals did not show statistically significant differences.

For the species with timber potential, 31 were identified in the unburned forest and 28 species in the burned forest. For species with non-timber use, we found 24 and 19 species in the unburned and burned forests, respectively. Finally, five species with multiple uses were found in both unburned and burned areas. The most abundant species with timber potential was *Drypetes variabilis* (angelca), followed by *Pterocarpus rohrii* (pau-sangue). In the burned area, *Drypetes variabilis* was also the most abundant species, followed by *Handroanthus serratifolius* (ipê-amarelo).

Among the species with non-timber potential, the palm *Attalea phalerata* (uricuri) was the most abundant species in the unburned area. In the burned area, the most abundant species was the pioneer species *Inga capitata* (ingá-branca). *Attalea phalerata* was present in both areas.

Among the multiple-use species both in the unburned and in the burned areas, *Spondias mombin* (cajá) was the most abundant. The number of individuals declined by about 20% between the unburned forests and the forest impacted by fire.

3.4. Open Forest with Bamboo and Palms

In open forest with bamboo and palms, the density (518 $\pm$ 129 individuals ha^{-1}) was reduced by 31% in the plots burned once and 57% in plots burned twice. There was a 39% reduction in the number of species with timber potential in forests that burned once and 53% in those that burned twice. Species with non-timber potential declined by 46% in once-burned forests and 72% in twice-burned forests, while multiple-use species declined by 50% in once-burned and 65% in twice-burned forests (Figure 3).

We identified 44 timber species in unburned areas, 39 species in areas burned once and 33 species in areas burned twice. For species with non-timber potential, 20 species were identified in unburned areas, 16 in areas burned once and 19 in areas burned twice. For multiple-use species, we identified eight species in unburned areas, seven species in areas burned once and four species in areas burned twice. The most abundant species with timber potential in unburned areas was *Drypetes variabilis* (angelca), and in the area burned once the most abundant was *Apeiba membranacea* (pente-de-macaco). In the areas burned twice, the most abundant species was *Ochroma pyramidale* (algodoeiro), which is classified as a pioneer species.

The most abundant species with non-timber potential in the unburned area was *Astrocaryum murumuru* (murmuru), followed by *Theobroma cacao* (cacau-da-mata) and *Euterpe precatoria* (açaí-solteiro). In the area burned once, the most abundant species were *Euterpe precatoria* and *Astrocaryum murumuru*. In the twice-burned areas, the most abundant species was *Euterpe precatoria*, followed by *Theobroma cacao*.

For species with multiple-use potential, the most abundant species in the unburned area were *Hevea brasiliensis* (seringueira) and *Spondias mombin* (cajá). In the areas burned once and twice the most abundant species remained *Hevea brasiliensis* (seringueira). The twice-burned areas showed the greatest reduction in the abundance of species with timber, non-timber and multiple-use potential.

3.5. Open Forest with Palms

In the unburned areas of the "open forest with palms" forest type, the density of individuals was 486 $\pm$ 61 trees ha^{-1}. Species with timber potential in the unburned area had 188 $\pm$ 15 trees ha^{-1}, with a reduction of 49% after the fire impact (96 $\pm$ 34 trees ha^{-1}). We found 109 $\pm$ 48 trees ha^{-1} with non-timber potential in unburned areas, and (117 $\pm$ 35 trees ha^{-1}) in the burned forests with an increase of 8%, due to the emergence of pioneer species after the fire with importance of use, although this was not statistically significant. Multiple-use individuals had a 17% reduction in density from the unburned to burned areas (Figure 3).

In open forest with palms, the most abundant species with timber potential in unburned areas was *Protium heptaphyllum* (breu-vermelho), and in burned areas it was *Ochroma pyramidale* (algodoeiro), followed by *Schizolobium amazonicum* (paricá), both pioneer species. In unburned areas, the most abundant species with non-timber potential were *Iriartea deltoidea* (paxiubão) and *Euterpe precatoria* (açaí-solteiro). In the burned area, *Zanthoxylum rhoifolium* (limãozinho), a pioneer species, was the most abundant.

In the multiple-use category, the most abundant species in the unburned area was *Hevea brasiliensis* (seringueira), followed by *Gallesia integrifólia* (pau-alho) and *Hura crepitans* (assacu). *Inga alba* (ingá-ferro), classified as a pioneer species, was the most abundant multiple-use species in the burned area, followed by *Hevea brasiliensis* (seringueira).

4. Discussion

Forests affected by fire are floristically and structurally distinct from unburned forests. Forest fires lead to a decrease in the density and diversity of potentially useful tree species [5], especially in forests burned more than once [19,44,45]. Our results show that about 25% of identified tree individuals have timber and non-timber potential, which can be reduced by up to 100% by the impact of fire, depending on the type of forest, the time after fire and the recurrence of fire. The effect of fire on the reduction in species of economic interest and traditional use varies among vegetation types, the time after the first fire and fire recurrence, in an isolated and synergistic way (Figures 2 and 3).

4.1. Impact of Fire on Species Potentially Useful to Humans

Species with timber potential showed the greatest reductions in tree density, ranging from 23% to 100% among the analyzed areas. Species with timber potential had a gradual reduction as a function of time since fire occurrence. Areas with the longest time since the fire event and with fire recurrence had the greatest reductions in the variables analyzed. This fact may be associated with the increasing mortality of trees up to 12 years after the fire [46] and with the structure and species composition of the forest [10,19,35,47]. It mainly reflects the recruitment of pioneers, the thickness of the tree bark [48] and the recurrence of fire [19,37].

Among the species with non-timber potential, there are woody trees and palms, which may suffer different impacts depending on their trunk and bark structures. Our results show a significant reduction in palms, such as *Oenocarpus bataua*, corroborating the results of Liesenfeld and Vieira [49] who showed that palms are practically extinguished by the impact of fire, especially those with aerial stems. In areas with little or no reduction or increase in non-timber potential (−1% to +8%), this can be explained by the high number of pioneer species, such as *Ochroma pyramidale*, *Apeiba membranacea* and *Inga alba*. An increase in the number of pioneers species after the impact of fire has also been observed in other studies [19,46,50].

The multiple-use species have the lowest density of all the vegetation types and are absent in arboreal and forested campinarana areas. The density of multiple-use individuals has a pattern similar to that of individuals with timber potential, which had a significant reduction in individuals after fire recurrence.

4.2. Changes in Floristic and Structural Composition in Fire-Affected Vegetation

The intrinsic structure of each vegetation type can help to understand the results. Gradually, and for all analyzed classes, forests burned two or three times were the most affected, with reductions in tree density from 50 to 100%. Both species with timber and non-timber potential had drastic reductions with recurrent fire. Broadly speaking, campinarana forests and open forest with bamboo and palms show a greater reduction in potentially useful species for humans.

Open forests with dominant bamboo and open forest with palms had no significant effect on reducing the total tree density between unburned and burned areas. For open forest with dominant bamboo, our hypothesis is that the massive natural death of bamboo in 2015, which was confirmed in the field by residents' reports and by the mapping produced by Dalagnol et al. [51], constituted another disturbance/alteration factor in the vegetation dynamics that favored forest regeneration with pioneers, even 14 years after the fire. The reduction in tree density was statistically significant for both timber- and non-timber-potential species in both areas. Open forest with palms is one of the types of forest with the shortest time after fire (9 years) and may be influenced by regeneration with pioneers, with an increase in the total number of trees by 35%, especially in the cases of *Urera baccifera, Sapium marmieri, Jacaratia spinosa* and *Zanthoxylum rhoifolium*, with more than 100 registered individuals. With a similar effect, the open forest with bamboo and palms had a higher number of species in the area burned twice, with a predominance of pioneer species such as *Cecropia distachya, Cecropia sciadophylla, Pseudolmedia laevis, Apeiba tibourbou* and *Ochroma pyramidale*.

Campinaranas have marked differences in both composition and structure [29] related to the intensity of degradation by fire. In unburned forests, there is a high abundance of *Brosimum rubescens* and *Sextonia Rubra*, which are timber potential species, and in *Oenocarpus bataua*, a non-timber potential species; these species are of great usefulness to the region's traditional populations. The impact of fire was drastic for most species, especially in the treed campinarana, where no species potentially useful to humans survived. Flores and Holmgren [47] have pointed out that, in white-sand vegetation (campinaranas) that have been burned more than once, the abundant tree species are of no economic value.

4.3. Implications for Future Studies

Our results demonstrate the importance of fire in decreasing the density of trees of species of economic interest and traditional use. These species have direct importance to the lives of traditional communities, Indigenous groups and populations that depend on the forest resources due to living far from urban centers. Moreover, these species are key for the emerging development of markets linked to the bioeconomy in the Amazon. With a view to continuing to advance scientific work in this area, we emphasize that the ideal would be research with an experimental design that could evaluate the same areas before and after a fire, but this would require a heavy investment in permanent plots to assess forest degradation in the Amazon. In any case, it is necessary to continue conducting experiments with procedures similar to those used in the present study, as otherwise no evaluation would be possible on the impacts of the forest fires that have occurred in the last 20 years. Thus, we recommend that further studies analyze the effect of fire occurrence and recurrence in Amazonia's many vegetation types based both on forest inventories of the experimental type and on forest inventories that analyze recent fires from unburned forest plots adjacent to plots of burned forest. These studies can contribute to the expansion of scientific knowledge and improved decision making on conservation and protection in the Amazon.

5. Conclusions

- Forest fires impacted the density of species potentially useful to humans in all use classes (timber, non-timber and multiple-use potential).
- Recurrent fire caused a drastic reduction in tree individuals potentially useful to humans.
- After the impact of fire, the analyzed areas showed a marked abundance of pioneer species. Some of these species have human use in all of the analyzed classes (timber, non-timber and multiple-use potential).
- Even with forest degradation by fire, some of the species that are useful to humans are maintained, despite a considerable reduction. All factors that degrade forest in the Amazon must be avoided, and, when degradation occurs, the remaining forests must be maintained due to their ecological, social, food and economic services.
- New studies should be carried out to improve understanding of all mechanisms of degradation affecting tree populations useful to humans in Amazonia's many vegetation types.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fire6060234/s1, Table S1. List of species with timber (TP), non-timber (NTP) and multiple-use (MU) potential. Table S2. List of pioneer species with potential use according to the literature review. Table S3. Parameters and statistics of the GLMM equations adjusted for the dependent variables as a function of the independent fixed and random effect variables. The parameters refer to the equations $[\log(\mathrm{TP}) = \mathrm{a} + \mathrm{b}(\mathrm{TAF}) + \mathrm{c}(\mathrm{FR}) + \mathrm{d}(\mathrm{FR} \times \mathrm{TAF}) + \varepsilon]$ for the dependent variable density of species with timber potential (TP) and $[\log(\mathrm{NTP} \mid \mathrm{MUP}) = \mathrm{a} + \mathrm{b}(\mathrm{FR}) + \varepsilon]$ for the dependent variables density of non-timber species (NTP) and density of multiple-use species (MUP). The fixed-effect independent variables are time after first fire event (TAF) and fire recurrence (FR). The independent variables for random effects are represented by the vegetation types (VT): FC = forested campinarana, TC = treed campinarana, OFDB = open forest with dominant bamboo, OFBP = open forest with bamboo and palms, OFP = open forest with palms. Values in parentheses indicate 95% confidence intervals.

Author Contributions: J.G.C. and S.S.d.S. Conceptualization, writing—original draft preparation, funding acquisition, P.M.F., L.O.A., P.M.L.d.A.G. and L.E.O.e.C.d.A.; field collection, writing—review, A.W.F.d.M., M.R.N.A., I.O., A.K., F.S.C., E.d.S.N. and G.d.C.S.; writing—review and editing, P.M.F., E.A.d.A. and R.O.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Conselho Nacional de Desenvolvimento Científico e Tecnológico—CNPq (Project Acre Queimadas—442650/2018-3); InterAmerican Institute for Global Change Research—IAI (Project MAPFIRE Processo SGP-HW 016). PMF thanks Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) 2020/08916-8, Fundação de Amparo à Pesquisa do Estado do Amazonas (FAPEAM) 0102016301000289/2021-33, FINEP/Rede CLIMA 01.13.0353-00 and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) 312450/2021-4. LOA thanks (FAPESP) grant numbers 2021/07660-2 and 2020/15230-5 and CNPq productivity scholarship process number 314473/2020-3.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: https://forestplots.net/en, accessed on 9 March 2023.

Acknowledgments: We thank Antônio José Barretos dos Santos (Tunico) for the botanical identifications. We are grateful to Universidade Federal do Acre Campus Floresta (UFAC), the Master's Program in Environmental Sciences-UFAC, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior CAPES)—Finance Code 001, the National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN) and the National Institute for Research in Amazonia (INPA) for their support in carrying out this research. PMF's research is funded by the National Council for Scientific and Technological Development (CNPq 312450/2021-4), São Paulo Research Foundation (FAPESP) (2020/08916-8), Research Foundation of Amazonas State (FAPEAM) (0102016301000289/2021-33) and the Brazilian Research Network on Climate Change (FINEP/Rede Clima 01.13.0353-00).

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

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SUPPLEMENTARY MATERIAL

Forest degradation in the southwest Brazilian Amazon: impact on tree species of economic interest and traditional use

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Table S1. List of species with timber (TP), non-timber potential (NTP) and multiple-use (MU) potential.

Table S2. List of pioneer species with potential use according to the literature review.

Table S3. Parameters and statistics of the GLMM equations adjusted for the dependent variables as a function of the independent fixed and random effect variables. The parameters refer to the equations: $[\log(TP) = a + b(TAF) + c(FR) + d(FR \times TAF) + \varepsilon]$ for the dependent variable density of species with timber potential (TP) ; $[\log(NTP \mid MUP) = a + b(FR) + \varepsilon]$ for the dependent variables density of non-timber species (NTP) and density of multiple-use species (MUP). The fixed-effect independent variables are time after first fire event (TAF) and fire recurrence (FR). The independent variable of random effect are composed by the vegetation types (VT), FC = Forested campinarana, TC = Treed campinarana, OFDB = Open forest with dominant bamboo, OFBP = Open forest with bamboo and palms, OFP = Open forest with palms. Values in parentheses indicate 95% confidence intervals.

Table S1. List of species with timber (TP), non-timber potential (NTP) and Multiple-use potential (MUP) potential.

Species	Family	TP	NTP	MUP	References
Abarema jupunba (Willd.) Britton & Killip	Fabaceae	x			[1]
Agonandra brasiliensis Miers ex Benth. & Hook.f.	Opiliaceae	x			[2];[3];[4]
Albizia niopoides (Spruce ex Benth.) Burkart	Fabaceae	x			[5]
Allantoma lineata (Mart. ex O. Berg) Miers	Lecythidaceae	x			[1];[6]
Amburana acreana (Ducke) A.C.Sm.	Fabaceae			x	[6];[8];[9]
Anacardium spruceanum Benth. ex Engl.	Anacardiaceae	x			[6];[10]
Andira inermis (W. Wright) DC.	Fabaceae	x			[11];[12];[13]
Antrocaryon amazonicum (Ducke) B.L. Burtt & A.W. Hill	Anacardiaceae		x		[14];[15]
Apeiba membranacea Spruce ex Benth.	Malvaceae	x			[16];[17]
Apuleia leiocarpa (Vogel) J.F. Macbr.	Fabaceae	x			[6];[7];[18]
Aspidosperma desmanthum Benth. ex Müll.Arg.	Apocynaceae	x			[6]; [11];[19]
Aspidosperma macrocarpon Mart. & Zucc.	Apocynaceae	x			[6];[20]
Aspidosperma nitidum Benth. ex Müll.Arg.	Apocynaceae		x		[21];[22];[23]
Aspidosperma vargasii A.DC.	Apocynaceae	x			[18];[24]
Astrocaryum aculeatum G. Mey.	Arecaceae		x		[25];[26];[27]
Astrocaryum murumuru Mart.	Arecaceae		x		[28];[29];[30]
Astronium lecointei Ducke	Anacardiaceae	x			[3];[6];[24]
Attalea butyracea (Mutis ex L.f.) Wess.Boer	Arecaceae		x		[28];[31];[32]
Attalea phalerata Mart. ex Spreng.	Arecaceae		x		[26]
Bactris gasipaes Kunth	Arecaceae		x		[26];[28];[34]
Batocarpus amazonicus (Ducke) Fosberg	Moraceae	x			[24];[35]
Bertholletia excelsa Bonpl.	Lecythidaceae			x	[6];[36];[37]
Bixa arborea Huber	Bixaceae	x			[6];[38]

Bowdichia nitida Spruce ex Benth.	Fabaceae	x			[6];[39]
Brosimum acutifolium Huber	Moraceae	x			[6];[19]
Brosimum guianense (Aubl.) Huber	Moraceae	x			[19];[40]
Brosimum lactescens (S. Moore) C.C. Berg	Moraceae		x		[41];[42]
Brosimum rubescens Taub.	Moraceae	x			[6];[19]
Calophyllum brasiliense Cambess.	Clusiaceae	x			[6];[11];[43]
Calycophyllum megistocaulum (K. Krause) C.M. Taylor	Rubiaceae	x			[44]
Calycophyllum spruceanum (Benth.) K. Schum.	Rubiaceae	x			[45];[46]
Cariniana estrellensis (Raddi) Kuntze	Lecythidaceae	x			[45];[47];[48]
Caryocar brasiliense Cambess.	Caryocaraceae		x		[49]
Caryocar glabrum (Aubl.) Pers.	Caryocaraceae	x			[3];[6];[11]
Caryocar villosum (Aubl.) Pers.	Caryocaraceae	x			[6];[7];[45]
Castilla ulei Warb.	Moraceae		x		[50]
Cedrela fissilis Vell.	Meliaceae	x			[6];[51]
Cedrela odorata L.	Meliaceae	x			[52];[53]
Ceiba pentandra (L.) Gaertn.	Malvaceae	x			[6];[45]
Clarisia racemosa Ruiz & Pav.	Moraceae	x			[6];[35]
Colubrina glandulosa Perkins	Rhamnaceae	x			[54];[55]
Copaifera multijuga Hayne	Fabaceae			x	[6];[50]
Cordia goeldiana Huber	Boraginaceae	x			[19];[45];[56]
Cordia nodosa Lam.	Boraginaceae		x		[57]
Couratari guianensis Aubl.	Lecythidaceae	x			[3];[6];[7]
Couratari longipedicellata W.A. Rodrigues	Lecythidaceae	x			[58];[59]
Couroupita guianensis Aubl.	Lecythidaceae		x		[60];[61]
Dalbergia brasiliensis Vogel	Fabaceae	x			[54]
Diclinanona calycina (Diels) R.E.Fr.	Annonaceae	x			[11]
Didymopanax morototoni (Aubl.) Decne. & Planch.	Araliaceae	x			[45];[62]

Dipteryx odorata (Aubl.) Forsyth f.	Fabaceae	x			[6];[52];[63]
Drypetes variabilis Uittien	Putranjivaceae	x			[3];[11]
Eriotheca globosa (Aubl.) A. Robyns	Malvaceae	x			[24];[35]
Eriotheca longipedicellata (Ducke) A. Robyns	Malvaceae	x			[6]
Erisma uncinatum Warm.	Vochysiaceae	x			[3];[6];[7]
Erythrina verna Vell.	Fabaceae		x		[4];[42]
Eschweilera coriacea (DC.) S.A. Mori	Lecythidaceae	x			[6];[64]
Euterpe precatoria Mart.	Arecaceae		x		[28]
Gallesia integrifolia (Spreng.) Harms	Phytolaccaceae			x	[6];[65]
Genipa americana L.	Rubiaceae			x	[54];[66]
Guazuma ulmifolia Lam.	Malvaceae		x		[50];[67];[68]
Handroanthus impetiginosus (Mart. ex DC.) Mattos	Bignoniaceae	x			[6];[51]
Handroanthus ochraceus (Cham.) Mattos	Bignoniaceae	x			[6];[69]
Handroanthus serratifolius (Vahl) S. Grose	Bignoniaceae	x			[6];[20]
Hevea brasiliensis (Willd. ex A. Juss.) Müll.Arg.	Euphorbiaceae			x	[6];[70]
Himatanthus articulatus (Vahl) Woodson	Apocynaceae		x		[71];[72]
Hura crepitans L.	Euphorbiaceae			x	[6];[73]
Hymenaea courbaril L.	Fabaceae	x			[6];[20]
Hymenaea oblongifolia Huber	Fabaceae	x			[6];[18]
Hymenolobium pulcherrimum Ducke.	Fabaceae	x			[6];[11]
Inga alba (Sw.) Willd.	Fabaceae			x	[74]
Inga capitata Desv.	Fabaceae		x		[75];[76]
Inga edulis Mart.	Fabaceae		x		[74];[75]
Iriartea deltoidea Ruiz & Pav.	Arecaceae		x		[26];[28]
Iryanthera juruensis Warb.	Myristicaceae		x		[77]
Jacaranda copaia (Aubl.) D.Don	Bignoniaceae	x			[78];[79]
Laetia procera (Poepp.) Eichler	Salicaceae	x			[6];[19]
Manilkara bidentata (A.DC.) A. Chev.	Sapotaceae	x			[6];[11]

Maquira sclerophylla (Ducke) C.C. Berg	Moraceae	x			[3];[6]
*Martiodendron elatum (*Ducke) Gleason	Fabaceae	x			[6];[19]
Matisia cordata Humb. & Bonpl.	Malvaceae		x		[77];[80]
Mauritia flexuosa L.f.	Arecaceae		x		[28];[81];[82]
Mezilaurus itauba (Meisn.) Taub. ex Mez	Lauraceae	x			[6];[19];[83]
Micropholis venulosa (Mart. & Eichler) Pierre	Sapotaceae	x			[56]
Myroxylon balsamum (L.) Harms	Fabaceae	x			[18];[19]
Ochroma pyramidale (Cav. ex Lam.) Urb.	Malvaceae	x			[45];[84]
Ocotea aciphylla (Nees & Mart.) Mez	Lauraceae	x			[64];[85]
Ocotea nigrescens Vicent.	Lauraceae	x			[19]
Oenocarpus bataua Mart.	Arecaceae		x		[28];[81]
Oenocarpus minor Mart.	Arecaceae		x		[86];[87]
Ormosia grossa Rudd	Fabaceae		x		[88]
Osteophloeum platyspermum (Spruce ex A.DC.) Warb.	Myristicaceae	x			[11];[85]
Parkia multijuga Benth.	Fabaceae	x			[6];[89]
Parkia nitida Miq.	Fabaceae	x			[11];[20]
Parkia pendula (Willd.) Benth. ex Walp.	Fabaceae	x			[6];[89]
Platonia insignis Mart.	Clusiaceae		x		[74];[90]
Platymiscium trinitatis Benth.	Fabaceae	x			[6];[91]
Pouteria caimito (Ruiz & Pav.) Radlk.	Sapotaceae			x	[19];[51]
Pouteria reticulata (Engl.) Eyma	Sapotaceae	x			[3]
Protium amazonicum (Cuatrec.) Daly	Burseraceae		x		[92]
Protium apiculatum Swart	Burseraceae	x			[11];[19]
Protium heptaphyllum (Aubl.) Marchand	Burseraceae	x			[6];[19]
Pterocarpus rohrii Vahl	Fabaceae	x			[5];[6]
Qualea tessmannii Mildbr.	Vochysiaceae	x			[93]
Roupala montana Aubl.	Proteaceae	x			[6];[93]
Schizolobium amazonicum Huber ex Ducke	Fabaceae	x			[9];[20];[35]

Sextonia rubra (Mez) van der Werff	Lauraceae	x			[19];[94]
Simarouba amara Aubl.	Simaroubaceae	x			[6];[45]
Socratea exorrhiza (Mart.) H. Wendl.	Arecaceae		x		[26];[28]
Spondias mombin L.	Anacardiaceae			x	[95];[96]
Spondias testudinis J.D. Mitch. & Daly	Anacardiaceae		x		[14]
Sterculia excelsa Mart.	Malvaceae	x			[6];[19]
Stryphnodendron pulcherrimum (Willd.) Hochr.	Fabaceae	x			[97];[98]
Swietenia macrophylla King	Meliaceae	x			[6];[99]
Symphonia globulifera L.f.	Clusiaceae	x			[6];[100]
Tapirira guianensis Aubl.	Anacardiaceae	x			[6];[9];[101]
Terminalia amazonia (J.F. Gmel.) Exell	Combretaceae	x			[6];[102]
Theobroma cacao L.	Malvaceae		x		[75];[103]
Theobroma speciosum Willd. ex Spreng.	Malvaceae		x		[104];[105]
Theobroma subincanum Mart.	Malvaceae		x		[75];[106]
Trattinnickia burserifolia Mart.	Burseraceae	x			[6];[19]
Vatairea paraensis Ducke	Fabaceae	x			[19]
Vatairea sericea (Ducke) Ducke	Fabaceae	x			[18];[93]
Zanthoxylum rhoifolium Lam.	Rutaceae		x		[42];[107];[108]

Table S2. List of pioneer species with potential use according to the literature review.

Speciess	Family	References
Abarema jupunba (Willd.) Britton & Killip	Fabaceae	[1]
Agonandra brasiliensis Miers ex Benth. & Hook.f.	Opiliaceae	[109]; [110]
Albizia niopoides (Spruce ex Benth.) Burkart	Fabaceae	[5]; [111]
Apeiba membranacea Spruce ex Benth.	Malvaceae	[112]
Calycophyllum spruceanum (Benth.) K. Schum.	Rubiaceae	[113] [114]
Caryocar brasiliense Cambess.	Caryocaraceae	[5]
Ceiba pentandra (L.) Gaertn.	Malvaceae	[115]; [116]
Colubrina glandulosa Perkins	Rhamnaceae	[66]
Cordia goeldiana Huber	Boraginaceae	[116]
Erythrina verna Vell.	Fabaceae	[117]
Erisma uncinatum Warm.	Vochysiaceae	[113]
Eschweilera coriacea (DC.) S.A. Mori	Lecythidaceae	[118] [119]
Genipa americana L.	Rubiaceae	[110]; [117]
Guazuma ulmifolia Lam.	Malvaceae	[66]
Handroanthus serratifolius (Vahl) S. Grose	Bignoniaceae	[117]
Inga alba (Sw.) Willd.	Fabaceae	[120]
Jacaranda copaia (Aubl.) D.Don	Bignoniaceae	[110]; [121]
Laetia procera (Poepp.) Eichler	Salicaceae	[122]
Maquira sclerophylla (Ducke) C.C. Berg	Moraceae	[110]
Ochroma pyramidale (Cav. ex Lam.) Urb.	Malvaceae	[112]; [123]
Pterocarpus rohrii Vahl	Fabaceae	[5]
Schizolobium amazonicum Huber ex Ducke	Fabaceae	[9]; [110]
Stryphnodendron pulcherrimum (Willd.) Hochr.	Fabaceae	[110]
Tapirira guianensis Aubl.	Anacardiaceae	[110]; [124]
Zanthoxylum rhoifolium Lam.	Rutaceae	[110]; [117]

Table S3. Parameters and statistics of the GLMM equations adjusted for the dependent variables as a function of the independent fixed and random effect variables. The parameters refer to the equations: $[\log(TP) = a + b(TAF) + c(FR) + d(FR \times TAF) + \varepsilon]$ for the dependent variable density of species with timber potential (TP) ; $[\log(NTP \mid MUP) = a + b(FR) + \varepsilon]$ for the dependent variables density of non-timber species (NTP) and density of multiple-use species (MUP). The fixed-effect independent variables are time after first fire event (TAF) and fire recurrence (FR). The independent variable of random effect are composed by the vegetation types (VT), FC = Forested campinarana, TC = Treed campinarana, OFDB = Open forest with dominant bamboo, OFBP = Open forest with bamboo and palms, OFP = Open forest with palms. Values in parentheses indicate 95% confidence intervals.

Area	***A***	***b***	***c***	***d***
Timber potential (TP)				
Average GLMM	4.51 (±0.34)	-0.31 (±0.25)	-2.37 (±1.55)	0.46 (±0.38)
FC	4.26	-0.31	-1.71	0.46
TC	4.44	-0.31	-2.64	0.46
OFBP	4.19	-0.31	-2.24	0.46
OFDB	4.42	-0.31	-2.93	0.46
OFP	5.23	-0.31	-2.24	0.46
Non-timber potential (NTP)				
Average GLMM	4.23 (±0.30)	-1.28 (±1.32)	-	-
FC	4.18	-2.55	-	-
TC	3.69	-3.19	-	-
OFBP	4.14	-0.65	-	-
OFDB	4.48	-0.02	-	-
OFP	4.68	0.08	-	-
Multiple-use potential (MUP)				
Average GLMM	2.63 (±0.29)	-0.49 (±0.15)	-	-
OFBP	2.90	-0.49	-	-
OFDB	2.38	-0.49	-	-
OFP	2.63	-0.49	-	-

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