DOCUMENTOS

375

ISSN 1980-3958
Setembro / 2022

AGRICULTURAL
RESEARCH AND
INNOVATION ON
THE 2030 AGENDA

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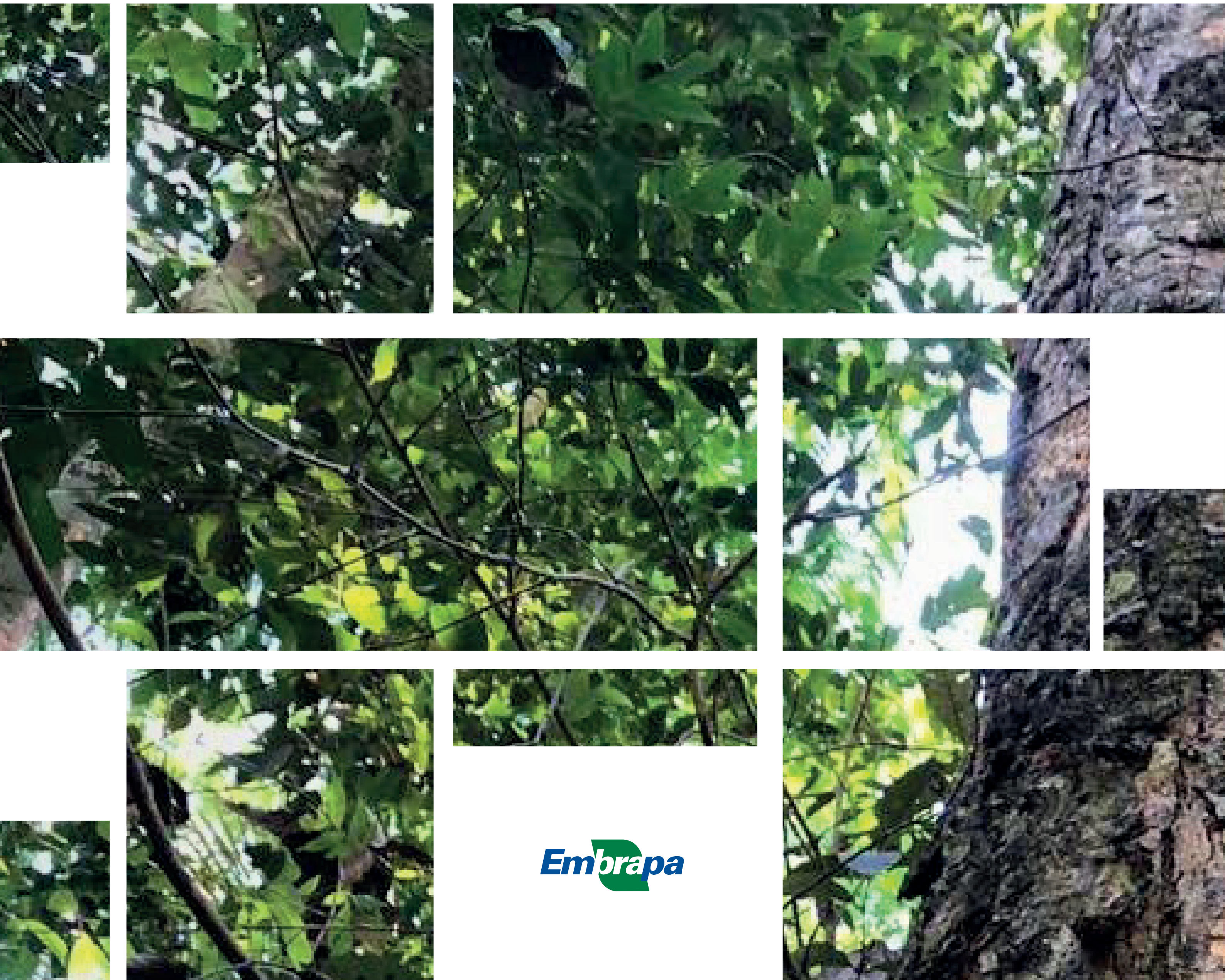

Embrapa

ISSN 1980-3958
Setembro/2022

Brazilian Agricultural Research Corporation
Embrapa Forestry
Ministry of Agriculture, Livestock and Food Supply

DOCUMENTOS 375

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2022

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Layout
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Cover
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1st edition
Digital publishing (2022)

Cataloging-in-Publication
Embrapa Florestas

Occurrence and growth of *Handroanthus* spp. in the Amazon region in the states of Mato Grosso and Acre, to assist in developing standards for forest. [recurso eletrônico] / Evaldo Muñoz Braz ... [et al.]. - Colombo : Embrapa Forestry, 2022.
PDF (78 p.) : il. color. - (Documentos / Embrapa Florestas, ISSN 1980-3958 ; 375)

Access mode: World Wide Web:
<http://www.infoteca.cnptia.embrapa.br/handle/item/221>

1. *Handroanthus serratifolius*. 2. *Handroanthus impetiginosus*. 3. Geographical distribution. 4. Developmental stages. 5. Preservation. 6. Forest management. 7. Environmental sustainability. I. Braz, Evaldo Muñoz. II. Canetti, Aline. III. Mattos, Patricia Póvoa de. IV. d'Oliveira, Marcus Vinicio Neves. V. Thaines, Fabio. VI. Oliveira, Mariana Ferraz. VII. Garrastazu, Marilice Cordeiro. VIII. Série.

CDD (21. ed.) 634.95

Francisca Rasche (CRB 9-1204)

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Foreword

It is always gratifying to be able to help advance research on native tree species and provide results to the community. Research on the occurrence of wood-producing species from native forests is strategically important for Brazil, in terms of the environment as well as the economy, and motivated the Embrapa Forestry team and its collaborators to conduct this research on *Handroanthus* spp. in two Brazilian states.

The area where species in this genus occur is presented along with considerations about populations, growth, and structure, carrying capacity and stock managed native forests, as well as other analyses. Results from analyses of production under different forest management conditions are also presented. This data is essential not only for environmental organizations but also for the productive sector, academia, research and government institutions, and technicians that are directly or indirectly involved with management of native forests.

This project is in line with Sustainable Development Goals 6, 8, 12, 15, and 17, since it addresses increased productivity and maintaining forest cover through managing native forests, involving systems that help boost efficient use of these natural resources and also promoting ecosystem conservation and biodiversity preservation. This text is the result of collaboration between different institutions and actors that work toward sustainable management of wood species in the Amazon Forest.

We hope that the data provided here will fill in the gaps on this topic, with a new focus on procedures for analyzing native tree species.

Erich Gomes Schaitza
Head of Embrapa Forestry

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Introduction

As an alternative for managing remaining forests, native forest management is the only economic activity involving land use and cover that ensures continuous coverage of forested areas (Seydack, 2012; Lundqvist, 2017), making it compatible with economic, social, and environmental development (Timofeiczyk Junior et al., 2005). Along these lines, the United Nations considers forest management to be an alternative for sustainable development and biodiversity conservation (Zimmerman; Kormos, 2012).

There are international initiatives that encourage forest management in the Amazon region, stimulating this activity instead of other uses that require changes in land use and cover, such as agriculture and cattle ranching. The World Bank is part of these international initiatives, promoting natural forest management certification in order to ensure that biodiversity and environmental sustainability are maintained (World Bank Group, 2013). Additionally, the United Nations Framework Convention on Climate Change (UNFCCC) is dedicated to creating rules that encourage forest management as an activity that helps reduce carbon emissions (UNFCCC Secretariat, 2008).

Considering the potential of native forest management in the Amazon as an alternative for sustainable economic activity, efforts should focus on optimizing this activity to ensure production of high-quality tropical wood as a renewable product. This requires planning founded on broad knowledge about commercial species and forest dynamics as a whole.

Brazilian legislation currently implements the multi-cycle regime for managing the Amazon Forest throughout the country. Only part of the commercial stock is utilized in this regime, since only trees with diameters exceeding the minimum cutting diameter (MCD) can be managed, considering each harvest cycle (Seydack, 2012). This keeps land cover practically unchanged. One of the main requirements for forest management is ensuring that a minimum stock of trees exists in the remaining diameter classes, in order to supply future harvest cycles (Carron, 1968; Seydack, 2012; Braz et al., 2012). Once the ideal MCD is determined, trees in the remaining diameter classes will supply the commercial classes for the next cycle, with periodical and ongoing renewal of individual trees; this strengthens understanding of the notion that wood is a renewable product. Detailed knowledge about the structure and dynamics of each species is necessary for effective production planning, resulting in higher yields and ensuring a supply of wood for future cycles.

Chazdon (2014) states that unlike converting forests for agricultural uses, using forests for wood maintains much of the original biodiversity and biomass. This researcher concludes that managed forests have high conservation value, particularly in comparison to exotic species, and are more diverse and similar to mature forests in their structure and composition. But whenever the reduction and even destruction of the Amazon Forest is mentioned, the main land use that comes to mind and is subject to criticism is logging, even in managed forests.

The species with the greatest economic value and major potential returns for producers in the Amazon region include the genus *Handroanthus* (known in Portuguese as ipê). These plants prefer strong sunlight and occur in primary and secondary forests, patches of secondary vegetation after clearing (*capoeiras)*, etc. (Lorenzi, 1992). They are abundant in open pastures, indicating their ease of cultivation and need for light, since in these areas they develop in full sun (Juárez Garcia et al., 2015).

Handroanthus spp. occur across the continent. In the SpeciesLink Network, botanical material from the species *H. serratifolius* (Vahl) S.O. Grose was registered in all of Brazil's states (SpeciesLink Network, 2021) except Rio Grande do Sul, while *H. impetiginosus* (Mart. Ex DC.) Mattos was registered in all but two states in northern Brazil (Amapá and Rondônia). In the Amazon, Schulze et al. (2008) reported the occurrence of *H. serratifolius* and *H. impetiginosus* in the states of Amapá, Amazonas, Mato Grosso, Rondônia, and Roraima, in different density classes. In Acre, among the commercial species*, Tabebuia serratifolia* (now *Handroanthus serratifolius*) ranked in the top ten species with the highest importance value index (IVI) in eight of the nine forest types studied (FUNTAC, 1992). The same text reported that natural regeneration of this species was found in seven forest types.

Although these species have wide geographical distribution and abundance, there are currently discussions in the forestry sector about placing *Handroanthus* species on the list of endangered flora species. This debate resulted from the publication of Technical Note 004/2019 by the Botanical Garden of Rio de Janeiro on March 20, 2019 (CNCFlora, 2019). This document contains several gaps with regard to logging and threats to flora and fauna species. There is confusion in the approach to timber logging; for example, data on trees resulting from suppression (shifting from forest to ranching use) are grouped together with data on trees from managed forests where the forest and the original land use and cover remain. The resulting overall logging data (which may include data from forest management) are cited as sources of deforestation, disregarding the fact that forest management maintains forest cover. Studies rarely include losses resulting specifically from deforestation to establish fields for planting or livestock raising.

The authors of Technical Note 004/2019 include considerations about the risk that forest management may contribute to the extinction of these species, but their studies are mainly based on the effects of large-scale deforestation to establish field crops or pastures. Additionally, the low densities of each tree species (which have always been common in primary forests in the Amazon region) (Heinsdijk, 1958; Pires; Prance, 1977; Martins, 1991) are associated with deforestation.

Assessments by non-specialists combined with misinterpretations of the structures of the *Handroanthus* genus to compromise the understanding of Brazilian technicians regarding the potential of forest management as an instrument to protect the environment, even though management is recognized worldwide as a way to ensure forest areas are maintained along with their related richness and functionalities (Zimmerman; Kormos, 2012).

As a result of the publication of Technical Note 004/2019, including the genus *Handroanthus* on the Convention on International Trade in Endangered species of Wild Flora and Fauna (CITES) list was suggested at a meeting held by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) on September 8, 2019 (Brazil, 2019). But at that meeting, timber producers emphasized that including the genus on the CITES list would make international buyers hesitant to use threatened species, since the markets themselves are already speculating about suspending purchases of timber from species on the list (Brazil, 2019). According to the producers, this would be devastating for the sector.

There is no doubt about the devastation caused by deforestation in the Amazon. But when the land use and cover of an area is converted, it is completely deforested; this is often preceded by burning (in other words, without even utilizing the wood). Adding species to lists like CITES does not seem to offer an alternative to halt or minimize the impacts of biodiversity loss from deforestation. When land is deforested, species are not protected, regardless of whether they are listed as endangered species.

Illegal logging would not be affected by including species on the CITES list, since these activities obviously do not comply with licensing processes for logging or selling the resulting wood. Illegal logging is a crime that takes place regardless of the species that is sold. Control should take place throughout the entire chain of custody from the record of origin for the wood, as in the case of certification processes and with monitoring tools such as the Forest Origin Document (*Documento de Origem Florestal*).

In this way, the real limitation that can result from including species on the CITES list will affect producers who legally sell wood from these species, especially via forest management. The legislation is very strict about licensing for this activity, and was developed precisely to ensure its sustainability. These requirements involve significant spending on activities such as forest inventories and fees for skilled professionals. For this reason, for the activity to be at least profitable, the producer should try to obtain maximum forest yield, according to the sustainability criteria. The species of greatest interest to the market are the subject of technical notes for inclusion in endangered species lists or are classified in legal ordinances as vulnerable, as in the case of *Handroanthus* spp. and others such as *Amburana acreana* (Ducke) A.C. Sm., *Aniba rosiodora* Ducke, *Apuleia leiocarpa* (Vogel) J.F. Macbr., *Cedrela odorata* L. (Spanish cedar), *Hymenaea parvifolia* Huber, *Hymenolobium excelsum* Ducke, *Mezilaurus itauba* (Meisn.) Taub. ex Mez, and *Virola surinamensis* (Meisn.) Taub. ex Mez (Brasil, 2014; 2021). The only way to assess the vulnerability of these species is via surveys (sample inventories) to determine real stocks, followed by careful interpretation of these data, but this type of study has not been documented. Evidently, just being economically attractive has been sufficient motive for species to be considered in discussions on incorporation into lists of threatened species.

This study analyzes the current situation of stocks of *H. serratifolius* and *H. impetiginosus* trees in the Amazon region, with an emphasis on the states of Acre and Mato Grosso. The goal was to understand the geographic distribution of these two species and their dynamics by studying the growth phases (from youth to senescence) and their relationships with the diameter structures found, among other analyses. The results will make it possible to assess the sustainability of managing natural populations of these species, according to current structures. They will also serve as a basis for decision-making on whether to include these species on lists of vulnerable species, and guide regulations for management.

Methodology

Database

Data from forest inventories and specialized literature were used in order to cover all the forest types present in Acre and Mato Grosso. The data set consisted of forest inventories from approved sustainable forest management plans (SFMPs) which were provided by the Acre Environmental Institute (IMAC-AC) and the Mato Grosso Secretary of the Environment (SEMA-MT), sample inventories, and results or reports published in the scientific literature. Data from permanent plots were used in the growth study in Acre, while samples were collected from trunks of *Handroanthus impetiginosus* and *H. serratifolius* trees in areas with SFMPs approved by SEMA-MT. In the following section, the different sources that composed the database are described in detail.

Forest census (100% inventories)

Inventories from annual production units (APUs) covered by SFMPs were selected and provided by the responsible regulatory institution in order to analyze the distribution of *Handroanthus* spp. in the states in question (Table 1). A total of 24 APUs were analyzed in Acre and 55 in Mato Grosso. The inventories selected for analysis did not contain records of recently cut trees, indicating that at the time of measurement, the forests closely resembled an intact natural forest structure. All SFMPs were located in the Amazon Forest and distributed across the main forest types of the biomes in the states under study.

Table 1. Characteristics of the areas covered by the forest management plans from which data from the pre-use forest census (DBH ≥ 35 cm) were obtained in forests in Acre and Mato Grosso, by forest type.

	Number of inventories	Total number of *Handroanthus* spp.	Total area (ha)	Number of *Handroanthus* spp. trees (ha^{-1})
		Acre		
FOA	15	7,905	24,770	0.320
FOD	9	2,956	16,571	0.180
Total	**24**	**10,861**	**41,340**	
		Mato Grosso		
Fefo	3	206	3,584	0.057
Fesav	3	116	1,727	0.067
FESV	20	14	17,270	0.001
FOA	14	4,988	13,458	0.371
FOD	15	5,778	18,611	0.310
Total	**55**	**11,102**	**54,649**	

OOF = Open Ombrophile Forest, DOF = Dense Ombrophile Forest, ESF = Evergreen Seasonal Forest, SFOF = transition zone between Seasonal Forest and Ombrophile Forest, and SFSAV = transition zone between Seasonal Forest and Savanna (IBGE, 2015).

The inventories used were pre-commercial, census type (100% inventories), which are required for approval of the SFMP (Brasil, 2006). According to environmental agency requirements, the diameter at 1.30 m from the ground (DBH) is measured for all trees in which this measurement exceeds 35 cm, and commercial heights are estimated visually. All trees are identified, coded, and georeferenced. Because these are inventories for commercial purposes, the trees are identified in the stands using common names (rather than species names).

It is important to note that identification in the field is often only possible at the genus level. Field campaigns do not always occur when the trees are flowering, and trees do not all flower at the same time, often making identification at the species level impossible (since several analytical identification keys are based on flower structures) (Alencar, 1998). Furthermore, many species contained in SFMPs belong to genera and families that are taxonomically complex and have high species richness, complicating identification in the field (Cysneiros et al., 2018).

Botanical identification of *Handroanthus* species in commercial inventories is generally limited to the genus, since the reproductive structures are not present year round. For this reason, in cases when data from pre-cutting census were used (in which there was no botanical confirmation), the genus *Handroanthus* was considered. A total of over 20,000 *Handroanthus* spp. trees were recorded in an area of approximately 100,000 hectares.

Diagnostic inventories

For the state of Acre, diagnostic inventories filed with SFMPs were provided by IMAC-AC (Table 2). These are sample inventories in which all trees with DBH ≥ 10 cm were identified and their diameters and heights measured. These inventories were used to analyze the diametric structure of the genus *Handroanthus* and the species *H. impetiginosus* and *H. serratifolius*, making it possible to understand the structure of the smaller diametric classes, since the inventories included more trees (DBH ≥ 10 cm) than the forest census (DBH ≥ 35 cm).

Table 2. Characteristics of the areas covered by the forest management plans from which data from the diagnostic inventories (DBH ≥ 10 cm) were obtained in forests in Acre, by forest type.

	FOA	FOD	Total
Number of inventories	9.0	7.0	16.0
Total number of *Handroanthus* spp. trees	198.0	62.0	260.0
Total area	82.3	45.8	128.1
Number of *Handroanthus* spp. trees, per ha	2.4	1.4	

OOF = Open Ombrophile Forest; DOF = Dense Ombrophile Forest (IBGE, 2015).

Sample inventories

Sample inventories were conducted in the two states under study in order to better understand the structure of *Handroanthus* species in the areas they prefer. The inventories were carried out in areas of OOF, where higher densities of these species are concentrated (Tables 1 and 2).

In Acre, the survey was carried out in the municipality of Acrelândia in community forest management areas belonging to APFAPD, the Porto Dias Agroextractive Settlement Project Family Agriculture Producers' Association. The sites made available for the study comprise 15 community forestry management production units totaling 1,431 ha which were operated over several years from 2015 to 2021. In Mato Grosso, the areas selected for sampling belonged to forest companies that authorized data collection.

Plots were allocated based on pre-use forest census, from which kernel density maps were generated using ArcGIS 10.5 software (ESRI) for the *Handroanthus* species, producing three density classes; the default search radius was used. Plots were randomly entered within density classes 2 and 3, at a 1% sampling intensity (Figure 1). The sample design was intended to direct the sampling to sites where specimens actually occurred and which are preferred by the genus in order to detect the trees' potential when they are found in more favorable conditions.

In Mato Grosso, 75 circular 50-m-diameter plots were allocated in two areas with a total of 15 ha inventoried. Approximately 8 ha were inventoried in areas without forest management considered primary forest, and the inventory in the remaining area was conducted where forest management had been implemented between 2009 and 2015. In Acre, 34 50-m-diameter circular plots were allocated, totaling 6.8 ha inventoried in managed forest areas.

Data on trunk diameter and quality and estimated height were collected for all individual trees in the genus *Handroanthus* with DBH ≥ 10 cm. Botanical sample material (for pressing/drying) was collected from the sampled trees whenever possible for specialist validation of the species. Natural regeneration of the species (seedlings with DBH < 10 cm) was recorded visually and in photographs.

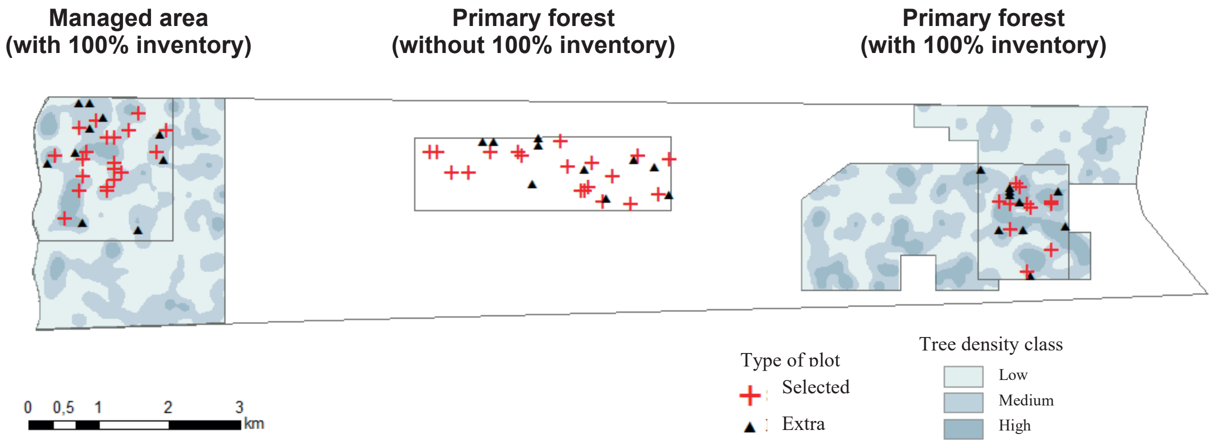

Figure 1. Diagram of plots allocated in one of the sampling areas of *Handroanthus* spp. in Open Ombrophile Forests in the municipality of Aripuanã, MT.

The specimens were identified by a specialist from the State University of Mato Grosso (UNEMAT), based on infertile dried plant samples and literature by the group (Gentry 1992; Ribeiro et al., 2021), the *Flora do Brasil 2020* report (Lohmann et al., 2020) and comparison with digitized materials available in virtual herbaria (such as JABOT, SpeciesLink, and REFLORA). The nomenclature and accepted names followed the usage in *Flora do Brasil 2020* (Lohmann et al. 2020, BFG, 2021a, 2021b, 2021c).

Permanent plots in Acre

Embrapa Acre provided growth increment data for *Handroanthus* spp. obtained in 52 permanent plots installed in 1992 in the municipalities of Acrelândia, Bujari, Lábrea, and Rio Branco. The permanent plots follow the standard Embrapa model (Oliveira et al., 2005; 2017) for size and measurements: generally 1 ha (100 m x 100 m) subdivided into 10 m x 10 m subplots.

Sample collection in Mato Grosso

Cylindrical cross-sections of the trunk (disks) approximately 5 cm thick were collected from *H. impetiginosus* and *H. serratifolius* trees in Colniza, MT which were felled in an area with a SFMP authorized by SEMA-MT. These samples were taken from the base of the first commercially available log, approximately 1 m above the ground. Four samples were collected from *H. impetiginosus* (DBH: 62–89 cm) and five from *H. serratifolius* (DBH: 69–81 cm).

Growth was determined by measuring growth rings. To improve visualization, the disks were dried naturally and then polished with different weight sandpapers. Eight rays were drawn on each sample, separated by angles of approximately 45°, and a stereoscopic microscope was used to mark the rings in all the rays. The growth rings were measured with 0.01 mm precision on a LINtab measuring table (Frank Rinn, Heidelberg, Germany) and with TSAP-Win software (Rinn, 1996). The growth series generated from measuring the rings were visually dated between rays from the same tree and subsequently between trees, to ensure that the year each growth layer formed was determined.

Analysis of occurrence

To analyze and visualize the density of *Handroanthus* spp. in the different forest types, the APUs with trees in this genus were selected from the forest census data provided by IMAC-AC and SEMA-MT (Table 1). Mean tree density (DBH ≥ 35 cm) was calculated for each APU, considering the number of trees and total area. The SFMPs were classified according to the forest type where they were found.

One APU per SFMP per forest type was selected in Mato Grosso to generate tree density maps. These maps were developed using the kernel density estimator in ArcGIS 10.5 software (ESRI); the default search radius was used. Five density classes were generated for each area, each occupying approximately 20% of the total area of the APU. Density maps were visually compared to digital elevation models for the study areas, which were obtained using data from the Shuttle Radar Topography Mission (SRTM) (Weber et al., 2004) to verify the influence of altitude on the natural occurrence of the species.

Forest census data were used to calculate the importance value index (IV) of the species found. In this case, common names were considered since this is how the species are commonly identified in these inventories. We opted to not replace common names with scientific names in the present study, since correct species-level botanical identification could not be determined.

The IV is generated using the species density, frequency, and dominance criteria in each plot according to equations 1 through 4 (Cottam; Curtis, 1956). In the forest census received for the APUs, the strip (sequence of the path between the boundaries of the polygon) to which each tree belonged was numbered, and each strip was considered a plot for recording frequency in this study.

$$DR_i = \frac{n_i}{N} \text{ x } 100 \tag{1}$$

$$DoR = \frac{g_i}{G} \text{ x } 100 \tag{2}$$

$$FR_i = \frac{\frac{U_i}{U_t}}{\sum_{i=1}^{S} \frac{U_i}{U_t}} \text{ x } 100 \tag{3}$$

$$IV_i\,(\%) = \frac{DR_i + DoR_i + FR_i}{3} \tag{4}$$

Where:

DR_i = relative density of *the i-th* species (%)

n_i = total number of individuals sampled from the *i-th* species ha^{-1}

N = total number of individuals sampled from all species ha^{-1}

DoR = relative dominance (%)

g_i = cross-sectional area of the *i-th* species ($m^2 ha^{-1}$)

G = sum of cross-sectional area of all species ($m^2 ha^{-1}$)

FR_i = relative frequency of the *i-th* species (%)

U_i = number of plots where the *i-th* species occurs

U_t = total number of plots

$VI_i (\%)$ = importance value index for the *i-th* species (%)

In order to demonstrate the proportion and distribution of the *Handroanthus* spp. trees that are categorized as “cut” or “remaining” within an APU, one APU was selected per forest type in Mato Grosso except SFOF areas (since few specimens of this genus were recorded in areas with this forest type). The classification introduced by the engineers in the census analyzed was utilized.

To complement analysis of the occurrence of the two main species of *Handroanthus* in the Amazon region (*H. impetiginosus* and *H. serratifolius*), the botanical records cataloged in the SpeciesLink Network (SpeciesLink Network, 2021) were obtained. The geographic distribution of the species according to the SpeciesLink Network was compared to the geographic distribution of the genus obtained from the previously analyzed data from the forest census.

Calculating remaining forests and *Handroanthus* spp. trees

Survey of the current situation in the forests

To quantify deforestation, the mosaics of forest areas in the MapBiomas Project (2021) in Acre in 1985 and 2020 were used, along with the mosaics from 1988 and 2019 for the Amazon biome in Mato Grosso. The area deforested during this period was calculated in the Geographic Information System, using the raster calculator and area calculator tools in ArcGIS 10.5 software (ESRI). Shapefiles of Indigenous lands (FUNAI, 2019) and conservation units (Brasil, 2018) were used to calculate the total forest protected area and deforested area since 1985 in Acre and since 1988 in Mato Grosso. Areas that currently cannot be included in sustainable management (Indigenous lands and full-protection conservation units) were considered protected areas. Remaining forests, deforested areas, and protected areas were also calculated individually for each forest type.

Survey of the current situation for *Handroanthus* species

The number of *Handroanthus* trees in both states was calculated according to the ratio of the remaining and deforested areas and the average densities in each forest type. For Acre, the densities obtained in the diagnostic inventories (DBH ≥ 10 cm) were used (Table 2). In Mato Grosso, the average densities from the forest census (DBH ≥ 35 cm) were used (Table 1). For Mato Grosso, the mean tree density of *Handroanthus* spp. with DBH between 10 cm and 35 cm reported by Schulze et al. (2008) was used to estimate the number of trees in this size range.

Analysis of diametric growth in Acre

Growth of *Handroanthus* spp. in Acre was analyzed by comparing the mean annual increment per diameter class between species (using data from permanent plots) using the non-parametric Kruskal-Wallis test ($p \leq 0.05$).

Analysis of diametric growth in Mato Grosso

Using the trunk samples collected in Mato Grosso, the mean increment per diameter class was analyzed using the non-parametric Kruskal-Wallis ($p \leq 0.05$), and growth equations were adjusted for each species and for *Handroanthus* spp. Before adjustment of the growth equations, the non-parametric Bootstrap method was applied with 100 iterations (Miller, 2004), creating growth trajectories by random combination of the measured growth rings to boost the accuracy of the models. Seven biologically-based growth models (equations 5–11) were adjusted: Chapman-Richards, Gompertz, Hossfeld IV, logistic, Lundqvist-Korf, Schumacher, and three-parameter Weibull (Zeide et al., 1993; Burkhart; Tomé, 2012), using non-linear regression in the PROC NLIN process in the SAS software.

Chapman-Richards: $$dbh = \beta_0 (1 - e^{-\beta_1 t^{\beta_2}}) \quad (5)$$

Gompertz: $$dbh = \beta_0 e^{-\beta_1 e^{-\beta_2 t}} \quad (6)$$

Hossfeld IV: $$dbh = \frac{t^{\beta_2}}{\beta_1 + \frac{t\beta_2}{\beta_0}} \quad (7)$$

Logístico: $$dbh = \frac{\beta_0}{(1 + \beta_1 e^{-\beta_2 t})} \quad (8)$$

Lundqvist-Korf: $$dbh = \beta_0 e^{\left(-\frac{\beta_1}{t^{\beta_2}}\right)} \quad (9)$$

Schumacher: $$dbh = \beta_0 e^{-\frac{\beta_1}{t}} \quad (10)$$

3-parameter Weibull $$dbh = \beta_0 (1 - e^{\beta_1 t^{\beta_2}}) \quad (11)$$

where:

dbh = diameter at 1.3 m

t = ime elapsed in years until the DBH considered is reached

$\beta_0, \beta_1, \beta_2$ = equation parameters

e = Euler’s number

The best growth equation was selected according to the standard error of the estimate, Syx (%), corrected Akaike and Bayesian information criteria (equations 12 and 13, respectively), and fitted to the actual data and distribution of residues, considering DBH ≤ 10 cm:

$$AICC = -2f(\hat{\theta}) + \frac{2\ (pn)}{n - p - 1} \tag{12}$$

$$BIC = -2 \log L\ (\hat{\theta}) + p \log n \tag{13}$$

where:

p = number of parameters to be estimated

n = number of sample observations

$f(\hat{\theta})$ = enhanced support function

L = maximum-likelihood function value

Growth curves for individual tree volume were generated using the diametric growth equations adjusted from the growth ring series, from the hypsometric relationship developed by Andrade et al. (2019) for *H. serratifolius* in Amazonas, and the volume equation adjusted by Cysneiros et al. (2017) for *H. impetiginosus* in the Jamari National Forest (Rondônia). The same hypsometric relationships and volume equations were used for both species and for the genus *Handroanthus*, since they were available in the literature.

From the growth curves for diameter and individual tree volume, the mean annual increment (MAI) and current annual increment (CAI) curves were derived, using equations 14 and 15. These curves identify the diameters at which the species and *Handroanthus* genus reach maximum CAI and where the MAI and CAI curves meet.

$$MAI_x = \frac{x_t}{t} \tag{14}$$

$$CAI_x = x_{t+1} - x_t \tag{15}$$

where:

MAI_x = mean annual increment, in DBH or in volume (m³)

CAI_x = current annual increment, in DBH or in volume (m³)

x = DBH or commercial volume accumulated at different times “t” on the growth curve (m³)

t = time relative to the growth curve

The point where the diameter CAI and MAI curves meet was used to understand when trees in these species are most vigorous and begin to decline. This concept was based on Weiskittel et al. (2011), who reported that an increase in tree diameter signals vigor, and that slowing of diameter increase is related to a higher probability of mortality and the start of the stagnation phase of growth and senescence (Kramer; Kozlowski, 1960; Nyland, 2007; Batista et al., 2014). Meanwhile, the volume maximizations were understood by comparing the MAI and CAI curves for volume.

Analysis of the diametric structure of *Handroanthus* spp.

For Acre, data from diagnostic inventories (DBH ≥ 10 cm; Table 2) were used to analyze the diameter structure, while in Mato Grosso forest census data were used (Table 1). Because the forest census measured trees with DBH ≥ 35 cm, the 35 cm diameter class (30-40 cm) is incomplete, and for the purposes of this study the number of trees in this class was multiplied by 2 in order to minimize the gap in the data.

The probability density function for the average diameter structure in each forest type was adjusted in each forest type studied using the fitdistr function in R software (RStudio Team, 2015). For Acre, since the diameter distribution of the real data followed the negative exponential form, the three-parameter Weibull function (equation 16) was adjusted. For Mato Grosso, the distribution of the real data was near normal, and for this reason the log-normal function was adjusted (equation 17).

$$f(dbh) = \left(\frac{c}{b}\right)\left(\frac{dbh - \alpha}{b}\right)^{c-1} e - \left[\left(\frac{dbh - \alpha}{b}\right)^{c}\right] \tag{16}$$

$$f(dbh) = \frac{e^{\left(-\frac{1}{2}\right)\left[\frac{(\text{in } dbh - \mu}{\sigma}\right]^{2}}}{dbh\ \sigma \sqrt{2\pi}} \tag{17}$$

where:

dbh = diameter at 1.30 m (cm)

$f\,dbh$ = variable density function dbh; dbh_{min}

μ = mean

σ = standard deviation

a, b and c = estimated parameters dbh_{min}

Adherence to the real data was evaluated using the Kolmogorov-Smirnov test (α = 0.05), and accuracy was determined by the standard error for the estimate.

The accumulated diametric structures obtained from the adjusted functions were also analyzed. The diameter structures obtained from the probability density functions in OOF were compared to those recorded in the sample inventory areas. For the sample inventory, diameter distributions were also analyzed before and after forest management.

Growth analysis of the *Handroanthus* spp. population in Acre

The volume growth curves for the *Handroanthus* spp. population in Acre were generated by combining the data on mean diameter increment recorded in the permanent plots and the probability density functions of the diameter distribution for OOF. To calculate the individual volume in each diameter class, the hypsometric ratio developed by Andrade et al. (2019) for *H. serratifolius* in Amazonas and the commercial volume equation adjusted by Cysneiros et al. (2017) for *H. impetiginosus* in the Jamari National Forest (Rondônia) were used. The same hypsometric relationships and volume equations were used for both species and for the genus *Handroanthus*, since they were available in the literature. The time required for trees to move to the next diameter class was calculated to estimate the approximate age of the tree in the center of each diameter class.

The accumulated commercial volume of the population was calculated from the individual accumulated volume values multiplied by the number of trees in each diameter class. The curves for MAI and CAI in volume for the population were derived from the population by diameter class and estimated age, according to equations 18 and 19. The volumes were calculated for the population in 100 ha, for better visualization.

$$MAI_v = \frac{V_t}{t} \tag{18}$$

$$CAI_v = V_{t+1} - V_t \tag{19}$$

where:

V = accumulated commercial volume for the population (m³ 100 ha^{-1})

MAI_v = mean annual increment in volume for the population (m³ 100 ha^{-1})

CAI_v = current annual increment in volume for the population (m³ 100 ha^{-1})

t = age estimated from the time required for trees to move to the next diameter class.

In these curves, the diameters at which the species and *Handroanthus* genus reach maximum CAI and where the MAI and CAI curves meet were identified in order to understand the times when volume growth of these species can be maximized.

Growth analysis of the *Handroanthus* spp. population in Mato Grosso

In order to estimate the growth of *Handroanthus* spp. at the population level in Mato Grosso, where growth data were obtained from growth rings, data from growth equations and probability density functions adjusted for the state (Figures 13 and 16) and for the sample area were combined.

To do so, we assumed that the diameter distribution of a species reproduces the same formation pattern that occurred in the past, serving as a basis to guide future management (Gotelli, 2008; Lundqvist, 2017). The following procedures were performed, according to Canetti et al. (2021):

- The output of the probability density functions (Figure 16) is the number of trees, and the input is the diameter of the trees. For this reason, it is possible to work directly with the diameter, not just with diameter classes. Using the growth equations (Figure 13) to generate the diameter values, the number of trees was estimated at each time “t”, which refers to the growth curve of the species. This made it possible to estimate the diameter distribution by species in time (time x number of trees ha^{-1}). Since the actual diameter distributions were established using data from DBH ≥ 20 cm, the calculations were made using this value.

- The number of trees at each time "t" was multiplied by the volume of the individual tree at each time, resulting in the production curve for the population (m³ ha^{-1}) at each time relative to the growth equation.
- The MAI and CAI were derived from the volume production curve for the populations, using equations 14 and 15.

Management simulations for *Handroanthus* spp.

Combinations of cutting cycles and minimum cutting diameters for *Handroanthus* spp. were tested, considering the different diameter structures and increments obtained in the present study, for Acre and Mato Grosso.

Projection by diameter class (Alder, 1995) was used to compare and select volume increments obtained from the different combinations of cutting cycles and MCD in the following scenarios:

- MCD defined by where the CAI and MAI curves for the population cross, and cutting cycle calculated from the time elapsed in the MCD, according to Canetti et al. (2021).
- MCD = 50 cm and 35-year cutting cycle, according to current legislation (Brasil, 2006).
- MCD defined by where the CAI and MAI curves for the population cross (Canetti et al., 2021), and the cutting cycle in the current legislation.
- MCD defined by the peak CAI values and the point where the CAI and MAI curves for the population cross, and 70-year cutting cycle.
- MCD = 60 cm and 70-year cutting cycle.

The mathematical process for simulations in the diameter class projection method was defined by equation (20).

$$N_{k,t+1} = N_{k,t} + I_k - O_k - M_k - H_k \tag{20}$$

where:

$N_{k,t+1}$ = number of trees in class k in period $t+1$

$N_{k,t}$ = number of trees in class k in period t

I_k = recruitment in class k during the period

O_k = number of trees that moved from class k to subsequent classes during the period

M_k = mortality in class k during the period

H_k = trees extracted during the period

The matrices were constructed starting from the 15 cm diameter class for 5-year intervals (k) until the desired cutting cycle was reached. When there were no data from the initial diameter classes, they were estimated from the available structure data until stability of the diameter structure was attained, based on the procedure used by Lacerda et al. (2013). The harvest volume (H_k) considered was the amount available in trees with DBH greater than the MCD.

The following data were used:

- Mean increment by diameter class: raw data from the permanent plots in Acre (Figure 12) and the growth equations developed for Mato Grosso (Figure 13). The number of trees that moved to subsequent classes (O_k) was calculated from the time to transition into the next diameter class, according to equation 21, described by Alder (1995),

$$O_k = \frac{t.i}{w} \tag{21}$$

where:

O_k = = number of trees that transitioned from class k to subsequent classes during the period, considering:

i = average increment for the diameter class k (obtained from the growth equation)

w = interval between diameter classes (10 cm, in this study)

t = period considered

- Initial diameter structure ($N_{k,t}$) obtained from the probability density functions for Acre and Mato Grosso (Figure 15 and Figure 16) and for the sample inventories in areas preferred by *Handroanthus* spp. (Figure 21 and Figure 22).
- Recruitment (I_k): 2.5% of the total number of trees in the diameter structure considered (based on Oliveira and Braz, 1998) was considered recruitment.
- Mortality (M_k): mortality data from Schulze et al. (2008) were used, reaching an average of 2.0% per year.

After obtaining the final diameter structure of the projection matrix per diameter class, the number of trees was converted into volume using the height diameter allometry model developed by Andrade et al. (2019) for *H. serratifolius* in Amazonas and the volume equation adjusted by Cysneiros et al. (2017) for *H. impetiginosus* in the Jamari National Forest (Rondônia), to obtain total production during the period considered. This production was divided by the cut-off cycles established to calculate the annual increase in population in order to proportionally compare production of the different MCD and cut-off cycles tested.

Results and Discussion

Occurrence of *Handroanthus* spp. in the Amazon Region in the states of Acre and Mato Grosso

Density and occurrence of *Handroanthus* spp.

We observed that when the forest census (DBH ≥ 35 cm, Table 1) were considered, the densities of *Handroanthus* spp. differed between states, SFMPs, and forest types (Figures 2 and 4).

The Open Ombrophile Forest (OOF) concentrated the highest densities of *Handroanthus* spp. in Acre and Mato Grosso. This shows the high potential of these states for producing *Handroanthus* spp., since they contain large areas of OOF.

Acre

In Acre, larger numbers of *Handroanthus* spp. trees were observed between the Emvira and Purus Rivers in the central region of the state, in OOF areas (Figure 2). This indicates that environmental factors such as microclimate, water availability, and soil type may determine the sites preferred by these species (Alvarez-Buylla et al., 1996; Ivanauskas; Assis, 2009).

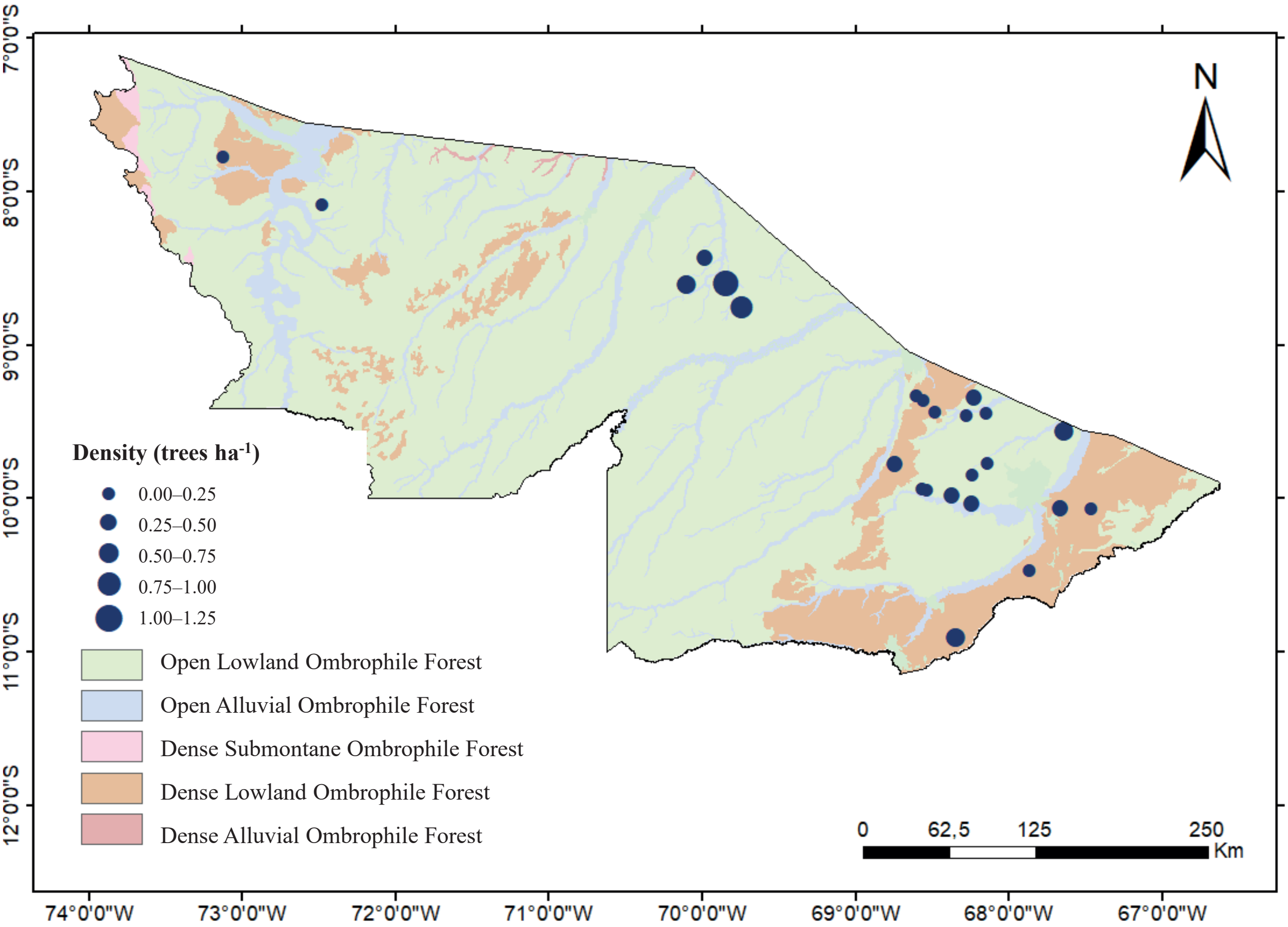

Figure 2. Average tree density (DBH ≥ 35 cm) in 24 sustainable forest management plans authorized by the Acre Environmental Institute (IMAC-AC) that contained *Handroanthus* spp.

The central-south region of the state of Acre is essentially comprised of conservation units (Brasil, 2018) and Indigenous lands (Funai, 2019), and because SFMPs are not permitted in these areas, no census data were available. But considering the high conservation status of these sites containing OOF, we can assume that substantial densities of *Handroanthus* trees can be found here, forming a significant reserve for conservation of these species.

The average proportion of the number of trees identified as yellow ipê, compared to those identified as purple ipê, ranged from 55% to 65% in census and diagnostic inventories, in both OOF and DOF. Amaro (1996) registered a similar proportion of yellow ipê trees in Acre (70%). This proportion of yellow ipê trees could be visible throughout the forest type, varying in accordance with preferred sites. But because there was no botanical confirmation of the data from the diagnostic and census inventories, we chose to work with *Handroanthus* at the genus level.

The densities of *Handroanthus* spp. were higher in the diagnostic inventories compared to the census (Figure 3), and were over twice as high in DOF.

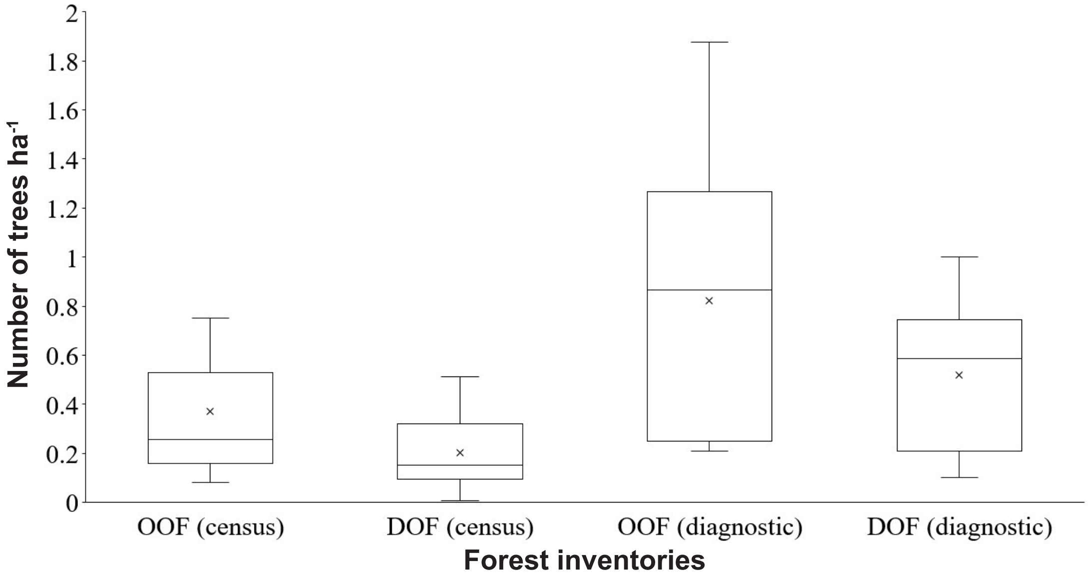

Figure 3. Comparison between the densities of *Handroanthus* spp. recorded in forest census and in diagnostic inventories (DBH ≥ 35 cm) in Acre.

However, the densities of the *Handroanthus* species recorded in the sample inventories (Figure 3) were similar to those from spreadsheet SC-19 (Rio Branco) of Project Radambrasil (1980) (Table 3), which also involved sampling, performed over four decades ago. They were also compatible with the densities recorded by Amaro (1996) in Acre, considering DBH ≥ 35 cm, 0.46 ha^{-1} for purple ipê trees and 0.83 ha^{-1} for yellow ipê trees.

In the forest census, the total area considered includes spaces without trees, such as areas with rivers or wetlands (which are very extensive in the state of Acre) that are counted in the total area of the APU. The diagnostic inventories and inventory from Project Radambrasil (1980) use sampling, and the samples are usually allocated in areas without these empty spaces, resulting in higher density averages.

Table 3. Number of trees ha^{-1} (DBH ≥ 30 cm) in the main wood-producing species in Acre noted on the SC-19 spreadsheet (Rio Branco) of Project Radambrasil (1980), by forest type.

Tree type (common name)	OOFa	OOFb	DOFb	Mean
Abiurana	2.678	2.560	3.572	2.937
Matamatá	1.130	1.100	1.886	1.372
Guariúba	0.581	0.780	1.286	0.882
Açacu	1.129	0.660	0.314	0.701
Caucho	0.258	0.900	0.820	0.659
Ipê	0.457	1.020	0.500	0.659
Tauari	0.226	0.360	0.600	0.395
Sumaúma	0.194	0.820	0.171	0.395
Cumaru-ferro	0.452	0.400	0.286	0.379
Cedro	0.129	0.460	0.171	0.253
Manitê (Murure)	0.290	0.140	0.171	0.200
Jatobá	0.000	0.000	0.457	0.152
Copaíba	0.097	0.200	0.143	0.147
Garapeira (amarelinho)	0.000	0.180	0.143	0.108
Faveira	0.065	0.020	0.029	0.038

OOFa = Alluvial Open Ombrophile Forest; OOFb = Lowland Open Ombrophile Forest; DOFb = Lowland Dense Ombrophile Forest.

Source: Project Radambrasil (1980).

Mato Grosso

In Mato Grosso, the regions with higher densities of *Handroanthus* spp. were evenly distributed in the Ombrophile Forest. However, the number of trees in these species was not representative in the Evergreen Seasonal Forest (ESF) (Figure 4).

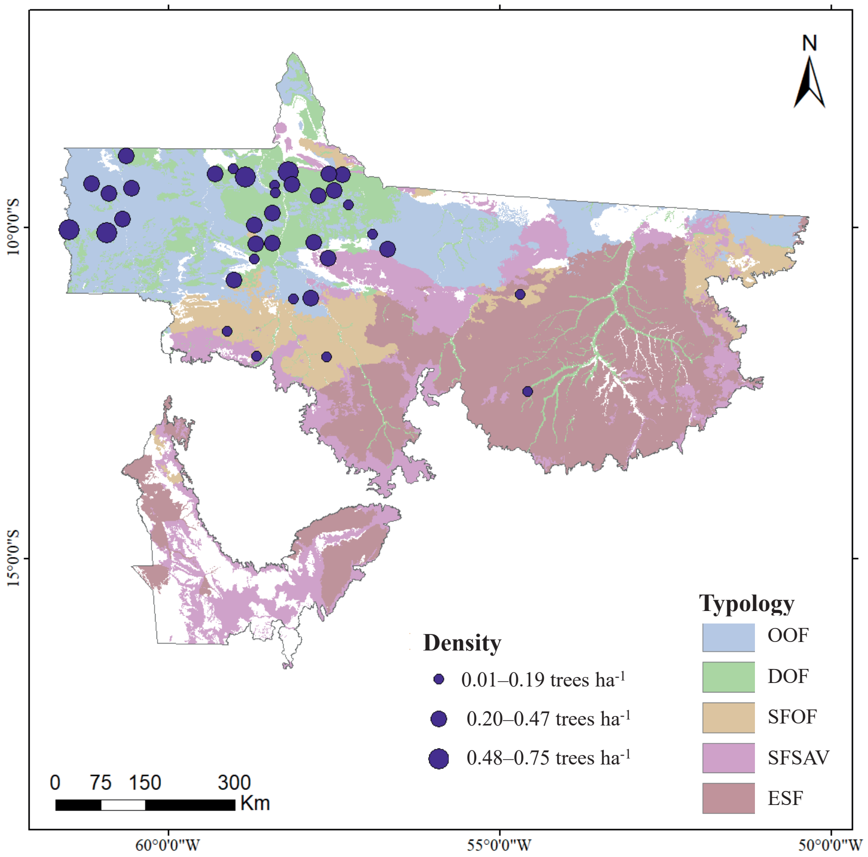

Figure 4. Mean tree density (DBH ≥ 35 cm) for 36 sustainable forest management plans authorized by SEMA-MT containing *Handroanthus* spp. distributed in Open Ombrophile Forest (OOF), Dense Ombrophile Forest (DOF), Evergreen Seasonal Forest (ESF), Seasonal Forest/ Ombrophile Forest transition zone (SFOF), and Seasonal Forest/ Savanna (SFSAV) transition zone in Mato Grosso.

Source: IBGE (2015).

The densities of *Handroanthus* spp. (Table 1; Figure 4) were compatible with the densities reported in spreadsheet SC-21 (Rondônia and Mato Grosso) of Project Radambrasil (1980) for all forest types (Table 2). They were also similar to the densities reported by Schulze et al. (2008) in different states of the Brazilian Amazon, ranging from 0.10 trees ha^{-1} to 0.45 trees ha^{-1} (DBH ≥ 30 cm) for *H. serratifolius* and from 0.08 trees ha^{-1} to 0.19 trees ha^{-1} (DBH ≥ 30 cm) for *H. impetiginosus*.

Data from Project Radambrasil (1980) for the main tree species commercialized in Mato Grosso showed that ipê trees (*Handroanthus* spp.) were among the fifteen species with the highest density by area, occupying fourth place (Table 4). They also showed that for more than 40 years, the densities of most timber species were already less than or equal to one tree ha^{-1}.

Table 4. Number of trees ha^{-1} (DBH ≥ 30 cm) in the Amazon's main timber-producing species, from the SC-21 spreadsheet (Juruena) of Project Radambrasil (1980) by forest type.

Tree type (common name)	OOF-SbC	OOF-SbP	DOF-Al	DOF-Sb	SFOF	SFSAV	OFSAV	Mean
Cupiúba	0,17	0,42	0,20	1,91	0,84	0,36	4,25	1,16
Cambará	0,84	0,18	0,40	1,17	0,76	0,94	3,25	1,08
Amescla	0,56	0,23	1,60	0,30	0,98	0,79	0,25	0,67
Ipê	**0,39**	**1,09**	**0,40**	**1,09**	**0,58**	**0,79**	**0,00**	**0,62**
Cedrinho	0,54	0,08	1,00	0,64	0,44	0,58	0,75	0,58
Garapeira	0,29	0,35	1,40	0,38	0,67	0,70	0,00	0,54
Cumaru	0,47	0,35	0,80	0,59	0,40	0,42	0,25	0,47
Itaúba	0,29	0,43	0,20	0,47	0,76	0,91	0,00	0,44
Jatobá	0,15	0,19	1,00	0,42	0,31	0,43	0,00	0,36
Tauari	0,18	0,61	0,00	0,25	0,22	0,30	0,00	0,22
Maçaranduba	0,14	0,13	0,00	0,42	0,00	0,12	0,00	0,12
Cedro-rosa	0,12	0,13	0,00	0,15	0,07	0,09	0,25	0,11
Muiracatiara	0,02	0,04	0,00	0,00	0,02	0,30	0,00	0,05
Angelim-pedra	0,13	0,03	0,00	0,02	0,00	0,09	0,00	0,04
Freijó	0,00	0,02	0,00	0,11	0,07	0,00	0,00	0,03

OOF-SbC = Submontane Open Ombrophile Forest with vines; OOF-SbP = Submontaine Open Ombrophile Forest with palms; DOF-Al = Alluvial Dense Ombrophile Forest; DOF-Sb = Submontane Dense Ombrophile Forest; SFOF = transition zone between Seasonal Forest and Ombrophile Forest; SFSAV = transition zone between Seasonal Forest and Savanna; OFSAV = transition zone between Ombrophile Forest and Savanna.

Source: Project Radambrasil (1980).

Note that with the results from Acre and Mato Grosso, less than one tree ha^{-1} is the density pattern for most species in the Amazon region (Pitman et al., 1999) and other tropical forests (Pires; Prance, 1977). Schulze et al. (2008) stated that the densities of *Handroanthus* species are low, and according to Technical Note 004/2019 issued by the Botanical Garden (CNCFlora, 2019), this was basis for the suggestion that the species be classified as vulnerable and added to the CITES list of threatened flora and fauna. But this concern with per-hectare density is mistaken when species density in the Amazon is considered. According to Durigan (2012), considering a species sampled with less than one individual per hectare as "rare" is an oversimplification; this author claims that such a classification is only possible between species within the same community. Most inventories of natural forests conducted by research institutions and universities in the past used 100 hectares as the minimum unit of reference (UFSM, 1979; FUNTAC, 1992; 1999).

The genus *Handroanthus* has: a) broad occurrence in Brazil (SpeciesLink Network, 2021) and in the state of Mato Grosso (Figure 2); b) occurrence in more than one habitat, since it occurs in different forest types (Figure 2); c) density that can be considered normal, since less than one tree ha^{-1} is the expected pattern for the Amazon (Pitman et al., 1999), although it also occurs in some places at densities that can be considered high (more than one tree ha^{-1}, as seen in Figure 3). These three criteria rule out the classification of *Handroanthus* as “rare,” according to Rabinowitz (1981).

Density and occurrence of *Handroanthus* spp. within SFMPs

Focused areas with more or fewer trees were distributed throughout the selected annual production units (APUs) for the density analysis, based on the forest census from Mato Grosso (Figure 5). In the APU areas located in OOF areas (Figures 5A and 5B) and in the transition zone between seasonal forest and savanna (SFSAV) (Figures 5G and 5H), the higher density of trees is apparently related to the higher relief elevation.

Substantial variations in density were visible in each APU. For example, in the area located in Dense Ombrophile Forest (DOF) (Figures 5C and 5D), the lowest density class (blue) had 22 times fewer trees than the highest density class (red). In SFOF and SFSAV forest types (Figures 5F, 5G, 5H, and 5I), the lowest density class had no trees. In other words, considering that each density class occupies approximately 20% of the total area of the APU, in 20% of the areas contained within these two APUs no individuals of this species were found (DBH ≥ 30 cm). Within an entire APU, certain regions may not be preferred by the species, resulting in underestimates of the actual number of trees per hectare.

Variations in the density of *Handroanthus* spp. in each forest type (Figures 2 and 4) and within each APU (Figure 5) indicate that environmental and microclimatic factors may be associated with the occurrence of the species (Alvarez-Buylla et al., 1996). For example, higher elevation (which appears to be related to higher occurrence; Figure 3) is associated with other variables such as water availability and soil type (Ivanauskas; Assis, 2009), and indicates locations preferred by the species.

Forest species are not randomly distributed, and can be found in specific climatic zones and soil types or over large geographical areas (Oliver; Larson, 1990). Additionally, these authors state that they may occur only in certain strata of the canopy or in association with other species, and the same area may be occupied by totally different groups of tree species at different times. This variation reinforces the importance of separately analyzing each area under management rather than determining general protocol for states, forest types, or biomes.

Thorough sampling is important to truly understand the distribution of the species (Durigan, 2009). If sampling is restricted to an area where clusters of higher tree densities are found or where the species naturally occurs less frequently, the results may lead to false conclusions. If tree numbers were overestimated due to inadequate sampling in high-density locations, projected available volumes would far exceed the actual volumes in the field. If a species is sampled in places with low natural occurrence it may be misdiagnosed as rare, with consequences that could have negative repercussions in the productive sector.

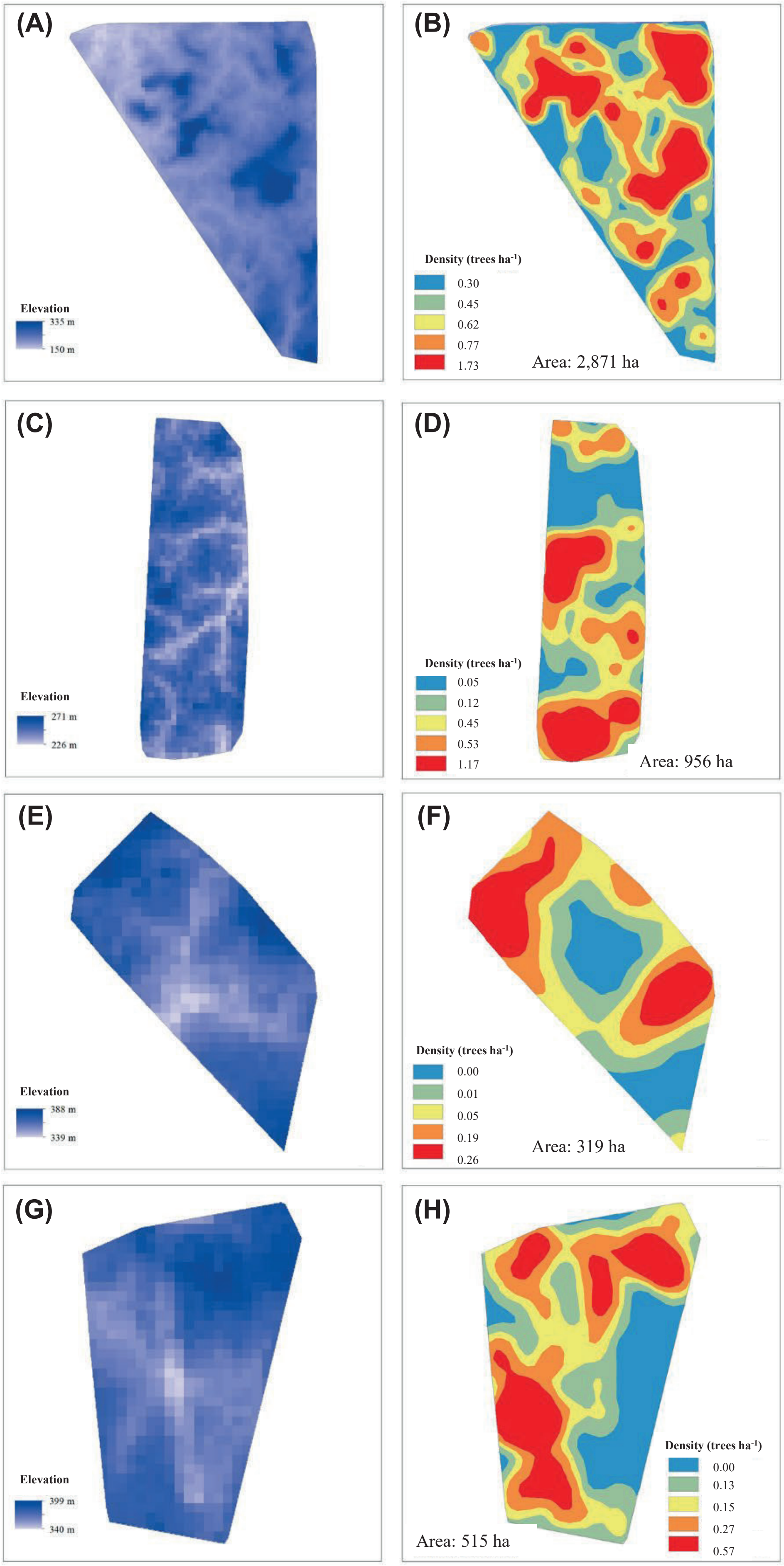

Figure 5. Elevation (left column) and standard tree density pattern (DBH ≥ 35 cm; right column) in sustainable forest management plans authorized by the MT State Secretary of the Environment in Open Ombrophile Forest (A, B), Dense Ombrophile Forest (C, D), transition zone between Seasonal Forest and Ombrophile Forest (E, F), and transition zone between Seasonal Forest and Savanna (G, H).

Source for elevation models: Weber (2004).

Representativity of *Handroanthus* spp. among Amazon Forest flora

Ipê species were among the 20 species with the highest importance value index (IV) in the two main forest types in Acre (Table 5). In Mato Grosso, in three of the five forest types found in the Amazon biome, ipê species were among the 15 with the highest mean IV (Table 6). Amaro (1996), in a study of IV along the BR-364 highway in Acre, reported that yellow ipê was among the ten species with the highest IV in eight of the nine forest types studied. Schulze et al. (2008) reported occurrences of these species throughout the Amazon, and in higher densities in portions of the states of Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, and Roraima. This shows the broad occurrence and importance of ipê species in the Amazon biome.

Table 5. Twenty species (common name) with the highest mean importance value index (IV) in Acre, based on forest census presented to IMAC (AC), by forest type.

Mean IVI rank	OOF	DOF
1st	Caucho	Guariúba
2nd	Ucuúba-vermelha	Pau-garrote
3rd	Cumaru-cetim	Abiu
4th	Cajá	Cedromara
5th	Samaúma-barriguda	Tauari
6th	Abiu	Caucho
7th	Samaúma-preta	Amarelão
8th	Branquilho	Tamarina
9th	Cedro	Cumaru-cetim
10th	Cumaru-ferro	Breu-vermelho
11th	Xixuá	Castanheira
12th	Guariúba	Cumaru-ferro
13th	**Ipê**	Bajão
14th	Muiracatiara	Jacareúba
15th	Matamatá	Caxeta
16th	Mirindiba	Cedro
17th	Matamatá-branco	Muiracatiara
18th	Cinzeiro	Mirindiba
19th	Manitê	Ingá
20th	Amarelão	**Ipê**
Mean number of species found	59	67

OOF = Open Ombrophile Forest; DOF = Dense Ombrophile Forest (IBGE, 2015).

Table 6. Fifteen species (vernacular name) with the highest mean importance value index (IV) in the Mato Grosso Amazon, by forest type.

Mean IV rank	OOF	DOF	SFOF	SFSAV	ESF
1st	Burra-leiteira	Amescla-aroeira	Cambará	Cambará	Cambará
2nd	Matamatá	Cega-machado	Angelim-pedra	Angelim-pedra	Amescla
3rd	Tauari	Angelim-pedra	Angelim-falso	Tachi	Canela
4th	Tachi	Tachi	Canela	Cumaru	Cupiúba
5th	Jatobá	Cupiúba	Jatobá	Cedrinho	Cedrinho
6th	Angelim-pedra	Jatobá	Farinha-seca	Currupicha	Cumaru
7th	Guariúba	Fava-orelha-de-macaco	Tachi	Cupiúba	Itaúba
8th	Amescla-aroeira	Cambará	Itaúba	Canela	Faveira
9th	Muiracatiara	Tauari	Uchi	Angelim-amargoso	Garrote
10th	Angico-branco	Caixeta	Cumaru	Jatobá	Angelim-pedra
11th	Abiu	**Ipê**	Cedrinho	Faveira-dura	Maçaranduba-falsa
12th	**Ipê**	Goiabão	Muiracatiara	Bacuri	Quaruba
13th	Caixeta	Garapeira	Angelim-amargoso	Sucupira	Caroba
14th	Mirindiba	Jutaí	Caju-da-mata	**Ipê**	Farinha-seca
15th	Roxinho	Maçaranduba	Mirindiba	Caixeta	Perobinha
Mean number of species found	41	48	26	33	27

OOF = Open Ombrophile Forest; DOF = Dense Ombrophile Forest; ESF = Evergreen Seasonal Forest; SFOF = transition zone between Seasonal Forest and Ombrophile Forest; SFSAV = transition zone between Seasonal Forest and Savanna (IBGE, 2015).

Assessing diameter distribution of remaining and harvested trees in APUs after forest management

In the APUs selected to demonstrate the categories in which *Handroanthus* spp. trees are classified, at least 25% of the trees with DBH ≥ 35 cm are maintained as remnants, as in the case of the APU located in the SFSAV area (Figure 6D). In areas where the species is more scarce (SFOF, for example), only one tree was selected for cutting (Figure 6C). In the areas of Ombrophile Forest (Figures 6A, 6B, 6C and 6D), where higher densities of *Handroanthus* trees are found, less than 40% of the trees with diameters exceeding the minimum cutting diameter of 50 cm (Brasil, 2006) were selected for cutting. Based on the SFMP data provided by IMAC-AC and SEMA-MT, approximately 0.1 ha^{-1} of *Handroanthus* spp. trees were permitted to be cut in SFMPs.

The proportion of trees remaining in the forest after use (Figure 6) shows the stock of remaining trees distributed throughout the area under management. These trees indicate that management is a valid strategy for species conservation (Braz et al., 2015) that complements preservation via protected forest areas, such as permanent preservation areas, full-protection conservation units, and Indigenous lands. Additionally, in places where fewer numbers of trees in this species are found, for example in SFSAV areas (Figure 6C), practically all the trees remain in the APU.

In the SFMP, Brazilian legislation (Brasil, 2006) determines that trees with diameters exceeding 50 cm (MCD) can be cut, but 10% must be retained for seed production. In this way, trees with diameters smaller than the MCD and seed producers are categorized as “remnants” within an APU. These remaining trees, especially those in diameter classes below the MCD, are vigorous (Braz et al., 2021) and accumulate wood volumes for the next cycle, thus ensuring the management is sustainable.

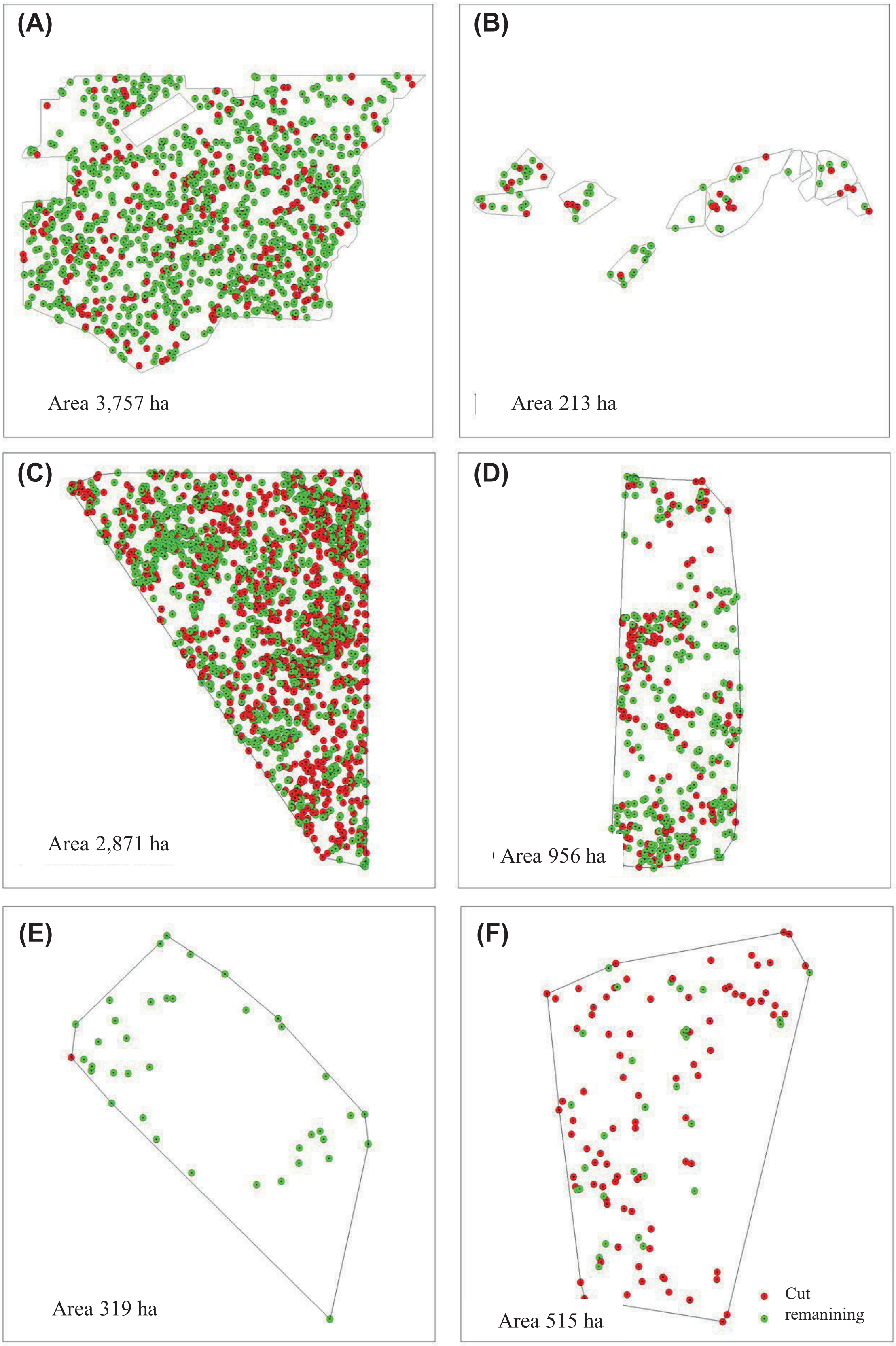

Figure 6. Proportion of trees (DBH ≥ 35 cm) authorized for cutting and remaining trees (below minimum cutting diameter and bearing seeds) in sustainable forest management plans authorized by the Acre Environmental Institute (IMAC-AC) in Open Ombrophile Forest (A) and in Dense Ombrophile Forest (B), and by the Mato Gross State Secretary of the Environment (SEMA-MT) in Open Ombrophile Forest (C), Dense Ombrophile Forest (D), transition zone between Seasonal Forest and Ombrophile Forest (E), and transition zone between Seasonal Forest and Savanna (F). The trees with DBH < 35 cm are not counted in the census, but it is important to remember that they are all kept as remnants.

Records of *Handroanthus* species in herbariums versus real occurrence

In Acre, 19 botanical samples of *H. serratifolius* were catalogued in the SpeciesLink Network (2021) in the municipalities of Mâncio Lima, Tarauacá, Sena Madureira, Senator Guiomard, and Brasileia, and three samples of *H. impetiginosus* were catalogued from the municipality of Sena Madureira (Figure 7). In the municipalities where high densities of *Handroanthus* spp. were recorded, such as Feijó (Figure 2), there were no records of any of the species in the SpeciesLink Network. In more remote regions of this state, farther from the BR-346 highway and mainly composed of conservation units (Brasil, 2018) and Indigenous lands (Funai, 2019), there were also no records of botanical samples of *Handroanthus* spp.

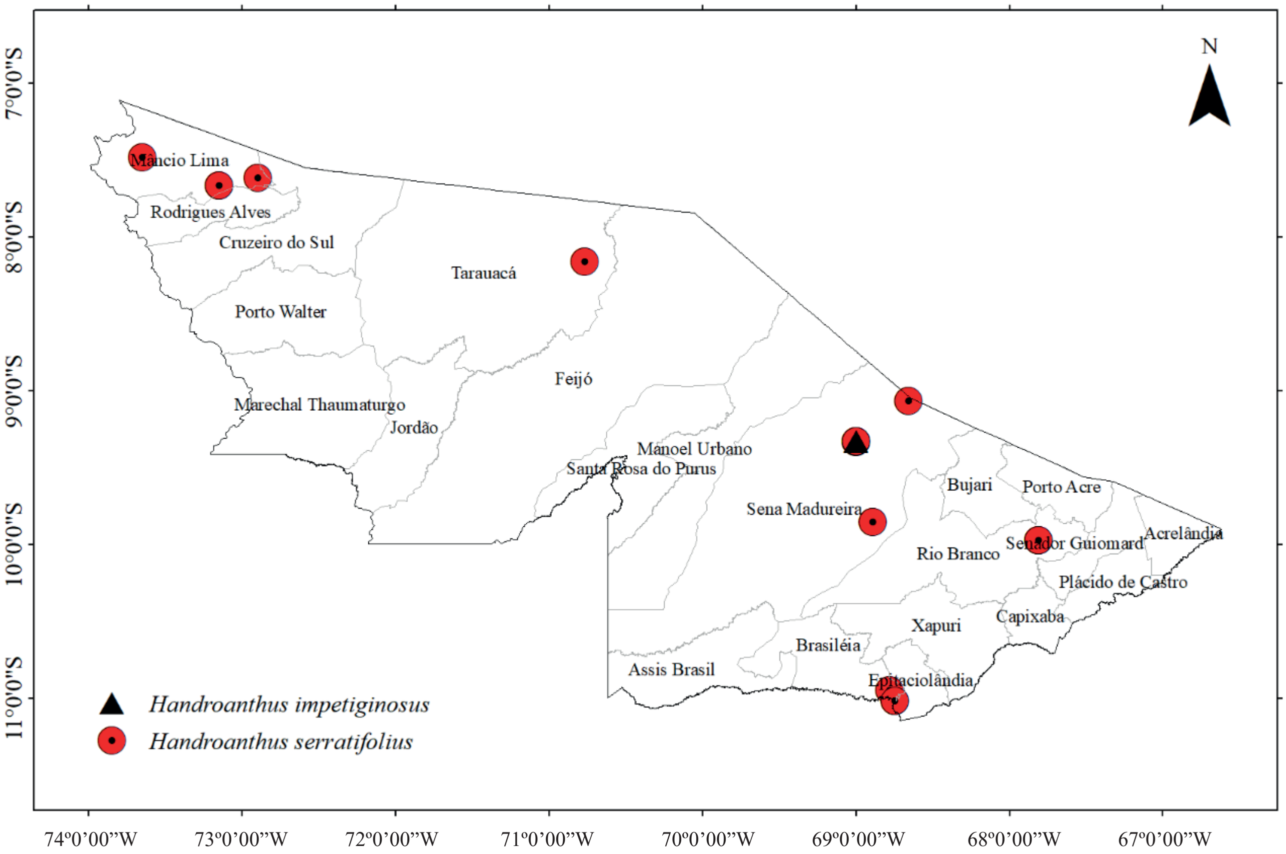

Figure 7. Distribution of the botanical samples of *Handroanthus impetiginosus* and *H. serratifolius* catalogued in the SpeciesLink Network in municipalities in the state of Acre.

Source: SpeciesLink Network (2021).

The samples of *H. impetiginosus* registered in the SpeciesLink Network for Acre (2021) were collected in 1933 and were concentrated in only one place within the municipality of Sena Madureira, and were registered with the same geographical coordinates. In the occurrence map for *H. impetiginosus* published by the National Center for Flora Conservation at the Rio de Janeiro Botanical Garden Research Institute (CNCFlora, 2012), which led this institution to classify this species as vulnerable, only the three points registered in the SpeciesLink Network were considered as occurrences for the species.

When we consulted various herbariums at Brazilian research and teaching institutions about why so few records of *Handroanthus* species exist, we learned that new records of species of this or other genera are only catalogued in very specific cases, and that if a high-quality copy already exists to ensure representation and identification of other samples, new records are unlikely to be added. According to the curators we consulted, only new specimens that enter the collection are registered in programs like Brams, REFLORA, and Jabot, which feed SpeciesLink. Specimens collected for other research projects and which are confirmed in herbariums are not documented. As a result, very few records are recovered, and most are quite old. The scientific literature clearly shows that samples of these species are identified by specialists from research and institutional institutions as part of flora surveys for various research projects, but they are not sent to be incorporated into the collections at herbariums (Freitas et al., 2017; Gama, 2017; Andrade et al., 2019; Vieira et al., 2021).

The records for *H. impetiginosus* and *H. serratifolius* in the SpeciesLink Network (SpeciesLink, 2021) for Mato Grosso showed that these species occur in all of the state's biomes, and approximately half of the samples were located in the Amazon (Figure 8).

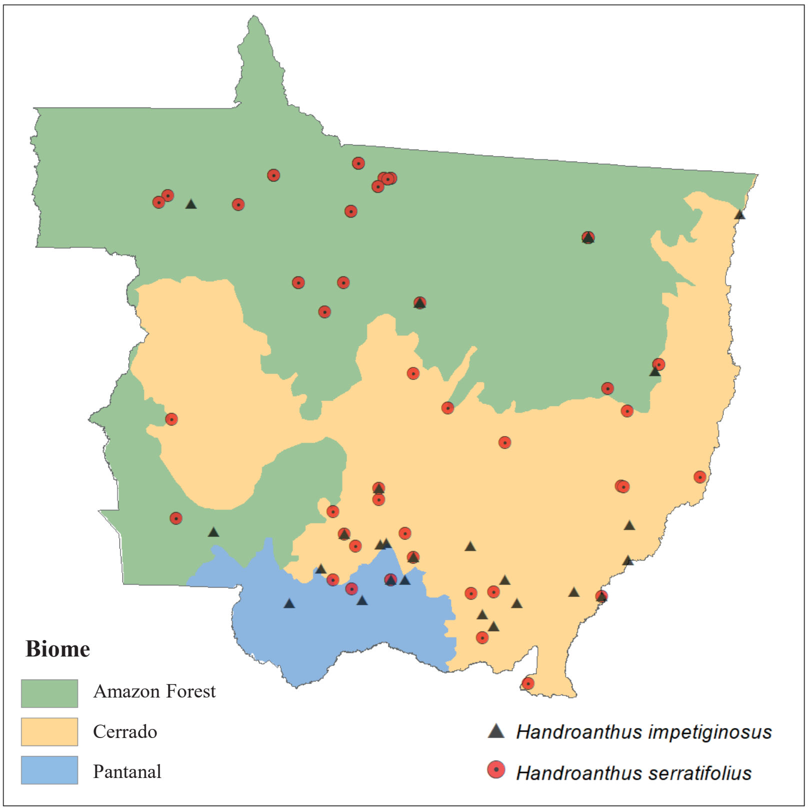

Figure 8. Distribution of botanical samples of *Handroanthus impetiginosus* and *H. serratifolius* catalogued in the SpeciesLink Network in municipalities in the state of Acre.

Source: SpeciesLink Network (2021) and IBGE (2015).

The density map for the genus *Handroanthus* generated from forest census in forest management plans (Figure 4) shows that herbariums did not have records of these species in some high-density sites (Figure 8), such as the northwest region. The microregion of Aripuanã, which according to the forest census has high densities of *Handroanthus* spp., has only one individual of *H. impetiginosus* and three of *H. serratifolius* catalogued in herbariums.

Of all the samples catalogued in herbariums in the state of Mato Grosso, 47% of *H. impetiginosus* and 33% of *H. serratifolius* are located in the microregion of northern Araguaia, especially in São José do Xingu (SpeciesLink, 2021). Most of these samples were recorded with the same geographical coordinates, indicating that they are all part of the same forest inventory. The high representativity of *Handroanthus* species in this microregion clearly indicates not higher occurrence, but rather greater sampling.

The microregions of Alta Floresta, Alto Pantanal, Cuiabá, and Sinop, home to the main forestry schools in the state of Mato Grosso, accounted for 24% of the cataloged samples of *H. impetiginosus* and 35% of *H. serratifolius*. The higher numbers of trees catalogued in these microregions are probably associated with scientific research at universities that often concentrate their research near campus because of logistics and budget constraints for fieldwork.

In this way, some trends are noted in the sites where botanical samples of the species are collected that could lead to errors in estimating species distribution based on these records.

The SpeciesLink Network integrates data from various herbariums around in the world, and the records serve as the basis for modeling species occurrence. Models of species occurrence, in turn, are used to classify species into vulnerability classes (CNCFlora, 2012; Brasil, 2014; 2021). But a lack of sampling for species cataloged in the herbariums can be seen when the forest census data from forest management plans are compared with those in the SpeciesLink Network. This gap in the data could lead to mistaken conclusions about the vulnerability of these species, since it does not represent their actual occurrence.

Species records in herbariums are a powerful tool that can help identify species in forest inventories, reporting which species occur in the region under study. But using these data to model species occurrence depends on farther-reaching collection of botanical material that covers the state as a whole, representing all the areas where these species actually occur. Until more representative sampling is conducted, only sampling data from herbarium should be used very carefully, since they present limitations.

Handroanthus **spp. trees in the remaining forests of Acre**

In 2020, remaining forests in Acre totaled 124,000 km², representing 75% of the state's territory (Figure 9). Between 1985 and 2020, an area of more than 14,000 km² was deforested (approximately 10% of the total area). But deforestation has slowed in the state of Acre in recent decades compared to the state of Mato Grosso, where more than 40% of the Amazon Forest has been deforested as the agricultural frontier expands (Figure 10). The lower deforestation rates in the state of Acre may be related to state management that is strongly based on environmental issues, protection of extensive forest areas by creating conservation units, and demarcation of Indigenous lands, expansion of forest management in private properties and public forests, and the creation of differentiated settlement projects (Franke, 2012).

The forest types most affected by deforestation were lowland Dense Ombrophile Forests (concentrated in the regions of Rio Branco and Brasileia) and Alluvial Open Ombrophile Forest around the large rivers. The concentrated changes in land use in these areas may be associated with the expansion of the agricultural frontier, proximity to municipalities with higher population density, and accessibility to transport routes (roads and rivers).

Considering the average density of *Handroanthus* spp. trees recorded in diagnostic inventories in Acre (Figure 2) and the area deforested between 1985 and 2020, we can infer that approximately 2.7 million trees in this genus with DBH ≥ 10 cm were cut as part of deforestation (land use change).

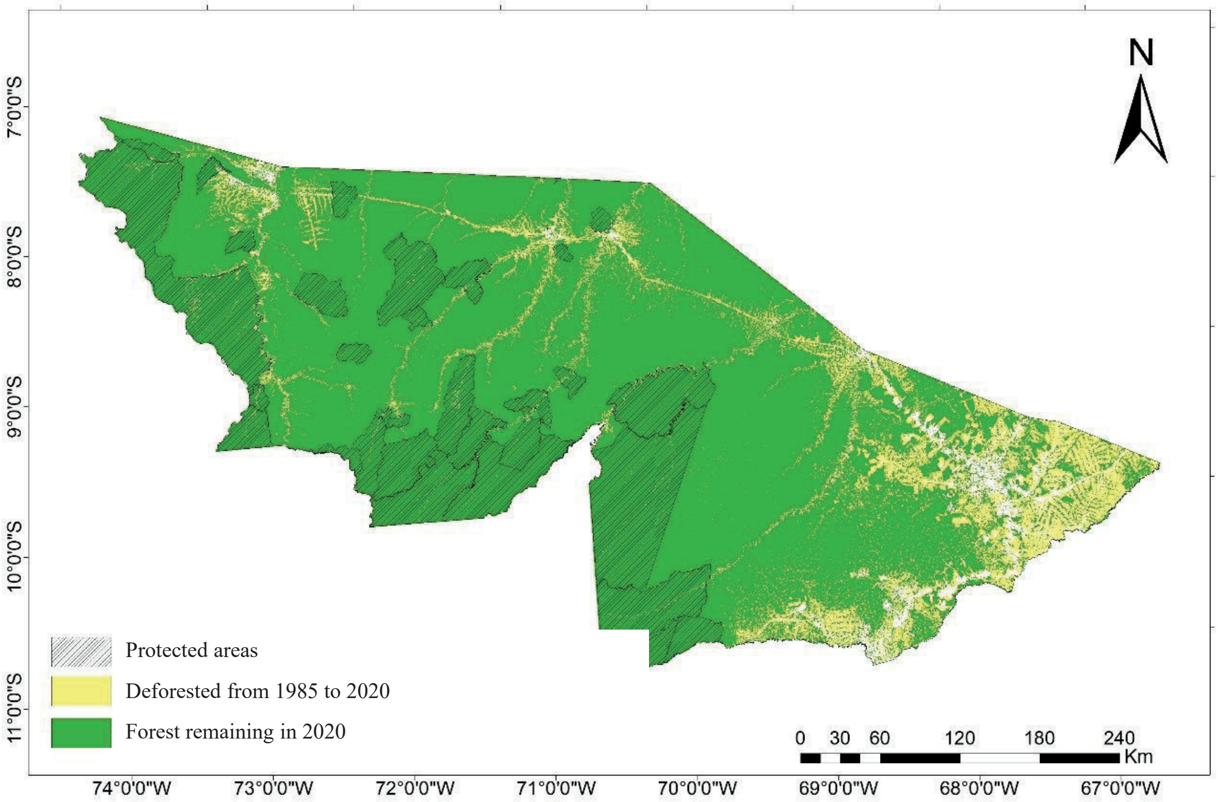

Figure 9. Clearing of the Amazon Forest in Acre between 1985 and 2020, including areas with forests, protected areas (full-protection conservation units, and Indigenous lands).

Source: MapBiomas Project (2021), Funai (2019), Brasil (2018).

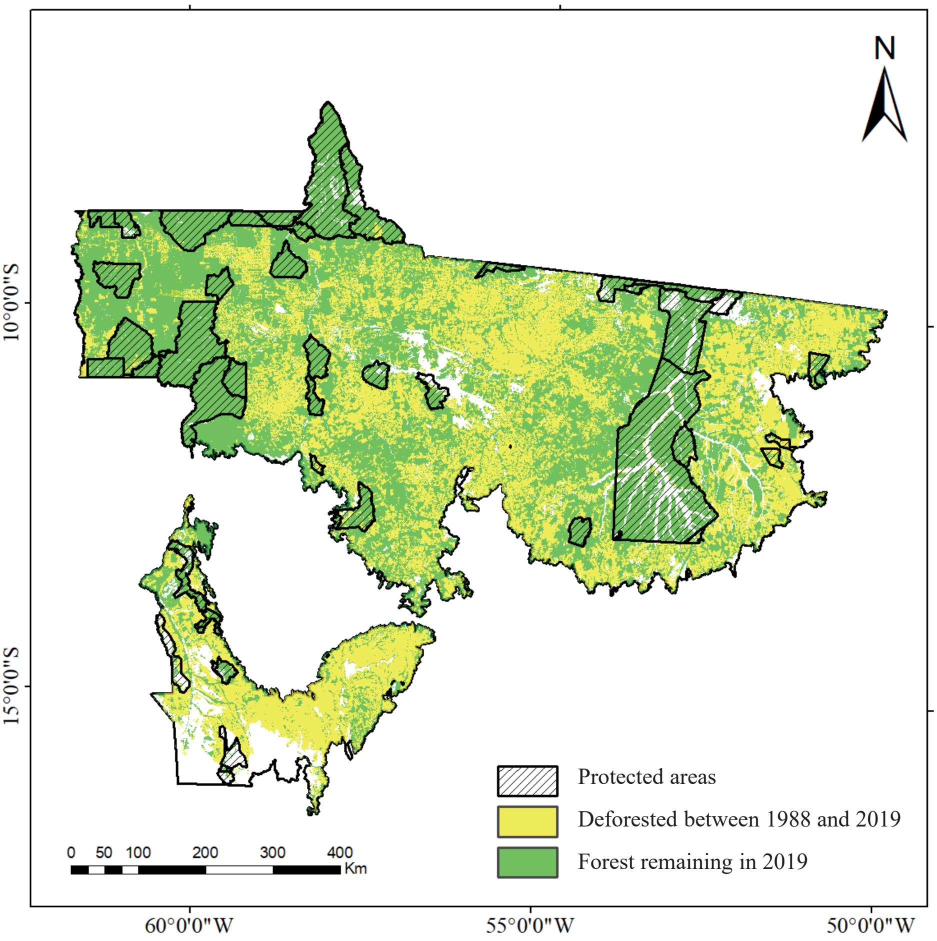

Figure 10. The Amazon in Mato Grosso in 2019, including forested areas, protected areas (full-protection conservation units and Indigenous lands), and areas deforested since 1988.

Source: MapBiomas Project (2021), Funai (2019), Brasil (2018).

Nearly all (99%) of the deforested area lay outside protected areas (full-protection conservation units and Indigenous lands); these areas are clearly important for conserving species in their natural habitat. In Acre, 20% of the state is composed of fully protected forests that occupy roughly 35,000 km², an area greater than all of Belgium. Most of these forests are OOF, where *Handroanthus* spp. occur the most, and protect huge stocks of these species.

Forest census for areas of remaining forest in Acre in 2020 were used to estimate that there were about 35 million *Handroanthus* spp. trees (DBH ≥ 10 cm), and that 31.7 million of these trees had diameters smaller than the MCD of 50 cm (Brasil, 2006) or were in fully protected areas where management could not be applied (Table 7). For *Handroanthus* spp. trees with DBH ≥ 50 cm which occur outside fully protected areas (about 4 million trees), SFMPs require 10% of the trees to be maintained as breeding stock. In other words, only 3.6 million of the *Handroanthus* spp. in Acre can be managed, representing approximately 10% of the total trees of these species.

Table 7. Areas of remaining forest and estimated number of Handroanthus spp. trees in 2020 in the main forest types found in Acre.

Category		Forest types		Total
		OOF	DOF	
Remaining forest area in 2020 (km²)	Total	109,646	13,922	123,569
	Not protected	77,148	11,372	88,519
	Protected	32,499	2,551	35,049
Handroanthus spp. trees in 2020	Total (DBH ≥ 10 cm)	34,372,707	1,886,758	36,259,464
	Manageable total (DBH > 50 cm)	4,218,281	347,983	4,566,264
	Total non-manageable (10 ≤ DBH < 50 cm and/or in protected areas)	30,154,426	1,538,775	31,693,201

OOF = Open Ombrophile Forest; DOF = Dense Ombrophile Forest (IBGE, 2015).

Source: MapBiomas Project (2021), Funai (2019), and Brasil (2018).

Handroanthus spp. trees in the remaining forests of the Amazon in Mato Grosso

In 2019, the Legal Amazon in Mato Grosso contained 252,790 km² of Amazon Forest biome (Figure 10); 76,066 km² comprised protected areas (full-protection conservation units and Indigenous lands). From 1988 to 2019, 41% of the Amazon Forest in this state was converted to other land uses, totaling 175,396 km².

In this scenario, protected areas like conservation units and Indigenous lands and areas under forest management are extremely important for maintaining and conserving species and the Amazon Forest as a whole. These areas form ecological corridors with average deforestation rates 70% lower than in non-protected lands (Schwartzman et al., 2013).

The importance of forest areas that remained without changes in land use or cover was evident when the proportion of remaining forest areas was compared with the deforested area in each forest type (Figure 10). Ombrophile Forest types (OOF and DOF) in the north of Mato Grosso contain the highest proportion of protected areas and remaining forests, and had the lowest rates of deforestation during the period of study. Besides the presence of large, protected areas, accessibility issues may have impeded deforestation in these forests, since they are farther from the large urban centers (IBGE, 2012).

The forest type with the largest area of remaining forest in proportion to total area is the DOF in northwestern Mato Grosso (Table 8), which was also the least deforested from 1988 to 2019 (Figure 10). In 2019 in DOF areas, 40,417 km^2 contained forests; 34% of this area was in full-protection conservation units and Indigenous lands. The SFOF and SFSAV forest types, mainly distributed in the central-south region of Mato Grosso, had the highest percentages of deforestation, accounting for 49% of the total area, and 2% of the deforested area was located within protected areas. These forest types also have a smaller proportion of protected area (approximately 21% of the total), spanning 12,072 km^2 in a total of 58,344 km^2 of remaining Amazon Forest.

Table 8. Remaining forest areas and estimated number of *Handroanthus* spp. trees (DBH ≥ 35 cm) present in the remaining Amazon forests in Mato Grosso in 2019, by forest type.

Category		Forest type					Total
		ESF	OOF	DOF	SFSAV	SFOF	
Area of remaining forest in 2019 (km^2)	Total	87,642	66,387	40,417	35,192	23,152	252,791
	Manageable	61,499	42,288	26,666	29,380	16,892	176,725
	Protected	26,143	24,099	13,752	5,813	6,259	76,066
Handroanthus spp. trees in 2019	Total (DBH ≥ 35 cm)	0	2,298,514	1,173,330	925,892	96,285	4,494,022
	Manageable total (DBH ≥ 50 cm)	0	979,048	624,268	708,528	51,593	2,363,437
	Total non-manageable (35 ≤ DBH < 50 cm and/or in protected areas)	0	1,319,466	549,063	217,364	44,692	2,130,584

OOF = Open Ombrophile Forest; DOF = Dense Ombrophile Forest; ESF = Evergreen Seasonal Forest; SFOF = transition zone between Seasonal Forest and Ombrophile Forest; SFSAV = transition zone between Seasonal Forest and Savanna.

Source: MapBiomas Project (2021), Funai (2019), and Brasil (2018).

Based on the remaining areas of natural forests in Mato Grosso (Figure 10; Table 8), there were an estimated 4.5 million *Handroanthus* spp. trees with DBH ≥ 35 cm in 2019, and approximately 1.5 million of these trees were in protected areas. Of the 3 million trees in areas that could be managed, about 400,000 had DBH measurements between 35 cm and 50 cm, and could not be managed because they were smaller than the minimum cutting diameter (MCD) established by law (Brasil, 2006). In other words, of the 4.5 million *Handroanthus* spp. trees in the Amazon of Mato Grosso (with DBH > 35 cm), approximately 2 million trees could not be managed because their DBH was smaller than the MCD and/or because they were located in protected areas, forming a substantial stock of trees for species conservation.

Additionally, considering that the average density of trees with DBH values between 10 cm and 35 cm was 0.30 trees ha^{-1} (Schulze et al., 2008), it is estimated that there are more than 7 million *Handroanthus* spp. trees in these diameter classes in the Amazon, a significant stock.

The mean density of *Handroanthus* spp. trees in the Amazon of Mato Grosso in 2019 was 0.48 trees ha^{-1} (DBH ≥ 10 cm), considering the mean density estimated by Schulze et al. (2008) for trees with DBH between 10 cm and 35 cm and the density of trees with DBH ≥ 35 cm, calculated according to the average number of trees per forest type (Table 8).

Based on the area of remaining forest in Mato Grosso (Table 8), 14 million hectares will remain as forests in the form of legal reserve areas (where only forest management is permitted), demonstrating the significant potential for protection and conservation of *Handroanthus*. Furthermore, there are 7.6 million hectares in preservation areas, since these include forests in Indigenous reserves and full-protection conservation units.

The high numbers of ipê trees in the remaining forests in Acre (Table 7) and Mato Grosso (Table 8), especially those with DBH values measuring less than the current MCD of 50 cm (Brasil, 2006) and within protected areas, ensures conservation of these species. Even when we consider the harvest of trees with DBH values above the MCD in areas authorized for forest management, the remaining stock is still substantial, with no indications that these species are at risk of extinction. Note that low-impact forestry (LIF) as a management technique must meet the following criteria: (a) minimize damage to the environment; (b) minimize operating costs and boost work efficiency; and (c) minimize waste from operations (Dionisio et al., 2018).

When LIF techniques are respected, forest management also favors natural regeneration, since clearings are opened and competition with larger trees is consequently reduced (Bentos et al., 2017; Schwartz et al., 2017). For this reason, the *Handroanthus* spp. trees maintained in fully protected areas as well as those in areas intended for forest management comprise a large reserve of these species that remains dynamic, reproducing and maintaining their diversity (Martins et al., 2012).

Conversion of land use and cover in Acre and Mato Grosso is principally the result of establishing areas for agriculture and ranching (MapBiomas Project, 2021), and the wood from this deforestation is often not used at all, but rather burned or simply left to rot. Again, conversion of land use and cover cannot be considered as part of the management of natural forests. In areas under forest management, the remaining trees form renewable commercial stocks for future cutting cycles (Seydack, 2012; Braz et al., 2012), and the land remains covered with forests.

For this reason, the risk to the survival of these species lies in the conversion of land use and cover to other uses (such as agriculture and urbanization), rather than forest management. This becomes clear when the number of *Handroanthus* spp. trees per hectare is calculated as a result of the conversion of land use and cover (0.48 trees ha^{-1}) in Mato Grosso (Figure 10); this value is approximately 340% higher than the number of trees authorized for cutting in an APU (0.14 trees ha^{-1}), calculated according to Table 7.

Botanical confirmation of *Handroanthus* spp. in the sample inventories

The species *H. serratifolius*, *H. capitatus* (Bureau & K. Schum.) Mattos, *H. impetiginosus,* and *H.* cf. *incanus* (A.H. Gentry) S.O. Grose were identified in the sampling inventory for Acre; the last species still requires confirmation with fertile material, and may represent a new species that has not been previously documented in the state. Because of the season when the sampling inventory was conducted (August), there were no trees with reproductive structures, and new samples including fertile material must be collected for definitive confirmation of the botanical identification.

In Mato Grosso, three different species were determined for the trees identified as ipê. The trees identified in the field as yellow ipê referred to the species *H. serratifolius* and *H. ochraceus* (Cham.) Mattos, and those considered purple ipê were the species *H. impetiginosus*. Fertile material could not be collected because of the season when the inventory was conducted. Two samples classified only up to the genus level appear to resemble *H. impetiginosus*, according to the botanist we consulted. Another sample also identified to the genus level may belong to a taxon that has not yet been described, or be an extension of some other taxon. Again, fertile material is required for definitive identification of these samples (those classified at the genus level and others).

Although there are different species of the genus *Handroanthus* in both states, they are all traded under the same common name as “ipê,” often with no differentiation between yellow or purple. A clear and significant limitation of forest inventories is botanical identification of species, since they often cannot be distinguished by the trunk, and fertile material is not always present (or the canopy cannot always be accessed) for sample collection.

Considering these difficulties, it would be useful to include samples collected from the species present as part of the pre-commercial inventory in order to expand knowledge about the occurrence of the genus *Handroanthus* and its specimens.

Diameter increase by diameter class

The mean diameter increments of *H. impetiginosus* and *H. serratifolius* did not differ statistically between species in Acre (Figure 11a) or Mato Grosso (Figure 11b). Growth was slower in the smaller diameter classes than the larger classes. The mean annual increments of trees with diameters in the 25–60 cm range remained relatively constant, with no statistical differences in either species. The maximum mean annual increment for *H. serratifolius* in both states was seen in trees in the diameter classes centered between 65 cm and 75 cm DBH, with average growth of 0.69 cm year^{-1} in Acre and 0.55 cm year^{-1} in Mato Grosso. The maximum mean annual increment for *H. impetiginosus* occurred in Acre, with 0.37 cm year^{-1} for trees in the diameter class centered at 35 cm and in Mato Grosso, with 0.60 cm year^{-1} for trees in the class centered at 45 cm. In Mato Grosso, diameter growth was more variable in *H. impetiginosus*, especially for trees in the classes centered at 45 cm and 55 cm.

In natural forest conditions without management, the diameter increases tend to be smaller than in managed forests. In Mato Grosso, for example, the gross increment measurements for *H. serratifolius* indicate that 20% of the annual increment exceeded 0.6 cm year^{-1}; for *H. impetiginosus*, 27% of the increment exceeded 0.6 cm year^{-1}. This shows the plasticity of increment in these species, and the potential for gains in wood productivity through adequate management. Greater increases in diameter can be obtained after silvicultural interventions in the forest, opening clearings that favor the growth of the species. Data on growth gains were obtained by Keefe et al. (2009) in Paragominas (Pará State), who removed competing vegetation (except natural regeneration of commercial species) from the forest each year and obtained average increments of 0.75 cm year^{-1} and a maximum of 1.90 cm year^{-1} for *H. serratifolius*. Diameter increments of this magnitude have already been observed for the species under plantation conditions with different spacings between the trees (Yared et al., 1988; Pimentel et al., 2018).

Data on the average increment per diametric class of *Handroanthus* in both states shows that *H. impetiginosus* can reaches higher average growth at smaller diameters (Figures 11A and 11B). Light-opportunistic species usually reach maximum DBH increases lower than climax species, since their growth is directed towards pursuing light until they reach the forest canopy. Once they reach this light, their growth tends to stabilize (Whitmore, 1990). On the other hand, late secondary and climax species have smaller and more constant increments because they survive below the forest canopy as they slowly wait for better light (Lamprecht, 1990). In this way, the increment trends by diameter class indicate that *H. impetiginosus* is a species with more opportunistic characteristics than *H. serratifolius*. This should be addressed in future research in order to understand the growth dynamics of these forest species.

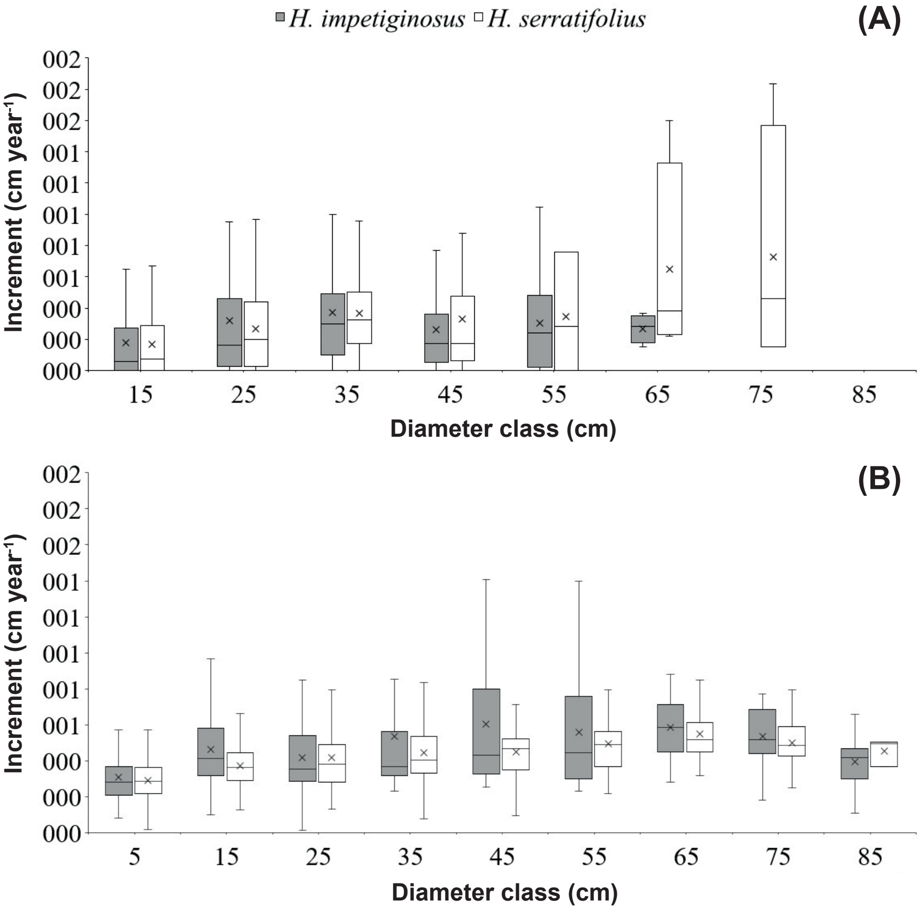

Figure 11. Box plot of the mean annual increment by diameter class for *Handroanthus impetiginosus* and *H. serratifolius* in Acre (A), from permanent plots, and in Mato Grosso (B), from dendrochronological data. Different letters indicate a statistically significant difference between medians, according to the non-parametric Kruskal-Wallis test ($p \leq 0.05$).

But even despite their intrinsic differences, the diameter increment did not differ between species for most commercial diameter classes (DBH > 50 cm) in either state (Figures 11A and 11B). This similarity reinforces that dynamic estimates of the two most important species of *Handroanthus* in the Amazon can be carried out at the genus level (Figure 12). This is important, since most pre-use forest inventories filed with the environmental agencies do not use species-level identification, because of the challenges of differentiating them in the field when the reproductive structures are not present (as mentioned above).

In the permanent plots in Acre, growth of at least 15 *H. serratifolius* trees was measured for diameter classes centered at < 55 cm, while for the classes centered at 65 cm and 75 cm, growth of fewer than five trees was measured. It is important to note that when data from permanent plots are obtained, trees subjected to suppression-type conditions are also included, masking the growth potential of the species. In Mato Grosso, where growth data were collected from growth rings in trees that expressed their growth potential, growth was seen to be constant in both species of *Handroanthus* up to the diameter class centered at 65 cm, and began to decrease after the class centered at 75 cm.

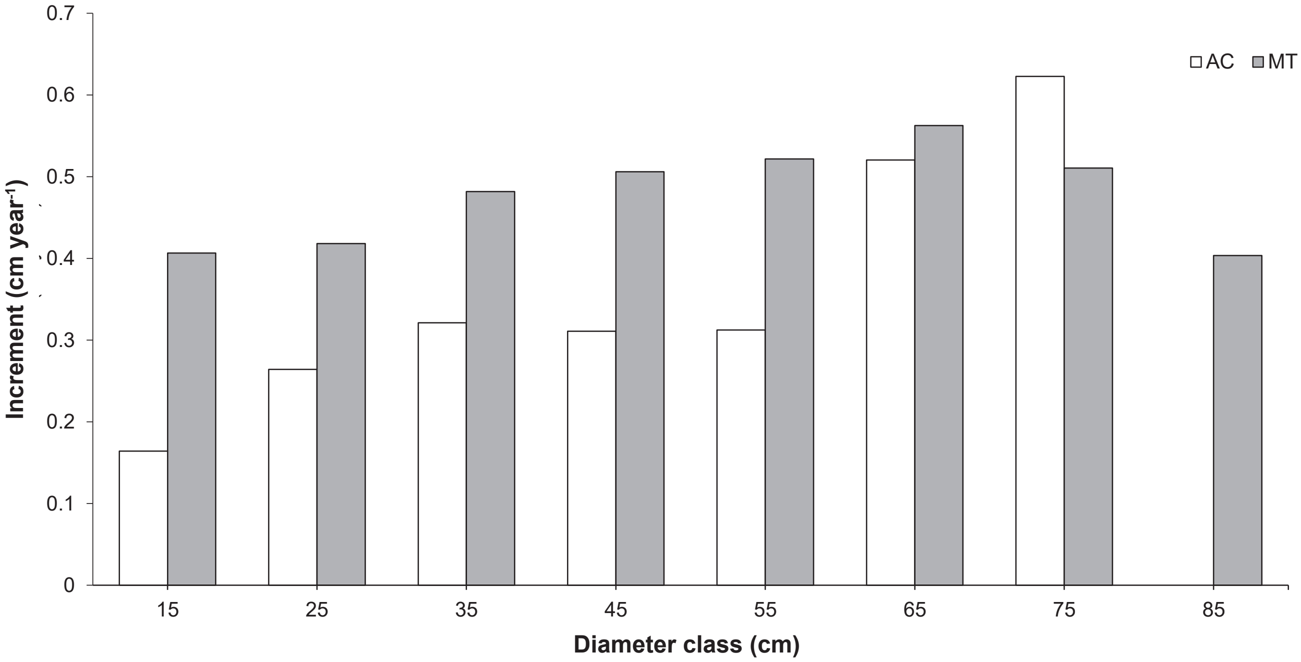

Figure 12. Mean annual increment by diameter class for *Handroanthus* spp. in Acre (from permanent plots) and in Mato Grosso (from dendrochronological data).

The mean increment for *Handroanthus* spp. in Acre (DBH ≥ 10 cm) was 0.36 ± 0.29 cm year^{-1}, and in Mato Grosso was 0.47 ± 0.23 cm year^{-1} (Figure 12). Araújo (2016) found a similar mean increment in a managed area in the state of Acre in DOF (0.42 cm year^{-1}), as did Andrade et al. (2019) in Amazonas (0.45 ± 0.17 cm year^{-1}). But these mean increments were higher than those recorded by Schulze et al. (2008) in permanent plots in Pará, where the values were 0.19 ± 0.22 cm year^{-1} and 0.31 ± 0.28 cm year^{-1} for primary and managed forests, respectively. Differences may be related to edaphoclimatic conditions in the study sites such as light availability, soils, competition between trees, humidity, or water availability (Alvarez-Buylla et al., 1996), or the suppressed trees that were present in the sample group.

Diameter growth equations for *Handroanthus* spp. in Mato Grosso

The Gompertz model best represented the growth cycle for the species and genus *of Handroanthus* spp. (Figure 13). The growth rate of *H. impetiginosus* was seen to be higher between 20 cm and 60 cm, reaching an asymptote and tending to stabilize earlier than *H. serratifolius*. *H. serratifolius*, however, tends to reach larger diameters. The equation adjusted for the genus showed an intermediate trend for both species.

The β_0 parameter in the adjusted growth equations represents the asymptote (in other words, stagnation in the growth of the species) (Burkhart; Tomé, 2012). The asymptotic value of *Handroanthus* spp. did not exceed 90 cm in diameter (Appendix 1), which means that in terms of general growth trends, wood production beyond this diameter is low and few trees will surpass this growth.

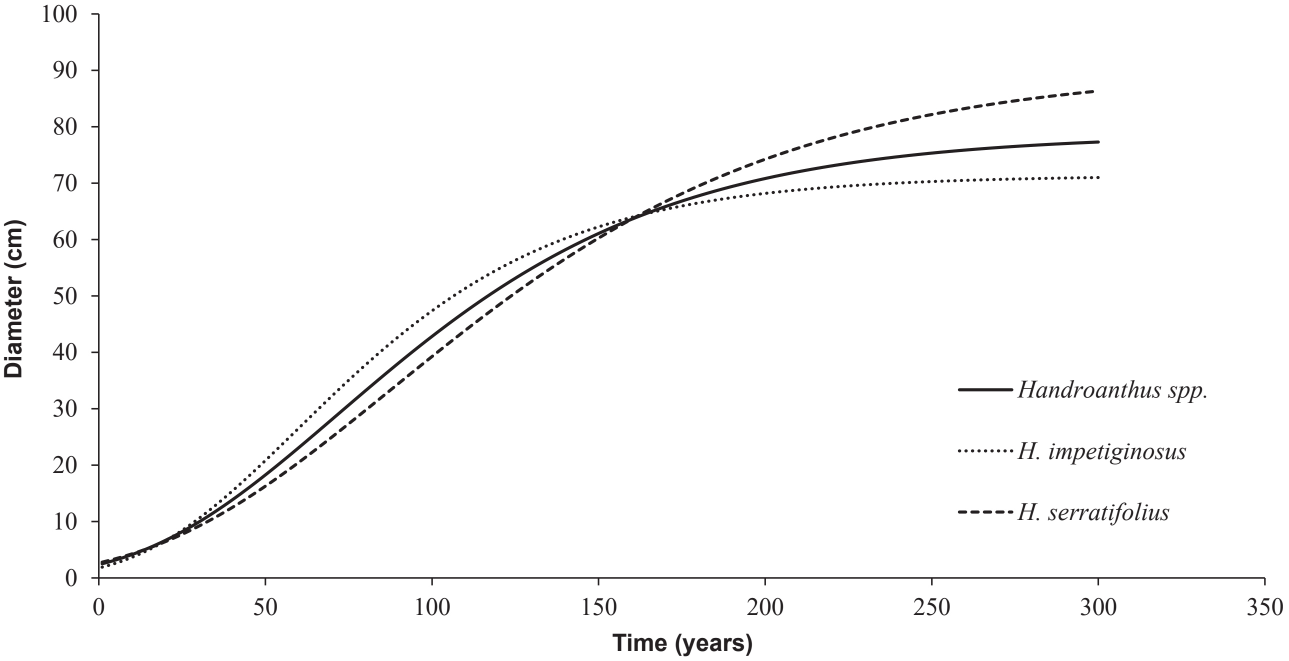

Figure 13. Growth equations adjusted for *Handroanthus* spp., *H. impetiginosus*, and *H. serratifolius* in Colniza, MT, using the Gompertz model (see equation parameters and statistics in the Appendix).

Individual diameter production curves for *Handroanthus* spp. in Mato Grosso

For *Handroanthus* in Mato Grosso, the maximum current annual increment (CAI) occurs at the 29 cm and 46 cm diameters, considering the curves for increase in DBH and in volume, respectively (Figures 14A and 14D). The values for the diameter at which stagnation in diameter growth occurs for the genus (where the CAI and MAI curves meet) are 47 cm and 66 cm, considering the increment curves for DBH and volume, respectively. For *H. impetiginosus*, diametric stagnation occurs at lower diameter values (Figures 14B and 14E), while these values are higher for *H. serratifolius* (Figures 14C and 14F).

Analysis of the MAI and CAI curves provides crucial information for planning sustainable forest management (Assmann, 1970). Identifying the points of maximum CAI and where the increment curves overlap indicates the range of maximum productive potential (full vigor) for the species (Miranda et al., 2018), and the increment curves in DBH best signal this potential (Nyland, 2007; Weiskittel et al., 2011). If intervention in the forest structure of the species occurs before the maximum CAI or after the maximum MAI, the volumetric production of the species will be used inefficiently from a forest management point of view, since the trees have not yet reached or have already exceeded their optimum growth phase (Schöngart, 2008; Braz; Mattos, 2015).

Andrade et al. (2019) derived the increment curves in volume for growth equations adjusted for *H. serratifolius* in Amazonas, and the maximum CAI occurred at approximately 70 cm, higher than the value found for the species in Mato Grosso (54 cm). As mentioned earlier, the average increments of the species in the Amazon are lower than in Mato Grosso, which could be one reason for this difference. This reinforces the importance of analyzing each environment individually (Canetti et al., 2021).

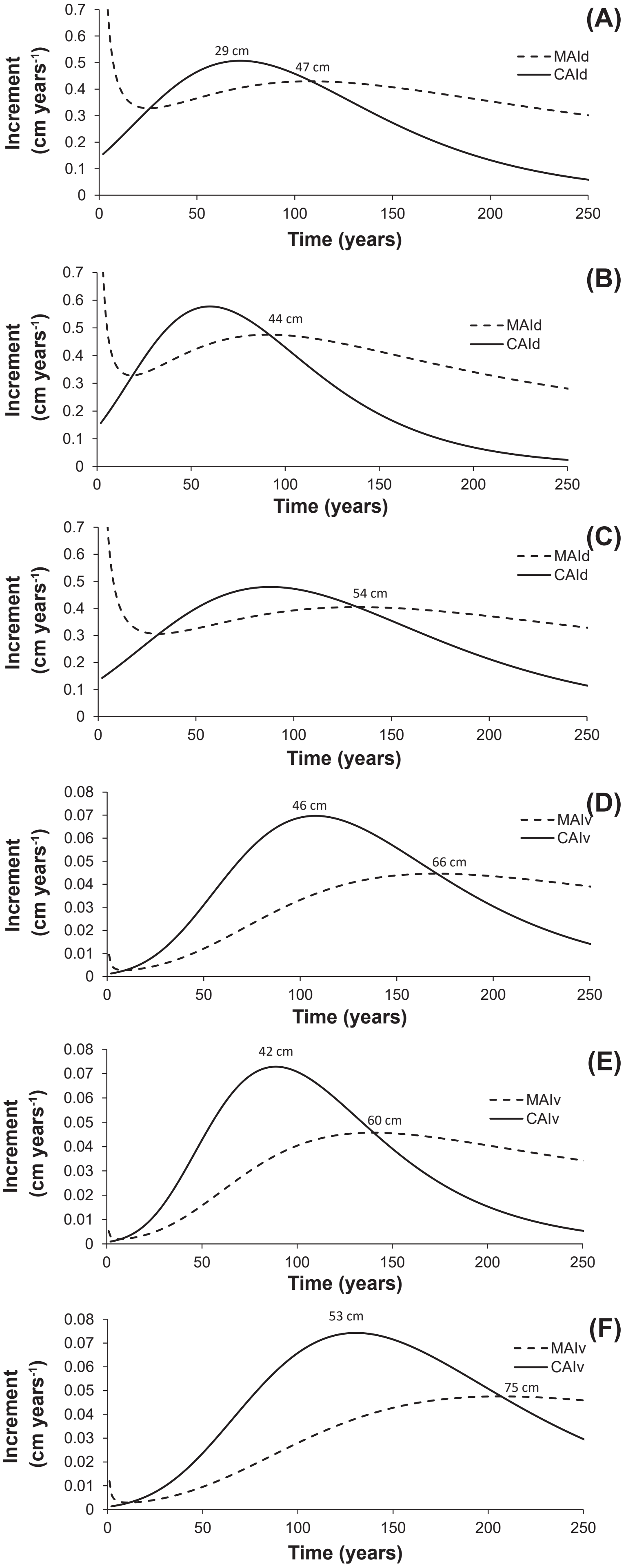

Figure 14. Individual maximization curves by diameter for *Handroanthus* spp. (A), *H. impetiginosus* (B), and *H. serratifolius* (C), and by volume for *Handroanthus* spp. (D), *H. impetiginosus* (E), and *H. serratifolius* (F) in Colniza, MT. MAId = mean annual increment in diameter (cm/year); CAId = current annual increment in diameter (cm/year). MAIv = mean annual increment in volume (m³ year^{-1}); CAIv = current annual increment in volume (m³ year^{-1}). The values in cm refer to the diameters where the points of maximum CAI occur and where the CAI and MAI curves meet.

When confronted with the real (gross) data for the average increment per diameter class (Figure 11B), there was indicative that the productive peak of the species is found at smaller diameters in the increment curves generated from the growth equations for individual trees (Figure 14). This difference results from the fact that when only the mean increments for diameter classes are considered, the higher means for the notable trees have a greater weight. When data from the growth equation are considered instead of real data, this represents a trend for the species where trees with lower and higher growth are given equal weight.

Diameter structure

Diameter structure in forest census (DBH ≥ 35 cm)

Adjustment of the probability density functions from the diagnostic inventories structure data in Acre (DBH ≥ 10 cm) indicated that for *Handroanthus* spp. (Figure 15A) and *H. serratifolius* (Figure 15C), the diametric structure decreased starting from the smallest DBH classes, while for *H. impetiginosus* (Figure 15B) the diametric classes centered at 15 cm and 25 cm presented approximately the same number of trees, with a gradual decrease from the diameter class centered at 35 cm.

For the forest census in Mato Grosso (DBH ≥ 35 cm), a difference was visible in the average diameter distributions of *Handroanthus* spp. between forest types (Figure 16), which had already been observed in the densities (Table 1; Figure 4). The Ombrophile Forests have a higher density, with a more abrupt drop in the number of trees from the diameter class with a higher number of trees (in the diameter class centered at 55 cm). The highest number of trees occurred in the diameter class centered at 55 cm for all forest types except for SFSAV, where it occurred at 65 cm DBH.

In both states, the diameter distributions were found to vary between forest types. For this reason, different numbers of *Handroanthus* spp. trees should be expected depending on the sampled forest type, confirming that direct comparison of inventories may lead to misinterpretations.

The findings that the largest increments occurred in the diameter class centered at 65 cm (Figure 12) and that the greatest number of trees occurred between 55 cm and 65 cm DBH in all forest types in Mato Grosso (Figure 16) also indicate that forest managers should be aware of the production potential of these classes, since they are the most important in terms of stock and wood production. After these diameter classes the species begins to decline (Kramer; Kozlowski, 1960; Nyland, 2007; Weiskittel et al., 2011), indicated by a drop in survival and growth rates (Braz et al., 2021).

The inverted-J diameter structure recorded for the *Handroanthus* species in Acre (Figure 15), with larger numbers of smaller trees, indicates the species is structurally stable because stocks exist to replenish the larger size classes (Kohyama, 1986; Muller-Landau et al., 2006; Wang et al., 2009). These considerations originate in the theories by De Liocourt (1898) and Meyer (1952) related to balanced forests that follow the negative exponential pattern, representing sustainability of the structure over time.

Still, it is important to emphasize that it is not only this type of diameter structure that represents the stability of a species in the forest, since there are several factors intrinsic to species and their dynamics that can result in distinct diameter distributions (Pascal, 2003).

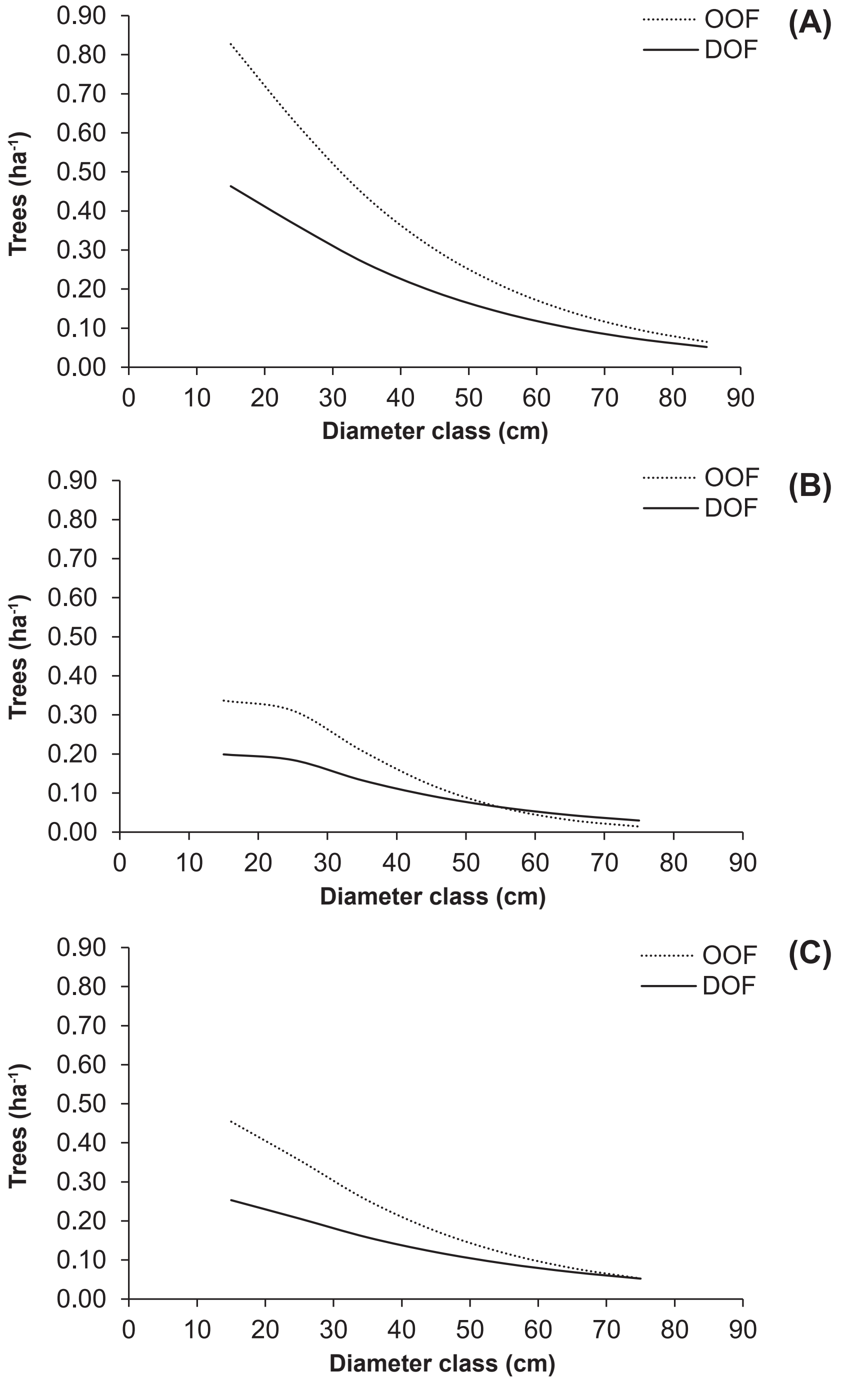

Figure 15. Weibull three-parameter probability density functions adjusted for *Handroanthus* spp. (A), *H. impetiginosus* (B), and *H. serratifolius* (C) in Open Ombrophile Forest (OOF) and Dense Ombrophile Forest (DOF) forest types, from diagnostic inventories in Acre. The adjustment parameters and statistics can be found in Appendix 2.

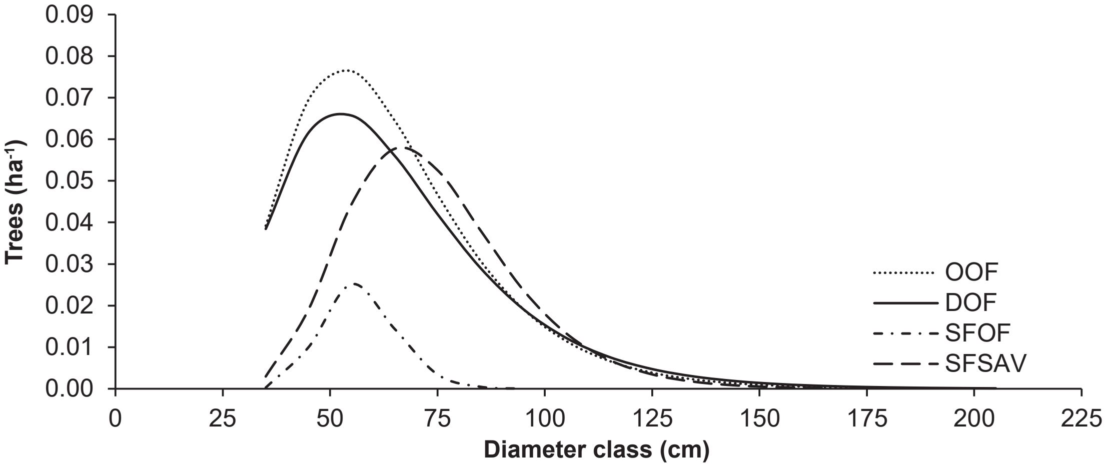

Figure 16. Log-normal probability density functions adjusted for *Handroanthus* spp. in Open Ombrophile Forest (OOF), Dense Ombrophile Forest (DOF), transition zone between Seasonal Forest and Ombrophile Forest (SFOF), and transition zone between Seasonal Forest and Savanna (SFSAV) forest types in Mato Grosso. The adjustment parameters and statistics can be found in Appendix 3.

De Liocourt (1898) and Meyer (1952) described the inverted-J pattern for all forest species as a whole, not for each species individually. But at the community level, the inverted-J format usually results from the prevalence of pioneer species and other timber species that reach small diameters over climax species (Teketay et al., 2010; Canetti et al., 2019). Yet experts often mistakenly apply this same theory to individual species, demanding the inverted-J format as a prerequisite for maintenance of the species in the forest (Rubin et al., 2006; Horn et al., 2012; Vieira et al., 2017).

Trees in unmanaged natural forests face strong competition, and over time the forest reaches its climax, characterized by a static balance, and produces only raw and non-net volumes of wood (Osmaston, 2010). Without clearings where light can enter, the growth and regeneration of smaller diameter classes may be impaired (Clark, 1990; Nyland, 2007), and in primary forests the species present a greater diameter distribution due to the higher stocks of stagnant and senescent trees accumulated over several decades (Dawkins; Philip, 1998). In this way, species in a primary forest without interventions tend to stagnate as they reach senescence and because of strong competition between trees and little access to light, which smaller trees need to grow.

According to O`Hara (2014), a wide variety of diameter distribution formats exist in uneven-aged forests. Lorimer and Halpin (2014) identified eight stages of population development for a given group of species. Species are likely to alternate between unimodal or negative exponential forms (Lorimer; Halpin, 2014; Holeska et al., 2017) even if they tend to repeat a certain structure (Gotelli, 2008), showing that the diameter structures are not stable. According to Holeska et al. (2017), the inverted-J diameter distribution is probably only a temporary condition in forests that could result from disturbances that open the canopy, favoring natural regeneration and continuous recruitment into smaller diameter classes.

Unimodal distributions in primary tropical forest species have already been registered by several authors (Condit et al., 1998; Dawkins; Philip, 1998; Pascal, 2003; Braz, 2010; Braz et al., 2014; Hossain et al., 2015; Canetti et al., 2021), as seen for *Handroanthus* spp. in Mato Grosso (Figure 16). Ecological characteristics of species can be one cause of unimodal distribution.

Wright et al. (2003) described two main factors that justify unimodal distribution in heliophile species: first, when these species live in shade conditions they are ephemeral and their survival is drastically reduced, especially for the smaller diameter classes that are below the canopy; second, trees with better light grow faster and reach the middle diameter classes, reducing the number of trees in the smaller classes.

Pascal (2003) mentioned that accumulation of trees in the intermediate diameter classes can result in competition, which causes reduced increment and in turn lower numbers of trees moving into the larger diameter classes. Moreover, when vitality and survival improve in the intermediate classes, they can accumulate more trees, leading to a unimodal structure (Pascal, 2003; O’Hara, 2014).

Variation in increments in the diameter classes can generate different patterns of diameter distribution, such as unimodal distribution (Leak, 2001). Slow growth rates at the beginning of the life cycle because of lack of light can disturb diameter distribution in the smaller diameter classes (Alder, 1995).

It is important to remember that despite the diversity found in tropical forests, diameter distributions are regressed by demographic characteristics of the population, such as growth, mortality, and other intrinsic characteristics of each species (Coomes; Allen, 2007; Wang et al., 2009). As such, diameter structure is not the only variable that represents forest health (Canetti et al., 2021), and a unimodal tendency is not an impediment to sustainable management; other factors must be considered, such as growth of the species in different diameter classes (Condit et al., 1998), characteristics related to the ecological group, and light availability in the forest (Pascal, 2003; Capretz, 2004; Wang et al., 2009; O’Hara, 2014).

In forests under forest management regulations, it is possible to guarantee the sustainability of production despite the different original structures (Nyland, 2007; O’Hara, 2014). For this reason, populations with different structural forms, productivity, and appearance can also meet the sustainability criteria (O’Hara, 1998).

Finally, it is important to remember that, even if long periods of time are needed for trees to pass between diameter classes to reach the legally established MCD, cutting will only be authorized after larger diameters are attained. Only trees with DBH values exceeding this MCD can be cut, and all the smaller classes will always be protected.

Accumulated diameter distributions

In OOF, where the density of trees was higher in both states (Tables 1 and 2), the decline in the accumulated diameter distribution curve for Acre occurred at 45 cm in all cases, with stabilization starting at approximately 65 cm in diameter (Figure 17). In DOF the decline started at 35 cm, but stabilization also started close to 65 cm.

In Mato Grosso, the accumulated curve for the number of trees per diameter class (Figure 18) started to decline from 70 cm, and stabilized from 100 cm in diameter.

The diameter distribution reflects the survival and dynamics of the species as a whole (Braz, 2010). Between 65 cm and 70 cm, a structural limit for *Handroanthus* spp. species can be seen in both states, with only isolated trees occurring. This structural limit represents the carrying capacity (Whittaker, 1975).

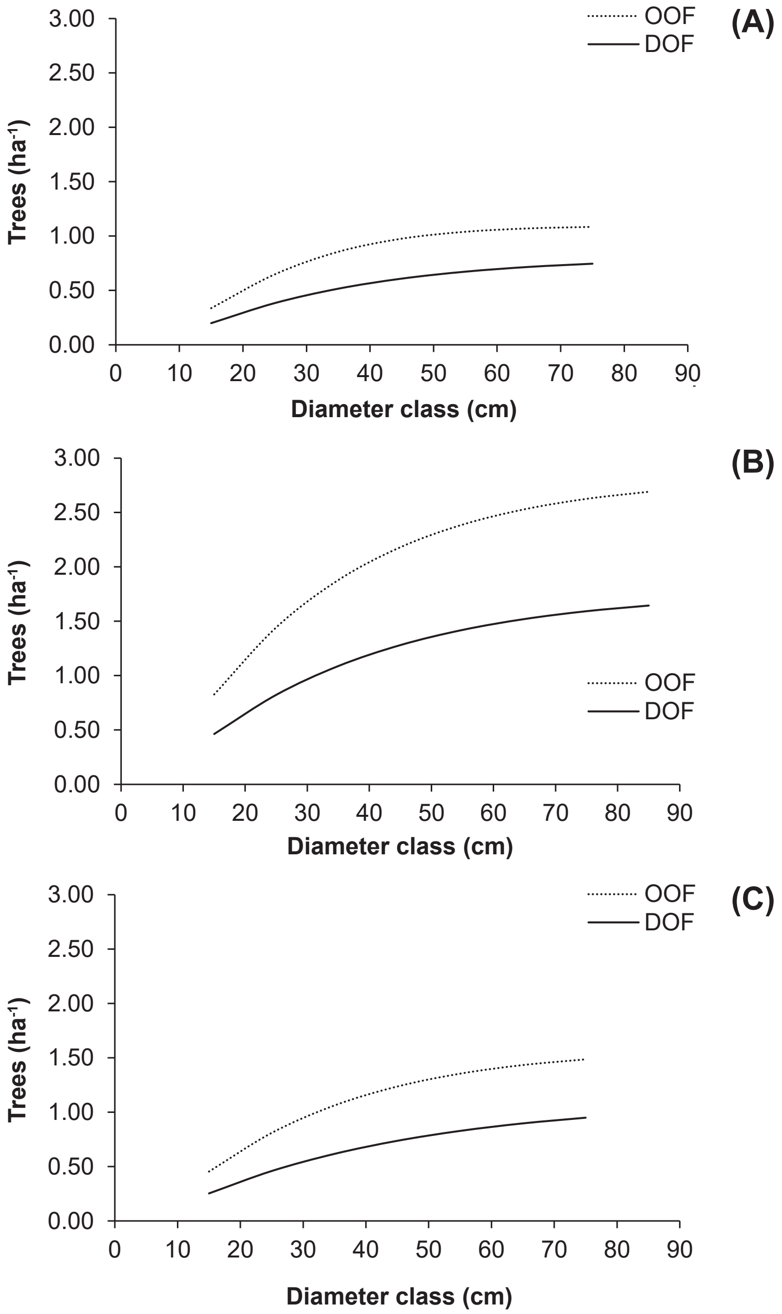

Figure 17. Accumulated diameter distributions for *Handroanthus* spp. (A), *H. impetiginosus* (B), and *H. serratifolius* (C) in Open Ombrophile Forest (OOF) and Dense Ombrophile Forest (DOF) forest types in Acre.

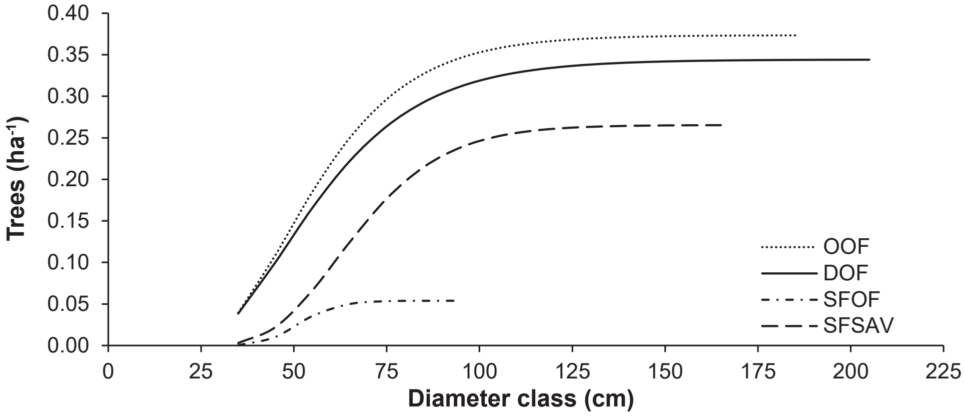

Figure 18. Accumulated diameter distributions for *Handroanthus* spp. in Open Ombrophile Forest (OOF), Dense Ombrophile Forest (DOF), transition zone between Seasonal Forest and Ombrophile Forest (SFOF), and transition zone between Seasonal Forest and Savanna (SFSAV) forest types in Mato Grosso.

Comparison with inventories in the literature

The diameter distributions obtained from diagnostic inventories were similar to data from previous inventories in the state of Acre (Project Radambrasil, 1980; Amaro, 1996; FUNTAC, 1997; Schulze et al., 2008), as seen in Figure 19. The inventory from Project Radambrasil (1980) was conducted over 40 years ago, and the diameter distribution was among the most similar for *Handroanthus* spp. in the diagnostic inventories from SFMPs filed with IMAC-AC (Figure 19A), showing consistent forest structure over the years. For *H. impetiginosus* (Figure 19B), there was greater abundance in the diagnostic inventories compared to the findings of Amaro (1996) and FUNTAC (1997), again indicating sensitivity to environmental characteristics. Although the diameter distributions recorded by Schulze et al. (2008) were similar to those in the diagnostic inventories, the most significant differences in some diameter classes were seen in this work, with the lowest number of trees. These differences could possibly be explained by environmental characteristics, especially because even though the forest inventories were conducted in the same forest types, they were done in very distant areas in other states.

Similarities and differences in diameter distribution by forest type were visible in the forest census and the inventories from Project Radambrasil (1980) in northwestern Mato Grosso and the inventories carried out by Schulze et al. (2008) in different states in the Amazon (Figure 20).

The number of trees in the forest census in the diameter classes centered at 35 cm and 45 cm was smaller in all forest types. However, the number of trees in the diameter classes centered at 35 cm in the census is an underestimate, since only trees with DBH over 35 cm were sampled, as required for SFMPs in the Amazon (Brasil, 2006), and consequently the diameter class centered at 35 cm is incomplete. In the technical information issued by IBAMA (Teixeira, 2021), a deficit in diameter classes centered below 50 cm may indicate that the effort to sample individuals is insufficient, since there is an operational standard (Brasil, 2007) stating that the minimum sampling diameter is 40 cm for pre-use forest census, differing from Normative Instruction 5 (Brasil, 2006). Furthermore, it is possible that the diameter classes centered below the MCD are neglected during inventories, since trees of this size have no commercial value (because they cannot be cut during the cycle in question).

In general, for DBH ≥ 50 cm, the diameter distributions in the SFMPs in Mato Grosso were similar to those in the other inventories for most diameter classes, except in SFOF (Figure 20). The similarity

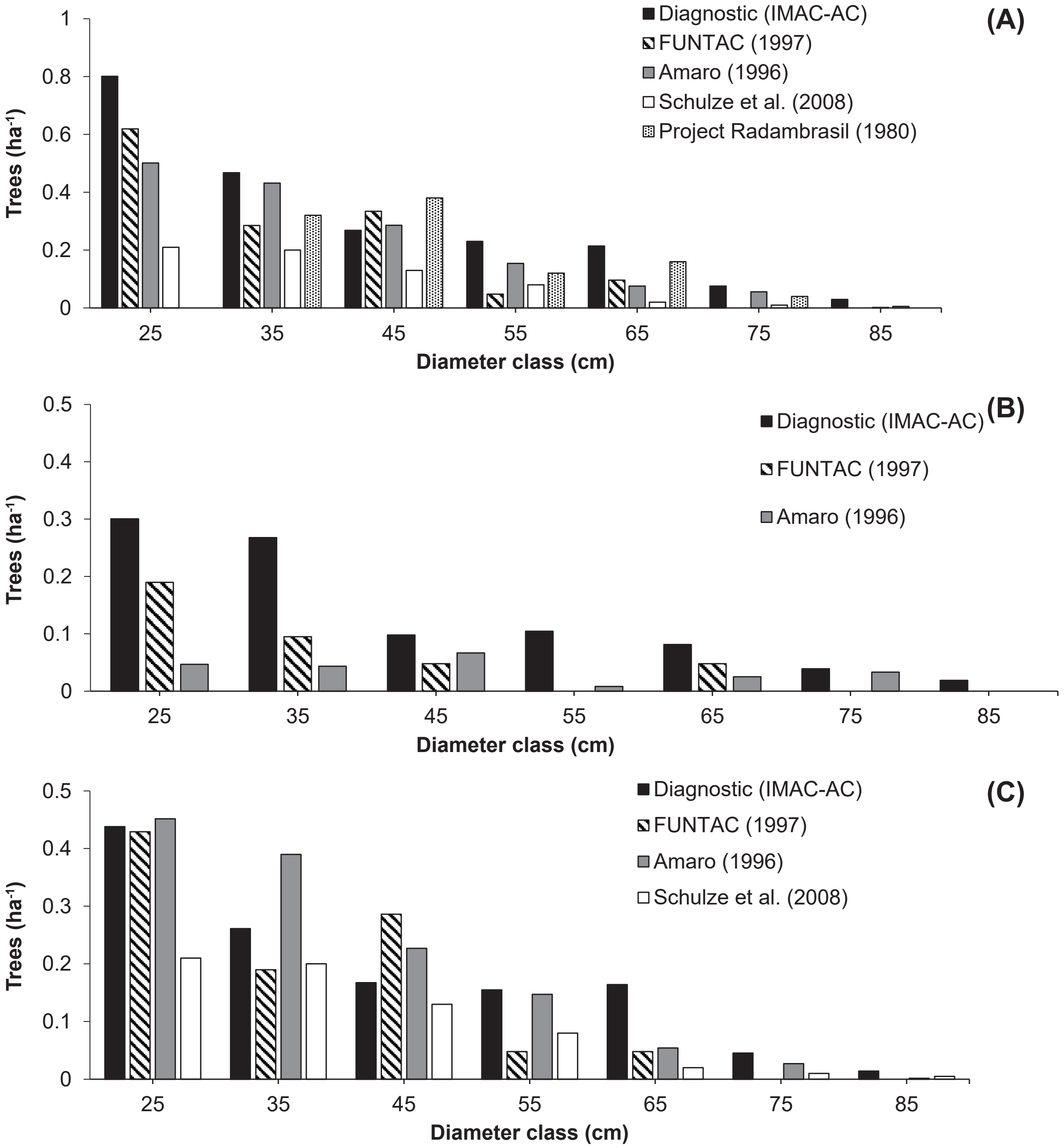

Figure 19. Comparisons of the diameter distributions for *Handroanthus* spp. (A), *H. impetiginosus* (B), and *H. serratifolius* (C) obtained from diagnostic inventories in sustainable forest management plans (SFMPs) provided by IMAC-AC with those present in FUNTAC (1997), Amaro (1996), Schulze et al. (2008), and Project Radambrasil (1980), all in Acre .

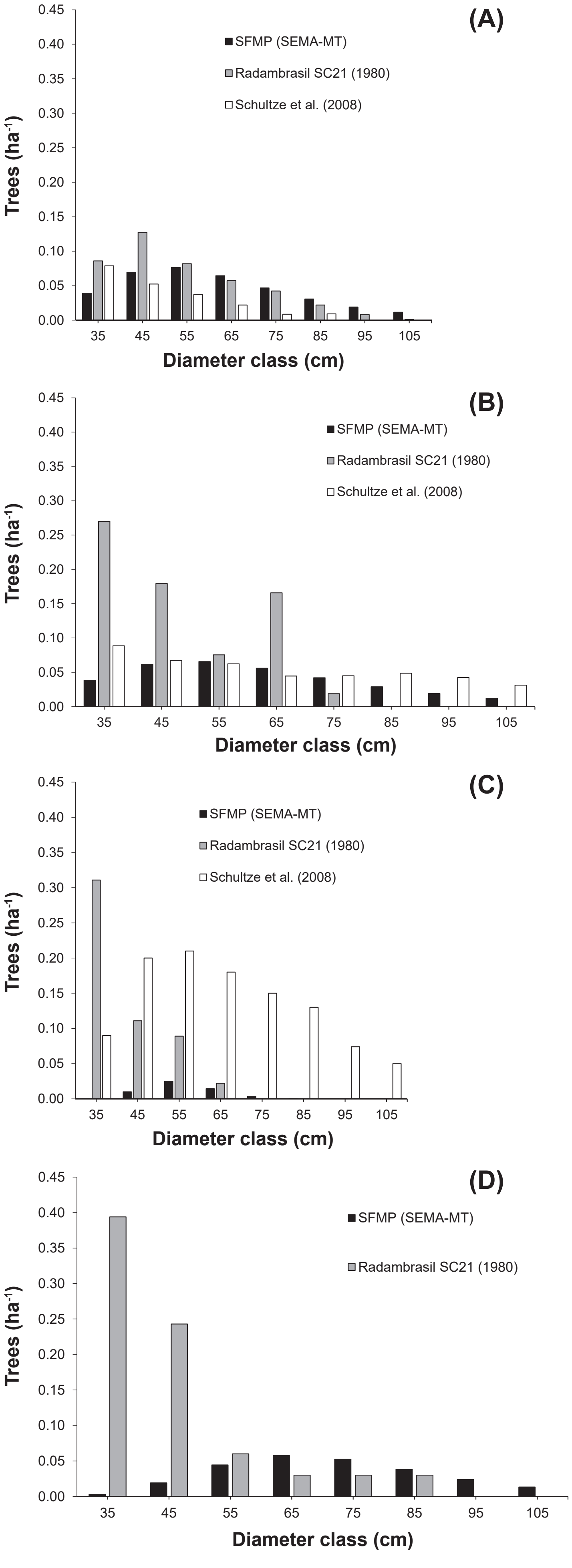

Figure 20. Comparisons of the diameter distributions for *Handroanthus* spp. obtained from inventories in sustainable forest management plans (SFMPs) provided by SEMA-MT with those presented in Project Radambrasil (1997) and Schulze et al. in Open Ombrophile Forest (A), Dense Ombrophile Forest (B), transition zone between Seasonal Forest and Ombrophile Forest (SFOF), and transition zone between Seasonal Forest and Savanna (SFSAV) forest types.

Source: Project Radambrasil (1980) and Schulze et al. (2008).

between data from recent inventories and from Project Radambrasil (1980) indicate that, like in Acre (Figure 19), the current diameter structures did not differ significantly from the findings four decades earlier, suggesting that *Handroanthus* species did not undergo structural changes or impact in the natural forests in recent years (Schulze et al., 2008).

The different diameter distribution in SFOF in Mato Grosso compared to data from other studies may result from the local characteristics of this forest type, especially because it is an ecotone where there is contact between different forest types. Data on SFOF in Mato Grosso were essentially collected in the west of this state, in a region very close to the Cerrado (Figure 4), although the forest type is considered a transition zone between Ombrophile and Seasonal Forests. The data from Schulze et al. (2008) for SFOF were collected in southern Rondônia, farther from the Brazilian Cerrado. The data from Project Radambrasil (1980) were obtained from the SC.21-Juruena spreadsheet, which covers northwestern Mato Grosso, also farther from the Brazilian Cerrado. The influence of the Cerrado on the data for SFMPs in SFOF forest types may explain the smaller number of trees in the Amazonian species of the genus *Handroanthus* in this type of forests.

The differences between the diameter structures observed in the different states, forest types, or sites reinforce the importance of specific management planning in SFMPs.

Diameter structure in the sampling inventories in areas preferred by *Handroanthus* spp. in OOF

In the preferred areas selected for the sample inventory in the municipality of Acrelândia, AC (Figure 21), the density of trees was much higher than in the diagnostic inventories and forest census filed with IMAC-AC (Figures 2 and 3, Tables 1 and 2). While no densities exceeding 2 trees ha^{-1} (DBH ≥ 35 cm) were found in the diagnostic inventories or census, an average of 8 trees ha^{-1} with DBH ≥ 10 cm and 6 trees ha^{-1} with DBH ≥ 35 cm was recorded in the sample inventory.

The diameter distribution recorded in the sampling inventory for the managed forest in Acrelândia (Figure 21A) followed the same inverted-J distribution pattern as in the diagnostic inventories provided by IMAC-AC and the inventories in the literature (Figure 19) conducted in non-managed forests. The accumulated diameter distribution indicates constant accumulation up to the diameter class centered at 55 cm, and reduction after this diameter is reached (Figure 21B).

In both sampled areas in Mato Grosso, the density of trees was higher than in the other inventories analyzed, and was similar to the findings in Acre, with 3.8 trees ha^{-1} considering trees with DBH ≥ 10 cm. For DBH ≥ 35 cm, there were 3.1 trees ha^{-1}. The diameter distribution followed a unimodal pattern, with a higher number of trees in the diameter class centered at 55 cm (Figure 22A), which had been recorded in the forest census for this state (Figure 17). For the accumulated diameter distribution (Figure 22B), the curve tended to stabilize after the diameter class centered at 65 cm. The results of the sample inventory corroborated the previous analysis, suggesting that the greatest survival of the species occurred up to the diameter class centered at 55 cm, with a strong decline from the diameter class centered at 75 cm.

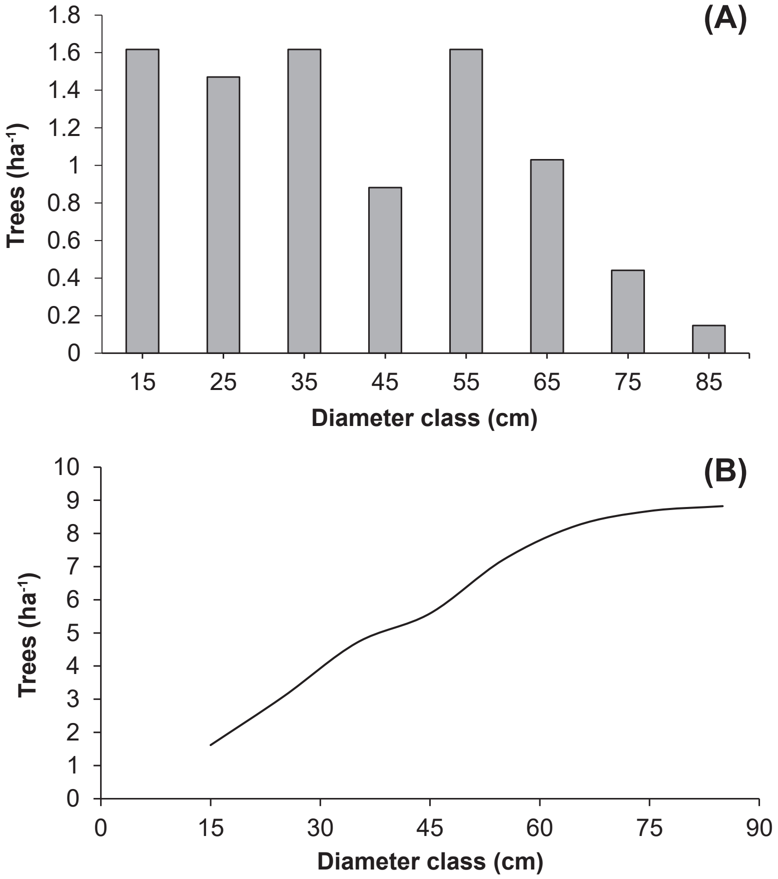

Figure 21. Diameter distribution (A) and accumulated diameter distribution (B) of *Handroanthus* spp. in Open Ombrophile Forest, obtained from sampling inventory (DBH ≥ 10 cm) in areas preferred by these species in the municipality of Acrelândia, AC.

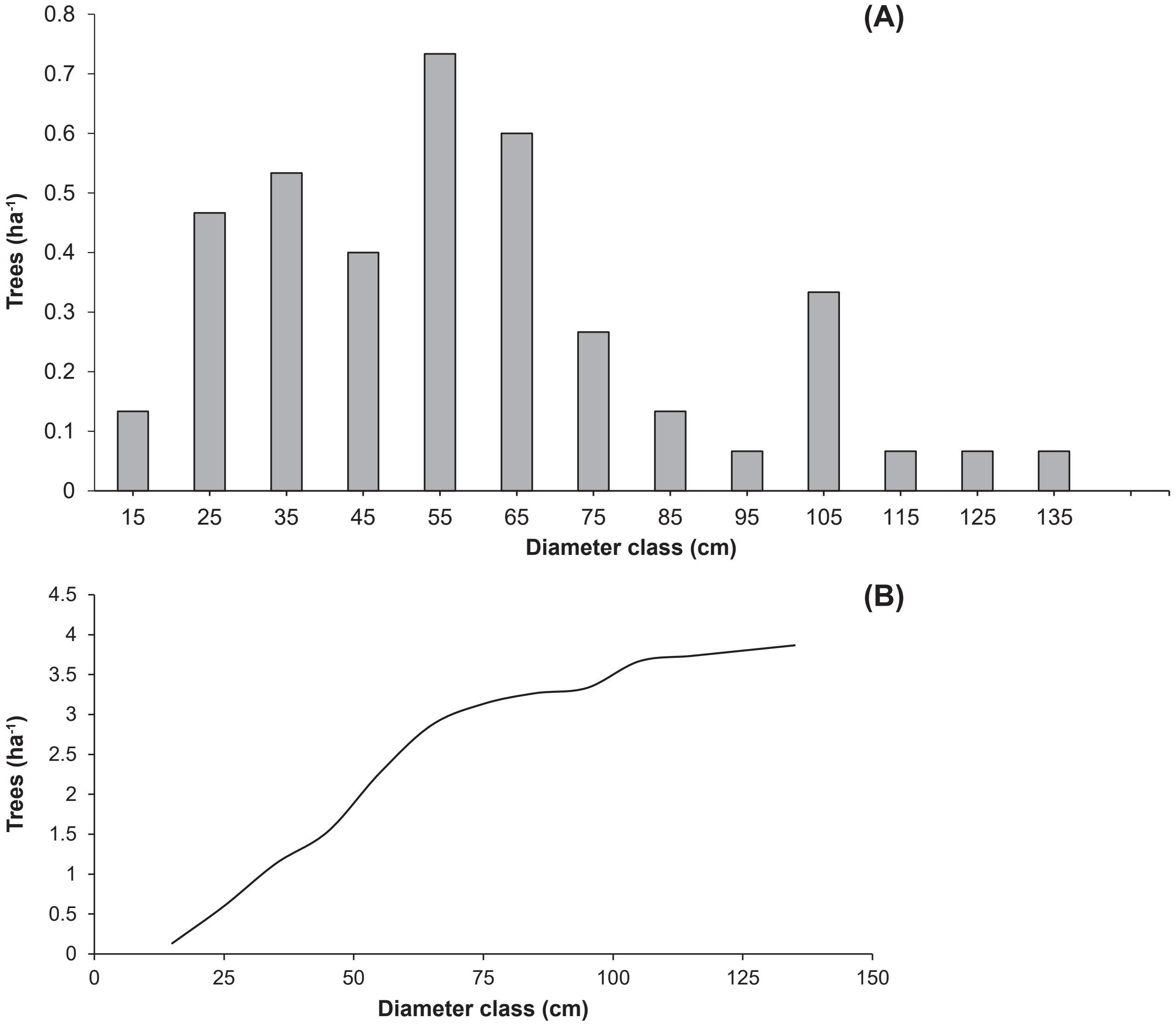

Figure 22. Diameter distribution (A) and accumulated diameter distribution (B) of *Handroanthus* spp. in Open Ombrophile Forest, obtained from sampling inventory (DBH ≥ 10 cm) in areas preferred by these species in Mato Grosso

Clearly, there are large variations in the population density of these species, even in the same forest types. The sample inventories were planned to record the occurrence of the species in the areas they prefer, and as expected, this yielded a much higher density of trees than the averages found in other inventories (Figure 19 and Figure 20), such as Project Radambrasil (1980) (Figure 23). As previously mentioned, this demonstrates the importance of analyzing each individual SFMP according to the specific characteristics of each site.

The sampling inventories for these two states (Figures 21 and 22) indicate the potential of *Handroanthus* species to achieve much higher population densities in areas favorable for their development. This variable population density suggests that sites can be managed to encourage the occurrence of these species. For example, since they are heliophile species (Lorenzi, 1992) and need light for regular development (Justiniano; Fredericksen, 2000), increasing the availability of light through forestry techniques would probably result in a higher density of individuals and higher growth rates. Opening clearings is fundamental for the natural regeneration of species that require light (Martins et al., 2012), which is the case with *Handroanthus* spp.; clearings can be opened naturally or through silvicultural interventions as part of forest management.

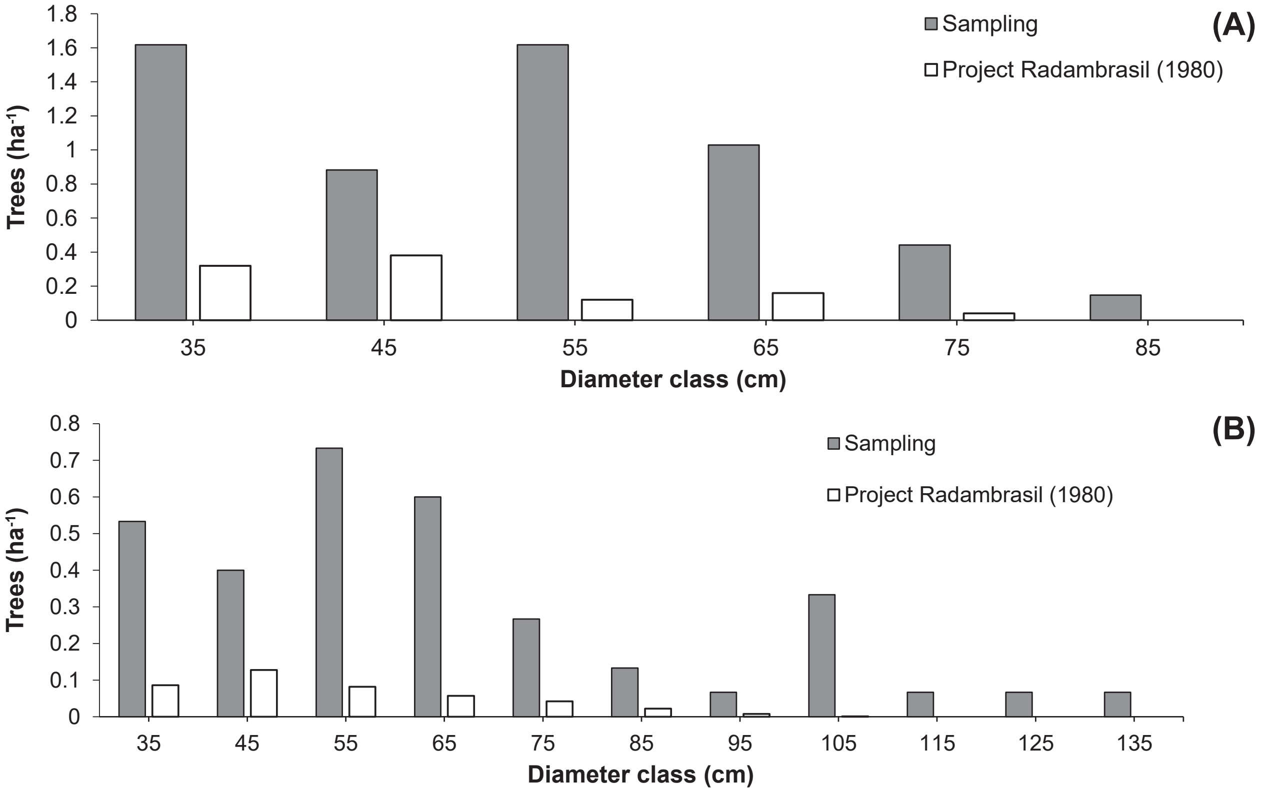

Figure 23. Comparison of the diameter distributions found in the sample inventories carried out in areas preferred by *Handroanthus* spp. and recorded in Project Radambrasil (1980) in Acre (A) and Mato Grosso (B).

Schulze et al. (2008) observed that recruitment of seedlings in these species is strongly restricted to the clearings produced by forest management and other disturbance zones. These authors state that the trees recruited in these clearings will be responsible for supplying wood for the next cutting cycles. Forest management can open clearings in a planned manner, and can be used strategically to favor certain species of interest and assist in conservation.

Comparison of managed and unmanaged areas

In the area sampled in the municipality of Aripuanã, MT, the mean density was 2.2 trees ha^{-1}, and in Colniza (MT) it was 7.5 trees ha^{-1} (Figure 24). In Aripuanã, the diameter distributions were similar in the managed areas and unmanaged areas in 2009 (Figure 24A), with greater differences in the diameter classes centered at 45 cm (more trees in the managed area) and the class centered at 55 cm (more trees in the unmanaged area). In Colniza, the number of trees was higher in the unmanaged area (10.4 trees ha^{-1}) than in the managed area (4.6 trees ha^{-1}) (Figure 24B). However, this difference mainly occurred in the diameter classes above the minimum cutting diameter (50 cm).

The large variation in tree density between Aripuanã and Colniza (Figure 24) reinforced that site-specific characteristics may result in different species structures, which was also noted in the findings for density and diameter distribution in the forest census between forest types (Figures 4 and 16 and Table 1) and between SFMPs (Figure 4). But even with different densities, as with the forest census (Figure 16), no substantial increase in trees was found from the diameter class centered at 60 cm onward (Figure 21B) in the sample inventory study areas prior to management, defining the carrying capacity that should be expected for *Handroanthus* species.

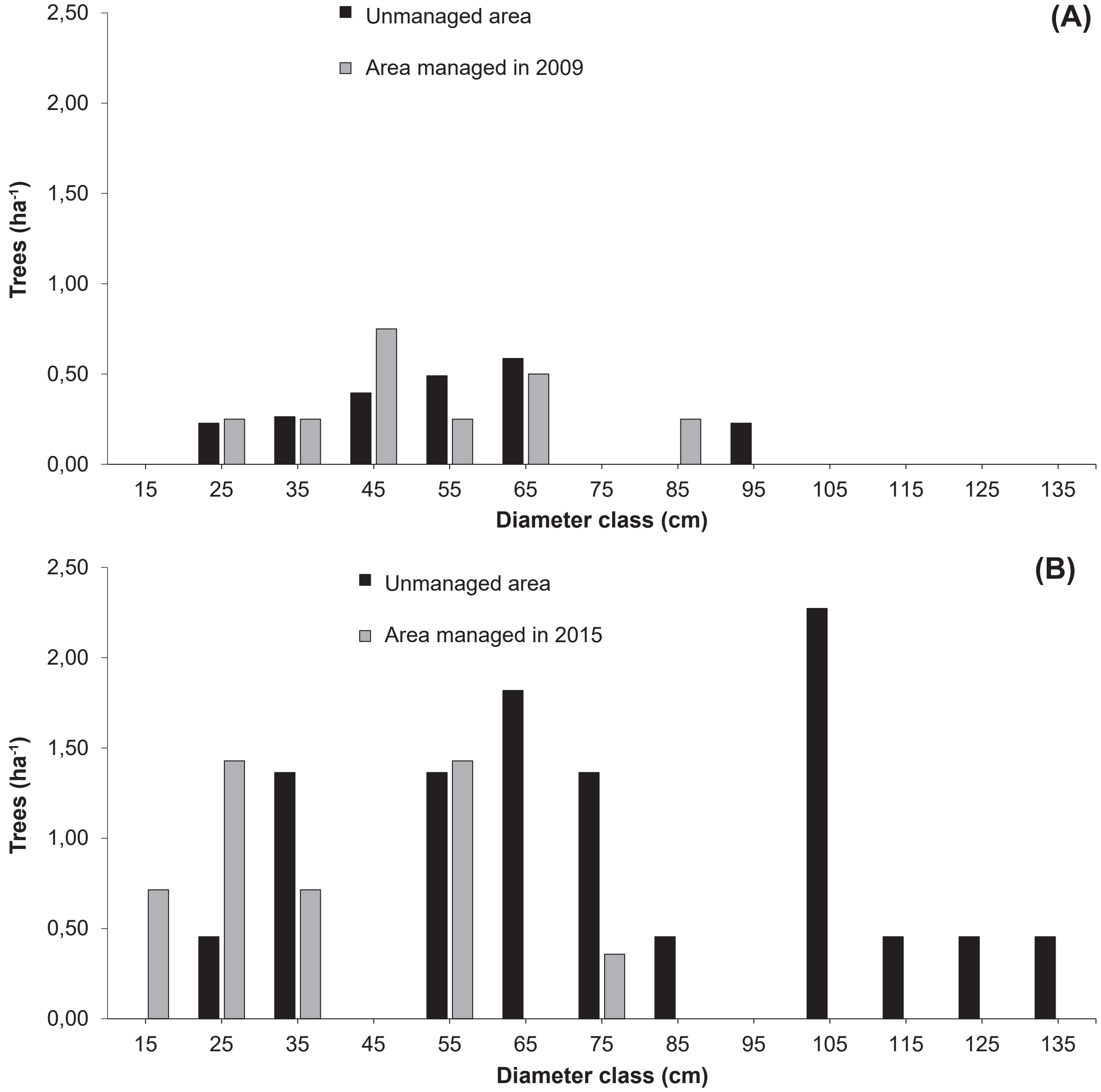

Figure 24. Diameter distribution of *Handroanthus* spp. in the sample inventoried areas, considering managed and unmanaged areas in Aripuanã, MT (A) and Colniza, MT (B).

The distribution in the area managed in Aripuanã in 2009 (Figure 24A) was similar to a neighboring unmanaged area with fewer trees in the commercial class (50 cm). However, the higher number of trees with DBH of 45 cm in the managed forest is a positive sign of their significant potential to move into the diameter classes above the MCD over the next 23 years (considering that the legally established cutting cycle is 35 years). Furthermore, the diameter classes centered at 55 cm and 65 cm, which had already been cut, exhibited advanced recovery even considering the short span of 13 years (with 22 years left until the end of the cycle).

In the area managed in Colniza six years earlier (Figure 24B), there was a greater difference between the managed and unmanaged areas. Special emphasis was given to the diameter classes with DBH exceeding 80 cm, which as expected were not present in the managed area. These diameter classes can be considered surplus and not the target of interest in managed areas, since (as seen earlier) these trees are older and less productive in terms of accumulating wood volume (Braz et al., 2021), and exceed the carrying capacity for the species in the area. However, the diameter class centered at 50 cm (MCD) had more trees than the primary forest, indicating total recovery of the commercial class. This result can be interpreted together with the lack of trees registered in the diameter class centered at 45 cm as indicative of how rapidly trees move out of this diameter class and supply the next class (55 cm) after forest management opens the canopy. These excellent results at Colniza should be considered important as well as positive information about the potential that management holds for these species, since only seven years had passed after felling (with 28 years left until the end of the cycle).

Wood production curves for the populations

Acre

The CAI and MAI curves for wood volume cross for the population of *Handroanthus* spp., *H. impetiginosus*, and *H. serratifolius* at 45 cm DBH (Figure 25) in Acre, indicating that trees with smaller diameters should remain in the forest since the species are still vigorous, with greater growth and more trees. Attention should consequently be paid to the production potential of the classes immediately prior to the diameter class centered at 45 cm, which are the most important in terms of stocking and producing wood for the next cycle. Tree species begin to decline after the full vigor phase (Kramer; Kozlowski, 1960; Nyland, 2007; Weiskittel et al., 2011), indicated by a drop in survival and growth rates (Braz et al., 2021).

According to Miranda et al. (2018), in polycyclic management systems trees that have already exceeded the diameters at which they express their greatest growth potential in wood volume (represented by the MCD) should be selected. For this reason, the diameter at which the greatest wood production occurs should be determined for each species, considering the individual growth pattern and demographic characteristics of the population.

According to Seydack (2000), demographic factors for populations of commercial species are essential to determine optimal management parameters. Within natural forest structures, the available stock of trees per diameter class is the key factor for projecting wood yield in terms of number of trees, basal area, and wood volume (Ong; Kleine, 1996), since this number indicates survival per diameter class. In other words, the time to recover the volume of managed wood in a cutting cycle is a function not only of the specific growth rates for the species, but also the number of trees present in the diameter classes with central values below the MCD (Brienen; Zuidema, 2006).

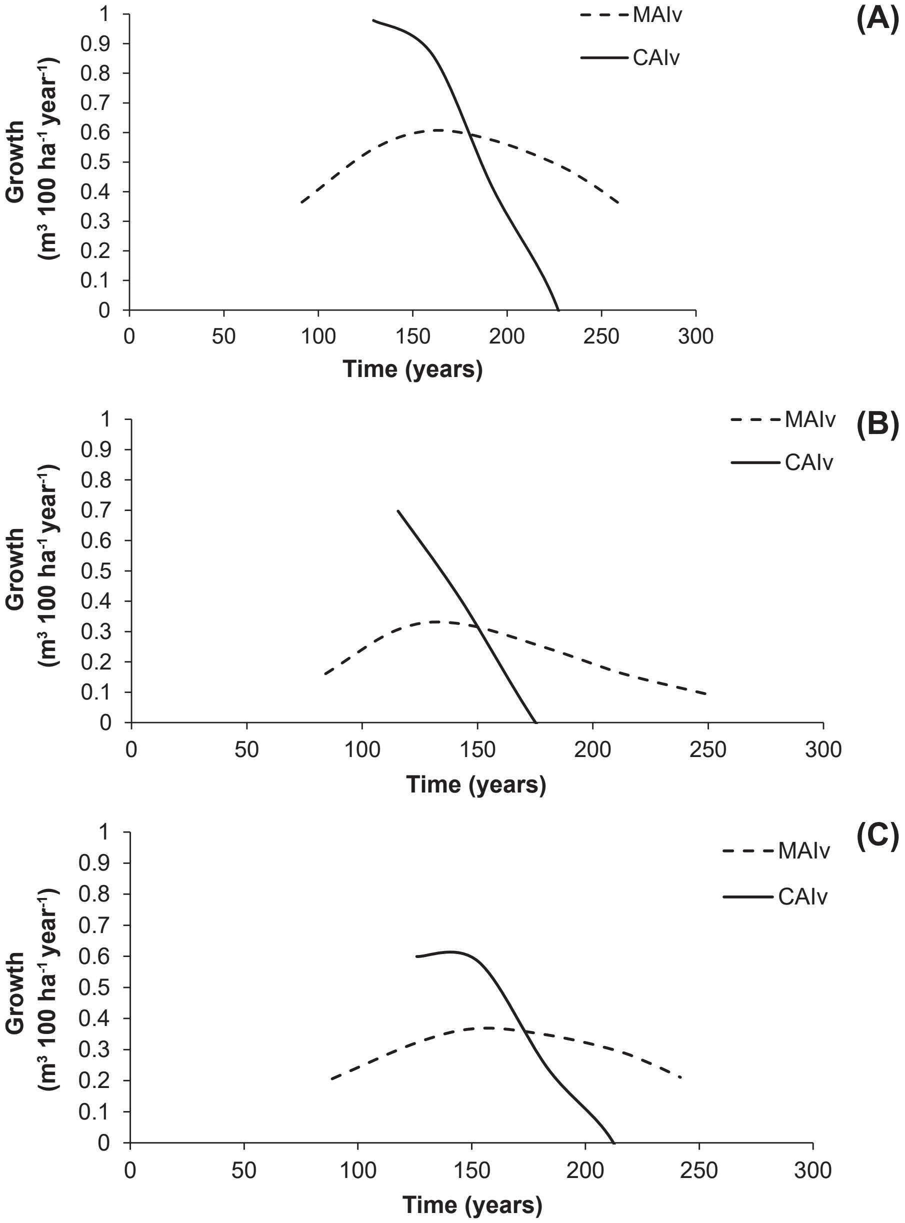

Figure 25. Maximization curves for the population in wood volume for ipê (*Handroanthus* sp.) (A), *H. impetiginosus* (B), and *H. serratifolius* (C) in Acre. MAIv = mean annual increment for the population, in volume; CAIv = current annual increment for the population, in volume. In all cases, CAIv and MAIv curves crossed near DBH = 45 cm.

Mato Grosso

The diameter values at which maximum CAI occurred and where the CAI and MAI curves for wood volume crossed (Figure 26) were lower than those recorded for the individual trees (Figure 14d). This is in line with the findings of Assmann (1970) for considering a set of trees: maximization is advanced due to the inclusion of mortality and reduction of the increment.

The points of the analyzed production curves were reached at similar diameter values, considering the distributions of the forest census and the sample inventory, showing a pattern for *Handroanthus* species in the state of Mato Grosso.

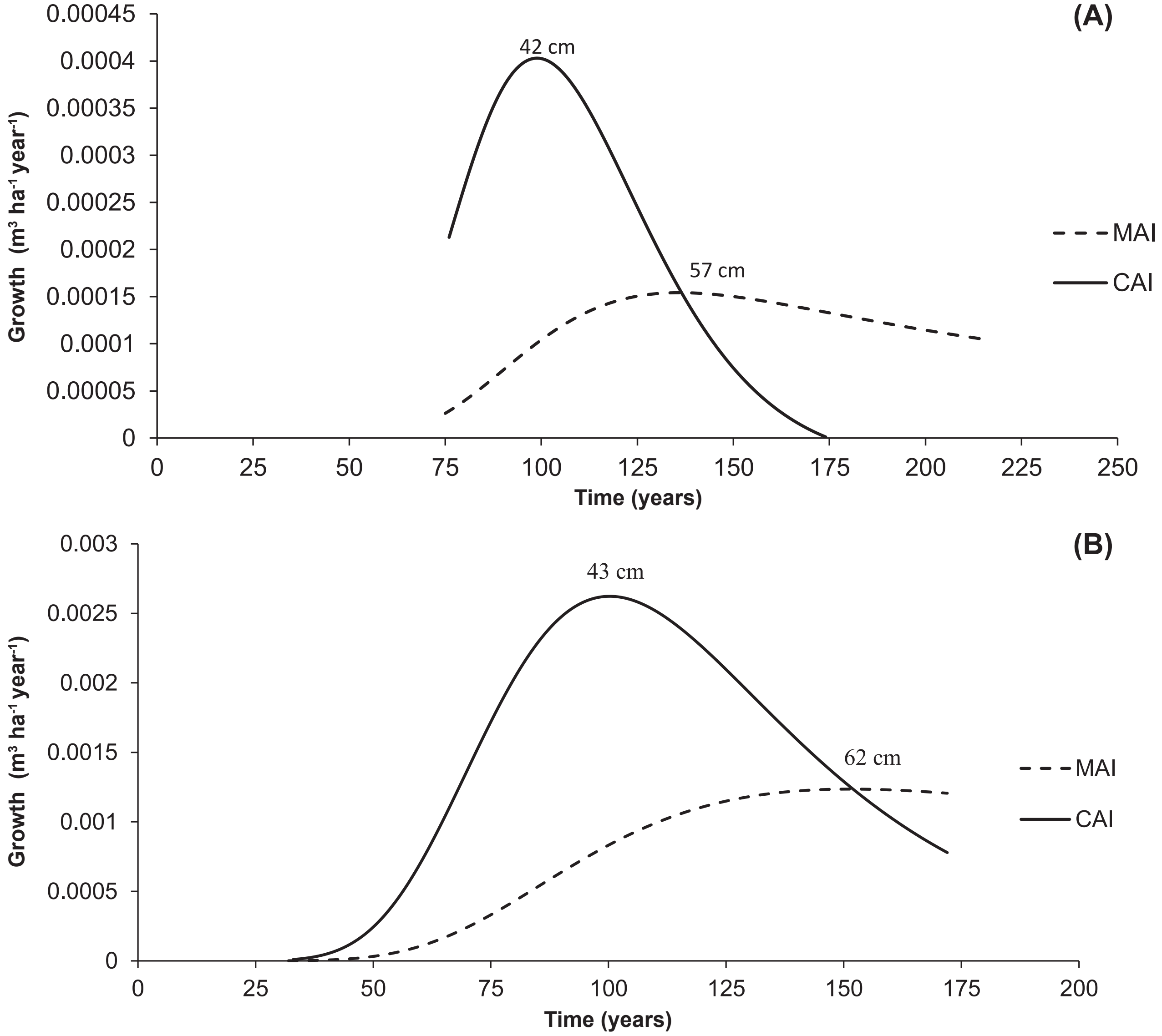

Figure 26. Production curves for the population of *Handroanthus* spp. in wood volume in Open Ombrophile Forest (OOF), considering probability density functions adjusted for census data provided by SEMA-MT (A) and obtained from sampling inventory carried out in areas preferred by the species (B). MAI = mean annual increment in wood volume (m³/year); CAI = current annual increment in wood volume (m³/year). The values in cm refer to the diameters where the points of maximum CAI occur and where the CAI and MAI curves meet.

Still, CAI and MAI curves for this population crossed at larger diameters than in Acre (Figure 25). This was expected, based on the difference in increments (Figure 12) and in diameter distributions between states (Figures 15 and 16).

Management simulations for *Handroanthus* spp.

In both states, the combination of cutting cycle and MCD resulted in a greater volume increase for all diameter structures evaluated in the simulations (Canetti et al., 2021), considering the MCD defined by crossing the CAI and MAI population curves (population rotation) and the cutting cycle calculated from the time to transition to the MCD (Table 9). Considering stable production, the method chosen by these authors for selecting management criteria was also included among the combinations of

MCD and cutting cycle that resulted in larger volumetric increments of wood. The combination of a long cutting cycle (70 years) and high MCD (60 cm) resulted in lower volumes of wood production, in all simulations.

Table 9. Volumetric increment and volume produced during the first cutting cycle and at stable status for *Handroanthus* spp., with different combinations of cutting cycles and minimum cutting diameters (MCD) and different diameter distributions.

Original inventory		Methods for selecting management criteria					
		MCD	Rot.$_{pop.}$	Legisl.	Rot.$_{pop.}$	Rot.$_{pop.}$	High
		Cycle	TT	Legisl.	Legisl.	Long	Long
AC diagnostic inventories (IMAC-AC)	Parameter	MCD (cm)	45	50	45	45	70
		Cycle (years)	25	35	35	70	60
	First cycle	Inc. (m^3 ha^{-1} year^{-1})	0.054	0.045	0.050	0.034	0.013
		Vol. (m^3 100 ha^{-1})	135.60	156.36	173.94	234.89	78.73
	Stable status	Inc. (m^3 ha^{-1} year^{-1})	0.013	0.013	0.013	0.011	0.004
		Vol. (m^3 100 ha^{-1})	33.04	46.67	46.65	79.04	24.93
Inventário amostral (AC)	Parameter	MCD (cm)	55	50	55	55	70
		Cycle (years)	25	35	35	70	60
	First cycle	Inc. (m^3 ha^{-1} year^{-1})	0.180	0.163	0.150	0.077	0.050
		Vol. (m^3 100 ha^{-1})	448.89	569.05	523.75	537.75	300.05
	Stable status	Inc. (m^3 ha^{-1} year^{-1})	0.036	0.040	0.035	0.024	0.012
		Vol. (m^3 100 ha^{-1})	91.08	139.49	121.01	168.11	73.94
MT censos (Sema-MT)	Parameter	MCD (cm)	57	50	57	57	70
		Cycle (years)	25	35	35	70	60
	First cycle	Inc. (m^3 ha^{-1} year^{-1})	0.017	0.011	0.012	0.005	0.004
		Vol. (m^3 100 ha^{-1})	41.48	39.59	43.38	35.38	26.08
	Stable status	Inc. (m^3 ha^{-1} year^{-1})	0.007	0.007	0.006	0.004	0.003
		Vol. (m^3 100 ha^{-1})	17.00	25.90	22.71	30.11	16.80
Inventário amostral (MT)	Parameter	MCD (cm)	62	50	62	62	70
		Cycle (years)	25	35	35	70	60
	First cycle	Inc. (m^3 ha^{-1} year^{-1})	0.131	0.078	0.091	0.024	0.029
		Vol. (m^3 100 ha^{-1})	326.73	272.88	319.53	171.31	174.86
	Stable status	Inc. (m^3 ha^{-1} year^{-1})	0.035	0.042	0.032	0.020	0.016
		Vol. (m^3 100 ha^{-1})	86.51	147.76	112.97	141.37	94.58

Legisl. = criteria used in Brazilian legislation (Brasil, 2006); Rot.pop. = diameter at which the production curves cross for the population; TT = transition time (the cutting cycle was calculated according to the time for the trees to transition into the diameter class containing the MCD). SEMA-MT = diameter distribution data from the breeding stock were obtained from forest census of SFMPs supplied by SEMA-MT; IMAC-AC = diameter distribution data from the breeding stock were obtained from diagnostic inventories of SFMPs provided by IMAC-AC; sampling inventory (AC and MT): diameter distribution data for the breeding stock were obtained from sample inventories conducted in areas preferred by *Handroanthus* spp.

As observed by Canetti et al. (2021), wood production could be maximized by considering specific population parameters. Combining cutting cycles and MCD based on growth and diameter distribution produced a higher increase in wood volume compared to generalized (legislation parameters) for all species.

The increase in MCD and in the cutting cycle resulted in the poorest simulated scenarios, with lower volumetric increments of wood than the other tested criteria. Indiscriminate increases in MCD and cutting cycle lead to the maintenance of trees that have already completed the full vigor phase and are in decline, growing at moderate rates and with relatively high levels of mortality. This “stagnant growth” could be converted into productivity by selective harvesting of mature trees in declining vigor, before they reach mortality (Seydack, 2012).

In all scenarios, the volume of successive simulated cutting cycles decreased until a steady state was reached, where production in each cycle was similar to the previous cycle, representing sustainable production (Figure 27).

The underlying principle of management is to improve the condition of the forest, converting its stock until an optimal level of commercial species can be obtained at a maximum increment (Glauner et al., 2003). Note that the second cycle did not produce the same volume of wood that was produced before activities began in the area in any of the simulated management scenarios. This was expected, since a forest without interventions accumulates a greater number of older trees with stagnant growth, resulting in a stock that exceeds the forest’s carrying capacity (Dawkins; Philip, 1998; Brienen; Zuidema, 2007; Osmaston, 2010). According to Braz et al. (2015), about 20% of the accumulation of basal area in a non-managed forest belongs to the middle stratum, which guarantees production for the next cutting cycle. Larger diameter classes, which have already moved beyond the full vigor phase, do not produce greater gross volumes of wood, only net values (Osmaston, 2010; Braz et al., 2021). This is because the slow growth does not compensate for the loss generated by higher mortality. For this reason, it makes no sense to make efforts to recover the volume of wood generated by these diameter classes in the next cutting cycles. The goal in managed forests is to produce a constant flow of wood, obtaining the highest annual increment possible.

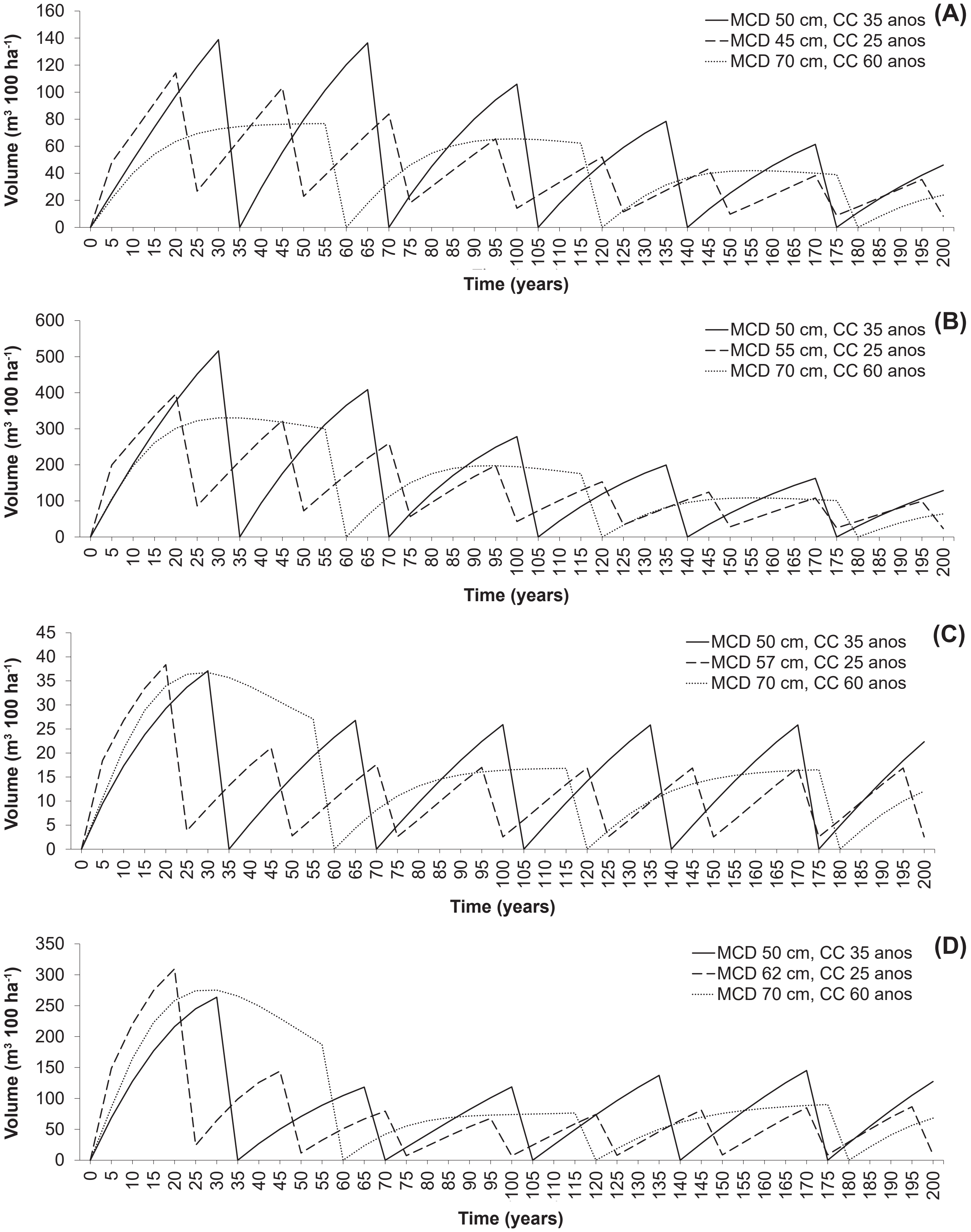

Figure 27. Simulated multiple cutting cycles (MCC) and minimum cutting diameters (MCD) for managing *Handroanthus* spp. in the Amazon Open Ombrophile Forest with diameter distributions contained in diagnostic inventories from SFMPs provided by IMAC-AC (A), sample inventories carried out in preferential areas in Acre (B), forest census from SFMPs supplied by SEMA-MT (C), and sample inventories carried out in preferential areas in Mato Grosso (D).

Natural regeneration of *Handroanthus* spp.

In natural regeneration of *Handroanthus* spp. in the areas sampled in Acre and Mato Grosso, many clearings were seen (Figure 28), with a significant presence of seedlings of these species. Amaro (1996) reported regeneration of yellow ipê trees in seven out of nine forest subtypes studied.

Photo by Fabio Thaines

Figure 28. Natural regeneration of *Handroanthus* spp. in the sampling inventory areas in Colniza (MT) and Aripuanã (MT).

Monitoring of regeneration is important to ensure supply of the larger diameter classes. This regeneration represents the supply of trees in the initial diameter classes for future cutting cycles, showing the area's capacity to support the structure of the commercial classes of the species under management.

Reproductive factors associated with maintaining the species in managed forests

The fecundity of trees is directly related to their size, and declining seed production is associated with their advanced age and decreased physiological activity (Qiu et al., 2021). Trees with diameters between the beginning of the reproductive cycle and the end of the full vigor phase (reproductive threshold) have the greatest potential to ensure maintenance of the species in the forest, since they contribute the most to the seed bank. For this reason, we again stress the importance of considering the species life cycle when defining MCD. Trees in full vigor must be kept in the forest, thus guaranteeing not only greater production of wood volumes but also reproduction of the population to supply natural regeneration and genetic conservation.

For the *Handroanthus* species in the Brazilian Amazon, no records were found indicating the DBH at which the reproductive phase begins. But flowering *H. serratifolius* trees were registered in an urban area in the Cerrado of Minas Gerais with DBH of 15 cm (Melo et al., 2009). In a tropical forest in Panama, the beginning of reproductive potential for *Handroanthus guayacan* (Seem.) S.O. Grose and *Tabebuia rosea* (Bertol.) DC. was recorded in individuals with DBH of 20 cm (Muller-Landau, 2008; Marchand et al., 2020). For *Jacaranda copaia* (Aubl.) D. Don, a light-dependent species also in the Bignoniaceae family (Wright et al., 2003), the minimum diameter to guarantee reproductive potential was 16 cm (Wright et al., 2005).

Considering that growth stagnation in individual trees of *H. impetiginosus* and *H. serratifolius* begins at 44 cm and 54 cm, respectively (Figure 13), and assuming that the beginning of the reproductive phase occurs around the time when the DBH reaches 20 cm, similar to species in the same family and/or genus (Wright et al., 2005; Muller-Landau, 2008; Melo et al., 2009; Marchand et al., 2020), the reproductive interval for *H. impetiginosus* is 24 cm (DBH 20–44 cm) and for *H. serratifolius* is 34 cm (DBH 20–54 cm), as represented in Figure 29. This means that according to the growth equations (Figure 13), the *H. impetiginosus* trees reproduced for approximately 45 years (from 49 to 93 years) or for 47% of their lifespan until growth stagnation began, and the *H. serratifolius* trees for 75 years (from 59 to 134 years) or 56% of their lifespan (Figure 18), remembering that these species reproduce annually (Calixto et al., 2007; Martins et al., 2008). Additionally, considering the interval between the beginning of the reproductive period and the currently applicable 50 cm MCD (Brasil, 2006), *H. impetiginosus* reproduces for 60 years and *H. serratifolius* for 66 years. This long reproductive period ensures that natural regeneration of the species is maintained for future cutting cycles. The time during which trees reproduce before reaching MCD in forest management will have a substantial impact on the genetic flow and genetic variability of the population.

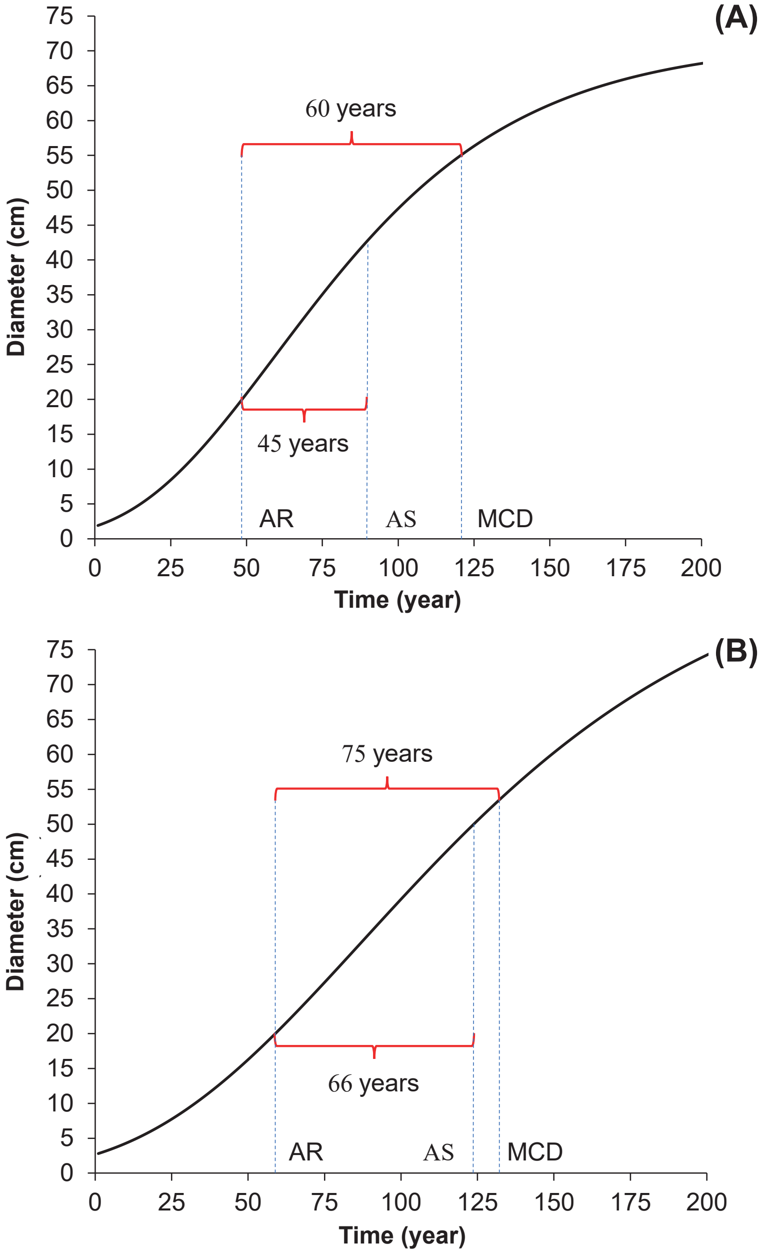

Figure 29. Reproductive period of *Handroanthus impetiginosus* (A) and *H. serratifolius* (B), considering the species growth equations. The period between the age at the beginning of the reproductive phase (AR) and age at growth stagnation (AS) was calculated, when the mean annual increment and current annual increment curves cross, and the age at minimum cutting diameter (MCD) specified in current legislation (Brasil, 2006).

Vinson et al. (2015) conducted research on *J. copaia* and concluded that most reproducing trees would be retained in the forest after management (MCD = 50 cm). For *Handroanthus* spp., 44% of the reproducing trees in this species would remain in the forest after cutting 90% of the trees with DBH > 50 cm (according to the current MCD established by law), considering the sampling inventory carried out in the open Ombrophile Forest (Figure 24). Natural regeneration will consequently be maintained after the trees that reach the MCD are cut, since the remaining trees will be in full physiological vigor.

From a reproductive point of view, opening clearings as part of forest management favors the development of seedlings and opens space for trees to have more access to light, boosting their physiological potential and, in turn, their reproductive capacity (Clark, 1990). In this way, forest management is a tool that is positively aligned with species conservation, as long as it is done in a way that has a low impact on the remaining vegetation, and if criteria are established to ensure that trees in full physiological vigor are maintained in order to produce wood and supply natural regeneration and gene flow for future cutting cycles.

Final considerations

Calculating areas where land use and land cover have changed from originally forested areas to agricultural uses as a negative effect of forest management is a misunderstanding, which we hope we have clarified with this work. We reiterate the importance of forest management that ensures the continuation of forests and their environmental services in perpetuity. Analyses and decision-making without this consideration can result in false assumptions for interpreting the threats that face timber species when they are poorly managed.

Handroanthus species occur in the Amazon at population densities that may vary according to environmental conditions and the forest structure. Preferential areas were detected, where higher species densities are found. Tree density also varies between forest types, and gradients may be found within the same forest type or even within an annual production unit (APU). For this reason, sites with lower species densities do not necessarily represent a decline in the population, but instead may reflect specific local characteristics. When planning forest inventories to identify species occurrence, these factors should be considered.

Densities below one tree ha^{-1} found in sustainable forest management plans (SFMPs) for *Handroanthus* spp. (DBH ≥ 35 cm) in Acre and Mato Grosso are compatible with the densities of most timber species found in the Amazon region, and are typical of the natural forests in the Amazon biome.

Species in the genus *Handroanthus* occur widely across the Amazon region and in all biomes. In Acre alone, approximately 12.5 million ha of Amazon Forest were registered in 2020; 3.5 million ha of this total were located within Indigenous reserves and full-protection conservation units, without counting permanent preservation areas. In Mato Grosso approximately 25 million ha of Amazon Forest were registered in 2019, with 8 million ha in Indigenous reserves and full-protection conservation units. The stock of *Handroanthus* spp. trees in these remaining forests supplements the role of the areas under forest management for conservation of these species.

Our analyses and the literature we consulted indicate that the volumetric increment varies widely among the species in the genus *Handroanthus*. The mean increment in diameter can be substantially increased through appropriate management. The sampled areas showed excellent recovery when suitable management standards were applied.

The increments for the species analyzed followed a pattern throughout their life cycle, starting their growth slowly, accelerating during the full vigor phase, and attaining stability when the trees reached a certain diameter. For this reason, diameter values exceeding those for growth stabilization should not be defined as the minimum cutting diameter (MCD) for forest management.

The occurrence of these species, when managed according to the criteria established by law, did not exhibit weaknesses in areas under forest management. The decline in diameter growth for *Handroanthus* species began from the diameter classes centered at 45 cm and 55 cm. The accumulated curve for the number of trees per diameter class tended to decrease from 70 cm, without exhibiting more structural value, and stabilized from diameters of 100 cm. This indicates that there is a structural limit for these species, in other words, a carrying capacity.

The diameter structures and population densities strongly resemble the structures recorded in primary forests for over 40 years in Project Radambrasil (1980), and we can infer that this did not change during this period. Considering the current composition of flora, there was no change in the classification of importance in relation to the other species when compared to the data from Project Radambrasil (1980).

The long reproductive interval that occurs between the start of the reproductive phase for *Handroanthus* spp. and the MCD, or between the start of the reproductive phase and the end of the full vigor phase, ensures that natural regeneration of the species is maintained for future cutting cycles, leaving no doubts that these trees can contribute to the genetic diversity of species.

Because these species are light-dependent, the literature notes that the *Handroanthus* genus requires canopy disturbances and the opening of clearings for better establishment and growth of individuals under regeneration. Because of the characteristics of these species, stimulus through public policies that encourage sustainable forest management can contribute to their conservation.

Considering factors such as population, area of occurrence, growth, and structure (past and present), carrying capacity and stock of natural forests under management, and reproductive maturity, it is our opinion that *H. impetiginosus* and *H. serratifolius* are not vulnerable.

We recommend using a variety of resources to evaluate the risks that tree species may face, including scientific and technical texts, forest inventories, satellite imagery, georeferencing, analysis processes, and statistical evaluations, in order to avoid conclusions that lack scientific support. We also recommend establishing a research network on this topic that includes academic and research institutions to guide forest inventory activities and expeditions to collect samples in order to complement studies on species of interest.

Acknowledgments

The authors wish to thank the State Secretaries for the Environment (SEMA-MT and IMAC-AC) for providing data on forest management plans; the Mato Grosso State Center for Wood Producing and Exporting Industries (CIPEM) for funding the sample forest inventory and sample collection for growth analysis; SINDUSMAD; UFMT, Sinop Campus, MT; the State University of Mato Grosso, Alta Floresta; Elaboré Projects and Forest Consulting; Embrapa Eastern Amazon; S. M. Agroflorestal Ltda; and Tecman Ltda. for support in organizing and collecting field data.

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Appendices

Appendix 1 - Statistical parameters and growth equation coefficients adjusted for the species and for the genus *Handroanthus* in Mato Grosso.

	Model	AICc	BIC	Syx (%)	β0	β1	β2
Handroanthus spp.	Chapman-Richards	5820	5841	21.82	97.5191	0.0092	1.6357
	Gompertz	5796	5817	21.64	78.7250	3.5042	0.0175
	Hossfeld IV	5820	5842	21.82	120.3000	18.3363	1.5400
	Logística	5817	5838	21.80	68.7823	0.0318	14.5144
	Lundqvist	5835	5856	21.93	669.4000	13.8881	0.3502
	Schumacher	5959	5975	22.89	110.6000	92.1490	
	Weibull	5819	5845	21.80	82.9991	0.0008	1.4901
Handroanthus impetiginosus	Chapman-Richards	2776	2794	30.95	76.6726	0.0156	2.0696
	Gompertz	2761	2778	30.54	71.3537	3.7001	0.0220
	Hossfeld IV	2778	2795	30.99	88.1623	45.8882	1.8317
	Logística	2749	2767	30.24	65.3092	0.0378	15.6204
	Lundqvist	2794	2811	31.41	181.1000	23.0597	0.6136
	Schumacher	2801	2814	31.63	104.2000	79.0221	
	Weibull	2770	2791	30.74	68.1577	0.0004	1.7174
Handroanthus serratifolius	Chapman-Richards	3094	3113	17.64	149.1000	0.0050	1.4421
	Gompertz	3075	3094	17.45	90.4774	3.5246	0.0144
	Hossfeld IV	3093	3112	17.63	193.2000	12.5347	1.3945
	Logística	3099	3118	17.69	74.4986	0.0281	15.1087
	Lundqvist	3104	3123	17.74	18,396.1000	13.8969	0.1767
	Schumacher	3262	3276	19.45	121.2000	107.4000	
	Weibull	3093	3117	17.62	117.1000	0.0007	1.3839

AICc = corrected Akaike information criterion; BIC = Bayesian information criterion; Syx (%) = relative standard error; β0, β1, β2, β-0. = equation parameters adjusted for non-linear regression. Equations with better adjustments for each species are shown in bold.

Appendix 2 - Statistical parameters and coefficients of log-normal probability density functions adjusted for the genus *Handroanthus* by forest type in Mato Grosso.

	Forest type	OOF	DOF	SFOF	SFSAV
Coefficients	α	4.09	4.10	4.04	4.27
	β	0.35	0.38	0.15	0.26
Statistics	Syx (%)	2.94	2.76	3.33	1.39
	Dcalc.	0.03	0.03	0.06	0.03
	Dtab.	2.20	2.28	5.86	2.64

α and β = estimated settings; Dcalc. = maximum absolute difference between the adjusted probability density function and the values observed in the field; Dtab. = tabulated Kolmogorov-Smirnov value (α = 0.05).

Appendix 3 - Statistical parameters and coefficients for the Weibull 3-parameter probability density function adjusted for *Handroanthus* spp. by forest type in Acre.

	Species	***Handroanthus* sp.**		***H. impetiginosus***		***H.* serratifolius**	
	Forest type	OOF	DOF	OOF	DOF	OOF	DOF
Coeficientes	a	11.87	14.06	9.99	14.9	12.43	14.96
	b	27.39	31.08	22.38	27.58	26.95	36.28
	c	1.05	1.03	1.34	1.06	1.07	1.01
Estatísticas	Syx (%)	6.29	3.76	3.62	7.69	3.86	102.51
	Dcalc.	0.06	0.04	0.02	0.04	0.02	0.4
	Dtab.	0.09	0.12	0.11	0.14	0.12	0.19

a, b, and c = estimated parameters; Dcalc. = maximum absolute difference between the adjusted probability density

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