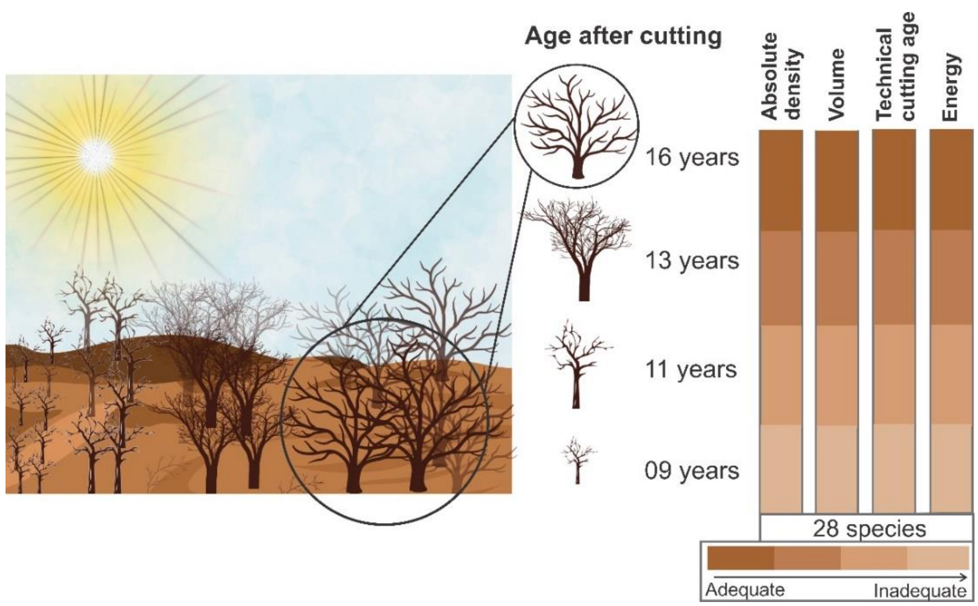
# Volumetric and Energy Production Assessment of Wood in Managed Forest in the Brazilian Arid Biome

Jéssica Lamonnielly Peixoto Epifanio de Lima,[a] Rosimeire Cavalcante dos Santos,[a] Renato Vinícius Oliveira Castro,[b] Frans Germain Corneel Pareyn,[c] Mônica Cristina Damião Mendes,[a] Izabelle Rodrigues Ferreira Gomes,[d] Fabíola Martins Delatorre,[e,]* Ananias Francisco Dias Júnior,[e] and Daniel Saloni [f,]*

*Corresponding authors: fabiolamdelatorre@gmail.com; desaloni@ncsu.edu*

*DOI: 10.15376.biores.19.4.7195-7215*

## GRAPHICAL ABSTRACT



# Volumetric and Energy Production Assessment of Wood in Managed Forest in the Brazilian Arid Biome

Jéssica Lamonnielly Peixoto Epifanio de Lima,[a] Rosimeire Cavalcante dos Santos,[a] Renato Vinícius Oliveira Castro,[b] Frans Germain Corneel Pareyn,[c] Mônica Cristina Damião Mendes,[a] Izabelle Rodrigues Ferreira Gomes,[d] Fabíola Martins Delatorre,[e,]* Ananias Francisco Dias Júnior,[e] and Daniel Saloni [f,]*

There is a growing demand for wood products from forests located in dry regions, which includes the Caatinga, a biome in Northeast Brazil. This study evaluates the relationship between volumetric production, energy potential, and the rotation cycle. Information was collected from forest stands in different stages of regeneration located in an arid region of Brazil. Based on the forest management plan, four fields were selected with post-logging ages of 9, 11, 13, and 16 years. This inventory recorded circumference at chest height, circumference at base height, total height, volume, stored energy, technical cutting age, and rainfall index. The results showed that the species that presented the most significant quantity of stems did not always correspond to those that obtained the most significant amount of biomass. The technical cutting age was determined at 16 years, aiming to maximize wood utilization. Regarding energy density, the 9-year-old field reached 7,281 kcal ha$^{-1}$, the 11-year-old field obtained 14,448 kcal ha$^{-1}$, the 13-year-old field recorded 41,526 kcal ha$^{-1}$, and the 16-year-old field reached 98,190 kcal ha$^{-1}$. The species that contributed most to energy accumulation included *Mimosa tenuiflora* with 3,740 kcal m$^{-3}$, *Piptadenia stipulacea* with 3,271 kcal m$^{-3,}$ and *Cenostigma pyramidale* with 3,101 kcal m$^{-3}$.

*DOI: 10.15376.biores.19.4.7195-7215*

*Keywords: Managed forest; Brazilian semi-arid; Forest growth; Energy biomass*

*Contact information: a: Federal University of Rio Grande do Norte (UFRN), Macaíba, Rio Grande do Norte, Brazil; b: Department of Forestry Engineering, Federal University of São João Del-Rei, Sete Lagoas, Minas Gerais, Brazil; c: Northeastern Plants Association (APNE), Recife, Pernambuco, Brazil; d: Department of Agricultural and Forestry Sciences, Federal Rural University of the Semi-Arid (UFERSA), Mossoró, Rio Grande do Norte, Brazil; e: Department of Forestry and Wood Sciences, Federal University of Espírito Santo (UFES), Jerônimo Monteiro, Espírito Santo, Brazil; f: Department of Forestry Biomaterials, College of Natural Resources, North Carolina State University (NCSU), Raleigh, United States;*
**Corresponding authors: fabiolamdelatorre@gmail.com; desaloni@ncsu.edu*

## INTRODUCTION

Although a globally significant biome, semi-arid forests have received limited study. Estimates of the extent of these forests on a global scale vary considerably, ranging between 1 and 7 million km² (Becknell *et al*. 2012; do Nascimento *et al*. 2023). Mainly defined as tropical forests that receive 250 to 2000 mm of rain annually and have a dry season, typically lasting at least 3 to 4 rainless months, semi-arid forests can constitute up to 42% of all tropical forest ecosystems (Nascimento *et al*. 2023). The Caatinga, a biome in the Brazilian semi-arid region, encompasses around 11% of the country's territory, occupying approximately 844,453 km² (IBF 2023). This region has vegetation adapted to extensive periods of drought and stands out for its remarkable biodiversity. According to 2018 data from the National Forest Information System (SNIF), the Caatinga is home to a total volume of wood close to 1,097 million m³ and a total biomass of 965 million tons (SFB, 2019). Biomass plays a resourceful role in the Caatinga ecosystem, finding applications in different spheres. In the industrial, commercial, and residential sectors, which cover activities such as red ceramic production, bakeries, pizzerias, and domestic use, wood is used as a source of fuel, as indicated in a study conducted by the Ministry of the Environment (MMA) and the Program of the United Nations for Development (UNDP) (IBAMA 2021). This study highlighted the relevance of the Caatinga natural resources for the development of the Northeast Region, revealing that the wood market created approximately 35 thousand permanent jobs and generated approximately 2 billion reais through the commercialization of approximately 70% of wood production in the region (SNIF 2021).

Due to social and economic changes, large areas of semi-arid forests are growing in Central America (Becknell *et al*. 2012; da Silva *et al*. 2022; do Nascimento *et al*. 2023). This increase highlights the importance of understanding wood stocks, but to date, relatively little research has been done on these ecosystems. The growing demand for energy resources in the world puts significant pressure on flora, especially in the priority search for firewood for energy generation (Barros *et al*. 2021). However, despite the importance of semi-arid vegetation as an energy source, information on the sustainable use of wood for this purpose is scarce. Therefore, it is crucial to evaluate the energy potential of wood obtained through sustainable management practices, taking into account not only firewood productivity and its energy properties but also the actual volume available at the time of exploitation and future perspectives (Souza *et al*. 2019; Santos *et al*. 2023).

This data can result in more stable and economically favorable methodologies with socioeconomic benefits. On a global scale, studies indicate that the Total Biomass Increment (ABI) relationship may be correlated with the stand's age, the growing season's length, and the average temperature during that period. However, additional research is needed to understand ABI in tropical forests further. It is worth noting that the relationship between the ABI and the age of the stand may vary, especially depending on the annual wood production, as indicated by previous studies (Ramananantoandro *et al*. 2016; Nascimento *et al*. 2023; Souza *et al*. 2023). This information is essential to understanding the cutting cycle adopted in forest management areas (do Nascimento *et al*. 2023). Therefore, it is crucial to carry out studies that cover aspects related to forest management, measurement, exploration, and regeneration of the annual increase of species to establish connections between volumetric productivity and wood quality, especially in the context of thermal energy generation (Dias Júnior *et al*. 2018; Smith *et al*. 2019; da Silva *et al*. 2022). Furthermore, a joint report by FAO and the Climate Conference of the Parties (COP 27) highlights the importance of sustainable forest management and the development of sustainable value chains, including energy production from these ecosystems (FAO 2022).

Therefore, the need to conduct studies addressing energy availability from wood legally obtained after post-cutting exploitation becomes evident in sustainable forest management practices. These studies provide valuable information that can guide decision-making regarding the cutting cycle in managed areas, focusing on energy generation through firewood. The present research is based on the hypothesis that considering post-cut firewood production, together with the technological characteristics of wood, can offer crucial insights into the energy production potential of these managed areas. This, in turn, allows the assessment of the ideal age for stand rotation. Therefore, the main objective of this study is to analyze the interaction between firewood production, the appropriate cutting cycle, and the amount of energy stored in wood based on information collected from fields in different stages of regeneration, subject to a management plan for sustainable forestry.

## EXPERIMENTAL

### Study Area and Arrangement of Sample Fields

The study was conducted in fields at Fazenda Milhã/Poço da Pedra, in the Agreste region of Rio Grande do Norte State, Brazil. Fazenda Milhã has a total area of 1,834.6 ha, 1,132.8 ha of native Caatinga vegetation under sustainable forest management, and an average wood yield of approximately 56.3 $m^3$ $ha^{-1}$ (Pelletier *et al*. 2019), and which is under the Sustainable Forest Management Plan (MFS). The fields are located between the municipalities of João Câmara and Jardim de Angicos, at coordinates 5°35'47.3"S and 35°51'59.6"W. The farm is located in the semi-arid region of northeastern Brazil under ordinance N° 80, proclaimed by the Superintendence for the Development of the Northeast (SUDENE) on June 27, 2021, which establishes the review of the delimitation of the Brazilian semi-arid region, including in the area of Sudene's performance (Brasil 2022). Precipitation is below 750 mm $year^{-1}$, while evapotranspiration exceeds 1,500 mm $year^{-1}$, resulting in a dry and hot climate. Relative air humidity ranges between 50 and 80%, and the average annual temperature is around 26 °C (Barros *et al*. 2021). Figure 1 shows the map of the area of the Sustainable Forest Management Plan at Fazenda Milhã, divided into 15 fields, a number compatible with the minimum cutting cycle proposed by the Ministry of the Environment (MMA), which is 15 years (Brasil 2020), with emphasis on the distribution of fields in this area.

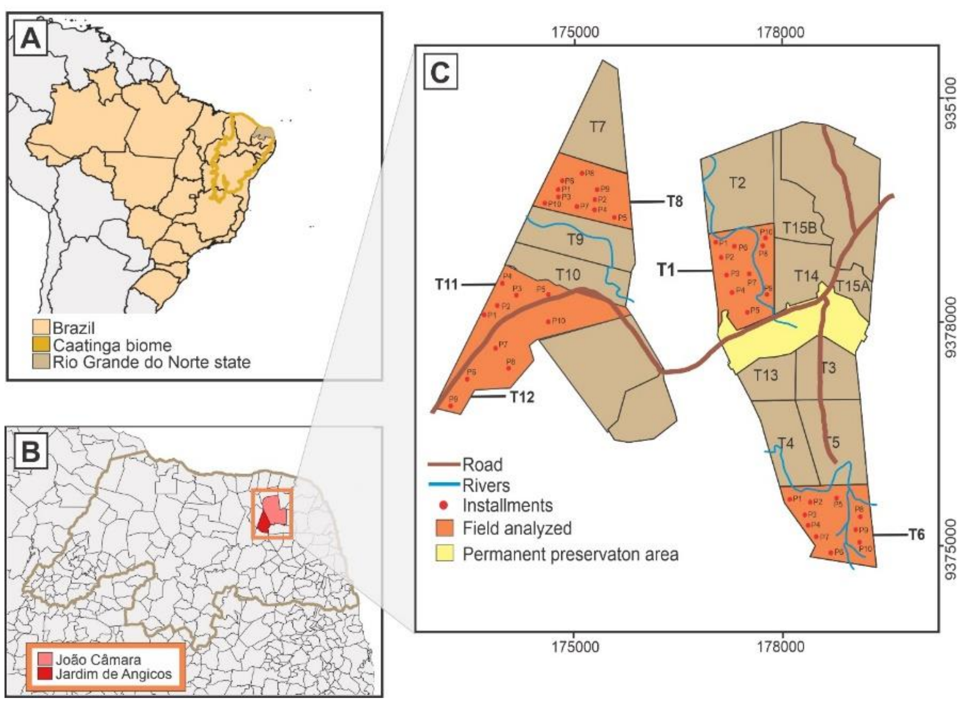



**Fig. 1.** Map of the state of Rio Grande do Norte, highlighting the municipalities of João Câmara, Jardim de Angicos and the capital Natal

The sampling units were determined with the aid of a GPS device (Garmin 62s), which geographically selected four specific fields: the first, called T-6, nine years post-cutting; T-11/12, 11 years after cutting; T-8, 13 years old after cutting; and T-1, 16 years post-cut. The definition of the field size followed the method of the Permanent Plot Measurement Protocol of the Caatinga Forest Management Network ASTM D2395-17 (ASTM, 2017), while the number of plots was established based on a maximum error of ± 20% in volume, with 90% probability.

## Inventory, Selection of Tree Samples, and Measurement of Total Woody Biomass

The forest inventory was carried out according to the methodology proposed by the Caatinga Management Network (Brasil 2022), wherein they measured four fields in ten plots each to characterize the forest population based on information on the horizontal structure of the forest and measurement data on dendrometric parameters. The following data were collected: (i) identification of tree and shrub species based on the popular name, followed by identification of the scientific name using literature; (ii) circumference at chest height (CCH), with circumferences equal to or greater than 6 cm measured at 1.30 height from the ground; (iii) circumference at the base (CBH) measured at 0.30 m above the ground using a tape measure and (iv) the total height measured (H) using a topograde ruler.

Species were selected as the most representative in the population based on a sum of the IVI (Importance Value Index) greater than 80% of the total value. Total values are usually lower than those used in this research (Souza *et al*. 2019; Pareyn *et al*. 2020). The estimate of the total aboveground volume of each individual was obtained using Eq. 1, with a form factor of 0.91, as described by Campos and Leite (2013),

$$V_r = \frac{\pi . DCH^2}{40000} \ x \ H_t \ x \ ff \qquad (1)$$

where $V_r$ is the estimated tree volume in $m^3$, DCH is the diameter at 1.3 m (cm), obtained by CCH / π; $H_t$ is the total height (m), and *ff* is the Form factor (0.91).

## Biomass Turnover Age Estimation

To estimate the growth curve, average production, and the most appropriate rotation age of each species within the study area, the production of the four fields was measured in two years (2017 and 2020). To this end, it was necessary to estimate the average growth curve of the local forest (Pareyn *et al*. 2020). It should be noted that the individuals were at different stages of post-cut regeneration. The model used to calculate the growth curve was the non-linear Weibull model, which represented the data more efficiently. This model has been widely used in the forestry sector, as it is highly practical; that is, it makes it easier to apply adjustments for different growth forms (Pareyn *et al*. 2020). Therefore, the Logistic Model software was utilized to make the necessary adjustments. The growth model is represented by Eq. 2, as indicated by Campos and Leite (2013),

$$y = \frac{a}{1+b*\exp(-cx)} + e \qquad (2)$$

where *y* is the volume, *a*, *b*, *c*, and *e* are model parameters, *x* is age, exp is exponential, and *e* is random error.

Additionally, from the calculations of the Average Annual Increments (AMI) and the Current Annual Increments (ICA), the most suitable age for cutting was estimated, mainly due to the stagnation of volumetric production.

### Characterization of Wood Properties

The individual volumes obtained, and their subsequent sum resulted in the total volume of the sample field, which was then extrapolated to hectares. Therefore, the inventory was processed by stratified casual sampling, using an acceptable error of ± 20% at 90% probability. The energy stock was determined based on the calorific value, according to the regulations DIN 51900-1 (DIN 2000), using an IKA C200 calorimeter. For the selected individuals, for which no values were found for basic density and higher calorific value, the average value weighted by the Importance Value Index (IVI) of the other species was used, as proposed by (Souza *et al*. 2019). Finally, the energy production per released field was determined based on the sum of all trees, which was extrapolated to one hectare.

### Rainfall Index Analysis

To analyze the influence of climate patterns on the volumetric growth of individual species and, consequently, on volumetric production, precipitation data were utilized from the municipalities of João Câmara and Jardim de Angicos, provided by the Agricultural Research Company of Rio Grande do Norte (EMPARN), spanning from 2003 to 2020. This is because, for the establishment and development of vegetation, it is crucial to consider the influence of precipitation over multiple years rather than relying solely on data collected at a single point in time. Using this data, anomalies in average annual precipitation were computed to assess the yearly rainfall patterns in relation to the climatological average. This made it possible to identify periods of above-average and below-average rainfall and consecutive intervals of rain and drought.

### Data Analysis

The data were subjected to normality (Shapiro-Wilk) and homoscedasticity (Scott-Knott) tests. The analysis of variance was carried out following a completely randomized design, with four independent variables (age of the field at 9, 11, 13, and 16 years post-cutting), with each field (years post-cutting) consisting of 10 plots, totaling 40 measurements. Pearson's correlation coefficient was calculated to evaluate the relationship between the age of the field and the variables studied. As for the forest inventory of the four fields, a margin of sampling error of 95% was adopted, considering the arithmetic mean of the fields and the standard error of the variables. The data analysis process was conducted using the R Core Team software.

## RESULTS AND DISCUSSION

Figure 2 presents the results of a forest inventory survey, enabling a phytosociological analysis of the four study areas. A total of 28 species were identified (see Figs. S1, S2, S3, and S4). Among these species, *Croton sonderianus* exhibited the highest absolute density in fields aged nine years (952 stems $ha^{-1}$), 13 years (2,312 stems $ha^{-1}$), and 16 years (1,110 stems $ha^{-1}$). However, in the 11-year-old field, the species *Cenostigma pyramidale* predominated, with 525 stems $ha^{-1}$.

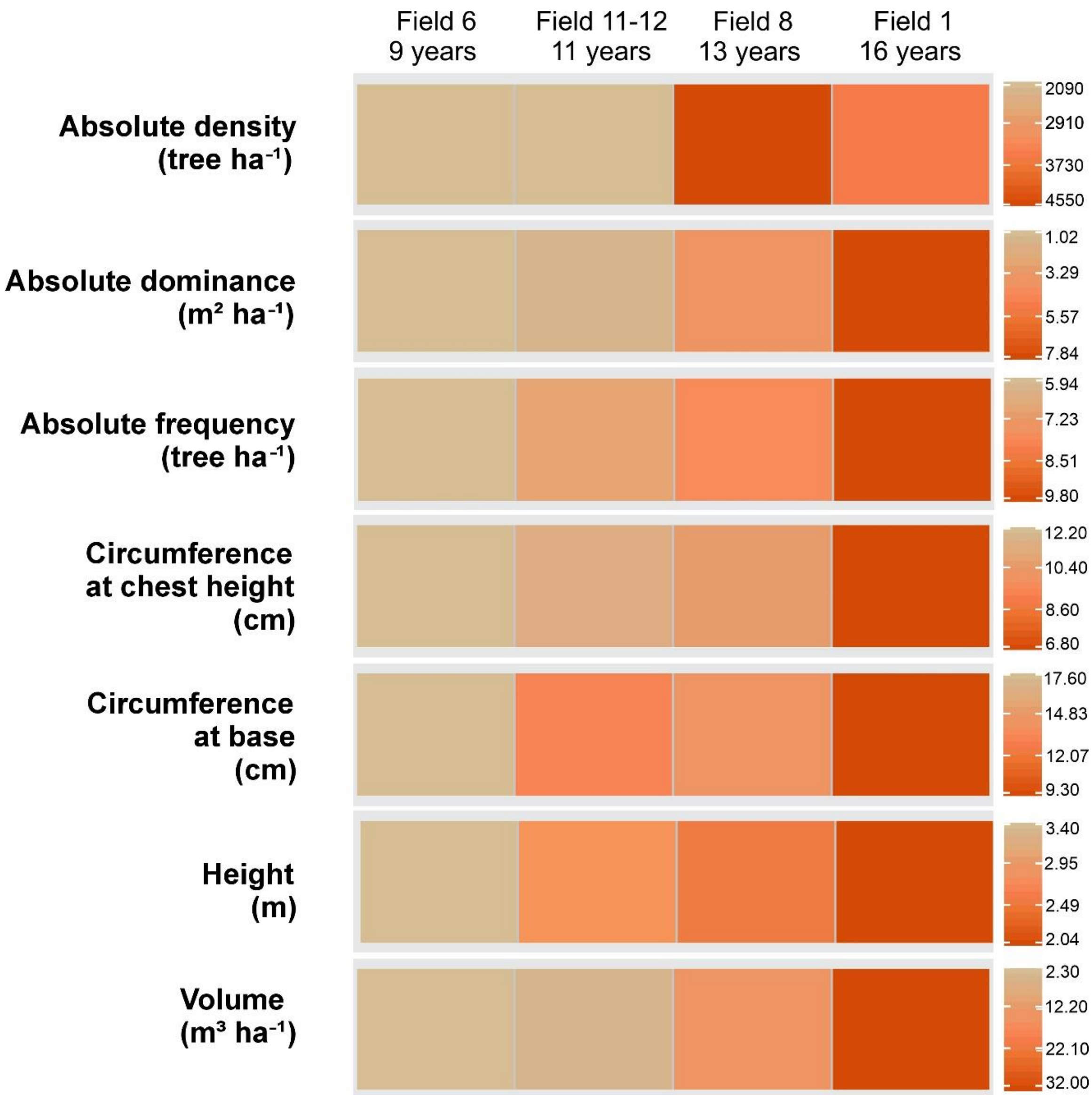



**Fig. 2.** Average forest inventory values in the field analyzed in different age groups

However, it is important to highlight that species with the highest number of stems per area may not always have the highest volume of biomass, as evidenced by the results from the 11 and 16-year-old fields. The number of boles per area is not a direct indicator of the total amount of biomass in a forest. Biomass can vary considerably between species due to individual stem size, wood density, growth rate, and stage of forest development (Gomes *et al*. 2021; Curvo *et al*. 2024). Absolute dominance varies between fields of different ages. For fields 9, 11, 13, and 16 years old, the following absolute dominances were recorded, respectively: 1.03, 1.70, 3.87, and 7.83 m² ha$^{-1}$. In the 16-year-old field, the species *Cenostigma pyramidale* stands out, representing 54.6% (4.42 m² ha$^{-1}$) of absolute dominance, showing the largest volume of biomass. On the other hand, in the 11-year-old field, *Mimosa tenuiflora* takes the lead with 32.9% (0.56 m² ha$^{-1}$) of absolute dominance. This pattern observed in the variation in absolute dominance between stands can be explained by the dynamic interaction of several ecological factors that influence the structure and composition of forest communities. In the field 9-year-old, intense competition between trees emerges as a preponderant factor (Cunha *et al*. 2020). At this early stage, competition for limited resources such as sunlight, soil nutrients, and water is particularly intense, given the high number of young, regenerating trees present (Becknell *et al*. 2012; Menéndez-Miguélez *et al*. 2015).

Based on calculations of the Importance Value Index (IVI), three predominant species were identified in each area investigated, which stood out as the most significant when considering criteria of density, dominance, and frequency. In the field nine years after cutting (Figure S1), the most relevant species were *Croton sonderianus* (31.9%), *Cenostigma pyramidale* (18.8%), and *Piptadenia stipulacea* (with 16.9% of IVI). In the field 11 years post-cut (Fig. S2), the most representative species included *Mimosa tenuiflora* (19.3%), *Piptadenia stipulacea* (with 18.2% IVI), and *Cenostigma pyramidale* (with 17.4% IVI). In the field 13 years after cutting (Fig. S3), the most prominent species were *Croton sonderianus* (33.1%), *Cenostigma pyramidale* (with 18.8% of IVI), and *Piptadenia stipulacea* (13.8%). In the field 16 years after cutting (Fig. S4), the most relevant species were *Cenostigma pyramidale* (32.1%), *Croton sonderianus* (16.5%), and *Aspidosperma pyrifolium* (12.7%), which stood out as the most influential species, exerting a significant positive impact on the amount of volume, biomass, and energy in the analysis field.

It is essential to highlight that this index enables the evaluation of the importance of each species within the study area, calculated through the summation of frequency, dominance, and density values (Barros *et al*. 2021). Additionally, it was observed that the results for the most significant species did not exhibit major disparities among the four fields investigated, suggesting a certain uniformity across the areas. This uniformity is of significant importance when considering the application of these forest fragments in energy production. The presence of more homogeneous raw materials in the field implies a reduction in the need for diverse treatments in the processing of the material, both in terms of transportation and biomass preparation (Curvo *et al*. 2024). This applies to direct use and heating or electricity generation (Santos *et al*. 2023). In the context of energy utilization, this positive characteristic contributes to minimizing variation in wood quality, moisture, and ash content while enhancing the calorific value, rendering the process more efficient and economically viable.

The circumference at breast height showed a proportional increase with the field's aging. In the interval from 9 years (with a diameter of 6.8 cm) to 16 years (with a diameter of 12.2 cm), an increase of 79.4% in tree diameter was observed (Table S1). This trend was also evident in the circumference at the base and height of the trees, indicating gradual growth. The circumference at the base recorded increases of 45.2%, 32.2%, and 89.2% in fields aged 11, 13, and 16 years, respectively, compared to the first inventory conducted at nine years. Analyzing tree height from the initial inventory to the final (at 16 years old), an increase of 41.7% was found. Additionally, chest circumference, base increase, and volume peak at older ages (Bowman *et al*. 2013; do Nascimento *et al*. 2023). Conversely, base height is initially smaller but progressively grows until the tree reaches the senescent stage, validating the findings of this study. Wood with a larger circumference, a substantial increase in base circumference, and greater height not only provides significant benefits for energy generation but also tends to contain a higher proportion of components such as lignin (Dias *et al*. 2020; do Nascimento *et al*. 2023). Lignin plays a crucial role in the calorific properties during biomass-to-energy conversion processes (de Souza *et al*. 2023).

The volume in the fields increased gradually with age, exhibiting increases of 87.3% between the 9-year-old field (2.36 $m^3\ ha^{-1}$) and the 11-year-old field (4.42 $m^3\ ha^{-1}$), 202% between 11 and 13 years old (13.33 m³ $ha^{-1}$), and 139.9% between 13 and 16 years old (29.0 m³ $ha^{-1}$) (Table S1). As the annual production regeneration unit ages (older cutting), its regeneration into wood increases, resulting in higher volumetric productivity (Fig. 2). The observed increase in wood productivity in this study is a consequence of the ecological succession process in the forest stand, wherein the wood volume tends to increase due to the continuous growth of trees during regeneration. However, it is crucial to consider that each species has different energy storage capacities. In other words, variations in the chemical constitution, basic density, and calorific value of wood contribute to species' energy density differences (Cunha *et al*. 2020).The abundance of wood not only streamlines the process, requiring fewer procedures to achieve the desired biomass amount, but also significantly reduces processing costs. This underscores not only the effectiveness but also the economic viability of larger trees for sustainable biomass production and energy generation (Kawai *et al*. 2023). Furthermore, it is pertinent to investigate the optimization of biomass from fields of different ages for energy generation. In this context, it is imperative to delve into the technical analysis associated with this approach. A notable example is the consideration of Cutting Technique Age (CTA), which represents a crucial parameter in determining the appropriate time for harvesting. Assessing tree maturity in relation to maximum biomass production and the impact of this decision on the sustainability of forest resources emerge as fundamental aspects to be explored. Figure 3 presents the representation of CTA considering the average annual increment and the current annual increment.

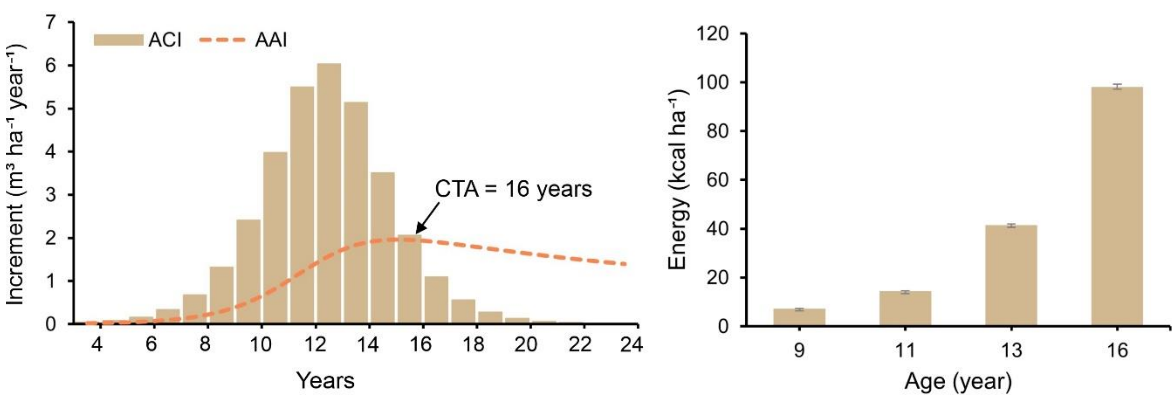



**Fig. 3.** Current annual increment (ACI), average annual increment (AAI), technical cutting age (CTA), and energy available in the tree strata in the four study fields

The most appropriate technical cutting age for the fields was determined to be 16 years. A comparative study by Barros *et al*. (2021) investigating the same area established a slightly higher ideal cutoff age of 17.3 years. The reduction in the technical cut-off age found in the present study can be explained by including data from the 2020 inventory, resulting in a shorter growth interval. This does not imply that vegetation will cease growing but rather that the growth rate will be considerably reduced (Cunha *et al*. 2020). This period represents the most suitable for volumetric exploration, making it economically more advantageous than waiting for additional growth. According to Normative Instruction n°1 of the Ministry of the Environment, the minimum cutting cycle established for the Caatinga is 15 years (Brasil 2022), considering only the woody stock in the exploited area. These results are significant, as they can determine the average accumulated volume, the cutting age, and the volume of wood accumulated in the last year, providing guidance on the optimal time to achieve maximum volume in the exploration area, thus resulting in greater energy production. The field with 16 years post-cutting demonstrated the highest energy accumulation, consistent with the ideal technical cutting age of 16 years and the total stock volume (Table S1).

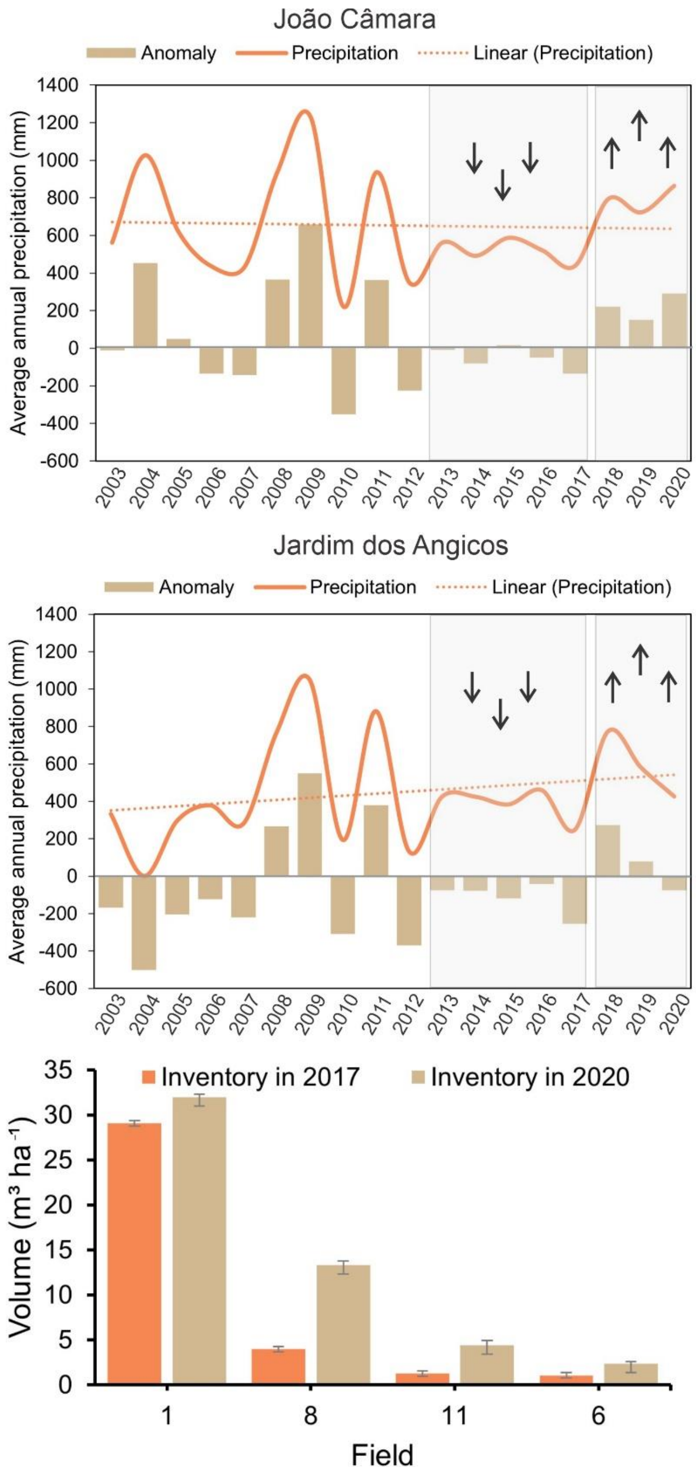



**Fig. 4.** Relationship between volumetric stock and precipitation and anomalies in average annual precipitation in the areas of João Câmara and Jardim dos Angicos from 2003 to 2020. Source provided by the Agricultural Research Company of Rio Grande do Norte (EMPARN 2023)

When analyzing Fig. 3, it is evident that, when correlating stored energy (kcal $ha^{-1}$) with the age of the different fields, the one with the longest growth period (16 years) stood out from the others, accumulating 98.2 kcal $ha^{-1}$, a value 1,249% higher than that of the youngest field (9 years old), which presented 7.28 kcal $ha^{-1}$. The species that contributed most to the energy accumulation were *Mimosa tenuiflora* with 3,740 kcal $m^{-3}$, *Piptadenia stipulacea* with 3,270 kcal $m^{-3}$, and *Cenostigma pyramidale* with 3,101 kcal $m^{-3}$.

Another element that can play a substantial role in influencing biomass stock and forest development is volumetric precipitation (Pareyn *et al*. 2020). Based on these findings, this study analyzed the rainfall from 2003 to 2020 (Fig. 4), adopting the selection of periods with different rainfall levels and investigating how these variations can influence the biomass stock.

In 2017, precipitation rates in the Jardim dos Angicos and João Câmara region, where the fields were analyzed, were below the estimated annual average of around 600 mm. However, in 2018 (794 mm) and 2020 (894 mm), during the second inventory, an 8.82% increase in rainfall was noted, exceeding the climatological averages for the municipality of João Câmara. In contrast, in Jardim dos Angicos, rainfall in 2020 (426 mm) was below the climatological average. Comparing the results obtained in this study with those achieved by Cunha *et al*. (2020), which examined the same areas and fields in 2017, revealed an increase in the volumetric stock of 56.0%, 71.9%, 70.4%, and 9.1% in fields 9, 11, 13, and 16 years post-cut, respectively, compared to 2020 values. Adequate water availability resulting from the increase in rainfall is vital for the tree photosynthesis process (Li *et al*. 2024), promoting healthy growth and contributing to the formation of quality wood. Water facilitates nutrient absorption by the roots, thereby boosting vegetative development. In rainier areas, trees may exhibit more spaced growth rings, affecting the wood density and, consequently, its properties for various industrial uses. The potential influence of wood quantity and quality, subject to variations in rainfall, can play a fundamental role in the pursuit of sustainable energy generation (da Silva *et al*. 2022; Li 2023).

This increase can be attributed to variations in rainfall levels in the post-cut period in these areas (Li *et al*. 2024). Studies conducted by Menéndez-Miguélez *et al*. (2015) and Pareyn *et al*. (2020) highlighted the preponderance of water availability as the crucial factor influencing biomass accumulation and forest growth. Becknell *et al*. (2012), when conducting an analysis covering 44 studies in tropical forest ecosystems characterized by seasonal droughts in different regions of the world, identified that average precipitation explained more than 50% of the variation in above-ground biomass, highlighting that areas with higher rainfall accumulated a significantly greater amount of biomass volume. A study by Pareyn *et al*. (2020) covered ten locations in the Northeast Region of Brazil, intending to relate 26 environmental factors to forest growth after management. The results of this research highlighted that, among the various factors analyzed, rainfall rates in the areas had the greatest influence. Another survey conducted by Sette Jr *et al*. (2016) identified significant variations in the growth of forest species, with maximum and minimum values correlated to precipitation, average temperature, and relative air humidity.

The results obtained from Pearson's correlation revealed striking positive and negative associations between the characteristics of fields at different stages of maturity, investigated regarding the volumetric and energy production of wood in forest management plan areas in an arid biome (Fig. 5).

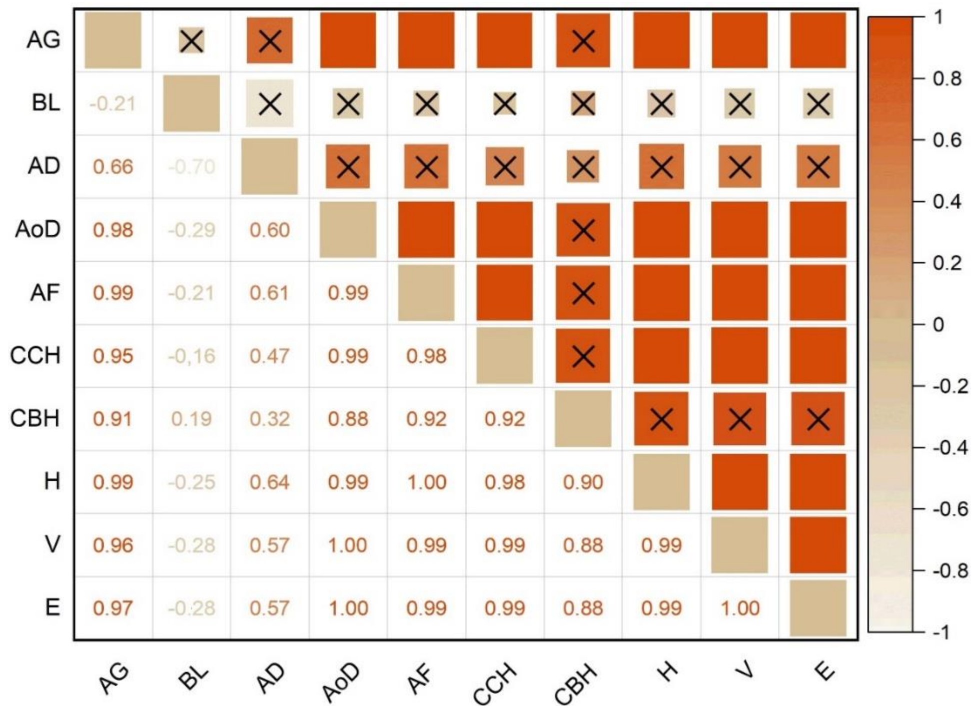



**Fig. 5.** Correlation matrix of the analyzes of the four fields studied at different post-cutting ages. Where: AG = age (year); BL = boles (boles ha$^{-1}$); AD = absolute density (tree ha$^{-1}$); AoD = absolute dominance (m$^2$ ha$^{-1}$); AF = absolute frequency (tree ha$^{-1}$); CCH = circumference at chest height (cm); CBH = circumference at base height (cm); *H* = height (m); *V* = volume (m$^3$ ha$^{-1}$) and *E* = energy (kcal ha$^{-1}$).

The present study demonstrated a consistent positive correlation between field age and several essential variables, including absolute dominance, absolute frequency, circumference at breast height, height, volume, and stored energy. These results indicate that as the field ages, there is a substantial increase in biomass abundance and energy generation per square meter. This finding reinforces the patterns observed in Figs. 2 and 3, where the temporal increase in the field is directly associated with the augmentation of these characteristics, suggesting a consistent relationship over time. Cunha *et al*. (2020) highlight that with increasing field age, there is a significant increase in volume and, consequently, in the energy stored in the trees, thus elucidating the data found in this study. However, it is crucial to strategically consider the ideal moment for this process, especially concerning the technical cutting age. This strategic choice is justified by the fact that, at this stage, the forest reaches a favorable balance between sustainable growth and maturity, creating ideal conditions to optimize not only biomass volume but also stored energy. Meanwhile, the number of boles exhibited a negative correlation with all variables analyzed in the study. It is important to highlight that the number of boles has no direct relationship with any of the biomass metrics investigated. This lack of correlation can be attributed to the varied and specific nature of the stems, which, although they influence the tree's structure, do not demonstrate linearity with the biomass indicators. Therefore, the number of stems does not prove to be a determining factor in the biomass variables studied.

This information underscores the importance of forest management, as it can enhance productivity in terms of firewood. The quantity of energy stored is greater in older fields, with longer cutting intervals, and this trend increases as the cutting interval of the area extends (Barros *et al*. 2021). This reinforces the significance of managing areas earmarked for firewood extraction to enhance firewood productivity in the exploited areas. Both the biomass quantity and the stored energy are strongly influenced by the structure of the fields studied, as the oldest ones tend to have a greater diversity of species and more robust trees (Souza *et al*. 2019; Pareyn *et al*. 2020). Although this study solely evaluates the energy potential of the study area, it is crucial to emphasize the pivotal role that forest management plans play when implemented in forested areas. These plans aim to maintain the sustainability of the system, contribute to the ecosystem's balance, and promote the growth and preservation of tree species of interest. Therefore, it is imperative to determine the ideal cutting age for each field based on inventory data from fields of different ages and production estimates at various times throughout the development of the fields studied.

## Practical Applications, Perspectives, and Future Challenges

The vast forests of native species in the neotropical semi-arid region play an increasingly important role in producing renewable energy and the sustainable management of natural resources. In recent years, there has been a significant increase in investments in this sector. A notable example is the Fund for the Promotion of Ecossocial Productive Landscapes (PPP-ECOS Fund), which launched a notice in 2023 focusing on the Caatinga biome, allocating R$4 million to finance projects aimed at the sustainability of native species, the development of Sustainable Management Plans for energy purposes and the conservation of the Caatinga. This support was made possible thanks to the Small Grants Program (SGP), a program of the Global Environment Facility (GEF) implemented by the United Nations Development Program (UNDP), as well as other donors such as the European Union (PNUD Brasil 2023). Given the growing investment in semi-arid forests, the results of this research highlight the notable potential of the wood analyzed. To maximize the use of these forests, it is imperative to adopt strategies that optimize their use and promote sustainability. A fundamental approach is the implementation of Sustainable Forest Management, which ensures the conservation of biodiversity, natural regeneration, and respect for tree growth cycles. This practice will significantly contribute to the long-term maintenance of the forest, balancing exploitation with conservation. Furthermore, investing in Efficient Conversion Technologies is essential. This includes the adoption of advanced combustion, gasification, cooking processes, and other innovations that maximize energy yield while reducing environmental impacts. Environmental Education with local communities is a powerful tool. Highlighting the importance of forest conservation, promoting sustainable practices, and highlighting the socioeconomic benefits of responsible management are fundamental steps towards involvement and awareness. Investment in Research and Development is essential to improve management techniques, select suitable species, and develop more efficient and sustainable technologies. This continuous improvement approach is vital to reconcile economic exploitation with environmental conservation. By adopting these strategies in an integrated manner, it is possible to enhance the use of semi-arid forests in a sustainable manner, promoting a balance between economic development and environmental preservation.

Based on the data obtained in this study, where the forests analyzed, specifically the 16-year-old field, present an estimated production of 98.2 kcal per hectare, and considering the average energy consumption per inhabitant, approximately 2,340 kWh per year in 2022, according to data from the Energy Research Company (EPE) and the Brazilian Institute of Geography and Statistics (IBGE), we can make projections for energy generation in different scenarios (EPE 2023; IBGE 2023). In the best-case scenario, with a conversion efficiency of 30%, one hectare could generate approximately 0.55 GWh per year. On the other hand, in the worst-case scenario, with an efficiency of 20%, the annual production per hectare would be around 0.35 GWh. Regarding population reach, in the optimistic scenario, yearly production of 0.55 GWh per hectare could contribute to meeting the energy needs of approximately 233 individuals. In the least favorable scenario, with an efficiency of 20%, an annual production of 0.35 GWh per hectare would be enough to meet the needs of around 148 people.

Considering the total extension of approximately 7 million km² of semi-arid forest biomes on a global scale, it is possible to reformulate the calculations to assess the potential for energy generation and its impact on the population. With an estimated production of 98.2 kcal per hectare and taking into account the entire extent of semi-arid forest biomes, one can calculate the total energy production. In the optimistic scenario, with a conversion efficiency of 30%, annual production would be approximately 3.2 million GWh. In the least favorable scenario, with an efficiency of 20%, annual production would be around 2 million GWh. Regarding population reach, in the optimistic scenario, an annual production of 3.2 million GWh could contribute to meeting the energy needs of approximately 1.4 billion people. In the least favorable scenario, with an efficiency of 20%, an annual production of 2 million GWh would be sufficient to meet the needs of around 933 million people. These projections provide a comprehensive understanding of the potential impact of these renewable energy sources, considering the vast expanse of semi-arid forest biomes on a global scale.

This data has a direct application in the management of natural resources, including the extraction of wood from Caatinga forests. Furthermore, they are fundamental for the production of energy from forest biomass, allowing the optimization of harvesting and electricity generation processes making them more efficient and economically viable. The uniformity in species distribution is an advantage, reducing the complexity of biomass processing. As demand for clean energy sources continues to grow, future prospects indicate an even more critical role for Caatinga forests. It is imperative that there is continual improvement of these studies to assess the sustainability of using forest biomass as an energy source. Future research should focus on refining forest management for biomass and energy production, including determining the ideal harvest age in different stands based on inventory data and estimates. These future investigations will add to scientific understanding, providing a clearer and more comprehensive understanding of the various factors that influence the accumulation of biomass and, consequently, energy production.

## CONCLUSIONS

1. Twenty-eight species were identified in the study areas, with *Cenostigma pyramidale*, *Piptadenia stipulacea*, *Mimosa tenuiflora*, *Croton sonderianus*, *Aspidosperma pyrifolium*, *Andira anthelmia*, *Combretum leprosum*, *Mimosa caesalpiniiifolia*, *Capparis flexuosa*, *Combretum laxum*, and *Jatropha mollissima* representing more than 80% of the Species Index Importance Value (IVI).
2. Species with a greater number of stems did not always result in a greater amount of biomass; the cutting age was determined at 16 years, indicating the ideal time for exploration with the greatest use of wood.

3. Energy density also varied, with the oldest field (Field 1 – 16 years old) reaching 98.2 kcal $ha^{-1}$ and the species *Mimosa tenuiflora*, *Piptadenia stipulacea*, and *Cenostigma pyramidale* contributing significantly to energy accumulation.
4. Finally, it is essential to highlight that this study represents only the starting point in a comprehensive exploration. By evaluating one of 15 fields in an area of caatinga vegetation, it became apparent that there are the vast opportunities that await investigation. As other fields reach the minimum harvest cycle, not only in the state of Rio Grande do Norte but also in other States within the Caatinga region, this pioneering study lays the foundation for additional research.

## ACKNOWLEDGMENTS

This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Financing Code 001. To Adailton J. E. de Carvalho for allowing us access to the sustainable forest management plan for Fazenda Milhã/Poço da Pedra. The Agricultural Research Company of Rio Grande do Norte (EMPARN), in the person of Dr. Gilmar Bristot, for providing us with precipitation data for the study area.

## REFERENCES CITED

ASTM D2395-17 (2017). "Standard test methods for density and specific gravity (relative density) of wood and wood-based materials," ASTM International, West Conshohocken, PA, USA.

Barros, M. F., Ribeiro, E. M. S., Vanderlei, R. S., de Paula, A. S., Silva, A. B., Wirth, R., Cianciaruso, M. V., and Tabarelli, M. (2021). "Resprouting drives successional pathways and the resilience of Caatinga dry forest in human-modified landscapes," *Forest Ecology and Management* 482, article 118881. DOI: 10.1016/j.foreco.2020.118881

Becknell, J. M., Kissing Kucek, L., and Powers, J. S. (2012). "Aboveground biomass in mature and secondary seasonally dry tropical forests: A literature review and global synthesis," *Forest Ecology and Management* 276, 88-95. DOI: 10.1016/j.foreco.2012.03.033

Bowman, D. M. J. S., Brienen, R. J. W., Gloor, E., Phillips, O. L., and Prior, L. D. (2013). "Detecting trends in tree growth: not so simple," *Trends in Plant Science* 18(1), 11-17. DOI: 10.1016/j.tplants.2012.08.005

Brasil. (2020). "Caatinga: Context, Characteristics and Conservation Strategies," (https://www.mma.gov.br/biomas/caatinga/item/191.html), accessed 19 Jan 2024.

Brasil. (2022). "Sudene Ordinance N° 80, of June 27, 2021. Establishes the working conditions and deliveries for the review of the delimitation of the Brazilian Semiarid region, included in Sudene's area of activity, to be submitted to its Deliberative Council.," (https://www.gov.br/sudene/pt-br/acesso-a-informacao/legislacao/hierarquia/portarias/portaria-ndeg-80-de-27-de-julho-de-2021), accessed 19 Jan 2024.

Campos, J. C. C., and Leite, H. G. (2013). "Forest measurement: Questions and answers," *Editora UFV* (5), 605.

Cunha, J., Nóbrega, R. L. B., Rufino, I., Erasmi, S., Galvão, C., and Valente, F. (2020). "Surface albedo as a proxy for land-cover clearing in seasonally dry forests: Evidence from the Brazilian Caatinga," *Remote Sensing of Environment* 238, article 111250. DOI: 10.1016/j.rse.2019.111250

Curvo, K. R., Silva, G. A. O., Castro, V. R., Gava, F. H., Pereira, B. L. C., and Oliveira, A. C. (2024). "Heartwood proportion and density of *Tectona grandis* L.f. wood from Brazilian fast-growing plantations at different ages," *European Journal of Wood and Wood Products*. DOI: 10.1007/s00107-023-02031-5

DIN 51900-1 (2000). "Testing of solid and liquid fuels – Determination of the gross calorific value by the bomb calorimeter and calculation of net calorific value – Part 1: Principles, apparatus, methods," Deutsches Institut Fur Normung.

Dias, A., Carvalho, A., Silva, M. E., Lima-Brito, J., Gaspar, M. J., Alves, A., Rodrigues, J. C., Pereira, F., Morais, J., and Lousada, J. L. (2020). "Physical, chemical and mechanical wood properties of Pinus nigra growing in Portugal," *Annals of Forest Science* 77(3), article 72. DOI: 10.1007/s13595-020-00984-8

Dias Júnior, A. F., Andrade, C. R., Protásio, T. de P., Melo, I. C. N. A. de, Brito, J. O., and Trugilho, P. F. (2018). "Pyrolysis and wood by-products of species from the Brazilian semi-arid region," *Scientia Forestalis* 46(117). DOI: 10.18671/scifor.v46n117.06

EPE (2023). "Electrical Energy Statistical Yearbook," Energy research company. (https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/anuario-estatistico-de-energia-eletrica), accessed 19 Jan 2024.

FAO (2022). "The State of the World's Forests 2022". Food and Agriculture Organization of the United Nations. (https://www.fao.org/brasil/noticias/detail-events/es/c/1507196/), accessed 15 Jan 2024.

Gomes, I. R. F., Santos, R. C. dos, Castro, R. V. O., Vidaurre, G. B., Silva, G. G. C. da, Rocha, S. M. G., Santos, C. P. de S., Costa, S. E. de L., Silva, M. K. A. G. da, and Lima, J. L. P. E. de. (2021). "Does spacing affect the production of clones for wood energy planted in the state of Rio Grande do Norte, Brazil?," *Scientia Forestalis* 49 (131). DOI: 10.18671/scifor.v49n131.25

IBAMA (2021). "Caatinga". Brazilian Institute of the Environment and Renewable Natural Resources. (https://www.gov.br/mma/pt-br/assuntos/biodiversidade-e ecossistemas/ecossistemas/biomas/caatinga), accessed 15 Jan 2024.

IBF (2023). "Bioma Caatinga," Brazilian Forestry Institute.

IBGE (2023). Industry Situational Indices - Brazil - Summary Table (Variation in %), September 2023 - November 2023. Brazilian Institute of Geography and Statistics.

Kawai, K., Kenzo, T., Ito, S., and Kanna, K. (2023). "Size-related changes in leaf, wood, and bark traits in even-aged," *Tropics* 32(1), MS22-06. DOI: 10.3759/tropics.MS22-06

Li, D., Li, X., Li, Z., Fu, Y., Zhang, J., Zhao, Y., Wang, Y., Liang, E., and Rossi, S. (2024). "Drought limits vegetation carbon sequestration by affecting photosynthetic capacity of semi-arid ecosystems on the Loess Plateau," *Science of The Total Environment* 912, article 168778. DOI: 10.1016/j.scitotenv.2023.168778

Li, K. (2023). "Evaluation energy flow and analysis of energy economy for agricultural yield production in different geographical regions of China," *Water Supply* 23(11), 4636-4644. DOI: 10.2166/ws.2023.261

Menéndez-Miguélez, M., Álvarez-Álvarez, P., Majada, J., and Canga, E. (2015). “Effects of soil nutrients and environmental factors on site productivity in *Castanea sativa* Mill. coppice stands in NW Spain,” *New Forests* 46(2), 217-233. DOI: 10.1007/s11056-014-9456-2

do Nascimento, C. S., de Almeida Cruz, I., do Nascimento, C. C., de Araújo, R. D., Higuchi, N., and dos Santos, J. (2023). “Technological properties of wood from small diameter in an area of forest exploitation of reduced impact in the tropical forest,” *European Journal of Forest Research* 142(5), 1225-1238. DOI: 10.1007/s10342-023-01588-3

Pareyn, F. G. C., Pereira, W. E., Salcedo, I. H., Riegelhaupt, E. M., Gomes, E. C., Menecheli, H. T. F., and Skutsch, M. (2020). “What controls post-harvest growth rates in the caatinga forest?,” *Agricultural and Forest Meteorology* 284, article 107906. DOI: 10.1016/j.agrformet.2020.107906

Pelletier, J., Chidumayo, E., Trainor, A., Siampale, A., and Mbindo, K. (2019). “Distribution of tree species with high economic and livelihood value for Zambia,” *Forest Ecology and Management* 441, 280-292. DOI: 10.1016/j.foreco.2019.03.051

PNUD Brasil, (2023). “PNUD in Brazil: For human, inclusive and sustainable development,” United Nations Development Program. (https://www.undp.org/pt/brazil), accessed 15 Jan 2024.

Ramananantoandro, T., Ramanakoto, M. F., Rajoelison, G. L., Randriamboavonjy, J. C., and Rafidimanantsoa, H. P. (2016). “Influence of tree species, tree diameter and soil types on wood density and its radial variation in a mid-altitude rainforest in Madagascar,” *Annals of Forest Science* 73(4), 1113-1124. DOI: 10.1007/s13595-016-0576-z

Santos, R. C., Pareyn, F. G. C., Santos, C. P. S., Minini, D., Rocha, S. M. G., Souza, F. J. O., Cezario, L. F. C., Dias Júnior, A. F., and Castro, R. V. O. (2023). “Quantification of wood biomass in an area of sustainable annual production in the Brazilian semiarid region aiming at generating renewable energy,” *BioEnergy Research* 16(2), 817-825. DOI: 10.1007/s12155-022-10495-1

Sette Jr, C. R., Tomazello F, M., Lousada, J. L., Lopes, D., and Laclau, J. P. (2016). “Relationship between climate variables, trunk growth rate and wood density of *Eucalyptus grandis* W. Mill ex Maiden trees,” *Revista Árvore* 40(2), 337-346. DOI: 10.1590/0100-67622016000200016

SFB, (2019). “Forests of Brazil at a glance,” Brazilian Forest Service.

da Silva, J. B., Santos Júnior, E. P., Pedrosa, J. G. T., Sales, A. T., Sampaio, E. V. de S. B., Menezes, R. S. C., Dutra, E. D., and Junior, P. R. (2022). “Energetic and Economic analysis of spineless cactus biomass production in the Brazilian semi-arid region,” *Energies* 15(14), article 5270. DOI: 10.3390/en15145270

Smith, H. E., Jones, D., Vollmer, F., Baumert, S., Ryan, C. M., Woollen, E., Lisboa, S. N., Carvalho, M., Fisher, J. A., Luz, A. C., Grundy, I. M., and Patenaude, G. (2019). “Urban energy transitions and rural income generation: Sustainable opportunities for rural development through charcoal production,” *World Development* 113, 237-245. DOI: 10.1016/j.worlddev.2018.08.024

SNIF, (2021). “The firewood market in the Northeast generates R$ 2 billion per year and guarantees employment equivalent to 35 thousand jobs,” National Forest Information System. (https://snif.florestal.gov.br/pt-br/ultimas-noticias/755-mercado-de-lenha-no-nordeste-movimenta-r-2-bilhoes-por-ano-e-garante-ocupacao-equivalente-a-35-mil-postos-de-trabalho), accessed 11 Jan 2024.

de Souza, C. A. A., Jardim, A. M. da R. F., de Souza, L. S. B., Júnior, G. do N. A., Alves, C. P., de Morais, J. E. F., Lopes, D. de C., Steidle Neto, A. J., Salvador, K. R. da S., and da Silva, T. G. F. (2023). "Intercomparison of micrometeorological variables, surface energy fluxes, and evapotranspiration in different landscapes of the Brazilian semi-arid region," *Agricultural and Forest Meteorology* 341, article 109679. DOI: 10.1016/j.agrformet.2023.109679

Souza, D. G., Sfair, J. C., de Paula, A. S., Barros, M. F., Rito, K. F., and Tabarelli, M. (2019). "Multiple drivers of aboveground biomass in a human-modified landscape of the Caatinga dry forest," *Forest Ecology and Management* 435, 57-65. DOI: 10.1016/j.foreco.2018.12.042

Article submitted: April 3, 2024; Peer review completed: May 11, 2024; Revised version received: July 31, 2024; Accepted: August 4, 2024; Published: August 14, 2024.
DOI: 10.15376.biores.19.4.7195-7215

## APPENDIX

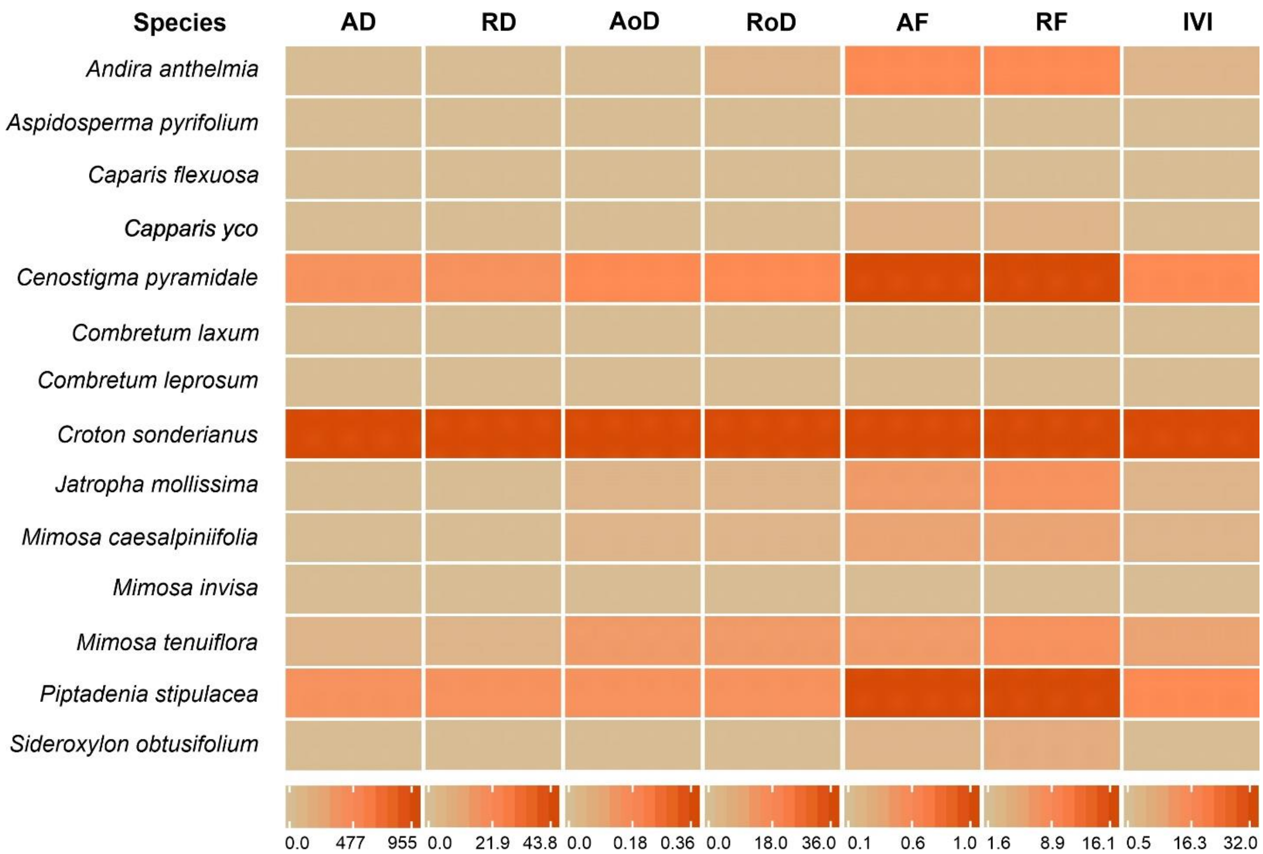



**Fig. S1.** Parameters of the horizontal structure of the fragment of the representative species of the population of the 9-year-old fields. Where AD (tree $ha^{-1}$), absolute density; RD (%), relative density; AoD ($m^2$ $ha^{-1}$), absolute dominance; RoD (%) relative dominance; AF (tree $ha^{-1}$), absolute frequency; RF (%), relative frequency; IVI (%), importance value index

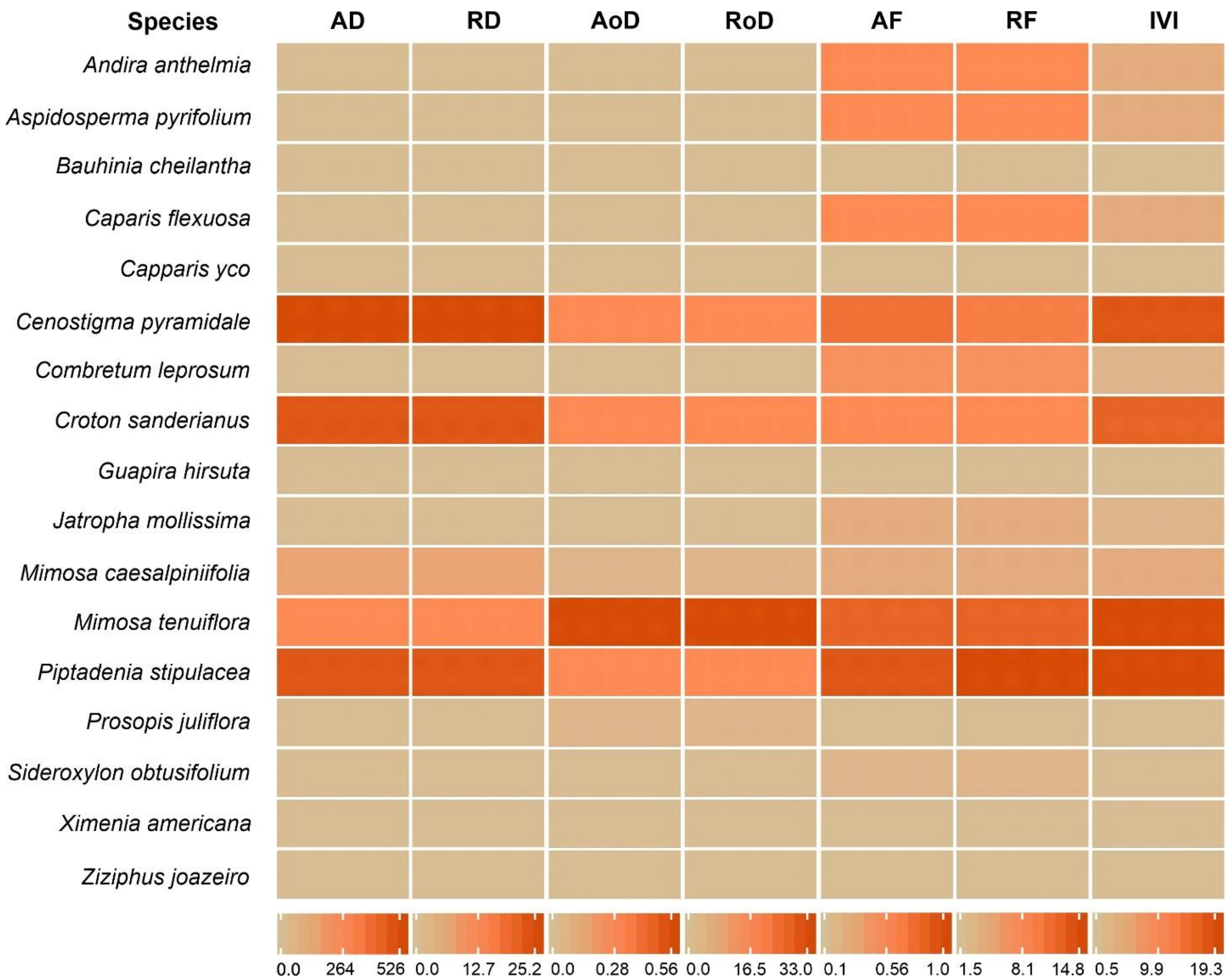



**Fig. S2.** Parameters of the horizontal structure of the fragment of the representative species of the population of the 11-year-old fields. Where AD (tree $ha^{-1}$), absolute density; RD (%), relative density; AoD ($m^2$ $ha^{-1}$), absolute dominance; RoD (%) relative dominance; AF (tree $ha^{-1}$), absolute frequency; RF (%), relative frequency; IVI (%), importance value index

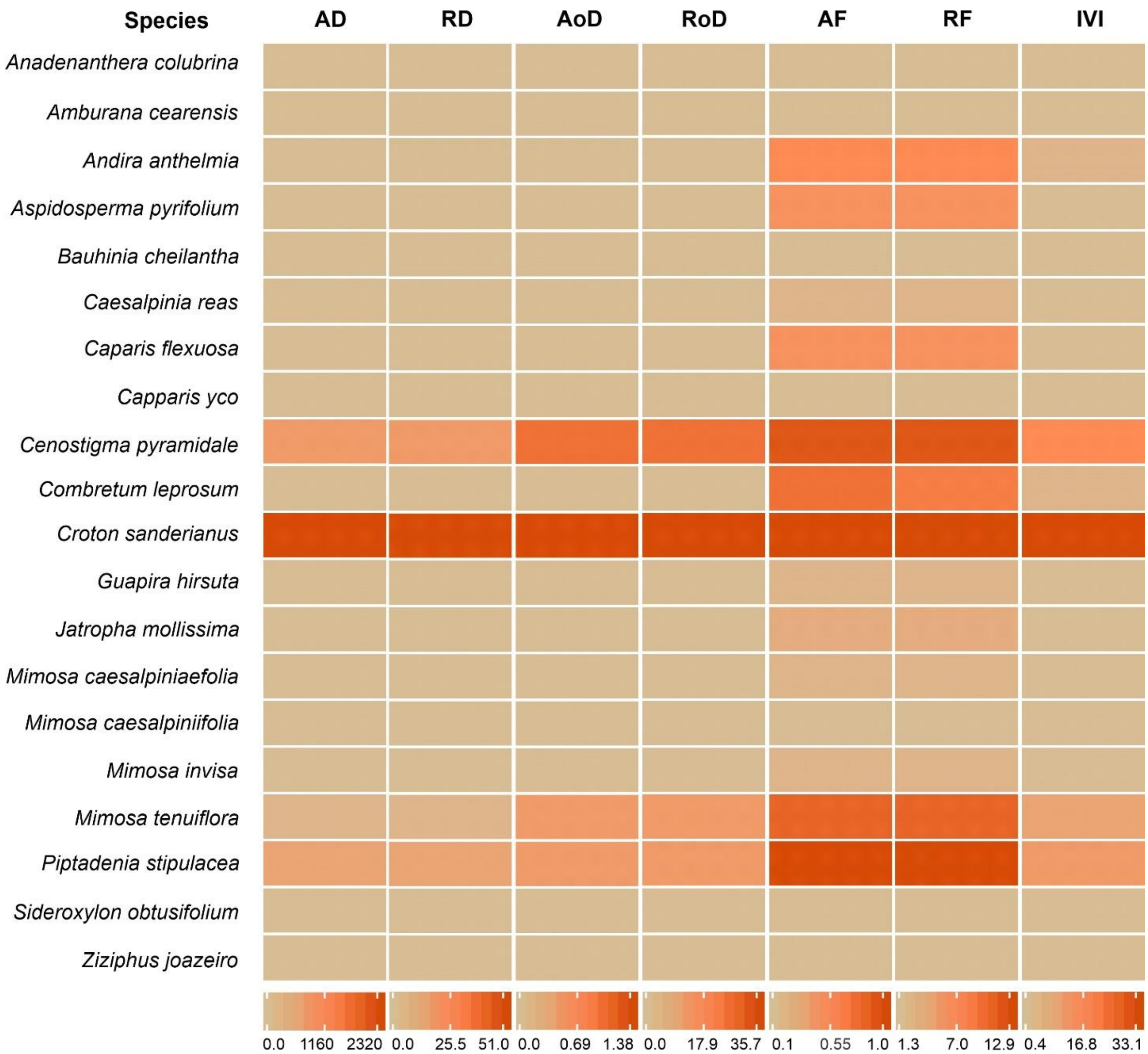



**Fig. S3.** Parameters of the horizontal structure of the fragment of the representative species of the population of the 13-year-old fields. Where AD (tree $ha^{-1}$), absolute density; RD (%), relative density; AoD ($m^2$ $ha^{-1}$), absolute dominance; RoD (%) relative dominance; AF (tree $ha^{-1}$), absolute frequency; RF (%), relative frequency; IVI (%), importance value index

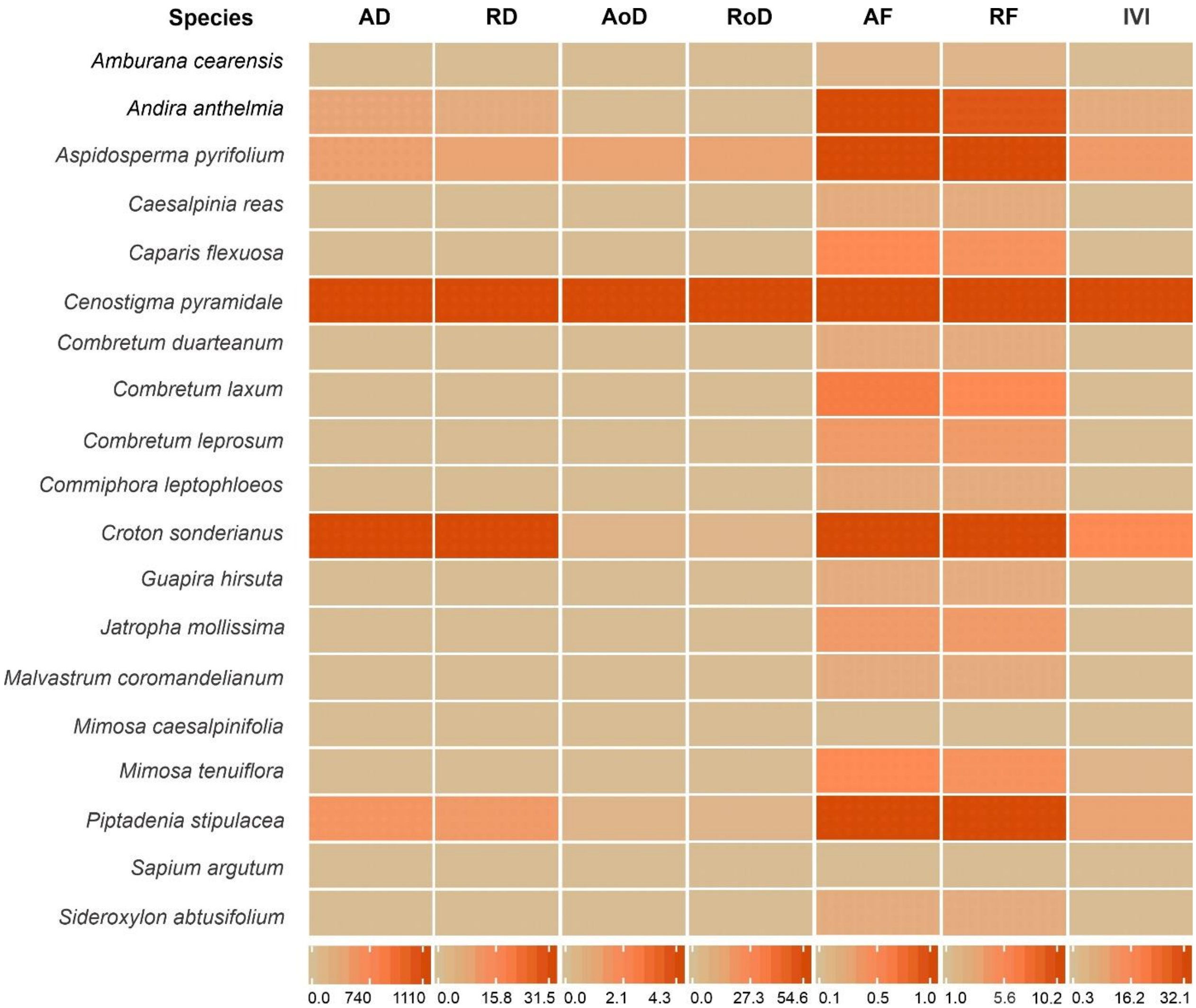



**Fig. S4.** Parameters of the horizontal structure of the fragment of the representative species of the population of the 16-year-old fields. Where AD (tree $ha^{-1}$), absolute density; RD (%), relative density; AoD ($m^2$ $ha^{-1}$), absolute dominance; RoD (%) relative dominance; AF (tree $ha^{-1}$), absolute frequency; RF (%), relative frequency; IVI (%), importance value index

**Table S1.** Variables in the Study of Fields of Different Post-cut Ages

| Age (year) | CCH (cm) | CBH (cm) | H (m) | V ($m^3$/ha) | Energy (kcal/ha) |
|---|---|---|---|---|---|
| 9 | 6.8 ± (0.039) | 9.3 ± (0.075) | 2.4 ± (0,014) | 2.36 ± (0.238) | 7.28 ± (0.06) |
| 11 | 7.6 ± (0.06) | 13.5 ± (0.19) | 2.6 ± (0.015) | 4.42 ± (0.50) | 14.45 ± (0.13) |
| 13 | 8.4 ± (0.079) | 12.3 ± (0.148) | 2.9 ± (0.017) | 13.33 ± (0.449) | 41.53 ± (0.43) |
| 16 | 12.2 ± (0.163) | 17.6 ± (0.254) | 3.4 ± (0.025) | 31.98 ± (0.313) | 98.19 ± (1.04) |

Note: CCH, circumference at chest height (cm); CBH, circumference at base height (cm); H, height (m); V, volume ($m^3$ $ha^{-1}$); (), standard error