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# Dynamic and Production Prognosis of a Miombo Forest, Using Transition Matrices in Pindanyanga-Manica

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**Abstract:** This study aims at evaluating and predicting the dynamic processes of Miombo forest using transition matrices. In three sample units of 50 m × 50 m were measured all trees with a circumference at breast height (CBH) not less than 31.4 cm, and measured the respective total heights. The first collection of variables occurred in 2002 shortly after the installation of the plots, and the second took place in 2013. The results showed that the miombo forest in Pindanyanga decreased the number of trees per unit area from 2002 to 2013. The reduction number of trees per hectare was more pronounced in smaller diameter classes. During the period observed the distribution of frequencies by diameter class showed a negative exponential distribution, and the mortality rate was higher than the recruitment, and was more pronounced in the juvenile phase of growth.

**Key words:** transition matrix, miombo forest, diameter distribution

## 1. Introduction

Among several types of vegetation formation in Mozambique, Miombo forests are the most predominant type. Occurring mainly in the north, this type of vegetation extends from the north up to the Limpopo River, and can be interspersed with coastal vegetation and the Zambezi Valley forests. But nevertheless, little is known in the country on the growth of these forests and the spatial distribution of the species.

The complexity of the natural forests due to the heterogeneity in the composition of species, ages and size greatly hinder the performance of the professional involved in the management of these forests. The projection of the diametric structure in time is of real importance for the management and economics of the native forests, since from these future diameters we can estimate the productions and define the interventions in the stands that assure the economic and ecological sustainability of the forests [1].

The evaluation of growth, mortality and recruitment in tropical forests can be done through the continuous inventory, using permanent plots, which is an efficient practice to observe the changes that occur over time in forest ecosystems [2].

The prognosis of production is usually accomplished using production models, which are based on growth data obtained from forest monitoring, at a given period of time. Among the most commonly used diametric distribution methods to predict the growth and production of native forests is the transition matrix.

The Markov chain or transition matrix is a stochastic process where the distributions of probability for its future development depend only on the present state, and the states are represented in terms of probabilistic vectors that can vary in the space-time (discrete or continuous), and if the space is discrete, then the Markov model is called the Markov chain [3]. The information on forest modeling using the transition matrix for this type of biome is almost non-existent,

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especially in Mozambique. Therefore, there is no other work available for comparison of results. This study aimed at evaluating and predicting the dynamic processes of a Miombo forest using the transition matrices, as a tool to assess the sustainability of such forest.

## 2. Material and Methods

### 2.1 Study Area

Data for this study were obtained in Mozambique in the province of Manica, Gondola district, and administrative post of Amatongas, in Pindanyanga village. The locality of Pindanyanga has a slightly undulating topography with an altitude ranging from 0-700 m. The soils vary from sandy to red and clayey. The climate is characterized by two seasons, which are, the rainy season from December to March, and dry season from April to November. The average annual rainfall is 1080 mm, and the average annual temperature is 21°C.

### 2.2 Methodology

The first collection of variables occurred in 2002 shortly after the installation of the plots, and the second took place in 2013. In each plot with 50 m × 50 m in size, all trees with a circumference at breast height equal to or greater than 31.4 cm were measured with tape measure, and with clinometer the respective total heights. Each measured tree was painted with white paint at breast height. For further localization of the same tree, there were two distances of the individual, one on the X-axis and the other on the Y-axis. The trees were first identified by the common name in the field, by the technicians and guide of the field, and then identified in the base of the “Check list” containing both vulgar and scientific names. Specimens were enumerated and transported for later identification. When it was not possible to identify the scientific name, the ordinary names were used. Cases were the scientific names or traditional name of the trees was not identified, the researcher used the coded NI (unidentified), and these trees were considered as different species.

In data processing, the choice of the diametric class amplitude depended on the appearance of the resulting transition matrix and the results of the simulations performed. The constant amplitude diameter distribution was established with seven classes, for all trees with diameter at breast height (DBH) not less than 10 cm, the first six classes having a 10 cm amplitude and the last with an open interval. DBH, which was obtained through the transformation of the CBH, served as a basis for calculating the basal area. The estimated volume including the bark of each specie was obtained by the model adjusted by Pereira and Nhamucho (2003) [4]:

$$Ln\ (v) = -9.85288895 + 2 * Ln(DBH) + Ln(H)$$

In which:

V = volume with bark

DBH = diameter at breast height

H = height;

The number of individuals per diameter class was distributed to all species, with their respective values of basal area and volume.

### 2.3 Transition Matrix

Mortality was determined by counting the number of trees that exited the system between the two inventories in the period indicated above, in terms of discrete and absolute values. The transition matrix is a simulation method that considers the diametric frequencies in the simulation start year ($Y_{it}$) in the form of a vector, multiplied by a matrix of transition probabilities between diametric class (G) to obtain the diametric frequencies of the final year ($Y_{t+\Delta t}$). Recruitment is also considered as a vector ($I_{it}$), which is added to the vector-matrix product described. Mortality was considered a vector included in matrix G in the last rows and columns. In matrix algebra, the simulation process for a period (t → t +1), with mortality included in the transition matrix, can be summarized as follows:

$$Y_{t+\Delta t} = G * Y_{it} + I_{it}$$

Of which:

$Y_{t+\Delta t}$ = number of trees projected

G = probability of transition by diameter class

$Y_{it}$ = frequency of the diameter class

$I_{it}$ = recruitment

For the product to be feasible, the matrix G must be square (number of rows = number of columns).

The observed ($Y_{it}$) and recruitment ($I_{it}$) frequency vectors represent physical units (trees) by diameter classes present at the beginning of the simulation and recruited during period t+1, respectively. The transition probability of each projection period was obtained from the transition matrix G whose elements are described below:

$$G = \begin{bmatrix} a_1 & 0 & 0 & 0 & 0 & \cdots & 0 \\ b_2 & a_2 & 0 & 0 & 0 & \cdots & 0 \\ c_3 & b_3 & a_3 & 0 & 0 & \cdots & 0 \\ 0 & c_4 & b_4 & a_4 & 0 & \cdots & 0 \\ 0 & 0 & c_5 & b_5 & a_5 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & 0 & 0 & 0 & c_n & b_n & a_n \\ m_1 & m_2 & m_3 & m_4 & m_5 & \cdots & m_n \end{bmatrix}$$

Of which:

$a_i$ = probability of the trees of class *i* being in class *i* during t → t +1;

$b_i$ = probability of the trees of class *i* to advance to the class *i +1* during t → t +1;

$c_i$ = probability of trees in class *i* advancing to class *i+2* during t → t +1;

$m_i$ = probability of trees of class *i* dying during the period t → t +1;

i = number of the diametric class, ranging from 1 to *n* (last class).

A matrix with the same amplitude of diametric grades was obtained. And in all matrices, the number of trees that remained, died or passed to the next class (s) during the period considered was determined for each diameter class. With the obtained values the probabilities of permanence in the class, transition between class and mortality of the trees were determined, respectively. In the construction of transition matrices, mortality was included in the last row and column.

*2.4 Kolmogorov-Smirnov Test*

The Kolmogorov-Smirnov test was used to compare tree frequencies per area unit at the two measurement occasions.

$$S_{n1}(x) = \frac{K}{n1}$$

Where K is the number of trees not greater than X. Similarly $S_{n2}$ (x) is defined for another sample. Thus, one obtains:

$$D_{cal} = max\,|S_{n1}(x) - S_{n2}(x)|$$

On what:

$D_{cal}$ = calculated deviation

$S_{n1}$ = distribution of accumulated probabilities in 2002

$S_{n2}$ = distribution of accumulated probabilities in 2013

$$D_{critical} = 1.63\sqrt{\frac{n_1 + n_2}{n_1 + n_2}}$$

On what:

$D_{critical}$ = tabulated deviation

$n_1$ = diametric frequencies in 2002

$n_2$ = diametric frequencies in 2013

Hypotheses:

$H_0$: $n_1 = n_2$

$H_1$: $n_1 \neq n_2$

## 3. Results and Discussion

The distribution of the trees within the diameters classes in the miombo forest in Pindanyanga from 2002 to 2013 is shown in Fig. 1. In the first inventory (2002) 471 individuals per area unit were recorded, and lastly 452 trees/ha were noted in 2013.

It can be observed that there was a slight reduction of 4%, in the number of individuals per hectare during this period, with greater expression in the first diametric class. This reduction was due to mortality (21%) which was higher than recruitment (17%).

The calculated deviation (0.111) was higher than the critical one (0.107), evidencing significant differences (p = 0.01) between tree frequencies per hectare observed in the miombo forest in Pindanyanga in the two inventories.

Ribeiro et al. (2002) [5]stated that depending on site conditions, the number of trees in the miombo forest, on average ranges from 200 to 300 individuals per hectare. The frequency of individuals per unit area advanced by these authors is below the number that was found in this study. Malimbwi et al. (2005) [6] found in two occasions different for 3 years (1996-1999), in permanent plots in a forest of miombo, 691 and 618/ha respectively, this frequency, much higher than that found in the present work. But, Isango (2007) [7] in his work on the structure and composition of miombo ecosystem, states that the number of individuals per unit area can vary from 74 to 1041. The differentiation of the frequencies of trees per unit area reported above can be justified according to Campbell et al. (1996) [8], which states that the origins of differences in composition and structure in miombo forest are not clear. But for these differences, geomorphological evolution, edaphic factors, mainly soil moisture and nutrients, the effects of fire, the impact of wild fauna, past and present land use, and other anthropogenic disturbances are implicated.

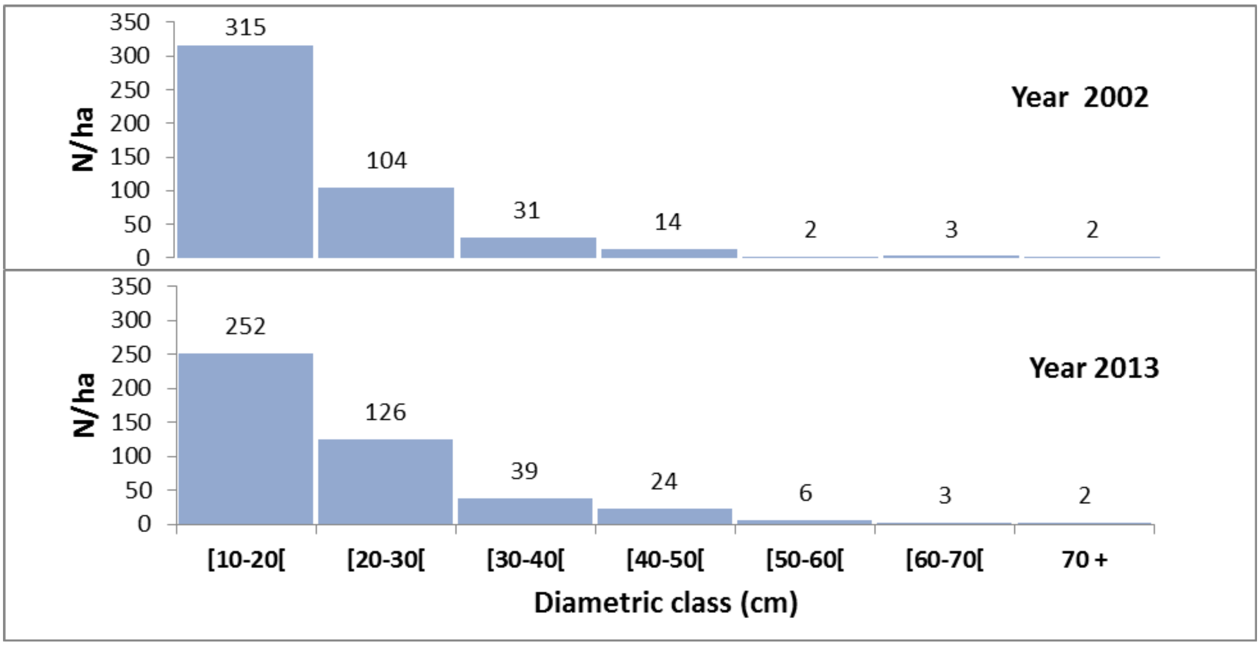


**Fig. 1 Diametric forest distribution of 2002 and 2013.**

It can be observed on both occasions that the number of trees per unit of area decreases as the diameters increase, following the common pattern in tropical forests, presenting typical forms of the negative exponential distribution, that is, inverted "J", where regeneration continues at one end and mortality at the other. In their studies in the miombo ecosystem, Malimbwi et al. (2005), Sawe et al. (2014), Lupala (2009) and Muboko et al. (2013) [6, 9-11], found similar results that follow the negative exponential distribution pattern.

According to Scolforo et al. (1998) [12] the highest concentration of individuals in the first diameter classes may characterize a stock community, which is a pattern in stable tropical forests with varying age and species composition. Pereira-Silva (2004) [13] corroborates that the negative exponential distribution model suggests that the populations that make up a community are stable and self-generative and that there is a balance between mortality and recruitment of individuals. The same author affirms that this type of diametric distribution ensures that the dynamic process of the forest persists continuously, since the natural death of the dominant individuals will give way to the development of natural regeneration. Lamprecht (1962) [14] concludes that the negative exponential diametric distribution model guarantees the existence and survival of the species.

In the first inventory (2002) of the permanent plots, the number of individuals in the first class only represented 67% (315 trees/ha) of the total, and the remaining six classes totalled 33% (156 trees/ha). While in the second inventory (2013) the first diameter class represented 56% (252 trees/ha) of the total, and the remaining classes accounted for 44% (200 trees/ha). It can be observed that from the second diameter class (20-29.9), the measurements in the second inventory did not present numbers of individuals per unit area less than the first measurement, for equal class intervals. At the two measurement occasions, there were very few individuals in the two largest diameter classes (3 and 2 trees/ha). This result may show that the life cycle of species that would reach larger diameters would not be complete. Other hypotheses would be the result of clandestine wood cutting by rogue forest operators and/or forest fires that predominate in this type of ecosystem (Miombo).

In the first inventory (2002) there was a basal area of 17.60 m²/ha, and in the last one (2013) there were 21.14 m²/ha. Therefore, there was an increase of 17% of basal area corresponding to a periodic annual increase of 0.321 m²/ha. On average, the basal area of miombo forest varies between 7 and 19 m²/ha [15].

The Fig. 2 illustrates basal area behaviour in the study period. The basal area of the trees with DBH < 30 cm in the first inventory represented 56%, while that of trees with DBH ≥ 30 cm represented 44%. In the second inventory, the basal area of trees with DBH < 30 cm represented 47%, and 53% for trees with DBH ≥ 30 cm.

The volume distribution per hectare per diameter class is shown in Fig. 3. The forest volume in the first measurement was 53.082 m³/ha, while in the second measurement it was 70.983 m³/ha. There was an increase of 25%, equivalent to an annual increase of 1.627 m³/ha/year. This volumetric increase resembles the growth value of the Mozambican forests found by Marzoli (2007) [16]. In his work in the miombo forest inside a reserve (protected area) Isango (2007) [7] found 78.8 m³/ha of volume, close to that found in the second measurement in this work.

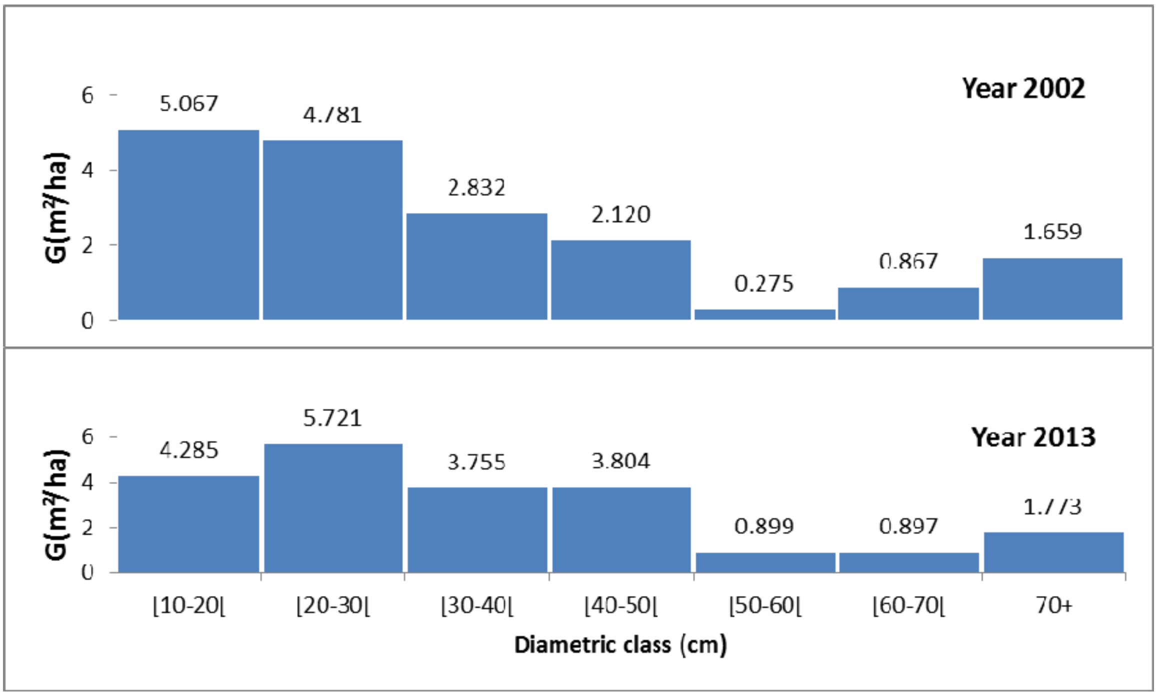


**Fig. 2 Total basal area of the forest by diameter class in 2002 and 2013.**

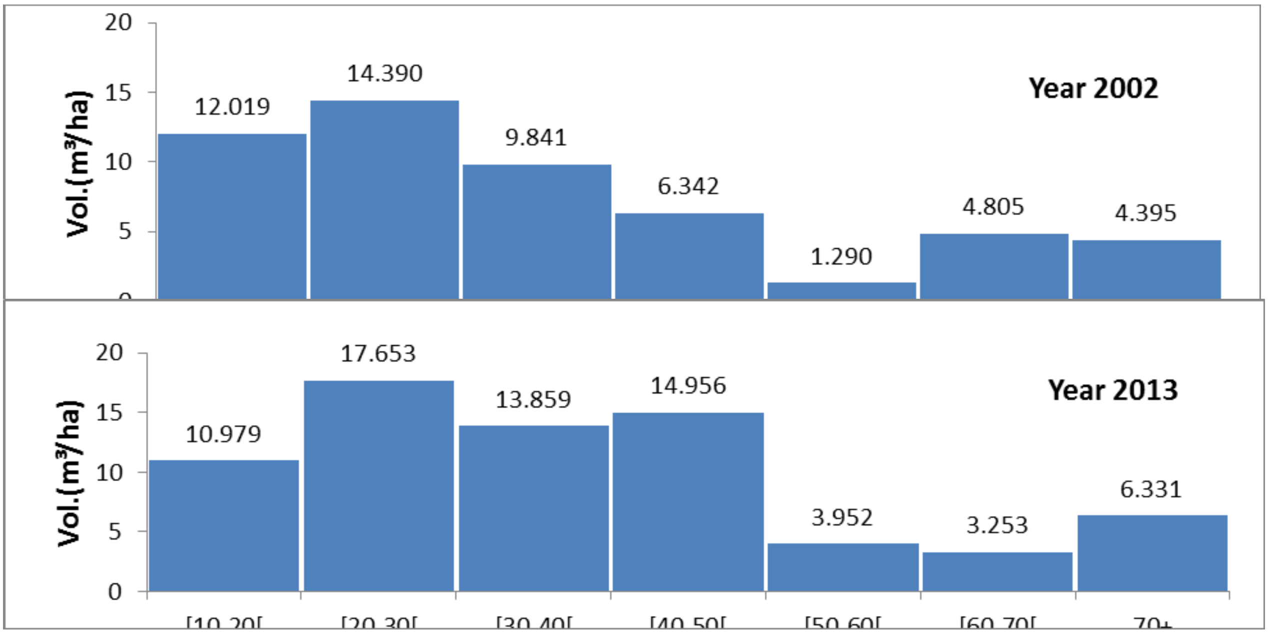


**Fig. 3 Total forest volume by diameter class in 2002 and 2013.**

The volume of trees with DBH < 30 cm in the first inventory represented 50%, and another half of the volume percentage for trees with DBH ≥ 30 cm. In the second inventory, the volume of trees with DBH <30 cm represented 40%, and 60% for trees with DBH ≥ 30 cm.

*3.1 Mortality and Recruitment*

During the period of the study, a mortality rate of 21% (1.9% per year) was recorded, corresponding to 3.99 $m^2$/ha of basal area and 12.947 $m^3$/ha of volume. In the same period, 82 trees were registered in the forest, equivalent to 17%, and this corresponds to 3.06 $m^2$/ha of basal area and 8.564 $m^3$/ha of volume. Smaller trees in the lower stratum show higher mortality than trees with higher DBH, probably as a consequence of severe competition in the juvenile stage of growth. Chidumayo and Frost (1996) [17] report in their study that the annual mortality rate in a miombo forest on fire protection is estimated at 0.4%. But for the forest that suffered late burning is estimated at 1.6% per year. The authors state that fire is the major cause of mortality in the miombo and varies among species.

The study forest has been influenced by human activities, where it uses fire annually to open new areas for agricultural production. These activities may have influenced the dynamics of this forest.

*3.2 Transition Matrix*

The transition probabilities between diameter classes of the miombo forest trees in Pindanyanga are presented in Table 1, in the form of a matrix Tp of 7 × 7 and with last line with probability of mortality.

It can be observed that the diametric classes 10 - 19.9 and 40-49.9 cm show a transition to only one class with the following probabilities: to remain in the same class (ai) after eleven years is 0.57 and 0.60 and to advance to the next class (bi) 0.17 and 0.20 respectively. The diametric classes 20-29.9 and 30-39.9 cm show a transition to more than one class, with the probabilities to remain in the same class 0.49 and 0.22 and advance to a class 0.22 and 0.30 respectively. The same diametric classes registered the same probability value, 0.04, for different transitions, with i+2 for the diametric class 20-29.9 and i+3 for 30-39.9 cm.

The remaining diameter classes showed no transition of trees to the following classes. The diameter class 60-69.9 cm presents probability values in which 50% of the trees remain in the same class and another 50% die. It can be observed some anomalies in the diametric classes, being the first one in the diametric class 50-59.9 cm that has probability of permanence of 100%, that is to say, all the trees of this diametric class will remain in this class, without there being transition to the classes below. This artificial effect may be due to insufficient database. Pulz et al. (1999) [18] argue that the prognoses of the diameter structure of the above diameter classes cannot exceed the class having an absorbent state. Therefore, there is a continuous increase of trees in this class, and this will be more intense as more prognoses are done, since the trees no longer leave this class. The authors also affirm that the occurrences of this state compromise the prognoses of the forest diametric structures and also prevent the steady state from being detected. And in the class > 70 the probability of mortality is 100%, that is, all the trees of this diametric class will die in the next simulation period of eleven years. Mortality probabilities in ascending order of diameter size: 0.27; 0.26; 0.43; 0.20; 0.00; 0.50 and 1.00.

Fig. 4 shows the observed frequency curves of the diameters distributions for all miombo forest in Pindanyanga, occurring in the transition period from 2002 to 2013, and the simulation for 2024.

**Table 1 Transition matrix obtained in forest in diameter class of the period 2002-2013.**

| Diametric class | 2002 | | | | | | | Mortality |
|---|---|---|---|---|---|---|---|---|
| 2013 | [10-20] | [20-30] | [30-40] | [40-50] | [50-60] | [60-70] | > 70 | |
| [10-20] | 0.57 | | | | | | | |
| [20-30] | 0.17 | 0.49 | | | | | | |
| [30-40] | | 0.22 | 0.22 | | | | | |
| [40-50] | | 0.04 | 0.30 | 0.60 | | | | |
| [50-60] | | | | 0.20 | 1 | | | |
| [60-70] | | | 0.04 | | - | 0.5 | | |
| > 70 | | | | | | - | 0 | |
| Mortality | 0.27 | 0.26 | 0.43 | 0.20 | 0.00 | 0.50 | 1.00 | 1 |

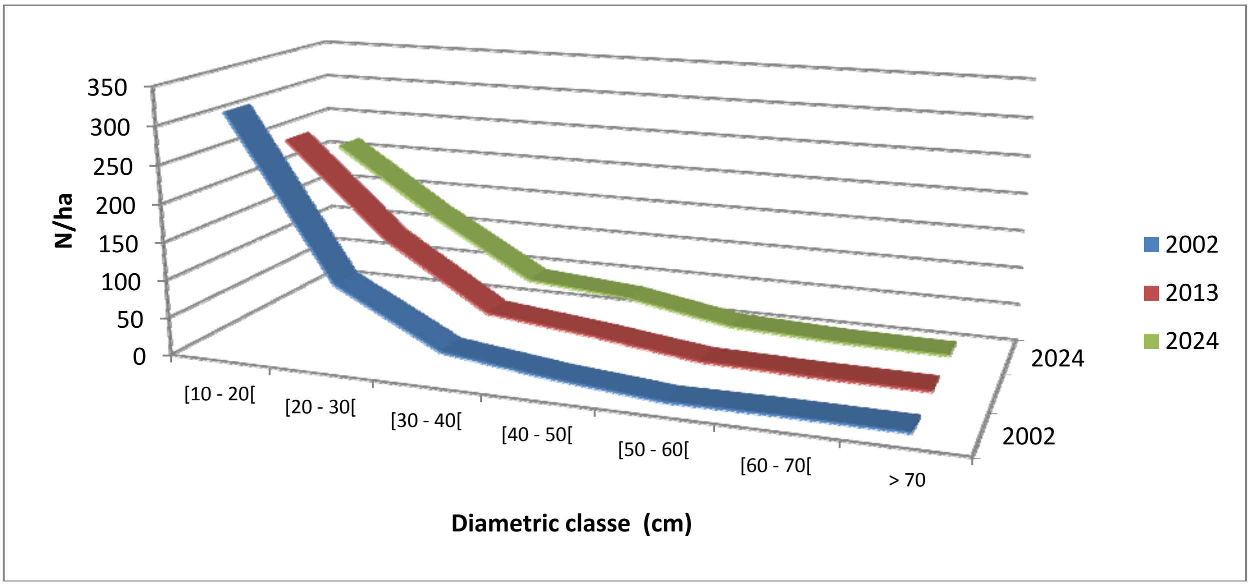


**Fig. 4 Observed (2002-2013) and simulated (2024) diametric distributions of the forest.**

It can be observed that the frequency of individuals per unit area over time reduces at a constant rate, being 4% in the observed period and 4% in the simulated period (2013 to 2024). This reduction is concentrated only in the first diametric class (10-20), reaching 20% in the observed period and 14% in the simulated period.

In the following diametric classes, except the last one in the simulated period, the frequency of trees per unit area in both periods (observed and simulated) was not lower than the first measurement. As shown in Fig. 4, the number of trees per hectare for each measurement period and in the projection follows the inverted "J" shape, but differing in frequency from one another.

Similar results were found by Stepka et al. (2010) [19] when predicting the mixed forest diameter structure, in which the number of trees per hectare decreased over time. The authors state that the decrease in the number of trees over the years occurs as a consequence of the mortality rate higher than the rate of entry. The model of the transition matrix has some disadvantages because the projections made are based only on the data of the two measurements in which were built, depending only on the present state of the forest. This demonstrates some inflexibility of the model, since possible changes in the pattern of forest growth would not be contemplated. Another finding is that the projection period can only be multiple of the period in which the probability matrix was constructed.

## 4. Conclusion

The miombo forest in the locality of Pindanyanga presented reduction of the number of trees per unit of the area in the period of 2002 to 2013. The reduction of the number of trees per hectare was more expressive in the smaller diameter class. During the observed and simulated period the distribution of the frequencies by diametric class presented negative exponential distribution, that is, inverted "J", a typical form of the natural forest. Despite the reduction in the number of individuals over time, there was an increase in the basal area, and consequently in the commercial volume. In the second inventory, the highest forest volume occurred in trees with a DBH of not less than 40 cm. The mortality rate was higher than that of the admission, and was more expressive in the juvenile phase of growth. The larger diameter classes of the forest (DBH ≥ 50 cm) do not present transition probability of trees for the following classes, but probability of remaining in the same diametric class or mortality.

The projection of forest dynamics can contribute to forest management in tropical forests (miombo forest) in determining the cutting cycle or to show the trends that the forest will present in the near future, so that the forest technician or entrepreneur knows the ideal moment and volume to handle the rainforest.

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