

Growth and adaptability of provenances and progenies of *Pinus maximinoi* h. E. Moore in northern Mozambique

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Abstract

The aim of this study was to evaluate the growth and adaptability of *Pinus maximinoi* provenances and progenies and to estimate the genetic variation that could be exploited in future breeding work. The company Floresta de Niassa Lda established a trial with four provenances and nineteen progenies in the Chimbonila district of northern Mozambique. The field trial was set up in a randomized block design with four repetitions and six-plant linear plots. At two, four and eight years of age, performance in total height, diameter at breast height (DBH) and survival were analysed. The results at eight years of age showed no significant variation between provenances for all variables analysed, and any of these provenances can be used for reforestation in northern Mozambique. The first group was composed of 9 (45%) of the best performing progenies, mostly from Yuscaran and San Jeronimo, and the second (last) group was composed of 11 (55%) of the worst performing progenies, mostly from Tatumbla and Coban. Most of the nine best classified progenies based on the predicted additive genetic effect and genetic gain belonged to Yuscaran and Tatumbla. On the other hand, most of the progenies at the level of the seventeen best classified individuals belonged to San Jeronimo and can be used for future breeding projects in northern Mozambique.

1. Introduction

Information available indicates that the first plantations in Mozambique date from the 19th century with the planting predominantly of *Eucalyptus* in the then Loureço Marques now Maputo, with the aim of drying the marshes in the lower part of the city (MINAG - Ministério da Agricultura 2009). The post-national independence period was marked by the development of plantations with fast-growing forest species to supply firewood and charcoal to the populations of the three largest urban centres, Maputo, Beira and Nampula and their surroundings, with the aim of reducing the pressure that was already beginning to be felt on the native forest around the large urban centres (MINAG 2009).

In this framework, the FO1 projects were created in Manica and FO2 in Marracuene, most of them with the species *Eucalyptus saligna*, *Eucalyptus grandis*, *Pinus patula* and *Casuarina equisetifolia*, which were abandoned at the height of the civil war of the 16 years, between 1977 and 1992 (MINAG 2006). Around 1980, the first forestry research was started, where the introduction and selection tests of species and provenances were carried out, seedling production tests in nurseries and tests of forestry techniques in the establishment of plantations. However, the expected success was not achieved, but they did contribute to doubling the forest area the country had at the time of the proclamation of independence, from 20,000 ha in 1975 to approximately 42,000 ha in 1992 (MINAG 2006).

After the end of the civil war, there was a need to attract new investments for plantations with fast-growing exotic species, with the aim of i) recovering unproductive land abandoned due to itinerant agriculture (INDE - Instituto Nacional do Desenvolvimento da Educação 2009); ii) creating jobs; and iii) reducing the pressure on native forests due to population growth (Landry and Chirwa 2011; Nube et al. 2016; Zanella et al. 2018). Niassa province attracted most of the investments due to the availability of land due to low population density.

Mozambique is well placed to expand the afforestation of multipurpose plantations, including an increasing need for forest products and the availability of land. Increasing the country's forest plantation area from the current 60,000 ha to over one million by 2030 would have the potential to create 250,000 jobs and produce \$1.5 billion in manufactured goods (MINAG 2009). According to the (Governo da Província do Niassa 2007) of the estimated potential for the province, the establishment of forest plantations of fast-growing species is based on selection criteria for areas suitable for commercial plantations. The Lichinga Plateau is the region with the greatest potential for the development of commercial plantations, and the most productive areas are located in the districts of Ngaúma, Sanga, Muembe and Lichinga.

The main species used to establish these plantations were *Eucalyptus grandis*, *Pinus elliottii*, *P. patula* and *P. taeda*, which already existed in the settlements dating from colonial times. Later, they were also introduced, *P. maximinoi*, *P. tecunumanii* and *P. oocarpa*, with the recommendation of the Central America and Mexico Coniferous Resources Cooperative (CAMCORE). The introduction of *Pinus maximinoi* species for the first time in Niassa, particularly in the district of Chimbonila, was established at the same time as the experiments, since there was no information on adaptability, growth, and production of

exotic species in the Niassa environment. However, the literature shows that this species is compatible with Niassa's soil and climate conditions. For its success and profitability, it is important to identify species that best adapt and grow rapidly, and this is only possible through species and provenance testing.

In this context, Empresa Florestas de Niassa Limitada (FdN), with the help of CAMCORE, established seven (7) experiments of tropical pine (López [s.n.]). One of these experiments is the object of the present study, which aims to evaluate the growth and adaptability of provenances and progenies of *P. maximinoides* H. E. Moore in the environment of Chimbonila, northern Mozambique. The research questions raised by Dias and Mbanze (2020) in the study on the growth and adaptability of provenances and family-within-provenance of *Pinus tecunumanii* in northern Mozambique are part of this study. These questions were answered from the evaluation of results at 2, 4 and 8 years of age of a *P. maximinoides* trial established in the test fields of the company Niassa Forests.

2. Materials And Methods

2.1. The sites

The experimental site was at Chimbonila, Niassa Province in Mozambique's North Region, belongs to Company Floresta de Niassa limited. The trial was situated at latitude 13°14'14,8"S and longitude 35°30'46,5"E at an altitude of 1180 meters above sea level (Fig. 1). The climate of the site is humid temperate (Cwb), with two well-defined seasons: Summers temperate and rainy and cold winters and dry. The area receives a mean annual rainfall over 1200 mm and may exceed this value and reach 1400 mm of rainfall and experience mean annual temperatures ranging from 18 to 24°C, but generally less than 22°C (Ministério da Administração Estatal 2014). The soils at the site are mostly clay, deep reds and have low susceptibility to erosion (Shimanikire 2011).

Insert Fig. 1

2.2. Seed Sources

The seeds used in this experiment are only part of the existing variation for the species, including Nicarágua, Guatemala and Honduras, which were obtained from the CAMCORE. This comprised 19 half-sib families and four (4) provenances of *P. maximinoides* and was used as a seed control from the Guatemala seed production area. The relationship provenances evaluated with their respective geographical locations are presented in Table 1.

Insert Table 1

2.3. Experimental design and establishment

The seedlings were planted on site in January 2011 using a randomized complete block design at the provenance level, followed by randomisation of families within provenances. There were four (4) replications and six (6) trees per family planted in line plots. The spacing adopted was 3.0 m x 3.0 m between plants with a double border around the experiment (Fig. 6 of appendix). There was no soil preparation, only manual pits with a depth of 35 cm were used for seedling planting.

At the time of planting, a hydrogel system was applied to radical the seedlings by immersion in a solution at a concentration of 10 g/litre. The cover fertilization was performed thirty days following planting, with NPK 100 g (17.38% – 28.51% – 4%) and adding 5% sulphur, 0.8% zinc and 0.5% boron per hole. These dosages were determined by analysis of soil samples made

earlier. Formation pruning was effectuated in 2013 to 2,8 years of age. Production pruning was effectuated in August 2015 and September 2017. Additionally, total cleaning was performed (weeds) once a year in the first 4 years after planting. Figure 2 shows two pictures of the test.

Insert Fig. 2

2.4. Data collection and analysis

2.4.1. Data collection

In this trial, data from three (3) measurements over time, from 2013 to 2018, i.e., from 2 to 8 years old, were considered. The parameters measured in the trial were height in meters (2, 4 and 8 years) and diameter at breast height (DBH) only at 4 and 8 years old. The height measurement was made with a "Vertex IV" hypsometer and a graduated stick with 10 cm accuracy when needed. The DBH of the trees was measured with a calliper. Survival was also evaluated from the living tree count in the second, fourth and eighth years.

Volume per tree was calculated using the following formula (Ladrach 1986) cited in Hodge and Dvorak (1999); Gapare et al. (2001); Hodge and Dvorak (2015): $Vol = 0,0003 \times DBH^2 \times Height$ (1).

where the volume is in cubic meters (m^3) and DBH is the over bark diameter at breast height (cm) and height in meters (m).

Survival was obtained from the count number of living trees and was expressed as a percentage relative to the number of unique experimental trees. According to the formula used by Cornacchia et al. (1998):

$$Surv\% = \frac{NIV}{NTI} \times 100$$

2

where NIV is the number of living individuals by provenance, and NTI is the total number of individuals per provenance.

A comparison of the relative position of each provenance in height growth was made on performance over the known methods discussed by Burdon (1998) and used by (Mora (2002). Thus, various ratings range from 0 to 100, and the formula is:

$$DR = \frac{X - X_{minor}}{X_{major} - X_{minor}} \times 100$$

3

where DR is the relative performance (%); X is the average of the evaluated origin; X_{minor} is the provenance of the worst performance; and X_{major} is the origin of better performance.

For comparison, the average annual volume increments of provenances were calculated by the formula used by Shimizu and Higa (1981); Kietzka (1988):

$$m^3/hayear = \frac{\bar{V} \times n \times \%Surv}{1 \times 100}$$

4

where $\bar{V}$ is the arithmetic average volume per tree; n is the number of trees planted per hectare; % Surv is the percentage of survival; and 1 is the age in years.

2.4.2. Data analysis

All analyses and results in this present work were based on eight years of data. Data were analysed using Selegen Reml/Blup (Federal University of Viçosa, Minas Gerais, Brazil) and the SPSS computer programme.

- i. Analysis of variance (ANOVA) was performed on DBH, height and survival at both sites for both provenances and families. If the ANOVA was significant, Tukey's test was subsequently performed to identify different groups of families in the provenances. Clustering dendrogram analysis and representation were performed to illustrate the above results of the ANOVA between different sources and progeny and thus identify similar groups regarding the growth characteristics (height, DBH and volume). The method used was the agglomeration Ward's and the Minkowski distance since all variables were continuous. The value of Eta² (variation percentage between the clusters) and the mean test between groups were used to determine the optimal number of clusters of provenances and progeny by retaining and thus obtaining a good standard view of joint variation among the provenances and progeny.
- ii. After identification of groups, the 9 best progenies were selected based on the predicted additive genetic effect and genetic gain (selection 45% of progeny). Based on the genetic improvement of the general average of the variable volume, they were also ranked in the top 17 subjects (4% will check the level of individuals of the progenies within provenances). This classification aims to select the best progenies and individuals with higher volumetric production for subsequent generations of breeding and commercial plantations. To select the variable with the highest influence on the productivity of the progeny, the Pearson correlation coefficient (PCC) between the volume and the height or DBH was used, depending on the variable with the highest PCC.
- iii. The estimates of the variance components and genetic parameters were based on the restricted maximum likelihood method (REML) of the individual progenies from statistical model 5 (Test half-sib progeny, with a randomized block design. This was done with the aid of the computer program SELEGEN-REM / BLUP (Resende 2014).

The calculation of variance components was obtained by the formulas proposed for (Resende 2007).

$$h_a^2 = \frac{\sigma_a^2}{\sigma_f^2}$$

5

where h_a^2 is the individual heritability in the narrow sense; σ_a^2 is the additive variance; and σ_f^2 is the individual phenotypic variance.

$$CV_{gi} (\%) = \frac{\sqrt{\sigma_a^2}}{\bar{X}} \times 100$$

6

where $CV_{gi} (\%)$ is the individual additive genetic coefficient of variation and $\bar{X}$ is the overall mean of the original population.

$$CV_d (\%) = \frac{\sqrt{\sigma_d^2}}{\bar{X}} \times 100$$

7

where CV_d (%) is the residual coefficient of variation of the experiment and σ_d^2 is the residual variance of the experiment.

Estimates of the gains with the selection of progeny were obtained according to the proposal by (Cruz 2005).

$$GS(\%) = \frac{GS}{\bar{X}_0} \times 100, \text{ being } GS = h_a^2 \times DS \text{ (8)}$$

where GS is the genetic gain by selection; DS is the selection differential; and $\bar{X}_0$ is the overall mean of the original population.

$$DS = \bar{X}_s - \bar{X}_0$$

9

where $\bar{X}_s$ is the average of the selected progenies.

3. Results

3.1. Relative performance of the provenances

Figure 3 presents the relative performance of 4 origins of *P. maximinoi* in 2, 4 and 8 years of evaluation, showing that the provenance of the San Jeronimo (SJ) maintained the same position qualifying of the relative performance in 2 and 4 years equal to 100% and having lowered its performance relative to 8 years for 93.79%. Another type of situation happens with the control (Common lot) that his relative performance is always increasing over the years (10.72%, 69.18% and 100%), having if detached like the second-best relative performance. Yuscaran (Yus) showed, on average, the third best relative performance, especially at 8 years.

Insert Fig. 3

The provenance of the Tatumbra (Tla) not only presented a performance very much down to 2 and 4 years but also tended to increase his performance with growth. For the original Coban (Cob), he presented the worst performance every year, except for 2 years, when it was 19.43%, which surpassed the control by nearly 9% to more.

3.2. Growth and adaptability of the provenances

The results of the ANOVA and mean test (Tukey) of different origins of *P. maximinoi* tested in Chimbonila are shown in Table 2. The degree of survival was significant at the 5% level at 2 years, and no differences were found in the last two years studied and ranged from 83.33 to 97.92% in the period. There were no marked differences from the heights in year 4, although the origins San Jeronimo (SJ) were higher than in the rest. At both two and eight years, there were no significant differences between the provenances. The DBH and volume parameters at 4 years or 8 years did not reveal significant differences between sources. The experimental coefficients of variation (CV%) in provenances were low for all parameters in the period studied, except for the volume to 4 years age.

Insert Table 2

The annual average increase ($\text{m}^3 * \text{ha}^{-1} \text{yr}^{-1}$) from all sources was higher than that of the control except for the Yuscaran origin (Yus) at 4 years, and there were no differences after 8 years (Fig. 4). The Mean Annual Increments of Coban origins (Cob), Tatumbra (Tla) and Yuscaran (Yus) produced the equivalents of 113.65% and 114.34%, 102.8% and 112.06% and 100.46% and 106.2% of the Annual Average Increase control at 4 and 8 years old, respectively. San Jeronimo (SJ) had a higher mean annual increment than the other origins and the control (150.81% and 127.58%) for years 4 and 8, respectively, although there were no significant differences for 8 years.

Insert Fig. 4

3.3. Variation in growth among the progenies

The results of Tukey's test for averaging pairs among the progeny from all sources are shown in Table 3. The Tukey test was performed after the ANOVA assumed that the progeny showed significant values of the DBH and volume to 8 years old, as shown in the accompanying Table 8 in the appendix.

For the DBH parameter, the best progeny were Coban (15–884), San Jeronimo (15–868 and 15–875) and Tatumbra (15–962), whereas no statistically significant differences between them were observed, and they had a relative superiority over the other, contrary to Tatumbra (15–950), which had the worst performance of all progenies.

Regarding the volume parameter, the average progeny 15–962 is the best of all, and the worst progeny is 15–950 for both Tatumbra provenances. An important observation is in relation to the control, which showed a growth above the average of progeny.

Insert Table 3

Person's correlation coefficients (CCP) showed a strong positive (> 0.9) and significant ($P < 0.01$) correlation between the DBH and volume parameters for all progenies (see the last column of Table 3).

To better visualize the average of the test results of the origins of Table 2 and Table 3, the progeny of a cluster analysis were made, and subsequently, an ANOVA and mean test were performed on their respective clusters. The results are shown in Table 4 and Fig. 5 and it can be easily observed that the two-cluster solution was the best choice.

Insert Table 4

The first cluster comprised the 9 (45%) best progenies, mainly of origins Yuscaran (Yus) and San Jeronimo (SJ), and showed superiority in all parameters (height, DBH and volume). The last cluster contained 11 (55%) progenies with performance below the overall average and was mainly composed of the family of the Tatumbra (Tla) provenance. The control also belongs to the last cluster.

Insert Fig. 5

3.4. Selection of progenies based on phenotypic characters

Table 5 presents estimates of variance components and genetic parameters of the progenies of *P. maximinoi* at 8 years old. It is noted that by breaking the individual variance components, most of the total phenotypic variance of all the studied parameters was residual variance due to (σ_d^2) and individual phenotypic variance (σ_f^2). The individual heritability in the narrow sense (h_a^2) allows us to predict moderately favourable conditions for the selection of families. However, the coefficient of determination of plot effects ($\mathbb{L}_e^2$) and the effect of provenances ($\mathbb{L}_p^2$) showed low magnitude values. The individual additive genetic variation coefficient ($CV_{gi}\%$) and genotypic variation coefficients among progenies ($CV_{gp}\%$) were high for all characters, and residual variation ($CV_d\%$) was of low magnitude for height and DBH and medium magnitude for the variable volume. Finally, the relationship between the genetic coefficient of variation and the residual coefficient of variation showed values close to and above one (1).

σ_a^2 : additive genetic variance; σ_e^2 : environmental variance between plots; σ_p^2 : genetic variance among provenances; σ_d^2 : residual variance; σ_f^2 : phenotypic variance at the individual level in the experiment; h_a^2 : individual heritability in the narrow sense; $\mathbb{L}_e^2$: coefficient of determination of plot effects; $\mathbb{L}_p^2$: coefficient of determination of the effects of origins; $CV_{gi}\%$: individual additive genetic coefficient of variation; $CV_{gp}\%$: coefficient of genotypic variation among progenies; $CV_d\%$: coefficient of residual variation.

Insert Table 5

Based on the predicted additive genetic effect (a) and genetic gain, nine (9) improved progenies were then classified, corresponding to 45% of the parent selection by volume, as shown in Table 6. It is noted that provenances Yuscaran (Yus) and Tatumbula (Tla) had a higher number of selected progenies, with three each. This was followed by the provenance San Jeronimo, with two selected progenies, and the Coban origin contributed only progeny.

Insert Table 6

Table 7 shows the desirable rating of the 17 (4%) best individuals selected from 20 progeny *Pinus maximinoi* continued for breeding. The classification criterion was based on the genetic improvement of the general average volume parameter. The San Jeronimo (SJ) origin contributed to the greater number of individuals selected, totalling 34% (6), followed by the Coban origin (Cob) to 29.4% (5) of selected individuals, all individuals of the progeny 15–884. The Tatumbula origin (Tla) contributed 23.5% (4) of individuals, and finally, the Yuscaran (Yus) contributed 11.8% (2) of individuals.

Insert Table 7

4. Discussion

4.1. Relative performance, growth, and adaptability of the provenances

The control (common lot) presented superior relative performance in relation to the other provenances tested in the Chimbonila environment (Fig. 2), demonstrating a greater potential for growth of seeds collected in the production area of seeds of *P. maximinoides* originating from Guatemala, as has been verified in other studies (Fier 2001). According to the general averages of height, DBH and volume in Table 2, they are similar to the values found by Gapare et al. (2001) for *Pinus maximinoides* in experiments that were evaluated in South Africa (12.6 m, 17.8 cm and 0.12 m³/tree).

When analysing the survival rates, there were no statistically significant differences, and all the varieties, including the control (common lot), showed average values above 90% with a coefficient of variation of high precision. Similar trends can be observed in the studies of Dias and Mbanze (2020) in Mozambique, leading to the assumption that for this species, the varieties show good potential for adaptability in the Chimbonila environment. The survival values of the present research are above those found (see, for example, (Kietzka 1988; Wright 1992; Gapare et al. 2001; Etti et al. 2004; Lopez-Upton et al. 2005; Santos et al. 2018)).

According to the results provided in Table 2, the growth and adaptability of *P. maximinoides* provenances of the trial established in the Chimbonila environment indicated an acceptable level of experimental accuracy by presenting values of low magnitude in all parameters evaluated and showing good statistical efficiency for the analysis. Gapare et al. (2001) and Santos et al. (2018) found coefficients of variation higher than those in the present research. However, there are also tests with coefficient values close to the present study, as is the case of Fier (2001).

The low values of the experimental coefficient of variation suggest a small phenotypic variation within plots, which explains the lack of genetic differences between provenances. However, in general, the experimental design was very reliable in capturing the growth and adaptability of progenies of *P. maximinoides* in the Chimbonila environment, since the coefficient of variation values of the measured variables were below 20%, as recommended by Pimentel Gomes (1990); Pimentel-Gomes and Garcia (2002).

The mean annual volumetric increment revealed no significant differences between the provenances at 8 years. Therefore, the volumetric increment is high, presenting an average of 21.22 m³/ha per year; however, it should be considered that this variable is directly influenced by the number of trees in the forest stand. The mean annual increment of the same provenances was well above the control but also above the results of other studies conducted in Africa (see, for example, (Hodge and Dvorak, 2012; Dias and Mbanze, 2020)).

4.2. Variation in growth among the progenies

The author did not detect significant differences at the 5% level between the means of the *P. maximinoides* varieties tested in Chimbonila at eight years of age for the characteristic height, DBH and volume. These results corroborate those of Nyoka (1994) and Fier (2001) that were observed in the regions of Zimbabwe and Brazil, respectively. Atie et al. (2018); Santos et al. (2018) reported significant variations among provenances of *P. maximinoides* in Brazil for height, DBH and volume, indicating that they can be explored in subsequent breeding cycles. However, the percentage variation between the best and worst mean DAP and volume of the progenies were 26.78% and 43.34%, respectively, which are characterized as significant differences, as presented in Table 3, suggesting that the population has moderate genetic variation and therefore a weighted possibility of genetic improvement by selection among progenies.

According to the analysis unfolding at the progeny level, it is possible to see two distinct groups of good and bad performance, indicating that not all progenies contribute in the same way to the overall performance of the progeny. The group with higher participation in the performance of the progenies contributed 45% of the progenies, as it was possible to identify with the help of cluster analysis. These progenies are predominantly from Yuscaran (Yus) and San Jeronimo (SJ).

High correlation coefficient values ($CC \geq 90\%$) were found between DBH and volume in tests of provenances and progenies of *P. maximinoides*, demonstrating that the selection can be based on DBH, without prejudice to the volume character, agreeing with what occurred with studies carried out by other authors for forest species such as (Munthali and Stewar 1998; Sampaio et al.

2000; Fier 2001; Sampaio et al. 2002; Nascimento 2010; Moreira et al. 2014; Souza et al. 2016; Biernaski 2018; Dias and Mbanze, 2020), among others.

4.3. Selection of progenies based on phenotypic characters

The estimates of heritability in the restricted sense (h^2_a) showed values of medium magnitude for all growth characters ranging from 0.18 to 0.32, indicating the existence of moderate genetic control for all characteristics. Heritability values from 0.01 to 0.15 are considered low; from 0.15 to 0.50 medium; and above 0.50 high (Resende 1995, 2002). The heritability found is similar to those obtained by Sampaio et al. (2000); Gapare et al. (2001); Biernaski (2018) and lower than those reported by (Wright et al. 1993). Resende (2002) noted that a heritability of 0.20 is a reasonable value for growth characteristics in forest species.

The coefficients of determination of plot effects (σ^2_e) were less than 5% for the DBH and volume characters and greater than 10% for the height character. According to Resende (2002), the recommended values for estimates of the coefficients of determination of plot effects (σ^2_e) are values equal to or lower than 10%. According to Farias Neto et al. (2008), these values demonstrate that there is greater genetic control than environmental variation between the plots and within blocks.

Judging by the values of coefficient of individual additive genetic variation ($CV_{gi}\%$) and coefficient of genotypic variation among progenies ($CV_{gp}\%$) obtained in all characters were high, indicating the existence of heritable genetic variation in the population, therefore, selection can be done at both individual and progeny levels. Coefficients of genetic variation above 7% are considered high by (Sebbenn et al. 1998).

Regarding the relationship between individual additive genetic variation coefficient ($CV_{gi}\%$) and coefficient of residual variation ($CV_d\%$), values were found to be close (height) and greater than one unit for DBH and volume characters. These results show a favourable situation for early selection at the DBH character level. This relationship, according to Vencovsky and Barriga (1992), when close to or greater than one unit indicates a very favourable situation for obtaining genetic gains with progeny selection.

Through the individual BLUP (best linear prediction without bias) procedure, the 9 best *P. maximinoi* progenies were selected with potential for a second-generation breeding programme, highlighting the Yuscaran (Yus) and Tatumbra (Tla) provenances with the contribution of 3 progenies within each provenance. It is important to report that the individual BLUP procedure is equivalent to the multi-effect index selection method (Resende et al. 1994; Resende 2002). The genetic values of the 9 progenies provided a genetic gain of 5.19%, increasing the average volume character from 0.1552 m³/tree to 0.1803 m³/tree.

The same method of progeny selection was applied to individual trees, where the 17 best individuals were selected for an effective population size (N_e) equal to 10.8 based on the volume character. It is noteworthy that the progenies 884 (Cob), 868 and 875, both from San Jeronimo, showed the best results, especially progeny 884, which was repeated 5 times. This selection increased the average of the character from 0.1552 m³/tree to 0.2089 m³/tree, presenting a genetic gain of at least 11.11%. The gains estimated with the selection can be considered promising due to the early age of the evaluation. Therefore, the effective population size is small (10.8), which limits the possibility of new selections. Resende (1995); Vieira and Shimizu (1998) emphasise that an effective population size of 60 is necessary to maintain genetic variability in recurrent selection in short- and long-term improvement. In the present study, to meet (effective population size of 60) the recommendations of Resende (1995); Vieira and Shimizu (1998), it would be necessary to select 352 individuals for the volume character to maintain the effective size at an acceptable level. With this number of selected individuals, it would provide a genetic gain of 1.7%, increasing the average volume from 0.1552 m³/tree to 0.1634 m³/tree. With this new average, it would still be acceptable to form an improved population for future generations since it is higher than the original average of the population.

5. Conclusions

Pinus maximinoi showed suitable growth and performance in the 4 provenances, including the control (common lot) in the Chimbonila region, and can be recommended for commercial plantations in the region.

There were no significant differences between the provenances studied in all growth characteristics at 8 years of age, and any of the provenances can be used for reforestation.

The phenotypic association between the growth characteristics DBH and volume is strong for all progenies, suggesting that selection can be made based on DBH, which is the variable of easy access.

The genetic control of the growth characters measured by the coefficient of determination of plot effects and coefficient of additive genetic variation demonstrated a high potential for genetic improvement of the population.

The selection of the 17 individuals with higher genetic values within the provenances evaluated allowed the elevation of the average volume from 0.1552 m³/tree to 0.2089 m³/tree, with genetic gains of 11.11%.

Declarations

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Authors' contributions:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Cremildo Riba Gouveia Dias, Laurina Adriano Guacha and Aires Afonso Mbanze. The first draft of the manuscript was written by Cremildo Riba Gouveia Dias, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Tables

Table 1 Provenance, progenies and soil and climate characterization of the place where the seeds were collected

Provenance	Country	State or Department	Number of Progenies	Latitude	Longitude	Elevation Range (m)	Rainfall (mm/year)	Temperature (°C)
Coban (Cob)	Guatemala	Alta Verapaz	4	15° 28'	90° 24'	1420-1440	2109	13.7 - 23.7
San Jeronimo (SJ)	Guatemala	Baja Verapaz	4	15° 04'	90° 14'	1280-1590	970	16.3 - 27.6
Tatumbula (Tla)	Honduras	Fco. Morazan	6	14° 01'	87° 07'	1400-1600	908	15.0 - 24.9
Yuscaran (Yus)	Honduras	El Paraiso	4	13° 50'	86° 55'	1500-1700	1300	16.9 - 27.7
Common lot	Guatemala			n.a	n.a	n.a	n.a	n.a

Source: Dovorak et al. (2000)

Table 2 Growth means (height, DBH and volume) and survival of the provenances of *P. maximinoi* (15-64-36C1)

Provenances	Height (m)			DBH (Cm)		Volume (m ³ /tree)		Survival (%)		
	2 years	4 years	8 years	4 years	8 years	4 years	8 years	2 years	4 years	8 years
Cob	3.17	6.51 ab	15.04	8.20	17.67	0.0149	0.1623	96.88 ab	96.88	95.83
SJ	3.53	7.23 a	15.87	8.95	18.10	0.0196	0.1778	100 a	98.96	97.92
Tla	3.08	6.36 b	15.52	7.93	17.38	0.0137	0.1639	93.75 ab	93.75	93.75
Yus	3.20	6.50 ab	15.65	7.78	16.93	0.0135	0.1554	95 ab	94.17	93.33
Common lot	3.13	6.84 ab	15.93	8.15	17.02	0.0157	0.1667	83.33 b	83.33	83.33
Mean ¹	3.22	6.69	15.60	8.20	17.42	0.0154	0.1652	93.79	93.42	92.83
F ratio	2.23 ^{ns}	3.42 [*]	1.38 ^{ns}	1.87 ^{ns}	1.57 ^{ns}	2.29 ^{ns}	0.66 ^{ns}	3.47 [*]	2.93 ^{ns}	2.20 ^{ns}
CV _{exp} (%)	7.43	5.69	3.90	8.05	4.40	20.19	12.22	7.21	7.53	8.15

Means followed by the same letter in the column were not significantly different by Tukey's test. ns = not significant * = significant at 5%; ** = significant at 1%; 1 = overall average of sources, including the control; CV_{Exp} = experimental coefficient of variation

Table 3 Means of comparison between progenies and correlation between height and DAP with volume for *P. maximinoi* (15-64-36C1) at 8 years

Country	Provenances	Progenies	Means (m)	Means (Cm)	Means (m ³ /tree)	PCC
Guatemala	Cob	15-884	15.76	18.69 a	0.1892 ab	0,964**
Guatemala	Cob	15-886	14.90	17.75 ab	0.1602 ab	0,957**
Guatemala	Cob	15-887	14.98	17.07 ab	0.1543 ab	0,961**
Guatemala	Cob	15-888	14.41	17.07 ab	0.1424 ab	0,968**
Guatemala	SJ	15-868	16.16	18.60 a	0.1915 ab	0,950**
Guatemala	SJ	15-870	16.03	17.09 ab	0.1604 ab	0,934**
Guatemala	SJ	15-872	14.84	17.87 ab	0.1624 ab	0,933**
Guatemala	SJ	15-875	16.49	18.73 a	0.1956 ab	0,966**
Honduras	Tla	15-949	14.46	18.22 ab	0.1629 ab	0,961**
Honduras	Tla	15-954	15.27	16.82 ab	0.1466 ab	0,974**
Honduras	Tla	15-957	16.63	17.79 ab	0.1822 ab	0,949**
Honduras	Tla	15-962	16.13	18.86 a	0.1998 a	0,965**
Honduras	Tla	15-950	12.97	13.81 b	0.1132 b	0,984**
Honduras	Tla	15-956	15.63	16.15 ab	0.1408 ab	0,951**
Honduras	Yus	15-899	15.64	17.82 ab	0.1753 ab	0,946**
Honduras	Yus	15-900	15.43	14.92 ab	0.1177 ab	0,950**
Honduras	Yus	15-902	15.61	17.26 ab	0.1584 ab	0,917**
Honduras	Yus	15-903	15.79	17.27 ab	0.1603 ab	0,960**
Honduras	Yus	15-893	15.56	16.90 ab	0.1541 ab	0.945**
Guatemala		Common lot	15.93	17.02 ab	0.1667 ab	0,969**
		DMS	4.02	4.44	0,08	

Means followed by the same letter in the same column are not significantly different by Tukey test for ($p \leq 5\%$); DMS - for the least significant difference test. PCC = Pearson correlation coefficient, ** significant at ($p\text{-value} = 0.1$). All values are correlated with the DBH.

Table 4 Results from ANOVA, Eta² and Tukey test of means for clusters of the different progenies and precedencies

	Cluster 1	Cluster 2	Total		
	9 (45%)	11 (55%)	20 (100%)	F	Eta ²
Height (m)	15.85 a	14.53 b	15.12	41.27***	0.696
DBH (cm)	17.73 a	16.01 b	16.79	16.51***	0.478
Volume (m ³)	0.175 a	0.137 b	0.154	32.32***	0.642

Values with the same letter in the row do not differ statistically by the Tukey test.

**** = Significant at $p \leq 0.01$

Table 5 Estimation of the component of variance (individual REML) and the genetic parameters of the progenies of *P. maximinoi* (15-64-36C1) at 8 years

Variances	Height (m)	DBH (cm)	Volume (m ³)
σ_a^2	1.006941	3.869552	0.001447
σ_e^2	0.749248	0.281688	0.000137
σ_p^2	0.085578	0.009222	0.000003
σ_d^2	3.715746	7.825566	0.002920
σ_f^2	5.557513	11.986028	0.004508
h_a^2	0.1812 ± 0.1157	0.3228 ± 0.1545	0.3211 ± 0.1540
C_e^2	0.134817	0.023501	0.030425
C_p^2	0.015399	0.000769	0.000720
CV_{gi}	6.627223	11.651817	24.510171
CV_{gp}	3.313611	5.825909	12.255085
CV_d	8.073539	8.521402	18.275483
CV_{gi}/CV_d	0.82	1.37	1.34
General average	15.14	16.88	0.1552

σ_a^2 : additive genetic variance; σ_e^2 : environmental variance between plots; σ_p^2 : genetic variance

among provenances; σ_d^2 : residual variance; σ_f^2 : phenotypic variance at the individual level in the

experiment; h_a^2 : individual heritability in the narrow sense; C_e^2 : coefficient of determination of plot effects;

C_p^2 : coefficient of determination of the effects of origins; CV_{gi} %: individual additive genetic coefficient of

variation; CV_{gp} %: coefficient of genotypic variation among progenies; CV_d %: coefficient of residual variation.

Table 6 Selection of the 9 (45%) best progenies of *P. maximinoi* (15-64-36C1) at 8 years

Sequence	Provenances	Progenies	a	Gain	New Average
1	SJ	15-875	0.0518	0.0518	0.2070
2	Tla	15-962	0.0470	0.0494	0.2046
3	Cob	15-884	0.0443	0.0477	0.2029
4	SJ	15-868	0.0364	0.0449	0.2001
5	Tla	15-957	0.0180	0.0395	0.1947
6	Yus	15-899	0.0156	0.0355	0.1907
7	Yus	15-903	0.0078	0.0316	0.1868
8	Yus	15-902	0.0041	0.0281	0.1833
9	Tla	15-949	0.0009	0.0251	0.1803
Original population average					0.1552

a: predicted additive genetic effect.

Table 7 Classification of the 17 (4%) best individuals of *P. maximinoi* (15-64-36C1), selected within progenies at 8 years

Sequence	Block	Prog.	Proc.	Tree	f	a	U + a	Gain	New Average	Ne
1	3	962	Tat	6	0.4989	0.1082	0.2634	0.1082	0.2634	1.0000
2	1	868	SJ	1	0.3687	0.0692	0.2245	0.0887	0.2439	2.0000
3	4	875	SJ	3	0.3247	0.0643	0.2195	0.0806	0.2358	3.0000
4	4	899	Yus	5	0.3398	0.0548	0.2101	0.0741	0.2294	4.0000
5	1	957	Tat	3	0.3412	0.0542	0.2095	0.0702	0.2254	5.0000
6	1	884	Cob	1	0.3103	0.0534	0.2086	0.0674	0.2226	6.0000
7	2	957	Tat	4	0.3215	0.0511	0.2063	0.0650	0.2203	6.4972
8	1	884	Cob	4	0.2984	0.0502	0.2054	0.0632	0.2184	7.0588
9	3	884	Cob	2	0.2776	0.0497	0.2050	0.0617	0.2169	7.2483
10	1	875	SJ	6	0.2763	0.0485	0.2038	0.0604	0.2156	7.8947
11	1	884	Cob	6	0.2861	0.0468	0.2021	0.0591	0.2144	7.8870
12	1	899	Yus	4	0.3232	0.0468	0.2020	0.0581	0.2133	8.5714
13	4	884	Cob	6	0.2622	0.0461	0.2013	0.0572	0.2124	8.4324
14	2	868	SJ	3	0.2629	0.0423	0.1975	0.0561	0.2113	9.1304
15	1	875	SJ	3	0.2528	0.0422	0.1974	0.0552	0.2104	9.5847
16	4	868	SJ	6	0.2586	0.0421	0.1974	0.0544	0.2096	10.0524
17	2	962	Tat	2	0.2462	0.0421	0.1973	0.0537	0.2089	10.7668
Original population average								0.1552		

Proc: Provenances; Prog: Progenies f: phenotypic value individual or field measurement; a: predicted additive genetic effect; u + a: genetic value predicted additive; Ne: effective population size.

Table 8 Analysis of variance between progenies of *P. maximinoi* (15-64-36C1) at 8 years (**Appendix**)

Mean Squares					
Source	DF	Height (m)	DBH (Cm)	Volume (m ³ /tree)	Survival (%)
Block	3	0.2528 ^{ns}	1.0887 ^{ns}	0.00121 ^{ns}	114.583 ^{ns}
Progenies	19	2.8310 ^{ns}	6.2688*	0.00218*	221.308 ^{ns}
Residue	57	2.3198	2.9767	0.00103	153.570
CV _{exp}		9.87	10.13	19.83	13.13
Mean ¹		15.43	8,16	0.1617	94.38

where * = significant at 5% probability; ** = significant at 1% probability; ns = not significant; 1 = overall mean of provenances, including the control; DF = degrees of freedom; CV_{Exp} = experimental coefficient of variation.

Table 9 Analysis of variance for the progeny level within provenances of *P. maximinoi* (15-64-36C1) at 8 years (**Appendix**)

Provenances	DF	Height (m)		DBH (Cm)		Volume (m ³ /tree)	
		MSq ^Z	Cv _{exp} (%)	MSq ^Z	Cv _{exp} (%)	MSq ^Z	Cv _{exp} (%)
Cob	3	1.2584 ^{ns}	5.81	2.3717 ^{ns}	6.29	0.0016 ^{ns}	17.25
SJ	3	2.0611 ^{ns}	6.88	2.2852 ^{ns}	5.03	0.0014 ^{ns}	11.95
Tla	5	6.8787 ^{ns}	15.30	13.1658 ^{ns}	17.22	0.0038 ^{ns}	29.33
Yus	4	0.0711 ^{ns}	5.64	5.0349 ^{**}	3.88	0.0018 ^{**}	10.80
Overall mean ¹		15.42		17.37		0.1625	

where * = significant at 5% probability; ** = significant at 1% probability; ns = not significant; 1 = overall mean of provenance, not including control; DF = degrees of freedom; Z = F test for progenies within provenances; CV_{Exp} = experimental coefficient of variation.

Figures

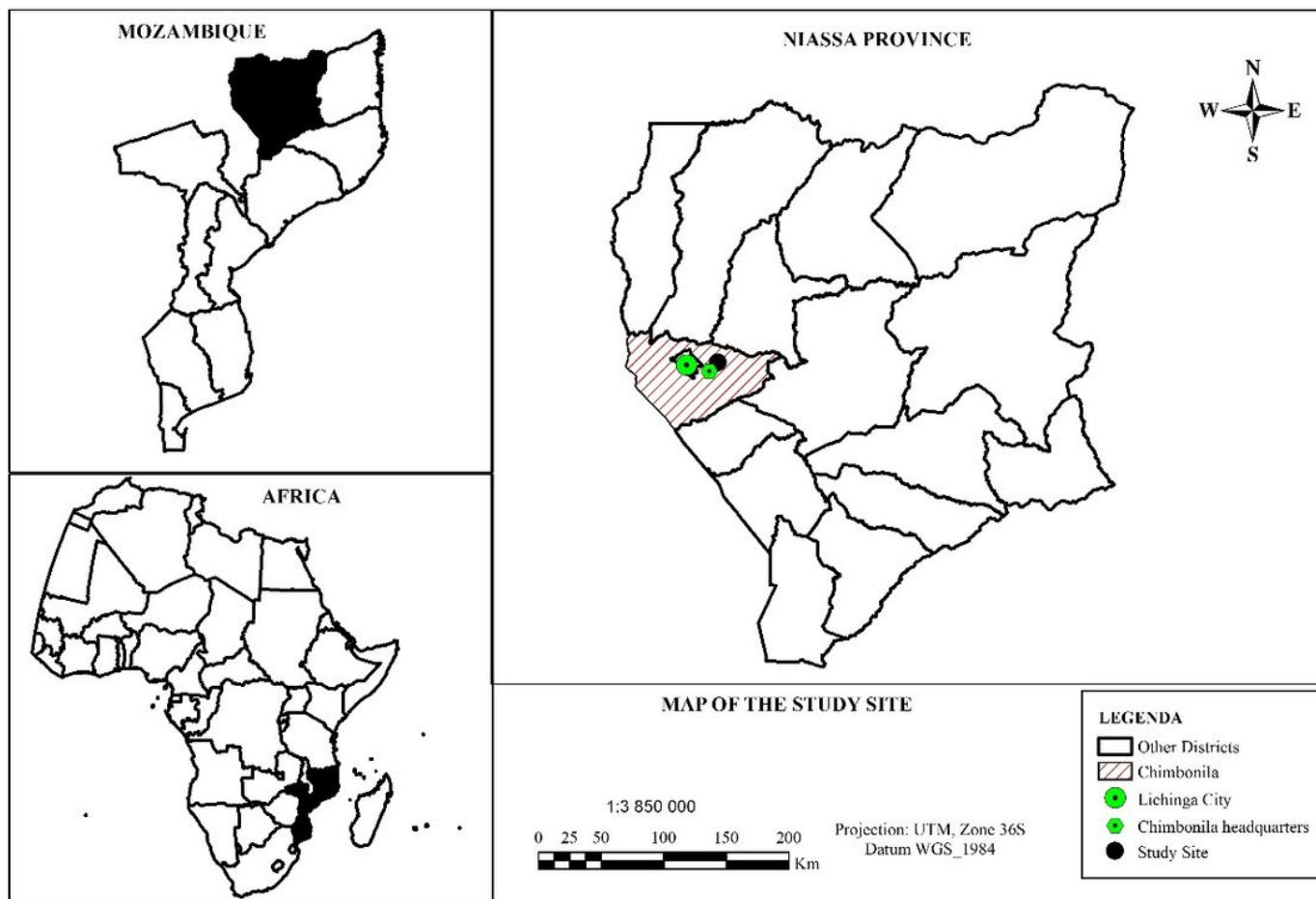


Figure 1

Geographical location of the study area

Fonte: O Autor¹ (2022)



Figure 2

Field trial of *P. maximinoi* established in the company Florestas do Niassa, Mussa locality. Photo taken at the age of 4, on the left, is the Camcore plaque of three experiments described, including the one of *P. maximinoi* evaluated in this study.

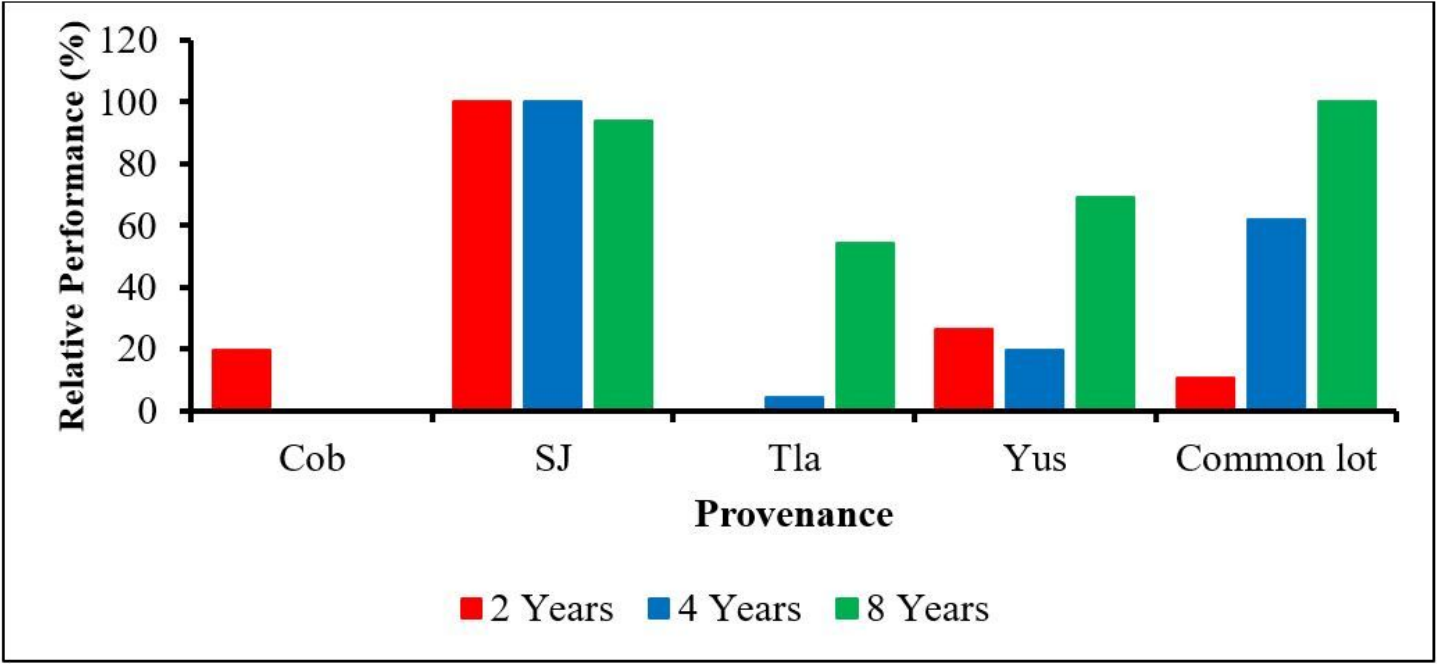


Figure 3
Relative performance of *P. maximinoi*(15-64-36C1) provenances in Chimbonila district

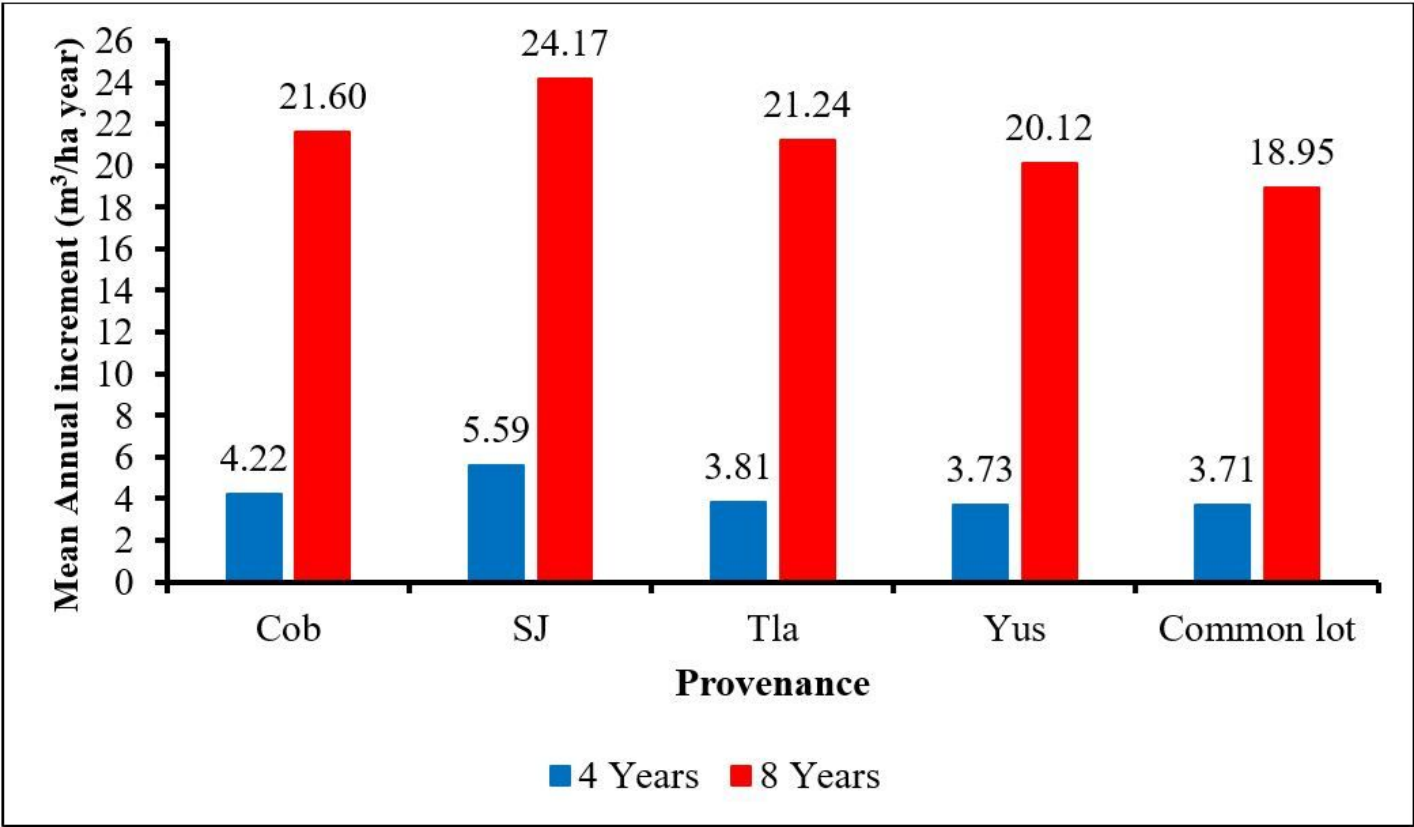


Figure 4

Mean annual increment (in volume) of the provenances of *P. maximinoi*(15-64-36C1)

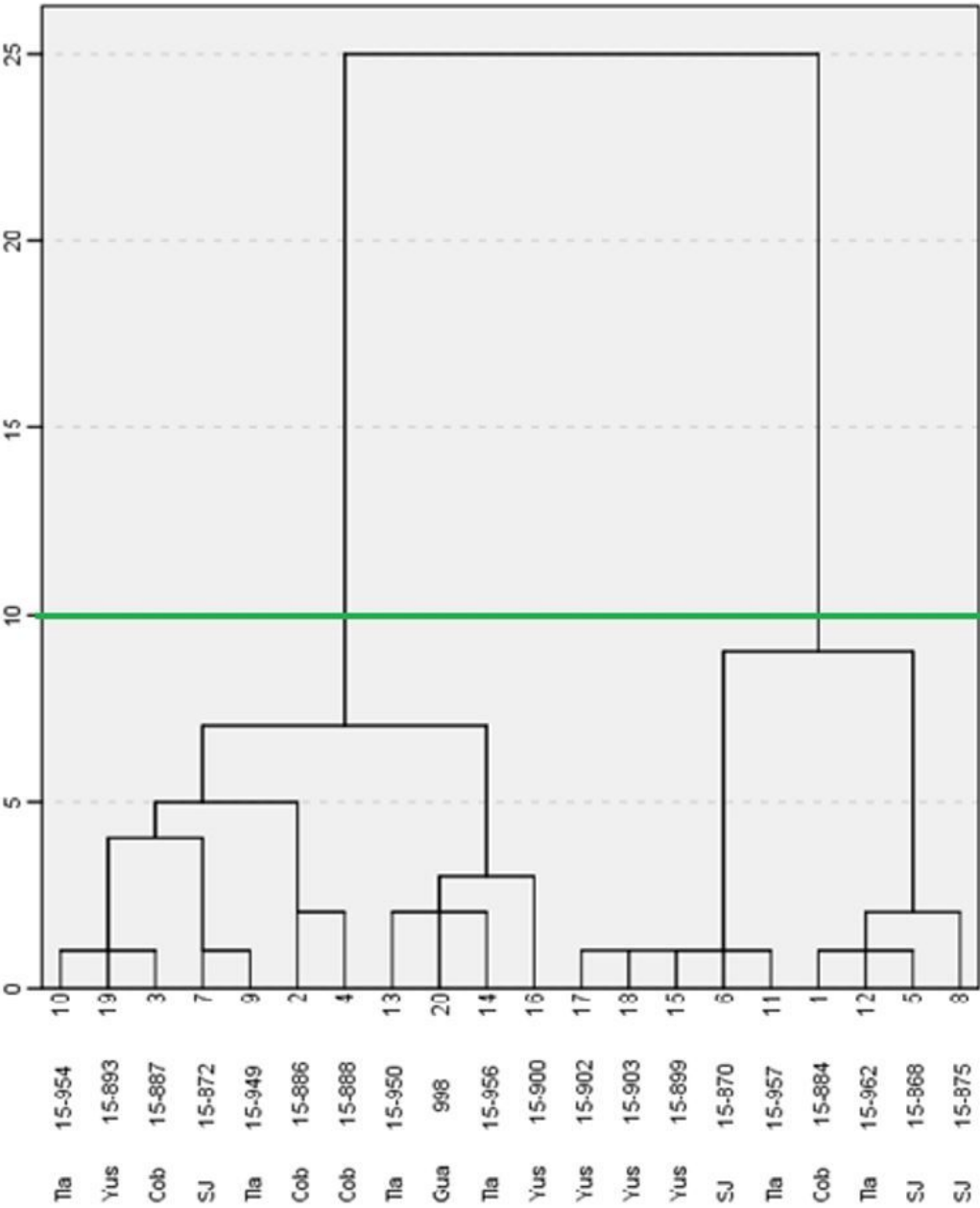


Figure 5

Cluster dendrogram of the different progenies and procedures of *P. maximinoi* (15-64-36C1) at 8 years

Supplementary Files

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