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Tree species with potential for reforestation in coastal zones of the humid tropics

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Abstract

Aim of study: The native species of warm humid climates *Ceiba pentandra, Tabebuia rosea, Gliricidia sepium, Enterolobium cyclocarpum* and *Brosimum alicastrum* are often included in Mexican reforestation programs. We evaluated the growth response in sandy soils of these species that could serve as pioneers in the restoration of coastal areas.

Area of study: Alluvial plain in Frontera, Tabasco, Mexico.

Material and methods: A total of 1080 plants were planted in 2014 and evaluated for 23 months in 30 plots under a randomized block design with six replications. The sample plots each occupied 36 m^2 (each with 16 plants). Survival percentage, stem height (SH), basal diameter (BD) and basal area (BA) were quantified. Survival and growth variables were analyzed using logistic regression and ANOVA for repeated measures, respectively.

Main results: At the end of the experiment (2016), high survival was demonstrated in *G. sepium* (88 %) and in *C. pentandra* (86 %), while *B. alicastrum* presented total mortality at six months. The highest values of SH and BD were presented in *C. pentandra* (2.9 m and 7.8 cm, respectively) and in *G. sepium* (2.6 m and 4.2 cm, respectively). *Gliricidia sepium* differed significantly from *C. pentandra* in terms of BA (5.9 *vs.* 23 m^2 ha^{-1}, respectively).

Research highlights: The native species *C. pentandra* and *G. sepium* presented high survival and growth in the sandy soils; *G. sepium* showed strong adaptation to the environment and *C. pentandra* offered suitable coverage, characteristics that are necessary for the success of reforestation and restoration programs.

Additional key words: basal area; *Ceiba pentandra*; *Gliricidia sepium*; stem height; survival

Abbreviations used: BA (basal area); BAp (basal area of each plot); BD (basal diameter); EC (electrical conductivity); SH (stem height)

Authors' contributions: GVS, PMZ and MDD performed the experiments. All authors conceived and designed the experiments, analyzed the data, wrote the paper and critically reviewed the manuscript for intellectual content.

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Introduction

Tropical humid forest plays an essential role worldwide as a reservoir of carbon, source of products of economic value and provider of ecosystem services and biodiversity; however, it is an ecosystem highly affected by deforestation (Sabogal *et al.*, 2013). In Mexico, the area of these forests has diminished dramatically in recent years (de la Cruz *et al.*, 2019), mainly due to the activities of commercial agriculture, livestock production and urban expansion (Kolb & Galicia, 2018). The establishment of plantations for restoration has been proposed as a tool for rehabilitation of the forests, with the tree canopy shown to influence the recruitment of new species and the trees themselves potentially acting as carbon dioxide sinks (Pedraza & Williams, 2003). Implementation of reforestation programs with native species in degraded zones favors an increase in both wildlife habitat and biodiversity (Giannini *et al.*, 2017).

Coastal zones rank among those that require the most attention, since climatic change has triggered severe problems in these areas, in terms of erosion and flooding with a consequent loss of land and biodiversity (Ramos *et al.*, 2016). These areas are characterized by the presence of sandy soils, with little water retention and intermediate fertility, pH values of between 6.3 and 6.7 and moderate salinity at certain times of the year (Palma *et al.*, 2007). The introduced species that thrive best in these zones include *Cocos nucifera* L., *Terminalia catappa* (Gaertn.) Eichler and *Casuarina equisetifolia* L. (Moreno & Paradowska, 2009). On the other hand, of a total of 55 native species, those best suited to this habitat include C*edrela odorata* L., *Diphysa robinioides* Benth., *Enterolobium cyclocarpum* (Jacq.) Griseb., *Bursera simaruba* (L.) Sarg., *Gliricidia sepium* (Jacq.) Kunth ex Walp., *Tabebuia rosea* Bertol. DC. and *Chrysobalanus icaco* L. (Moreno & Paradowska, 2009).

This study evaluated the growth response of five native species of the warm humid climate that could serve as pioneers in the reforestation of coastal areas: *Ceiba pentandra* (L.) Gaertn.), *T. rosea*, *G. sepium*, *E. cyclocarpum* and *Brosimum alicastrum* Sw. Some of these species have been selected previously for reforestation programs in tropical zones of Latin America and Africa (van Breugel *et al.*, 2011; Abengmeneng *et al.*, 2015). However, there have been few studies addressing their growth in sandy soils or their response to high temperatures and unstable rainfall regimes as a probable future scenario brought about by climatic change.

Material and methods

Study species

Species were selected considering their suitability and the availability of seedlings in the nurseries of the National Forestry Commission (CONAFOR, by its Spanish acronym), Gerencia Villahermosa (an official body responsible for plant propagation and distribution for reforestation) and Vicoplan (Viveros y Comercializadora de Plantas Jobel S.C. de R.L. de C.V).

Gliricidia sepium is a multipurpose legume, generally used for live fences, fodder and pest control, and is an excellent contributor of organic material through its interaction with symbiont organisms (mycorrhizal fungi and nitrogen-fixing bacteria) (Canul *et al.*, 2018; Villanueva *et al.*, 2019; Ramos *et al.*, 2020). *C. pentandra* is a fast-growing and highly valued tree; even in different regions of Africa where its wood is used to make canoes and domestic utensils (Abengmeneng *et al.*, 2015). In Latin America, *B. alicastrum* has extra value as a food-producing tree for humans and livestock. *E. cyclocarpum* is used to provide shade for livestock and its seeds are used in handcrafts (Román *et al.*, 2007; Bonilla & Holl, 2010), while *T. rosea* is used for timber and as a shade tree in pastures (Pineda *et al.*, 2016). The natural habitats of these tree species are in dry and humid tropical forests of different successional status (Pennington & Sarukhán, 2005; Román *et al.*, 2007).

Study site

The study area is located in Felipe Carrillo Puerto, in Centla, Tabasco, Mexico (18°53’1.54” N, 92°72’32.55” W: 2 masl). The climate is warm humid with abundant rains in summer (INEGI, 2019). During the 23 month period of evaluation, the average minimum and maximum temperatures were 20.0 ± 2.7 °C and 29.7 ± 3.5 °C, respectively. Rainfall was recorded at 1284.4 mm in 2014 (March-December), 2217 mm in 2015 (January-December) and 262.5 mm in 2016 (January-February) (Fig. 1). The soils are sandy in texture and classified as Arenosols (Palma-López *et al.*, 2007). Soil pH was 6.9 and electrical conductivity (EC) was 0.608 dS m^{-1} (mean values from three compound samples taken at random in each block at a depth of 15 cm). Analysis was conducted with a Multi-Probe System YSI 556 MPS,

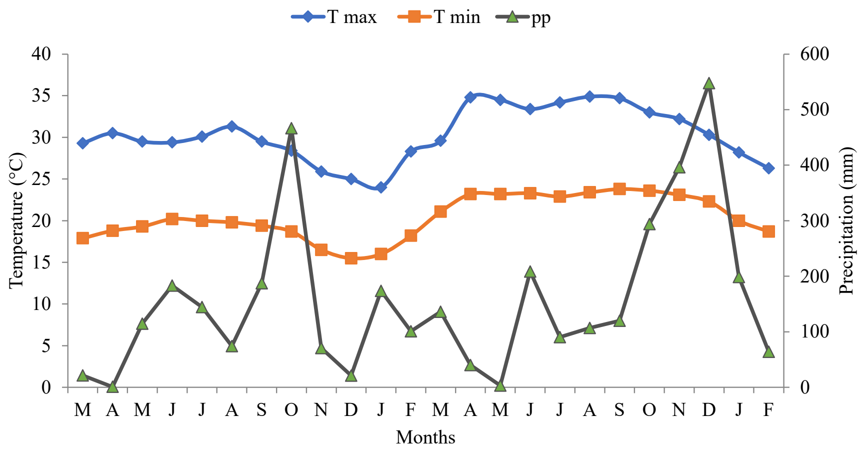

Figure 1. Temperature and rainfall conditions recorded during the growth evaluation period of the study (March 2014-February 2016) in Felipe Carrillo Puerto, Centla, Tabasco, Mexico. Source: National Water Commission (CONAGUA, 2016).

using the methodology established in NOM-021-RECNAT-2000 (2000). The reference vegetation close to the experimental plots was a secondary forest, represented by trees such as *B. simaruba, Guazuma ulmifolia* Lam., *C. odorata, T. rosea, G. sepium*, *Swartzia cubensis* (Britton & P. Wilson) Standl. and *Piscidia piscipula* (L.) Sarg, among others (Manuel Núñez Piedra, CONAFOR, *pers. com*.).

The area was cleared of weeds using a tractor, and seedlings of each species were planted in a 1.5 m × 1.5 m grid within 5 quadrangular plots of 9 m × 9 m (81 m^2). A total of 1080 seedlings of five species were planted in 30 plots; 36 plants of the same species were established per plot (of which, to avoid edge effects, only the 16 plants in the center of each plot were measured) with a total of 96 sample plants per species. Five plots for each species were placed in a randomized complete block design, with six replications. The seedlings were six months old at planting and healthy in appearance, set in a root ball. The average values of stem height (SH) and basal diameter (BD) of the plants at the moment of planting were: 0.43 m and 0.84 cm (*T. rosea*), 0.27 m and 0.60 cm (*E. cyclocarpum*), 0.64 m and 1.2 cm (*G. sepium*), 0.54 m and 1.2 cm (*C. pentandra*) and 0.45 m and 0.5 cm (*B. alicastrum*).

Manual irrigation was carried out (supplying approximately 4 L per plant, twice a week), but only during the spring of 2014, which was the dry period of the plantation year. Manual weeding was conducted every four months throughout the whole study period. *G. sepium* presented a shrub-like growth that produced various stems, and was pruned to leave only the most vigorous of these in order to subsequently measure a single stem only. In *B. alicastrum*, total mortality was recorded at six months of study, and this species is therefore excluded from the results.

Survival was recorded and growth was evaluated by measuring SH and BD. These measurements were taken at the time of initial plantation and then at three-month intervals until month 18, with a final measurement taken at 23 months after planting. The basal area of each plot (BAp, m^2) was calculated (Eq. 1) and this value was further extrapolated to hectare level as basal area (BA, $m^2\,ha^{-1}$) (Eq. 2). The BD (cm) of all plants in each plot was used for this purpose (Serrada-Hierro, 2008) as follows:

$$BAp = \left(\frac{\pi}{40000}\right) \cdot \left(\sum BD_i^2\right) \quad (1)$$

$$BA = \frac{BAp \cdot 10{,}000}{Sp} \quad (2)$$

where: $\sum BD_i^2$ is the sum of the squared value of the stem BD of all of the individuals quantified in the plot; and Sp is the surface area of the plot in m^2.

Statistical analysis

In order to confirm compliance with the assumptions of normality, the Kolmogorov-Smirnov test was applied to the data. Since this assumption was not fulfilled, the data were transformed to a natural logarithm in order to carry out the statistical analysis.

A two-way ANOVA was conducted for the vegetative growth of the four surviving species in order to determine differences among species. Survival was analyzed using a logistic regression for each of the seven measurement dates in Proc Logistics. The effect of two factors (block and species) on the probability of survival on each of the measurement dates (3-23 months) was evaluated using the following mathematical formula:

$$p_{ijk} = \frac{1}{1 + \exp\left(-Z_{ijk}\right)}$$

in which

$$Z_{ijk} = log\left(\frac{p_{ijk}}{1 - p_{ijk}}\right) = \mu + \alpha_i + \beta_j$$

where μ is the general population mean, α_i is the effect of the *i-th* block and β_j is the effect of the *j-th* species.

These parameters were estimated using the method of maximum likelihood. SH, BD and BA were analyzed with a repeated measures (over time) model, using a linear mixed model with two inter-subject factors (species and block) in a random block design and one intra-subject factor (measurement date), with eight levels. A structure of first-order auto-regressive and heterogeneous variances (ARH1) was used for each species, with a total of 36 parameters of variance estimated using the method of restricted maximum likelihood (REML). This variance structure was selected because it gave the best values for the Bayesian Information Criterion (BIC).

In addition, comparisons were made with the least square means estimated by the model, using the Tukey-Kramer test with a significance level of 0.05. Individual contrasts were applied to compare total growth during the experiment and comparisons were also made among particular species at a given sampling date. Normality of the studentized residuals was analyzed using the Kolmogorov-Smirnov test. All tests and statistical analyses were performed using the software SAS 9.4 (SAS Inst. Inc., Cary, NC, USA, 2017).

Results

The highest probabilities of survival at the end of the study (23 months) were found in *G. sepium* (0.88) and *C. pentandra* (0.86) (Fig. 2a). *T. rosea* (0.54) and *E. cyclocarpum* (0.52) presented lower survival probabilities

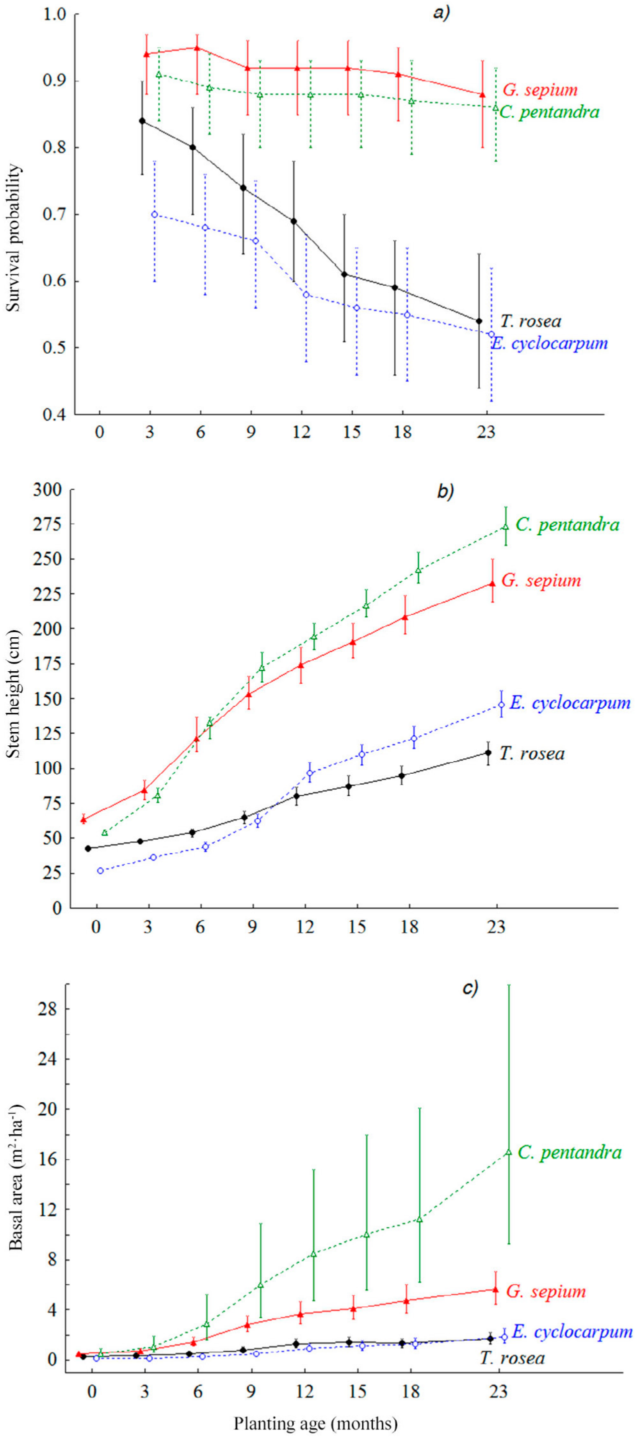

Figure 2. Probability of survival (a), stem height (b) and basal area (c) of four tree species planted in Felipe Carrillo Puerto, Centla, Tabasco, Mexico. The error bars represent the standard error of the means

(Fig. 2a). At the end of the experiment, the difference between the species with the highest and lowest survival probabilities was 36%.

According to the statistical analysis of the (natural logarithm) transformed data we found highly significant differences among the species in three variables for the period studied (23 months): SH ($F_{3,375}$ = 285.3, p<0.01), BD ($F_{3,375}$ = 211.3, p<0.01) and BA ($F_{3,15}$ = 37.62, p<0.05). The interaction species × measurement date (plantation age) was found to be significant for SH ($F_{21,2024}$ = 34.1, p<0.01) and for BA ($F_{21,2016}$ = 16.3, p<0.01). The Least Squares Means and the confidence intervals were converted by reversing the data transformation, as shown in Fig. 2b for SH and Fig. 2c for BA.

Discussion

Species survival

Survival of *C. pentandra* and *G. sepium* was "excellent", according to the classification of Elliot *et al.* (2003). These species have previously presented high survival rates, as demonstrated in the study of de Souza *et al.* (2010), who recorded 97.2% survival in *C. pentandra,* which had grown for six years in full sunlight in the Brazilian Amazon. In the case of *G. sepium,* González *et al.* (2017) reported survival that exceeded 86% at two months after transplanting in the Chamela-Cuixmala Biosphere Reserve (Jalisco, Mexico), which is characterized by its tropical dry forest and Regosol soil. It should be noted that *G. sepium* is commonly planted as live fencing and remains in the site for around 15 years, according to observations carried out in Tacotalpa, Tabasco, Mexico, where there a warm-humid climate prevails (Villanueva *et al.*, 2015). Both of these species are considered pioneers in the successional process and present ecophysiological characteristics that give them greater tolerance to water stress and high solar radiation (Mayoral *et al.*, 2017; Guimarães *et al.*, 2018; Valverde & Arias, 2020). The association of *G. sepium* with nitrogen-fixing bacteria gives the species a greater opportunity for establishment (Canul *et al.*, 2018).

Survival of the species *T. rosea* and *E. cyclocarpum* was "acceptable" and that of *B. alicastrum* was "unacceptable", according to the categories established by Elliot *et al.* (2003). However, when *B. alicastrum* was established in pastures in coastal dune soils in Veracruz (Mexico), its survival was reported as 48.5% (Laborde & Corrales, 2012). This tree species is late successional and is therefore unsuited to low soil moisture conditions (Laborde & Corrales, 2012).

Species growth

The soil conditions of low fertility and sandy texture, low availability of water due to the free draining character of the soil texture and low precipitation and high temperatures during the study period were favorable for growth of *C. pentandra* and *G. sepium*, but limiting for the other two species. A prolonged drought was recorded during the period of study in 2014 and 2015, and these two years were consecutively catalogued as the warmest since 1971 (CONAGUA, 2014, 2015, 2016).

The SH of *C. pentandra* recorded at 23 months after planting agrees with previous data recorded for trees of the same species 18 months after planting in pastures in the Lacandon area of Chiapas, Mexico (Román *et al.*, 2012). In addition, fertilized plants were reported to reach heights of up to 10 m in 55 months in the Brazilian Amazon, in a soil classified as a Latosol (de Souza *et al.*, 2010). With regard to *G. sepium*, de Oliveira *et al.* (2016) reported plant heights of 3.0-4.3 m in plantations from cuttings established in a Ferric Lixisol soil in Caatinga region, Brazil, which thus exceeded the values obtained in this study.

In terms of stem BD, growth values ≥ 4 cm, as shown for *C. pentandra* and *G. sepium* in our study, are considered "acceptable" by Román *et al.* (2012) for tropical trees. These results are similar to those recorded by Joslin *et al.* (2016), in which *C. pentandra* presented an average BD of 4 cm one year after being planted in a loam soil with no fertilization in the Brazilian Amazon. Silva *et al.* (2012) found that *G. sepium* reached BD values of 4.8 cm when planted at a density of 800 trees ha^{-1} one year after being planted in the Mossoro region (Brazil), a dry tropical zone.

In this experiment, *C. pentandra* presented the highest growth in BA, which agrees with the highest records of BD and survival obtained for this species in Atlantic Coastline plantations of Honduras 26 months after being planted in sandy soils (PROECEN, 2003). However, lower values (13 m^2 ha^{-1}) have also recorded in a succession experiment conducted within a protected natural area (Laguna Cartagena, Puerto Rico) characterized by low-deep stony soils with good drainage (Weaver & Schwagerl, 2008).

Propagation of *G. sepium* is generally carried out using cuttings, so studies of BA in plants obtained from seeds are scarce. In this study, the species showed a BA value higher than the average value of 4.4 ± 1.5 m^2 reported by Park *et al.* (2010), who evaluated *G. sepium* 2 years after its plantation in silty and clay soils under tropical conditions at Río Hato, Panama. This species was associated with another four species (*Acacia mangium* Willd., *Ochroma pyramidale* (Cav. ex Lam.) Urb., *Erythrina fusca* Lour. and *Pachira quinate* W.S. Alverson). Silva *et al.* (2012), in an experiment carried out in a zone typified by dry weather in Mossoro, Brazil, stated that *G. sepium* plantation densities of 400 and 1200 plants ha^{-1} produce minor differences in terms of plant height. These authors did record an inversely proportional relationship between plantation density and the crown diameter of individual trees.

In this study, *T. rosea* and *E. cyclocarpum* recorded low height growth values of 1.2 m and 1.6 m, respectively. However, these values are similar to those of a study conducted in Mérida, Venezuela, of *T. rosea* under fertilized sandy loam soil conditions in which, 18 months after planting, the trees measured 1.2 m in height on average (Araque *et al.*, 2009). Likewise, individuals of *E. cyclocarpum* reached a SH of 1.2 m in four years when planted in soils previously used for pasture in the central area of Veracruz, Mexico (Laborde & Corrales, 2012).

On the other hand, *E. cyclocarpum* trees sown in Otoch Ma'ax Yetel Kooh, a natural reserve located between Campeche and Quintana Roo, Mexico, in which soils are known as rendzinas and lithosols, presented a SH of 50 cm after 24 months, which are low rates according to this analysis. In contrast, this legume can reach SH values of 5.5 m after two years in an African savanna environment (Arigbede *et al.*, 2012).

In *T. rosea,* the recorded value of stem BD in this study was 2.9 cm (Table 1), which is similar to those found by Plath *et al.* (2011) in Colon, Panama, in fertile soils. The average growth in BD was 2.9 cm two years after being transplanted and even greater, at 3.1-5 cm (Araque *et al.*, 2009), in the studied conditions previously mentioned. The leguminous *E. cyclocarpum* had a low stem BD (3.1 cm); however, under the conditions of the African humid tropics, the BD reached 7.2 cm in 24 months (Arigbede *et al.*, 2012).

In the same context, *T. rosea* presented a BA of 2.9 m^2 ha^{-1}, similar to that found in silvopastoral systems from natural regeneration evaluated in Jinotega, Nicaragua (de Sousa *et al.*, 2016), in which the wooded region had a BA = 2.5 m^2 ha^{-1} and 14 m in height, and also similar to that reported in a mixed plantation including four more species (2.5 m^2 ha^{-1}) in Sardinilla, Panama (Salisbury & Potvin, 2015). Under natural conditions, *E. cyclocarpum*

Table 1. Growth variables measured (means ± standard error) in four tropical tree species at 23 months after planting.

Species	Stem height (cm)	Stem basal diameter (cm)	Basal area (m^2·ha^{-1})
Ceiba pentandra	289.7 ± 36.52	7.8 ± 1.33	23.0 ± 7.7
Gliricidia sepium	258.5 ± 23.00	4.21 ± 0.35	5.9 ± 1.0
Enterolobium cyclocarpum	164.7 ± 13.86	3.1± 0.23	2.1 ± 0.5
Tabebuia rosea	120.7 ± 5.12	2.9 ± 0.14	1.7 ± 0.2

may present a higher (12 m^2 ha^{-1}) (Bonilla, 2019) or lower (1.4 m^2 ha^{-1}) BA (Park *et al.*, 2010).

The tree species included in this study are considered to be of fast growth (Araque *et al.*, 2009; Plath *et al.*, 2011; Silva *et al.*, 2012). However, as stated by van Breugel *et al.* (2011), the same species can present different responses depending on soil texture, fertility and moisture content and the particular management practices employed. Other influential elements include the incidence of herbivory and the successional status of species, which are related to their capacity to compete with other plants (Plath *et al.*, 2011). Bonilla & Holl (2010) attributed one low growth to light interference and competition with other plants. They deduced that, considering their pioneer characteristics, growth of these species would be higher in open areas with no vegetation.

Although *T. rosea* did not present a good performance in the study area, its foliage has certain anatomical traits that might help it to tolerate high radiation through the presence of indument, a thick and ridged cuticle that acts to reflect excess light and vascular veins in the mesophyll that protect the tissue from excess radiation and facilitate water conservation (Araque *et al.*, 2009). However, stomatal conductance can be inhibited at high temperatures (>32 °C) and photosynthetic rate can diminish (Araque *et al.*, 2009) as was the case in the present study.

Studies of the origin of *E. cyclocarpum* populations in Oaxaca, Mexico, therefore displayed differences in the recorded annual increase of height, BD and survival, according to the rainfall characteristics, as well as chemical and physical soil properties of each survey area (Hernández *et al.*, 2019).

The results obtained in this experiment increase the possibilities of using native species in reforestation and restoration programs in the dry tropics. *Ceiba pentandra* and *G. sepium* both meet the criteria for effective reforestation and are tree species with a high survival ratio, capable of crown expansion and high primary production in the sites where they have been planted (Douterlungne *et al.*, 2015). *G. sepium* would be useful for increasing soil fertility in degraded ecosystems and providing fodder and fuel, as well as efficient carbon capture, in addition to its common use in agroforestry systems to provide shade for coffee and cocoa (Wishnie *et al.*, 2007; Villanueva *et al.*, 2015; Pantera *et al.*, 2021).

Moreover, rapid growth in SH, BD and BA would fulfill the objective of quickly reaching complete tree cover, and thus effect a possible acceleration of the ecosystem recovery process (Freitas *et al.*, 2019). Reintroduction of native species can significantly increase levels of organic material in a system and serves to accelerate secondary succession in degraded and abandoned agricultural and livestock production areas (Román *et al.*, 2007).

It should be noted that, in an active restoration program, establishment of plants via the plantation method may be more expensive than direct sowing or passive restoration, given the costs implied in the maintenance of seedlings in nurseries and transplanting them to the field site (Freitas *et al.*, 2019). However, ecological restoration is urgently required in order to counteract the high deforestation rate and this method may be very effective in terms of increasing floral and faunal diversity, as well as litter and biomass (Crouzeilles *et al.*, 2017).

The present study was conducted in a coastal soil in which the pH and EC did not present an impediment to the survival and growth of plants; the soil pH was almost neutral and EC was lower (0.608 dS m^{-1}) than in saline soils (4 dS m^{-1}). In order to enhance the potential of these promising species, a suitable fertilization program considering soil type is required (de Souza *et al.*, 2010; Hall *et al.*, 2011), as well as appropriate spacing among trees in order to facilitate improved growth and development.

In summary, *C. pentandra* and *G. sepium* presented high survival and growth rate in stem height and basal area after 23 months from planting. These species maintained high plantation density and could thus be considered as useful species for reforestation and restoration programs in coastal zones given their favorable adaptation to the environment. *E. cyclocarpum* and *T. rosea* presented low survival values (technically), while *B. alicastrum* did not survive after six months from the time of plantation, demonstrating that the environmental conditions in open coastal soils did not favor this species.

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