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Evaluation of native tree species for the rehabilitation of deforested areas in a Mexican cloud forest

R.A. PEDRAZA and G. WILLIAMS-LINERA*
*Instituto de Ecología, A. C., Apartado Postal 63, Xalapa, Veracruz 91000, México; *Author for correspondence (e-mail: lupew@ecologia.edu.mx; phone: +52 228 8421800; fax: +52 228 8187809)*

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Abstract. Four native tree species (*Liquidambar styraciflua*, *Juglans pyriformis*, *Podocarpus matudae*, and *Carpinus caroliniana*) were evaluated for their suitability in rehabilitating degraded areas of Mexican cloud forest. Plant survival and growth in height and diameter were determined in three mixed-experimental plantations with different land use histories; their performance was compared with two on-farm plantations started by landowners for forest restoration. Nearby forest fragments were controls for soil compaction. An experimental plantation with remnant trees had the highest plant survival (82%), height, basal diameter and relative growth rate. The plantation with the steepest slope had high plant survival (63%) and growth. The plantation characterized by dominance of grasses and compacted soils had the lowest survival (22%) and growth. On-farm plantations had good establishment of planted trees (5–10 species planted), and facilitated the recruitment of 9–11 woody species. *Carpinus* and *Liquidambar* appear to be suitable species for reforestation in all these areas. *Podocarpus* grew relatively slowly, although it performed well in two experimental sites. *Juglans* had high survival (76%) under the stressful conditions of the most adverse site, and therefore may be useful for rehabilitation of degraded sites. Differences among species and sites strongly suggest that species success depends on plantation site quality.

Introduction

After forest conversion to agriculture or pastureland, forest recovery may occur through secondary succession. However, when the probability of recreating initial conditions is low or recovery time too long, human intervention may be required to ameliorate land degradation (Bradshaw 1983; Brown and Lugo 1994; Lamb 1998). The establishment of plantations has been proposed as a tool for forest restoration of degraded lands through their effects on vegetation structure, microclimate, and soils. Several studies have demonstrated that the overstory composition of plantations influences the recruitment of new species (Parrotta 1992, 1995; Guariguata et al. 1995; Haggar et al. 1997; Parrotta et al. 1997; Lamb 1998; Holl et al. 2000; Otsamo 2000b). Other advantages of plantations are their ability to act as sinks of carbon dioxide and thus mitigate greenhouse effects (Masera et al. 1997).

In Mexico, ca. 50,000 ha/y were reforested between 1985 and 1990 for restoration purposes, and in 1998–1999 the reforested area increased to 203,000–225,000 ha/y. However, the rate of survival of seedling transplants varied between 34–43%

(Masera et al. 1997; SEMARNAP. 2000). The low success rate of most reforestation projects is associated with the lack of incentives for landowners to manage and maintain plantations after such large planting campaigns (Masera et al. 1997). The 1998 National Forest Census reported 55 commercial plantation projects over 33,473 ha throughout the country. Exotic tree species were used in 14 of these projects, occupying 45% of the planted area. Native tree plantations were dominated by coniferous trees in 33% of the area, whereas tropical broadleaved trees were planted in only 22% of the area. The most commonly planted trees were exotic species such as *Eucalyptus* spp., *Gmelina arborea* and *Tectona grandis*, and in lesser quantities, native tree species such as *Cedrela odorata* and *Swietenia macrophylla* (SEMARNAP. 1999).

Approximately 2,500 Mexican tree species appear to have potential for use in forestry projects (Rzedowski 1993), but few of these species have been studied to date. Vázquez-Yanes et al. (1999) selected 233 native tree species as potential native trees for restoration, but *Pinus* is the only genus which has been examined in long-term trials, providing information to select appropriate species, provenances, and progenies for use in plantations (Barrett 1980). In recent years, research and publications on Neotropical broadleaved tree species useful in plantations and rehabilitation efforts has been increasing (Butterfield 1993; Chaverri et al. 1997; Haggar et al. 1997, 1998; Cuevas and Lugo 1998; Lamb 1998; Standley and Montagnini 1999; Holl et al. 2000). However, interventions to rehabilitate degraded habitats of Neotropical montane forest using plantations are rare. Some recent rehabilitation efforts include Chiapas, Mexico (Camacho-Cruz et al. 2000; Ramírez-Marcial 2002), Talamancas (Holl et al. 2000) and Heredia (Chaverri et al. 1997), Costa Rica, as well as the central Andes of Colombia (Cavelier 1995; Murcia 1997; Cavelier and Santos 1999).

Tropical montane cloud forest (TMCF) is the most diverse type of vegetation in Mexico. While TMCF covers only 1% of the land surface of the country it is home to 10% of the flowering plant species. Many tree species of cloud forest provide good quality timber, which is used locally for many purposes (Rzedowski 1996; Challenger 1998). Cloud forests contain around 450 tree species in total (Rzedowski 1996), though only one TMCF species, *Liquidambar styraciflua*, has been studied in detailed trials designed to determine its suitability for use in plantations (McMillan and Winstead 1976; McCarter and Hughes 1984; Falcon 2000).

This study is part of a long-term project to determine strategies for the conservation and restoration of a tract of threatened TMCF surrounding Xalapa, a major urban center in the state of Veracruz, Mexico. Our study evaluated mixed plantations as a tool for cloud forest rehabilitation (sensu Brown and Lugo (1994)) in deforested areas. The principal hypothesis of this study was that the performance of native tree species used on plantations depends on the specific patterns of degradation exhibited by each site in the region. The objectives were 1) to determine plant survival and growth in height and diameter of four native tree species used in mixed-experimental plantations at three sites, 2) to predict the future performance of the experimental plantations by comparing them with older plantations started by local stakeholders, and 3) to evaluate the success of different species in sites that differ in their degree of perturbation.

Table 1. Site characteristics of five native tree species plantations in central Veracruz, Mexico. Sites 1, 2 and 3 are experimental plantations established in 1998. Sites 4 and 5 were planted in 1995 and 1991, respectively, by landowners. Variables are altitude, plantation area and slope. Total annual precipitation and mean temperature were obtained from the nearest meteorological stations. Soil variables are soil compaction, bulk density, pH, and organic matter percent (O.M. %). Values between parentheses are the same variable measured in a nearby forest fragment. ** $p < 0.01$, * $p < 0.05$

Study Site	1	2	3	4	5
Altitude (m)	1875	1400	1350	1340	1325
Area (ha)	3.14	0.23	0.99	45	1.01
Slope (°)	37	24	17	6	6
Precipitation (mm)	1350	1650	1750	2200	1650
Temperature (°C)	12	16	18	17	16
Soil variables					
Compaction (kg/cm^2)	13.2 (10.1)	16.0 (11.5)**	20.7 (11.1)**	20.9 (15.2)**	17.0 (11.5)*
Bulk density (g/cm^3)	0.91 (0.53)	0.92 (0.82)	1.49 (0.73)	1.23 (0.73)	0.89 (0.82)
Soil humidity (%)	46(45)	30(33)	42(37)	21(21)	43(33)
pH (1 : 2)	4.2 (3.7)	5.6 (4.2)	5.0 (3.8)	4.5 (4.6)	5.1 (4.2)
O. M. percent	12.4 (19.6)	8.9 (21.8)	8.4 (12.0)	16.4 (14.3)	15.2 (21.8)

Material and methods

Study sites

The study was carried out in central Veracruz, Mexico (19° 30′ N, 96° 54′ W), in an area located just south and west of Xalapa, the state capital. Historically, this region was covered almost completely by TMCF. At present, the forest in this area is fragmented with forest remnants occupying only 10% of its original area. The most abundant tree species in the study area are *Quercus xalapensis*, *Liquidambar styraciflua*, *Q. leiophylla*, *Carpinus caroliniana*, *Clethra mexicana*, *Turpinia insignis* and *Q. germana*. The climate is mild and humid throughout the year with three well–defined seasons: a relatively dry–cool season (November–March), a dry–warm season (April–May), and a wet–warm season (June–October) (Williams-Linera 2002). In this area, we selected five study sites: three old fields in which experimental mixed plantations were established in 1998 (sites 1, 2 and 3), and two plantations established by landowners in 1991 and 1995 as an effort to reforest their property (sites 4 and 5). Site data are presented in Table 1.

Site 1 was clear-cut in 1990, for timber and charcoal, and then abandoned. Site 2 was deforested ca. 1980 and converted to pasture. After 10 y of use, the pasture was abandoned. When we started a plantation at this site, a ten-year old field was present, although it had been partially cleared with machete once per year. Site 3 was clear-cut in the 1950’s to create a pasture, and more recently has served as a public lawn. In 1997, 72 ha were donated to the University of Veracruz and 75% of this area is being rehabilitated.

Sites 4 and 5 belong to landowners concerned with the preservation and restoration of native forests. They decided to rehabilitate native vegetation in part of their land by planting mainly native trees from nurseries, and transplanting seedlings from adjacent forest fragments. The sites had been in pasture since the 1970’s when the original forests were cut, and both were planted with seedlings at a spacing of 3 m, mostly with native tree species (see below). Site 4 was planted in 1995 with 50,000 tree seedlings in 45 ha and the plantation was left without maintenance. Site 5 was planted in 1991 at the same density as site 4, and periodically weeded, though trees present before and after plantation establishment were allowed to persist.

Vegetation structure, floristics, and soils

Prior to establishing the experimental plantations, vegetation structure and floristic composition were determined at all study sites. Sampling units had different areas according to the size of the target vegetation. At sites 1, 2 and 3, woody vegetation < 2 m tall was identified in ten 2×2 m randomly located plots. Since site 2 had a tree stratum, we used ten 2×50 m transects to determine basal area and density of the woody vegetation > 2 m tall. In sites 4 and 5, we measured all trees ≥ 2 m tall (planted trees and colonizers) in 20, 5×5 m, randomly established plots. Basal diameter of these trees was measured twice, in July 1998 and in March 2000.

In each plantation and in nearby forest fragment, soil compaction was measured with a penetrometer ten times in five random sampling locations. Also, in each site, four soil samples were collected at 0 to 10 cm depth and mixed into a composed sample per site to estimate bulk density, percent of soil humidity, and organic matter content (Table 1).

Tree species

The four native tree species tested in the mixed plantations were *Liquidambar styraciflua* L., *Carpinus caroliniana* Walt., *Juglans pyriformis* Liebm., and *Podocarpus matudae* Lundell (nomenclature follows Sosa and Gómez-Pompa (1994)). The tree species were selected because they were abundant in the nearby forest fragments (Williams-Linera 2002), they have wood properties with market potential (Carmona 1979), and because previous management observations in a local experimental nursery indicated that they are easily propagated. Additionally, although these tree species grow in the forest interior and are considered characteristic of the cloud forest, *Liquidambar*, *Carpinus* and *Juglans* may also occur in almost pure stands following forest disturbance. *Podocarpus* has been observed growing in the forest interior only.

Seedling source

Tree seedlings were obtained from a pilot study program promoting the use of native species in governmental reforestation programs (PRONARE or National Reforestation Program) in central Veracruz (Pedraza 1998). Seeds were collected from several regional forest fragments. Germinated seedlings were grown in a nursery in plastic bags with soil collected in situ, and 2000 plants were used in the experimental plantations. Those plants were left in an open space and, before they were moved out of the nursery to the field, height and basal diameter were measured in 50 randomly selected individuals per species, and the mean height and diameters (± one standard error) were used as initial seedling size. The age of the seedlings were 11 mo for *Liquidamba*r, 17 mo for *Juglans*, 16 mo for *Podocarpus*, and 23 mo for *Carpinus*.

Plantation design and establishment

The plantations were established in plots of 30 × 36 m at sites 1 and 2, and 15 × 36 m at site 3, with six replicate plots at each site. Within each plot, trees of the four species were randomly planted in three lines of ten plants each at sites 1 and 2, and of five plants each at site 3. A total of 180 tree seedlings per species were planted at sites 1 and 2, and 90 trees of each species were planted at site 3. Plants were moved in their bags to the plantations, except at site 1, where bare root transplant was required due to inaccessibility to vehicles. At this site, seedlings were planted immediately following transportation by foot, which lasted less than an hour. Plant spacing was 3 × 3 m. Trees were planted in holes 30 × 30 cm and 35 cm depth. Plantations were not irrigated or fertilized but they were manually weeded every six to eight months.

Vegetation at all sites, except for trees, was cleared by machete prior to transplantation. The resulting debris was left in place to protect sites from erosion. At site 1, because of the steep slope, the natural vegetation was left in strips to protect the soil from erosion. Sites 2, 1 and 3 were planted in July, September, and November of 1998, respectively.

Measurements of seedling performance

Four months after transplantation, the percentage of seedling survival was measured per species and site. The height (m) and basal diameter (cm) of each species was measured at 4, 11, and 18 mo after transplanting in the experimental sites. The relative growth rate (RGR) in height and basal diameter was estimated for plants growing in the three experimental plantations because RGR incorporates initial plant dimensions. RGR based on height or diameter was estimated using the following formula (Hunt 1978):

$$RGR=(\ln h_2-\ln h_1)/t_2-t_1$$

where h is height or diameter measured at times 1 and 2, and t_1 and t_2 are time in months.

To compare experimental plantations to on-farm plantations, annual increment (I) in height (m/yr) or diameter (cm/yr) were calculated per species and plantation using the formula:

$$I=h_1-h_2/t$$

where h is height or diameter measured at times 1 and 2, and t is time in years. We selected *Liquidambar* as a performance indicator of one species among the five plantation stands. It was selected for comparison between the experimental and on-farm plantations because it was present in the five sites, and it is a dominant tree species in the regional forests.

Statistical analyses were performed using the JMP software program (SAS Institute, Cary, NC 1997). Since the plant survival experiment ended before all individuals die, survivorship curves were analyzed as censored data (Pyke and Thompson 1986; SAS Institute, Cary, NC 1997). We used the product-limit (Kaplan-Meir) survival analysis, which is a nonparametric test for comparing the distribution of life-spans of groups; Wilcoxon statistics was used to test homogeneity between the groups. The response variables (height and diameter of species) among sites were analyzed by repeated-measures ANOVA; RGR was analyzed using two-way ANOVA. Once the ANOVA model was estimated, contrasts as a function of the least square means of the pertinent effect were used. Values of soil compaction were compared between each plantation and nearby forest fragment using two-sample t-test. Relationships between height and diameter of *Liquidambar* and overall plantation with age were assessed using regression analysis. All reported values are means $\pm$ one standard error.

Results

Vegetation structure and floristic composition

The five experimental sites had different disturbance histories, and consequently they differed in some soil characteristics, vegetation structure and floristic composition. In general, soils were acidic and had relatively high organic matter content. Site 1 had similar soil compaction level to the nearby forest. Sites 1 and 2 had better soil conditions than site 3 which had higher bulk density and soil compaction, and lower organic matter content. The on-farm plantation in sites 4 and 5 also had compacted soils, however, they had a higher percent of organic matter than the experimental plantations (Table 1).

Site 1 was in a state of arrested succession. After 10 y of abandonment, the tree stratum had not recovered. *Pteridium aquilinum* var. *arachnoideum* and *Rubus pringlei* were the dominant species. However, diversity was relatively high; we recorded 31 native species of herbs and shrubs, as well as seedlings of *Alnus jorullensis*, *Sambucus canadensis* and *Quercus* sp. Site 2 was very diverse with 47 species $<$ 2 m tall, mostly herbs and shrubs but also juveniles of seven tree species, and 11 woody species $>$ 2 m tall. The tree stratum had a density of 380 individuals/ha. Some individuals (*Quercus xalapensis*, *Q. germana*, *Carpinus caroliniana* and *Liquidambar styraciflua*) were remnant trees of the original forest. Secondary trees such as *Lippia myriocephala*, *Rapanea myricoides* and *Acacia pennatula* were also growing in this old field. In contrast, site 3 had only a layer of herbs, consisting mostly of the grasses *Paspalum conjugatum*, *Cynodon dactylon*, and *Cynodon plectostachyus*. The only trees were a few scattered individuals of *Acacia pennatula* (6 trees/ha).

Private plantations showed similar trends. At site 4, at 56 mo old, 14 woody plant species were growing, five that were planted originally (*Fraxinus uhdei* (640 trees/ha), *Liquidambar styraciflua* (340 trees/ha), *Juglans pyriformis* (100 trees/ha), *Mimosa scabrella* (80 trees/ha, a non-native tree), and *Cedrela odorata* (40 trees/ha)), and nine colonizers. Some spontaneous colonizers were native species such as *Clethra mexicana*, *Persea* sp., *Trema micrantha* and *Rapanea myricoides* which increased the density of the plantation to 1500 individuals/ha. The plantation in site 5, at 104 mo had 21 woody plant species, 14 species were planted, and seven species were colonizers. The density of woody plants increased to 2580 individuals/ha. Planted trees were *Cedrela odorata* (200 trees/ha), *Liquidambar styraciflua* (180 trees/ha), *Persea americana* (140 trees/ha), *Rhamnus capraefolia* (120 trees/ha), *Meliosma alba* (100 trees/ha), *Platanus mexicana* (40 trees/ha), *Leucaena leucocephala* (20 trees/ha), and fruit trees. Individuals of secondary tree species such as *Acacia pennatula*, *Rapanea myricoides* and *Lippia myriocephala* were colonizers, but some individuals were present prior to plantation establishment (landowner, pers. comm.).

Survival analysis

Survivorship curves of seedlings differed significantly among the study sites (Wilcoxon test, $X^2 = 960$, $p < 0.0001$; Figure 1). Site 2 had the highest seedling survival (82.2% ± 3.4) and site 3 had the lowest (22.2% ± 5.5). Survival also differed among species (Wilcoxon test, $X^2 = 67$, $p < 0.0001$). Mean percent survival was higher for *Juglans* (69.2% ± 5.8) and *Carpinus* (63.1% ± 8.4) than for *Liquidambar* (46.5% ± 7.8) and *Podocarpus* (44.0% ± 8.8).

Plant species survival varied significantly across study sites. At site 1, survival was significantly different among species (Wilcoxon test, $X^2 = 14.5$, $p = 0.002$). *Carpinus* was more successful than the other three species, which displayed a marked decrease in survival at the first census (Figure 1). At site 2, all the species had higher survivorship than *Liquidambar* (Wilcoxon test, $X^2 = 84$, $p < 0.0001$; Figure 1). At site 3, survival of *Juglans* (76.2% ± 4.2) and *Carpinus* (47.1% ± 4.9) was higher than for *Liquidambar* (38.7% ± 3.2) and *Podocarpus* (33.7% ± 4.1; Wilcoxon test, $X^2 = 104$, $p < 0.0001$). Percent survival of seedlings decreased sharply from the initial (92.9 % ± 1.9) to the last census (22.2% ± 5.5; Figure 1).

Height, diameter and relative growth rate

Overall tree height increased from 0.86 ± 0.03 m at 4 mo, to 0.90± 0.03 m at 11 mo and 1.09 ± 0.03 m at 18 mo of establishment. Mean heights differed among sites ($F = 28.4$, $p < 0.001$) and species ($F = 13.8$, $p = 0.003$). Plants at site 1 were shorter than plants growing at sites 2 and 3. *Carpinus* and *Liquidambar* were larger than *Juglans* and *Podocarpus* (Figure 2).

Basal diameter of plants increased from 0.85 ± 0.04 cm at 4 mo to 1.14 ± 0.04 cm at 11 mo and 1.50 ± 0.04 cm in mo 18. Plants growing at site 2 were significantly larger in mean diameters than plants at sites 3 and 1 ($F = 34.6$, $p <$

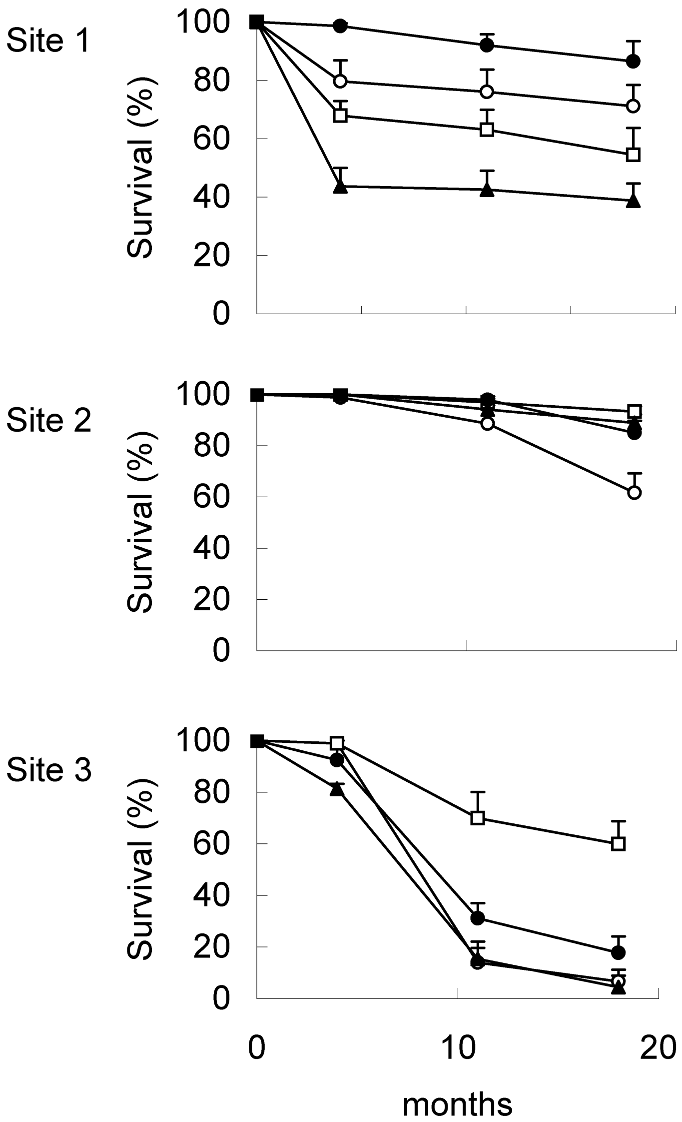

Figure 1. Survival percent to 18 mo of four native tree species in mixed plantations at three sites in central Veracruz, Mexico. ○ *Liquidambar styraciflua*, □ *Juglans pyriformis*, ▲ *Podocarpus matudae*, ● *Carpinus caroliniana*. Vertical lines are one standard error of the mean

0.001; Figure 3). *Juglans* reached the largest mean diameter followed by *Liquidambar* and *Carpinus*; *Podocarpus* had the smallest basal diameter ($F = 10.8$, $p = 0.003$).

Plants at site 3 had a lower RGR in height than plants at sites 1 and 2 ($F = 9.5$, $p < 0.001$; Table 2). Plants at site 2 had a higher RGR in diameter than plants at sites

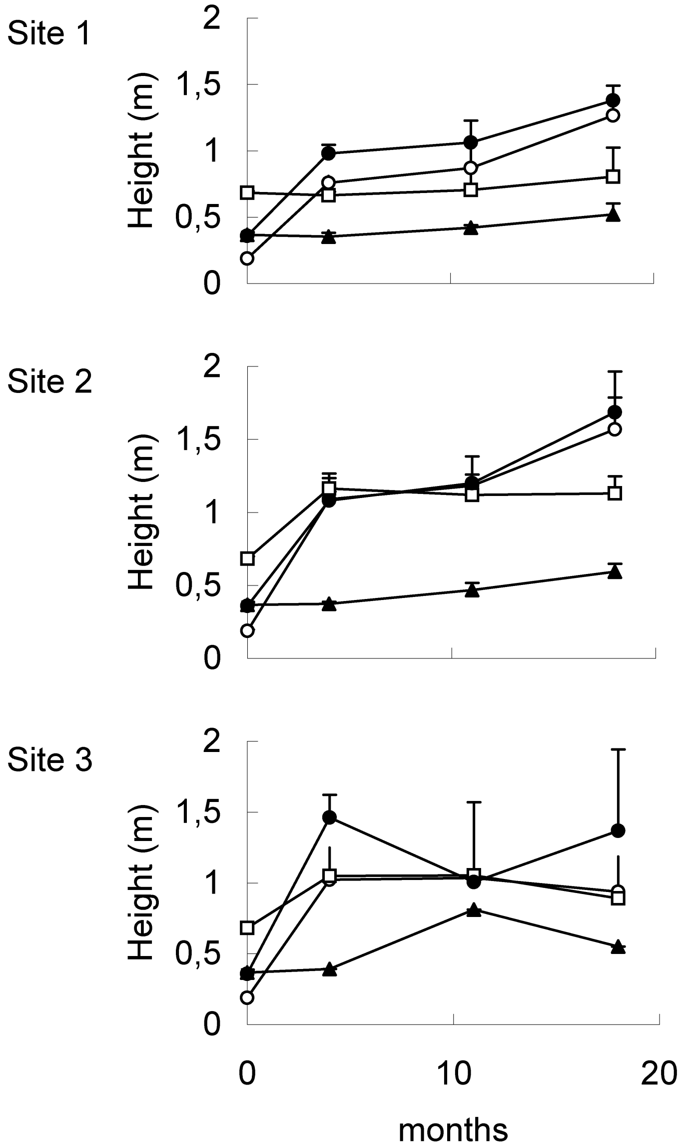

Figure 2. Mean height (m) to 18 mo of four native tree species in mixed plantations at three sites in central Veracruz, Mexico. ○ *Liquidambar styraciflua*, □ *Juglans pyriformis*, ▲ *Podocarpus matudae*, ● *Carpinus caroliniana*. Vertical lines are one standard error of the mean

1 and 3 ($F = 10.8$, $p < 0.001$; Table 2). RGR in height and diameter also differed among species ($F = 7.7$, $F = 6.1$, respectively, $p < 0.001$) because *Juglans* had a lower RGR in height than the other three species, and *Liquidambar* and *Podocarpus* had a higher diametric RGR than *Carpinus* and *Juglans* (Table 2).

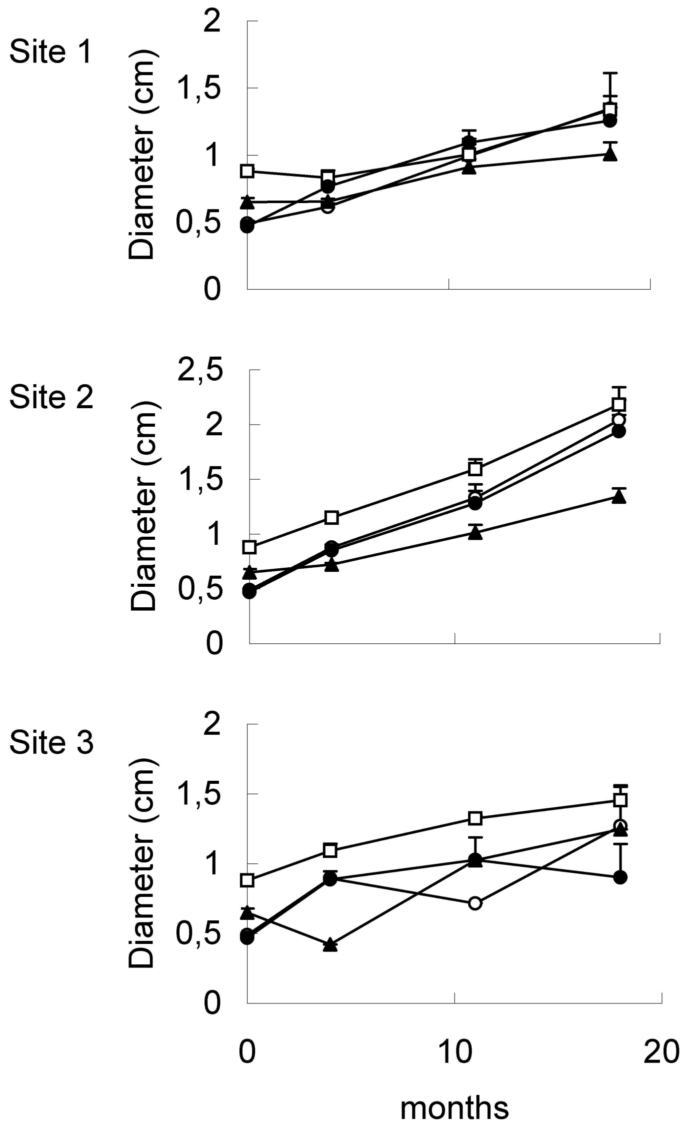

Figure 3. Mean basal diameter (cm) to 18 mo of four native tree species in mixed plantations at three sites in central Veracruz, Mexico. ○ *Liquidambar styraciflua*, □ *Juglans pyriformis*, ▲ *Podocarpus matudae*, ● *Carpinus caroliniana*. Vertical lines are one standard error of the mean

Annual Increment

Height and basal diameter were significantly and positively correlated in each experimental plantation except at site 3 (site 1 and 2, $r^2 = 0.35$ and 0.41, $F = 37.9$ and 47.9, respectively, $p < 0.001$). Site 3 was the only experimental plantation that

Table 2. Relative growth rate (RGR) in height (m/mo) and basal diameter (cm/mo) between 4 and 18 m after planted for *Liquidambar styraciflua*, *Juglans pyriformis*, *Podocarpus matudae*, and *Carpinus caroliniana* in the three experimental plantations in central Veracruz, Mexico. Values are the mean (± one standard error). Means in the same row or column accompanied by the same superscript do not differ significantly at alpha = 0.01.

Sites	1	2	3	Mean of all sites
RGR in height				
Liquidambar	0.034 (.006)	0.025 (.004)	−0.011 (.013)	0.024 (.005)^{a}
Juglans	0.005 (.007)	−0.005 (.001)	−0.018 (.010)	−0.006 (.005)^{b}
Podocarpus	0.029 (.005)	0.030 (.003)	0.024 (.000)	0.029 (.003)^{a}
Carpinus	0.026 (.003)	0.032 (.004)	−0.015 (.022)	0.021 (.006)^{a}
Mean	0.023 (.003)^{a}	0.020 (.003)^{a}	−0.013 (.008)^{b}	0.015 (.003)
RGR in basal diameter				
Liquidambar	0.053 (.004)	0.058 (.006)	0.022 (.017)	0.050 (.005)^{a}
Juglans	0.021 (.008)	0.042 (.005)	0.016 (.006)	0.026 (.004)^{b}
Podocarpus	0.025 (.005)	0.044 (.004)	0.078 (.078)	0.038 (.005)^{a}
Carpinus	0.036 (.007)	0.058 (.004)	0.003 (.017)	0.037 (.007)^{b}
Mean	0.034 (.004)^{b}	0.051 (.003)^{a}	0.017 (.008)^{b}	0.037 (.003)

showed a negative growth increment in height. Also, for each species, we found a positive correlation between height and basal diameter (*Liquidambar*, *Juglans*, *Podocarpus* and *Carpinus*, $r^2 = 0.73$, −0.38, 0.58 and 0.42, $F = 107.4$, 32.6, 50.2 and 31.6, respectively, $p < 0.001$).

Increments in height (m/yr) and diameter (cm/yr) of the overall five plantations were significantly correlated with the mean height ($r^2 = 0.78$, $F = 90.2$, $p < 0.001$) and diameter ($r^2 = 0.79$, $F = 96.7$, $p < 0.001$), respectively. We found that *Liquidambar* growth increment in height and diameter was higher than the average increments of all species over all plantations. When *Liquidambar* and overall plantation increments were fitted to a linear regression, we found a significant linear increase in height ($r^2 = 0.76$, $F = 58.1$, $p < 0.001$) and diameter with age ($r^2 = 0.79$, $F = 67.6$, $p < 0.001$; Figure 4).

Discussion

Plantations of native trees established on deforested lands had differential survival and growth apparently in response to differences in site conditions. The ecology of the selected species also plays a crucial role in the performance of the trees in each site. *Liquidambar* and *Carpinus* are light demanding and display the highest growth rates, *Juglans* is an intermediate in shade tolerance, and *Podocarpus* is the most shade tolerant and has the slowest growth of the selected species (Williams-Linera (1996), Challenger (1998), Vázquez-Yanes et al. (1999), GWL unpubl. data). Land use history and some soil characteristics are important factors to explain superior performance of the plantations in sites 2 and 1. There was a trend indicating that soil compaction in the fields previously dedicated to cattle pasture was higher than compaction in nearby forest fragments (Table 1). This trend of increased soil

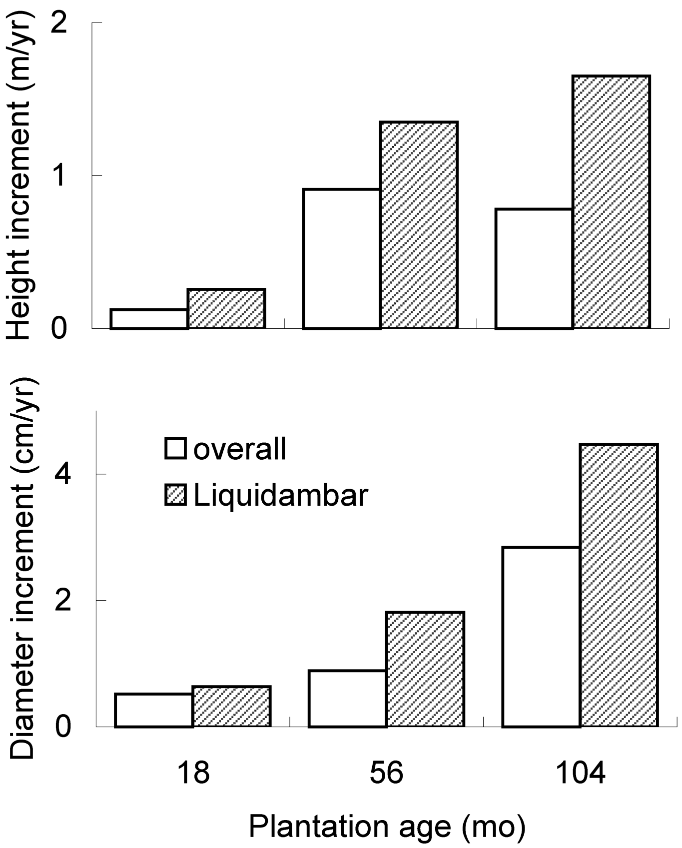

Figure 4. Mean height increment (m/yr), and mean basal diameter increment (cm/yr) for the overall plantations (open bars) and for *Liquidambar styraciflua* (shaded bars) at five plantation sites in central Veracruz, Mexico

compaction in the pasture compared to forest has been documented in other studies (e.g., Reiners et al. (1994), Holl and Quiros-Nietzen (1999)).

The plantation with the highest average survival and growth was site 2. This site represents an old field with advanced natural regeneration. The soil is significantly more compacted than the soil in the nearby forest; however, the presence of an open tree stratum ameliorates the microclimate, minimizing the effects of full irradiation. The microenvironment of this site may facilitate the establishment of newly planted trees since the presence of remnant trees or the maintenance of scattered shrubs or short trees can enhance growth of planted seedlings (Parrotta et al. 1997; Holl et al. 2000; Otsamo 2000b). The difference in survival between *Liquidambar* and the other three species at this site was due to root damage to *Liquidambar* by pocket gophers (*Orthogeomys* sp.). Nevertheless, mean seedling survival (82%) was within the survival range reported for fourteen native trees from a four-year old plantation at La Selva, Costa Rica (77%; Butterfield and Espinoza (1995)), and survival of three species during 19 mo in Kalimantan, Indonesia (71–97%; Otsamo (2000a)) and was higher than the survival of seedlings of nine tree species planted in abandoned pastures in Amazonia, where survival was less than 20% after two years (Nepstad et al. 1996).

Seedlings at site 1 also had good survival and relative growth. The high initial mortality may be related to bare root planting, however, this technique was satisfactory and it was the most practical since the location was remote. This site, which experienced no cattle trampling in the past, exhibited the same level of soil compaction as the contiguous forest fragment (Table 1), but had a very steep slope that prevented easy plantation establishment. To ensure soil protection and to prevent landslides, strips of *Pteridium aquilinum* and natural vegetation were left between rows of planted trees; weeding prevented any invasive growth of *Pteridium* until trees were taller than the fern. Species performance differed on these steep slopes with *Carpinus* and *Liquidambar* having higher survival than *Podocarpus* and *Juglans*. The former two species grow well in open sites and they have been observed in early successional sites (Challenger 1998; Vázquez-Yanes et al. 1999). However, *Podocarpus* is a shade tolerant and may require less exposed sites, and *Juglans* less pronounced slopes, probably because it is a difficult-to-root tree (RAP, pers. obs.).

Site 3, with the highest soil compaction and dominated by grasses, represented the most degraded site with the lowest tree survival and relative growth. In this site, *Juglans* survived well, but had the poorest performance in height growth because of stem dieback, although all seedlings resprouted in a few weeks (RAP, pers. obs). Additionally, seedling survival might have been affected because of late planting (onset of the relatively dry–cool season). Also, herbivory on leaves and buds by leaf cutter ants (*Atta* sp.; dry–cool season 1999) and grasshoppers (*Melanoplus* sp.; dry–warm season 1999) occurred twice during the study period, and this may also explain low survival rates. In site 3, grasses did not interfere with the growth of the experimental seedlings. Soil water content was higher in the pasture than in the nearby forests, although they were statistically similar (Table 1). Similar situations have been reported in other regions. In Paragominas, Brazil, seedlings of all tree species experienced severe herbivory by leaf cutter ants in abandoned pastures compared with low herbivory in mature forest and forest gaps (Nepstad et al. 1996). In a montane forest in Costa Rica, seedling growth in abandoned pastures was limited by seedling competition with pasture grasses, high light intensity, and rabbit herbivory (Holl and Quiros-Nietzen 1999; Holl et al. 2000). However, Aide and Cavelier (1994) found that in the Sierra Nevada de Santa Marta, Colombia, grasses did not inhibit the germination or growth of seedlings, that grasses had a positive effect on microclimate, and concluded that it is not necessary to eliminate the grasses in the most degraded areas to restore a forest habitat.

The three experimental sites also differed in degree of disturbance. Thus, in order to compare them to the older plantations started by landowners we used *Liquidambar*, which proved to be a good indicator of the performance of the five plantations. It had higher height and diameter increments than the mean of all species at each site. The annual increment in height, both for the whole plantations and for *Liquidambar* increased from the 18 mo old experimental plantations to the older sites 4 and 5. These increments were in the range of values reported for an 11-year-old mixed plantation in Heredia, Costa Rica (1.2 m/yr, Chaverri et al. (1997)) and above height increments of 60 cm/yr that Parkash (1999) estimated as increments desirable for young trees used on reforestation programs. The increase in diameter of the three experimental plantations, the older plantations, and of *Liquidambar* alone were all above the range of increments measured in a nearby mature cloud forest (0.29 cm/yr) and in a managed cloud forest (0.83 cm/yr) in the Botanical Garden, Xalapa, Veracruz, Mexico (Williams-Linera 1996), in a four-year old plantation of fourteen native species in La Selva, Costa Rica (1.7 cm/yr; Butterfield and Espinoza (1995)), and in a mixed 11-year old plantation in Heredia, Costa Rica (0.73 cm/yr; Chaverri et al. (1997)).

The presence of natural regeneration in the landowners plantations (56 mo and 104 mo) support the observations that native tree species plantations are encouraging the establishment of some TMCF species. The presence of secondary species such as *Lippia myriocephala* and *Rapanea myricoides* and primary species such as *Clethra mexicana*, *Crataegus mexicana* and *Persea americana* were recorded within the on-farm plantations. Several studies have documented the importance of plantations in promoting regional biodiversity (Parrotta 1992; Guariguata et al. 1995; Haggar et al. 1997).

In summary, *Carpinus and Liquidambar* might be suitable species for reforestation programs in cloud forests and, apparently, endure the bare root planting technique. *Podocarpus* performed well at site 2, and 76.2% of *Juglans* plants survived under the stressed conditions of site 3. *Juglans* could be used in degraded sites, but because badly degraded sites may be unsuitable for just native species, it may be necessary to try other maintenance treatments and incorporate other tree species in the plantations, even, using certain exotics as suggested by several authors (e.g., Brown and Lugo (1994), Lamb (1998)).

The five plantations differed in floristic composition, and land use history intensity; however, they represent the variety of situations that exist in the region. This is obvious but not trivial, we are looking for plantation design strategies incorporating actual cloud forest conditions. Some of the key elements of these strategies should include careful site evaluation, a respect for biotic diversity and local site variation (Brown and Lugo 1994). Species performance relative to nutrient conservation and productivity in order to conserve or replenish plantation soil fertility should also be considered (Parrotta 1992; Brown and Lugo 1994; Cuevas and Lugo 1998; Standley and Montagnini 1999). We learned from the five plantations that optimum conditions vary among native tree species, and need to be considered when they are used in a particular site. In addition, insect and small mammal herbivore damage may cause high mortality and therefore need special attention. Plantations of native trees in deforested areas are an important component of the whole conservation strategy of the TMCF in the region of Xalapa. Apart from the conservation of forest fragments, degraded areas also have to be rehabilitated and recovered for wood, non-timber products or to increase biodiversity. We believe that special emphasis should be placed on the use of native trees as they offer a premium on biodiversity conservation apart from any economic arguments.

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