PROVENANCE AND FAMILY PERFORMANCE OF *PINUS TECUNUMANII* AT 12 YEARS OF AGE IN THE CERRADO REGION OF BRAZIL

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ABSTRACT

Thirteen provenances and 73 open-pollinated families of *Pinus tecunumanii* Eguiluz and J. P. Perry from the highland areas in southern Mexico, Guatemala and Honduras, were established in two field trials near Brasilia in the cerrado region of Brazil. The trials were assessed at 12 years of age for productivity and quality traits. The three best provenances of *P. tecunumanii* for individual tree volume were San Jerónimo (0.22 m^3), La Soledad (0.20 m^3) and Montebello (0.20 m^3) and were superior to the local commercial control of *P. oocarpa* Schiede ex Schlecht. (0.17 m^3). The Central American provenances overall were more productive than the Mexican sources and had a lower incidence of forks (11% vs. 18%) and broken-tops (2% vs. 4%). Phenotypic correlations between height growth and forking percent and height growth and broken tops were unfavorable and significant. Individual tree heritability for volume was greater in the Central American provenances (0.43±0.12) than in the Mexican sources (0.22±0.08). The good survival and growth of *P. tecunumanii* combined with some of the lowest recorded rates of stem breakage in the tropics suggests that the species has great commercial value in the cerrado of Brazil.

Keywords: high elevation, provenance variation, genetic gain, heritability

INTRODUCTION

Most of central Brazil is a savanna called "cerrado" that comprises an area of approximately 204 million hectares or 25% of the Brazilian territory. The cerrado is found primarily in the states of Bahia, Goiás, Maranhão, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Piauí e Tocantins, and to a lesser extent in the states of Amazonas, Amapá, Pará, Rondônia, Roraima and São Paulo. The topography of the this region ranges from flat to low rolling hills which facilitates the use of mechanization for agricultural purposes. The soils in the cerrado are of ancient origin, are highly leached and most often belong to the Oxisol order. These are typically low in calcium, magnesium, potassium and sodium but have high aluminum contents and soil acidity (GOEDERT *et al.* 1980). Under natural conditions these soils are often infertile. The climate in the cerrado is mostly tropical. The average rainfall varies from 800 to 2000 mm per year but most normally ranges between 1100 and 1600 mm (LOPES & COX 1977).

When aforestation and reforestation activities began in central Brazil in the 1970s, there was little knowledge about what tree species should be used. Species, provenance, and progeny trials were initially established by the Forestry Research and Development Program (PRODEPEF) and subsequently by the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) using seeds collected by international agencies such as the Central America and Mexico Coniferous Resources Cooperative (CAMCORE), North Carolina State University, USA, and the Oxford Forestry Institute (OFI), University of Oxford, UK. Early pilot plantings indicated that both tropical pines and eucalypts survived well. However, when these studies became seven to eight years of age, the growth of the eucalypts began to stagnate but the pines continued to grow well through age 14 years, with survival unchanged (MOURA 1995). One of the most promising pines in the international series of trials was *Pinus tecunumanii* Eguiluz & J. P. Perry, a species native to the highlands of southern Mexico and Central America. It had superior height growth to *Pinus caribaea* var. *hondurensis* (Sénécl.) W. H . Barrett & Golfari and *Pinus oocarpa* Schiede ex Schlecht. in most provenances trial in the cerrados (MOURA *et al.* 1991, MOURA 1995). *P. tecunumanii* also exhibited excellent stem form, small branches and good self pruning ability.

Pinus tecunumanii is a closed-cone pine in the same taxonomic group as well known species like *P. radiata* D. Don and *P. patula* Schiede ex Schlecht. & Cham. It occurs from southern Mexico to central Nicaragua on relatively fertile soils in areas where rainfall often exceeds 1000 mm per year (DVORAK & DONAHUE 1992, DVORAK 1998). Two groups of *P. tecunumanii* are recognized in Mexico and Central America, those populations that grow at high elevation from approximately 1500 to 2900 m altitude and sources that occur at elevation from about 450 to 1500 m. This division between the two sub-populations has been made based on a combination of subtle morphological differences (DVORAK 1985), monoterpene differences (SQUILLACE & PERRY 1993) and unique RAPD molecular markers (FURMAN *et al.* 1997).

This paper reports on the growth performance and genetic parameters of *P. tecunumanii* in two 12 year-old provenance/progeny trials, established by EMBRAPA/CAMCORE in the cerrado of Brazil. The 13 provenances included in the studies come from the high elevation, subtropical areas of Mexico (Chiapas), Guatemala and Honduras, and most had never been tested before in Brazil. Genetic gains from family and within family selections are estimated and recommendations are made for future tree breeding programs in the cerrado.

Materials and methods

Seed collections were made in 13 provenances located above 1500 m altitude in Chiapas, Mexico, Guatemala, and Honduras by the CAMCORE Cooperative in 1983 (Table 1). The provenances included, San José, Las Piedrecitas, Chempil, Jitotol and Montebello (Chiapas, Mexico) San Jerónimo, San Lorenzo Km 33, Km 47, La Soledad and San Vicente, (Guatemala), and Las Trancas and Celaque (Honduras). Most of the provenances sampled can be clustered into distinct groups based on their geographic proximity to each other or similarities in the ecological zones that they inhabit (Figure 1). For example, San José, Las Piedrecitas and Chempil all occur in close proximity on the San Cristobal de las Casa plateau in central Chiapas. Jitotol, located approximately 65 km northwest of this cluster,

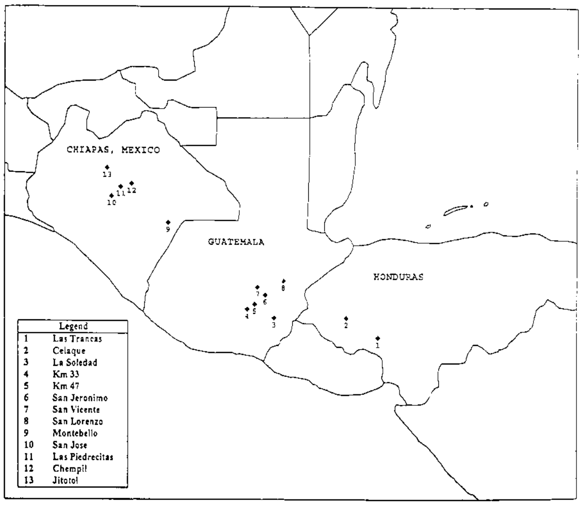

Figure 1. Location of the *Pinus tecunumanii* seed collection sites in Mexico and Central America used in the tests at Planaltina, Federal District, Brazil

Table 1. Provenances of *Pinus tecunumanii* included in the two CAMCORE genetic tests at Planaltina, Federal District, Brazil

Provenance	Country	Elevation (m)	Latitude	Annual rainfall (mm)
Las Trancas	Honduras	2130	14°07' N	1579
La Soledad	Guatemala	2427	14°31' N	1543
San Vicente	Guatemala	1945	15°05' N	1700
San Lorenzo	Guatemala	2000	15°05' N	1700
San Jerónimo	Guatemala	1735	15°03' N	1200
Km 47	Guatemala	2100	14°35' N	1543
Km 33	Guatemala	2100	14°35' N	1543
Celaque	Honduras	1785	14°33' N	1273
Chempil	Mexico	2120	16° 45' N	1146
Jitotol	Mexico	1705	17° 02' N	1701
Las Piedrecitas	Mexico	2430	16° 22' N	1252
Montebello	Mexico	1705	16° 06' N	1909
San José	Mexico	2322	16° 42' N	1252

Control lot 200: *P. tecunumanii* from San Jeronimo, Guatemala
Control lot 405: *P. oocarpa* from Agudos, Brazil

is an outlier because it occurs in a more tropical ecosystem at lower altitude (Table 1). Montebello, a Chiapas population that is located only a few kilometers from the Guatemalan frontier in the western foothills of the Sierra de Los Cuchumantanes, shares more climatic and edaphic similarities with provenances in the western mountains of Guatemala, than it does with populations in the San Cristobal highlands.

San Jerónimo, San Vicente and San Lorenzo all are found in mountains of the same geologic origin (eastern Sierra de Los Cuchumantanes and Sierra de Las Minas) that transect central Guatemala in a west to east direction. Provenances Km 33, Km 47 and La Soledad occur 65 km south of the Sierra de Las Minas in the departments of Guatemala and Jalapa, in an equally impressive but less extensive mountain chain. These three provenances are found within 40 km of each other.

The provenances of Celaque and Las Trancas, Honduras occur 80 km from each other in a series of mountain ranges in the southwestern part of the country. These are located approximately 150 and 230 km, respectively, from San Lorenzo, the easternmost Guatemalan source sampled in the study.

In each provenance, between 10 and 25 trees were selected based on volume and stem form. Some selected trees in old growth forest in places like San Jerónimo were 55 m tall and more than 80 cm diameter. Selection standards were reduced when the geographic dimensions of the stand were small in order to maintain a representative sample size for both gene conservation and genetic testing. Seeds were collected, kept separate by mother tree, and sent to North Carolina State University for distribution.

Seeds for eighteen provenance/progeny tests were sent to CAMCORE members in Brazil, Colombia and South Africa (DVORAK & SHAW 1992). Four tests were sent to EMBRAPA, two of which were established at Planaltina, Federal District, near Brasilia (latitude 15° 35' S, longitude 47° 42' W). The Planaltina site is located at 1100 m elevation and receives, on the average, 1550 mm of precipitation each year but with a well pronounced dry season of six months (Köppen Aw-rainy tropical). The soils are deep Oxisols, highly leached and relatively infertile.

The five Mexican provenances, represented by 38 open-pollinated families were placed in one test, and the eight Central American sources represented by 35 open-pollinated families were represented in the other. The tests were planted adjacent to each other in a compact family block design, with nine blocks and six trees row plots per family. Trees were established at 3 m by 3 m spacing following CAMCORE test guidelines. Three to eight families represented each provenance. Even though there were no open-pollinated families common to the two tests, two control lots were included in both field trials. One control lot (#200) was *P. tecunumanii* from a bulk seed collection of the best phenotypes at San Jerónimo, Guatemala made by the Banco de Semillas Forestales (BANSEFOR), the National Seed Bank, in 1982. This bulk collection included seeds from some of the same mother trees represented as individual families in the EMBRAPA/CAMCORE provenance/progeny test. The other control lot was a Brazilian source *P. oocarpa* (#405) from a seed stand owned by the Companhia Agro Florestal Monte Alegre (CAFMA), Agudos, São Paulo. The *P. oocarpa* seed stand was derived from seed collected in Honduras in the early 1970s. Each test was surrounded by two border rows of *P. oocarpa.*

At the time of field planting and 90 days after establishment, each seedling received a mixture of 100 g super phosphate, 40 g of KCl, 3 g of Boron and 2 g of $ZnSO_3$. Fifty percent of this mixture was used at each application.

A number of measurements were taken in the study from 2 to 12 years of age. Only 12 year results will be reported here. The traits measured at 12 years of age were survival, height, diameter at breast height (dbh), volume, stem form, branch diameter, broken-top, and forking. Individual tree stem volume over bark was calculated using a formula for juvenile pines proposed by LADRACH (1986):

$$v = 0.00003\, d^2 h$$

where v is volume in m³, d is diameter at breast height in cm and h is total tree height in m.

Branch diameter and stem form were assessed using a subjective 1 to 3 scale, with 1 being the poorest and 3 the best (BALOCCHI 1990). A "yes" or "no" assessment was used to assess the incidence of broken main stems and forking.

The two trials were analyzed separately because of their different provenance and family composition. The statistical model used was:

$$y_{ijkm} = \mu + r_i + p_j + rp_{ij} + f(p)_{k(j)} + e_{ijkm}$$

where: μ = grand mean; r_i = (i = 1..r) effect of the ith block; p_j = (j = 1...p) effect of the jth provenance; rp_{ij} = the interaction of the i^{th} block and the j^{th} provenance; $f(p)_{k(j)}$ = (k = 1..k) the k^{th} family effect within each j^{th} provenance: $rf(p)_{ik(j)}$ = the interaction of the i^{th} block and the kth family within provenance; e_{ijkm} = the interaction of the mth tree in the i^{th} block and the k^{th} family in the j^{th} provenance.

Individual tree values were used in the analyses for all traits except for survival, broken tops and forking.

The data for survival, broken tops and forking were transformed using arcsine-square roots prior to conducting the analyses of variance (STEEL & TORRIE 1980). The analyses of these 3 traits were conducted on plot means thus *rf(p)* term was not included in the model and the error term is e_{ijk} which is the interaction of the *i*th block and the k^{th} family in the j^{th} provenance.

Provenances effects were considered fixed and all other effects were considered random.

The analyses of variance (ANOVA) for all traits were conducted with the Statistical Analysis System (SAS) Generalized Linear Model (GLM) procedure type III sums of square. Waller (SAS 1990). Duncan multiple range tests were used to determine if differences among provenances and families were significant.

Approximate F tests were made using the procedure proposed by SATTERTHWAITE (1946).

Variance components were estimated by the VARCOMP procedure (SAS 1990). In the model, the provenance effect was considered fixed. Individual, family and within family heritability for all traits were calculated in the usual way except that the coefficient of relationship was assumed to be 0.33 because some degree of inbreeding (about 10 %) was thought to be occurring in the relatively small populations from which the open-pollinated seed was collected in Central America and Mexico (VÁSQUEZ & DVORAK 1996). Increasing the coefficient of relationship from 0.25 to 0.33 made heritability estimates more conservative (SQUILLACE 1974).

The formula used to estimate heritability were:
Individual tree heritability

$$h_i^2 = (3*\sigma^2_{f(p)})/(\sigma^2_{f(p)} + \sigma^2_{rf(p)} + \sigma^2)$$

Family heritability

$$h_f^2 = \sigma^2_{f(p)}/(\sigma^2_{f(p)} + \sigma^2_{rf(p)}/r + \sigma^2/nr)$$

Within family heritability

$$h_w^2 = (2*\sigma^2_{f(p)})/(\sigma^2_{rf(p)} + \sigma^2)$$

where: $\sigma^2_{f(p)}$ = components of variance for families within provenances; $\sigma^2_{rf(p)}$ = components of variance for block*family within provenances; σ^2 = error component of variance; n = number of trees in plot; *r* = number of blocks.

Heritability calculations for survival, broken top, and forking based on plot means was calculated according to the following model:

Family heritability

$$h^2_{f(p)} = (\sigma^2_{f(p)})/(\sigma^2_{f(p)} + \sigma^2/r)$$

where: $\sigma^2_{f(p)}$ = components of variance for families within provenances; σ^2 = error component of variance; *r* = number of replications.

Phenotypic correlations between growth and quality traits were calculated using Pearson's product-moment method (SAS 1990). Correlation analyses were based on family and provenance means.

The best trees in each study were selected based on volume using an index that combines the individual phenotypic value with the family performance and weights them based on family and within-family heritability (BALOCCHI 1990). The index has the form of:

$$I = \mu + (h_f^2 P_f + h_w^2 P_w)$$

where: μ = provenance mean; *I* = index value; h^2_f = family mean heritability; P_f = deviation of a family mean from the provenance mean; h^2_w = within-family heritability, P_w = deviation of an individual value from the family mean.

Independent culling levels were set for stem straightness and branch diameter and trees with forks, and other defects were deleted from consideration.

RESULTS

Central American sources

Survival of the high elevation populations of *P. tecunumanii* in the cerrado was 84% vs. 87% for the *P. oocarpa* control. Provenance means for survival were significantly different and varied from 72% for Km 47 to 89% for San Jerónimo (Table 2). Survival at the family level ranged from 56% to 94%.

Average height, dbh and volume for the Central American provenances of *P. tecunumanii* were 15.4 m, 19.7 cm and 0.19 m^3, respectively, and compared favorably with of *P. oocarpa* (Table 2). Provenance and family differences were highly significant for the traits of height, dbh, stem volume and branch diameter. (Table 2). The most productive provenances of *P. tecunumanii* from Central America were San Jerónimo and La Soledad, Guatemala. Growth differences between the best and worst provenance were 1.7 m for height, 1.8 cm for dbh and 0.05 m^3 for volume. The individual tree volume of the *P. tecunumanii* control lot from San Jerónimo was the same as that for the individual families from San Jerónimo, as expected. Using seeds from the best provenance, San Jerónimo, would

Table 2. Provenance trials means of *P. tecunumanii* from Central America, assessed for height, diameter breast height (dbh), volume, survival, stem form, branch diameter, forking and broken tops at Planaltina, Federal District, Brazil at 12 years of age.

Provenance	Height[a]	Dbh[a]	Volume[a]	Survival[a]	Stem form[a]	Branch diameter[a]	Forking[b]	Broken top[b]
Celaque	16.0 ab	19.4b	0.19bcd	88.4a	1.3cbd	2.2cd	17.9	1.0
San Jerónimo	15.6bcd	21.0a	0.22a	88.9a	1.3cbd	2.0ef	8.6	1.4
San Vicente	15.5cd	19.6b	0.19cd	84.3bac	1.2cd	2.2cde	8.3	1.3
San Lorenzo	15. 5cd	19.5b	0.19cd	80.2bdac	1.4cb	2.2cd	12.5	1.7
La Soledad	15.4d	20.2ab	0.20abc	86.1ba	1.3cbd	1.9f	13.4	0.9
Las Trancas	15.3d	19.6b	0.19cd	88.0a	1.2cd	2.2cde	14.5	0.8
Km 33	15.0e	19.2bc	0.17de	79.6bdac	1.2d	2.2cb	3.5	2.4
Km 47	14.3e	19.2bc	0.17de	71.6d	1.5a	2.1cde	11.5	4.0
Control 200	15.8bc	20.9a	0.22ab	80.1bdac	1.4b	2.1de	8.7	0.0
Control 405	16.3a	19.1bc	0.19cd	87.0ba	1.2d	2.6a	12.2	0.0
Test mean[c]	15.4	19.7	0.19	84.0	1.3	2.1	11.2	1.5

[a] Different letters indicate significance at 0.05 probability level
[b] No significant differences among provenances
[c] The control lots are not included in the test mean

result in a volume gain of 22% over material from the worst populations, Km 33 or Km 47. The best open-pollinated family produced two times more volume than the worst family. The best individual tree volume was 0.41 m^3 and the worst was 0.11 m^3 in the test out of a total of 2,038 trees.

The overall mean for stem form and branch diameter was 1.3 and 2.3 respectively vs. 1.2 and 2.6 for the *P. oocarpa* control (Table 2). Several of the fastest growing provenances also had the best stem form. Las Trancas and Km 33 had below average stem form. The best growing provenances, San Jerónimo and La Soledad, had the largest branch diameters.

Forking percents for *P. tecunumanii* averaged 11% vs. 12% for *P. oocarpa.*. Provenance mean values ranged from 4% to 18% but were not significant in the analysis. This may be due to the low frequency of the binomial trait and the unbalanced nature of the data set. Important significant differences in forking were found at the family level where values ranged from 2 to 35%. Only 2% of the trees in the test had broken tops. Provenance and family effects for broken-tops were not significant.

Individual tree heritability (h^2_i) for growth traits ranged from 0.38 to 0.43 and family heritability (h^2_f) varied from 0.82 to 0.86. Stem form and branch diameter had individual tree heritability of 0.14 and 0.28, respectively (Table 3).

Selecting the best 35 top ranked trees for volume in the test for incorporation into a production seed orchard would result in an estimated genetic gain of 70% at 12 years of age in the next generation. If one chooses the best 35 trees for volume, but first eliminates all trees with poor branching and stem form (score of 1) and all trees with forks and broken tops, the estimated gain in volume in the next generation would be 62%.

Table 3. Individual tree heritability (h^2_i) and standard error (SE), within-family heritability (h^2_w), and family heritability (h^2_f) for volume of *P. tecunumanii* from Central America, assessed at Planaltina, Federal District, Brazil at 12 years of age.

Trait	h^2_i ± s.e.	h^2_w	h^2_f
Height	0.39±0.11	0.31	0.82
Dbh	0.38±0.11	0.30	0.85
Volume	0.43±0.12	0.33	0.86
Stem form	0.14±0.05	0.10	0.60
Branch diameter	0.28±0.08	0.21	0.79
Forking	–	–	0.67

Mexican sources

Mean survival percent of the Mexican sources of *P. tecunumanii* was 84-%, the same as for the Central American populations. There were no significant survival differences between provenances of the Mexican sources. Family mean survival ranged from 74% to 93% (Table 4).

Provenance and family means for Mexican sources were highly significant for height, dbh, stem volume and branch diameter. Forking was significant for provenances but not for families within provenances. Differences in broken-top means were not significant

Table 4. Provenance trial means of *P. tecunumanii* from Mexico, assessed for height, diameter breast height (dbh), volume, survival, stem form, branch diameter, forking and broken-tops at Planaltina, Federal District, Brazil at 12 years of age.

Provenance	Height[a]	Dbh[a]	Volume[a]	Survival	Stem form[a]	Branch diameter[a]	Forking[b]	Broken-top[b]
Montebello	6.0a	19.8b	0.20a	85.4	1.3bc	2.3b	11.8b	3.1
Chempil	14.8c	19.2bc	0.18b	83.3	1.6a	2.0c	18.8ab	3.8
Jitotol	14.2d	18.8cd	0.16c	81.6	1.0d	2.0c	10.5b	3.9
San José	13.4e	17.9d	0.14d	83.8	1.2c	1.9cd	26.5a	5.4
Las Piedrecitas	12.8f	17.0e	0.12e	82.8	1.2c	1.9cd	19.6ab	4.6
Control 200	15.4b	21.2a	0.22a	80.2	1.2bc	1.7d	11.2b	2.0
Control 405	14.8c	17.0e	0.14cd	87.0	1.4b	2.5a	10.3b	0.0
Test mean[c]	14.3	18.6	0.16	83.5	1.3	2.0	17.7	4.2

[a] Different letters indicate significance at 0.05 probability level.
[b] No significant differences among provenances
[c] The control lots are not included in the test mean.

either for provenances or families within provenances.

Height, dbh and stem volume for the Mexican provenances of *P. tecunumanii* were 14.3 m, 18.6 cm and 0.16 m^3, respectively (Table 4). The overall volume production of the Mexican sources was approximately 18% less than the Central American sources. The lower productivity of the Mexican sources was due mainly to poorer performance of the provenances from the San Critstobal de las Casas plateau, especially San José and Las Piedrecitas. Montebello, from the western foothills of the Sierra de Los Chumunatanes was the best source from Mexico. It was taller than the excellent Guatemalan control lot of *P. tecunumanii* from San Jerónimo, but had smaller diameter growth and therefore had 10% less volume, overall. Differences between the best and worst provenance of *P. tecunumanii* in Chiapas, Mexico were 3.2 m for height, 2.7 cm for dbh and 0.07 m^3 for stem volume. Individual tree volume varied from 0.09 m^3 to 0.29 m^3 in a population of 1,693 trees. The local *P. oocarpa* control ranked below Montebello in volume production (Table 4).

The overall mean for stem form and branch diameter in the Mexican populations was 1.3 and 2.0 respectively (Table 4). There was no great difference between Mexican and Central American sources for these traits. Chempil had the best stem form and Montebello the best branching habit of the *P. tecunumanii* populations. As found in the test of Central American sources, the *P. oocarpa* control has finer, smaller branching patterns than *P. tecunumanii*. The San Jerónimo *P. tecunumanii* control had proportionally larger number of trees with thicker branches than the provenances from Mexico.

The mean percentage of forked trees in the test was 18%, 7% higher than recorded for trees of Central American sources. The provenance means for forking varied significantly from 10 to 27% with those sources from the highest altitudes in Chiapas forking more than those from lower elevation (Table 4). The San José and Las Piedrecitas provenances had significantly higher percentage of forked trees than the other provenances. The two controls had mean forking percents well below the trial average.

The percentage of broken-top trees in the trial of Mexican sources was 4.0% and not much different than provenances in Guatemala and Honduras. Provenance and family differences in broken top percent were not significant (Table 4).

Individual tree heritability (h^2_i) for growth traits ranged from 0.20 to 0.22 (Table 5), approximately half that found for trees in the Central American provenances (Table 3). Individual tree heritability for stem form in the Mexican populations was 0.14 and similar to that found in the Central American populations. The individual tree heritability for branch diameter was 50% less in the Mexican populations than in the

Table 5. Individual tree heritability (h^2_i) and standard error (SE), within-family heritability (h^2_w) and family heritability (h^2_f) for volume of *P. tecunumanii* from Mexico, growing in Planaltina, Federal District, Brazil at 12 years of age.

Trait	h^2_i ± s.e.	h^2_w	h^2_f
Height	0.22±0.09	0.16	0.67
Dbh	0.20±0.07	0.15	0.77
Volume	0.22±0.08	0.17	0.77
Stem form	0.14±0.07	0.10	0.61
Branch diameter	0.14±0.06	0.10	0.64
Forking	–	–	0.18

Table 6. Pearson's product-moment correlation for provenance means for height, diameter at breast height, (dbh), volume, forking, broken-top, branch diameter, and stem with latitude, altitude and rainfall of seed collection sites for Mexican and Central American sources of *P. tecunumanii* at Planaltina, Federal District, Brazil, at 12 years of age.

	Height	Dbh	Branch diameter	Forking	Broken-top
Latitude	–0.52ns	–0.55ns	–0.40ns	0.45ns	0.81***
Altitude	–0.59*	–0.49ns	–0.62*	0.45ns	0.08ns
Rainfall	0.45ns	0.37ns	0.55ns	–0.60*	–0.17ns
Height		0.86***	0.61*	–0.44ns	–0.74**
Dbh			0.33ns	–0.57*	–0.66*
Branch diameter				–0.52ns	–0.36ns
Forking					0.33ns

* $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$;

Table 7. Pearson's product-moment correlations for family means of Central American sources of *P. tecunumanii*, assessed for height, diameter at breast height, (dbh), volume, forking, broken-top, branch diameter, and stem form at Planaltina, Federal District, Brazil, at 12 yearas of age.

	Dbh	Volume	Stem form	Branch diameter	Forking	Broken-top
Height	0.66***	0.78***	0.01ns	–0.37ns	–0.01ns	–0.24ns
Dbh		0.98***	0.00ns	–0.68***	–0.02ns	–0.32ns
Stem form				0.16ns	0.28ns	0.18ns
Branch diameter					0.03ns	0.03ns
Forking						0.30ns

* $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$;

Central American ones (Table 3 and 5).

Selecting the best 35 top-ranked trees for volume in the test for the production orchard would result in a estimated genetic gain of 57%. Selecting on volume but eliminating all the defective and very crooked trees out of the population (score of 1) estimated gain in volume would be 45%.

Correlation results for the Central American and Mexican sources

Phenotypic correlations between latitude, altitude, rainfall growth and quality traits at 12 years of age with provenance means of the Central American and Mexican sources combined are presented in Table 6. There was a significant negative correlation ($r = -0.59$) between provenance height growth in the cerrado and altitude of the collection site in Mexico and Central America. The provenance mean for branching was significantly correlated to provenance height (r = 0.61), tall trees produced branches with large diameter; and was significantly negatively correlated to the elevation of the collection site (r = –0.62). Provenances from higher altitudes produced trees with smaller branch diameters than provenances from lower altitudes. Most interestingly, there was a non-significant correlation or a negative correlation between branch size and the degree of broken tops. There was a significant negative correlation between provenance mean height and diameter and the percentage of broken tops. There was significant positive correlation between percent broken-top means and latitude primarily due to the above average stem breakage of the provenances from the San Cristobal plateau.

Phenotypic correlation of family means between growth traits and quality traits at 12 years of age are presented in Tables 7 and 8 for the two sub-populations. For the Mexican sources, there was a weak to moderate (but statistically significant) correlation between height growth and stem form, and height and branch diameter. In the Central American sources there was a moderately strong positive correlation ($r = 0.68$) between dbh and branch diameter.

DISCUSSION

With the possible exception of the plateau regions of Malawi, the central cerrado of Brazil offers the best

Table 8. Pearson's product-moment correlation for family means of Mexican sources of *P. tecunumanii*, assessed for height, diameter at breast height, (dbh), volume, forking, broken-top, branch diameter, and stem form at Planaltina, Federal District, Brazil, at 12 yearas of age.

	Dbh	Volume	Stem form	Branch diameter	Forking	Broken-top
Height	0.80***	0.91***	0.40ns	0.39*	−0.29ns	−0.08ns
Dbh		0.96***	0.27ns	−0.01ns	−0.30ns	0.12s
Stem form				0.18ns	0.20ns	−0.06ns
Branch diameter					−0.15ns	0.41*

* $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$;

possible latitude and altitude match with Central America to successfully grow *P. tecunumanii*. The growth of the high elevation sources of *P. tecunumanii* is not as fast in the cerrado as in the mountains of Colombia (OSORIO & DVORAK 1993) or in the highlands of eastern South Africa (DVORAK & SHAW 1992) because of the relatively infertile soils and long dry seasons. However, the growth of the species in the cerrado is superior to locally improved *P. oocarpa*, and in comparison to other sites where *P. tecunumanii* has been tested, has one of the lowest incidence of top breakage (< 5%) anywhere in the tropics or subtropics (DVORAK *et al.* 1993, PARFITT & VAN DER SIJDE 1993, PARFITT 1996).

Results from this study suggest that future sources of seeds for the high elevation provenances of *P. tecunumanii* in the cerrado should come primarily from Guatemala, particularly San Jerónimo and La Soledad, and the extreme southeastern section of Mexico near Montebello. Provenances from the San Cristobal de las Casas plateau in central Chiapas should be avoided, especially the sources San José and Las Piedrecitas.

The provenance performance for volume in this series of 18 tests in Brazil, Colombia, and South Africa is remarkably similar across sites (OSORIO & DVORAK 1993, DVORAK & SHAW 1992). San Jerónimo and Montebello were the most productive sources while others like Km 33, Km 47, Las Piedrecitas and San José performed poorly. The poor performance of provenances like Las Piedrecitas and San José reflects poor adaptation to the cerrado. However the poor performance of Km 33, Km 47 and San Lorenzo may be due to inbreeding effects. These three provenances in Guatemala are all less than five hectares in size and may contain as few as 40 mature trees. Efforts need to be made to include at least several trees from these provenances in the *P. tecunumanii* breeding population for further testing.

Estimates of individual tree heritabilities for volume in these studies in Brazil were of the same magnitude as those found for sister trials in Colombia by OSORIO & DVORAK (1993). Even though we report on the estimated gains from the selection of the best 35 trees in each of these tests at Planaltina, in actuality a combined selection index has been generated by CAMCORE that includes data from nearly 50 *P. tecunumanii* tests of high elevation sources established throughout the tropics and subtropics including the results from the EMBRAPA tests at Planaltina (Gary Hodge, CAMCORE, North Carolina State University, pers. comm.). The genetic correlations were of sufficient magnitude from one region to another to make marginal gains from exchange of genetic material among cooperative members in different countries (HODGE 1996). The future breeding base of *P. tecunumanii* from high elevations for the cerrado and EMBRAPA will therefore not only come from the several trials reported on in this paper, but from testing programs of CAMCORE members in places like Colombia, South Africa, and Zimbabwe. At present, CAMCORE has sampled 31 provenances and 756 mother trees of *P. tecunumanii* from high elevation sources in Mexico, Guatemala, Honduras, El Salvador and Nicaragua (DVORAK & DONAHUE 1992).

This study also supports the findings of others that growth rate and the percentage of stem breakage in *P. tecunumanii* is not positively correlated. Furthermore, the fact that stem breakage was low across all provenances and families would suggest that environmental conditions may be of more importance as a factor in determining the incidence of the problem than was originally thought.

There are still several research questions that need to be addressed as large scale operational plantings of *P. tecunumanii* develop in the cerrado. First, what are the nutritional requirements of *P. tecunumanii* in the cerrado and what would be the response to fertilization? Second, are the high elevation sources of San Jerónimo and Montebello better adapted to the region than the very promising low elevation sources from Belize, Honduras and Nicaragua, like Mountain Pine Ridge, Villa Santa and Yucul? Is the wood quality of *P.*

tecunumanii from both low and high elevations the same when planted in the cerrado? Will the low and high elevation sub-population produce good seed yields in the cerrado? Orchards may need to be moved to coastal Brazil where seed production is known to be better (DVORAK & LAMBETH 1992). Finally, will hybrids between *P. tecunumanii* and *P. caribaea* var. *hondurensis* or *P. oocarpa* show hybrid vigor over parental types when established in the marginally fertile soils of the cerrado?

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