
Volume 253, issues 1–3, 15 December 2007
Completing this volume
ISSN 0378-1127
ELSEVIER
Forest Ecology and Management

Available online at www.sciencedirect.com
ScienceDirect
Forest Ecology and Management 253 (2007) 81–88
Forest Ecology and Management
www.elsevier.com/locate/foreco

# Growth and frost damage variation among *Pinus pseudostrobus*, *P. montezumae* and *P. hartwegii* tested in Michoacán, México

Héctor Viveros-Viveros [a,1], Cuauhtémoc Sáenz-Romero [b,*],
Javier López-Upton [a,1], J. Jesús Vargas-Hernández [a,1]

[a] *Programa Forestal, Colegio de Postgraduados, Km 36.5 Carr, México-Texcoco, Montecillo, Edo. de México 56230, Mexico*
[b] *Instituto de Investigaciones Agropecuarias y Forestales (IIAF), Universidad Michoacana de San Nicolás de Hidalgo (UMSNH), Km 9.5 Carr., Morelia-Zinapecuaro, Tarímabaro, Michoacán 58880, Mexico*

Received 28 February 2007; received in revised form 5 July 2007; accepted 5 July 2007

## Abstract

To study the variation in growth traits, survival, and frost damage between four taxa, *Pinus pseudostrobus* typical (represented by four provenances) and its variety *P. pseudostrobus* var. *apulcensis* (two provenances), *Pinus montezumae* (two provenances) and *Pinus hartwegii* (one provenance), seeds of stands of natural distribution were obtained in the States of Michoacán, Puebla, Hidalgo and Veracruz, México. Provenances were evaluated at two field sites located in forests of the Native Indian Community of Nuevo San Juan Parangaricutiro, Michoacán, at contrasting altitudes of 2200 and 2800 m. Evaluations made when seedlings were between 15 and 27 months old, indicate that there were large differences in initial growth and in frost damage between the taxa: typical *P. pseudostrobus* was the species with the largest growth although also the one of the largest percentage of frost damage; *P. pseudostrobus* var. *apulcensis* shows both intermediate total height and frost damage with respect to typical variety and to *P. montezumae* and *P. hartwegii*. Height growth of *P. montezumae* and *P. hartwegii* was lower than the growth of typical *P. pseudostrobus* and the *apulcensis* variety, although they presented the lowest percentage of frost damages. In order to reforest sites at Purépecha Plateau in Michoacán, it is suggested to use typical *P. pseudostrobus* on sites relatively free from frost occurrence, and to use *P. montezumae* on sites with frost occurrence. It is not recommendable to use *P. pseudostrobus* var. *apulcensis* (susceptible to frost occurrence and not having the best growth rate) or *P. hartwegii* (with the lowest survival rate). *P. pseudostrobus* var. *apulcensis* is a distinguishable taxon of *P. pseudostrobus*, due to its growth characteristics, which support the taxonomic classification according to some authors.

*Keywords:* Provenances; Height growth; Frost damage; Survival; *Pinus pseudostrobus*; *Pinus pseudostrobus* var. *apulcensis*; *Pinus montezumae*; *Pinus hartwegii*

## 1. Introduction

Frost damage is one of the main causes of seedling mortality in restoration ecology reforestation made in México (Sáenz-Romero et al., 2003; Bello-Lara and Cibrián-Tovar, 2000). Pine seedling mortality after 1 year of plantation has an average of 62% in the State of Michoacán, western México, and frost damage causes 14% of it; the combined effect of inadequate species selection, drought stress and frost damage causes 46% of mortality (Sáenz-Romero and Lindig-Cisneros, 2004). Frost damage also causes growth reduction, loss of stem straightness, and increases susceptibility to fungi and other pathogen infections (Alden and Hermann, 1971; Anekonda and Adams, 2000). Thus, the selection of appropriate species and provenances adapted to frost occurrence is a relevant factor to increase seedling survival and growth in reforestation programs. However, it is necessary to select species and provenances adapted to the plantation sites finding an appropriate balance between growth potential and frost resistance, because it has been demonstrated that provenances with greater frost resistance also have less growth potential (Rehfeldt, 1983, 1985; Jonsson et al., 1986).

*Pinus pseudostrobus* Lindl., *Pinus montezumae* Lamb. and *Pinus hartwegii* Lindl. are three ecologically and economically very important species in the Neovolcanic Axis of central México, due to their relatively large distribution and extended

---

[*] Corresponding author. Tel.: +52 443 295 8323; fax: +52 443 295 8324.
*E-mail addresses:* hectorvv@colpos.mx (H. Viveros-Viveros), csaenz@umich.mx (C. Sáenz-Romero), uptonj@colpos.mx (J. López-Upton), vargashj@colpos.mx (J.J. Vargas-Hernández).
[1] Tel.: +52 595 952 0246.

0378-1127/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2007.07.005

use for saw timber, cellulose and fire-wood (Stead, 1983; Perry, 1991). Although the tree species are phylogenetically closely related (Stead, 1983; Stead and Styles, 1984; Favela, 1991), they have evolved with different characteristics for adaptation to the different environments in which they naturally grow. *P. pseudostrobus* is the one of the three species that grows at lower altitudes and has larger growth potential. Its variety *P. pseudostrobus* var. *apulcensis* grows at lower elevations and dryer sites than typical *P. pseudostrobus* (Perry, 1991). In contrast, *P. hartwegii* is the pine that grows in México at the highest altitudes but also has a reduced growth potential. *P. montezumae* has growth potential and intermediate altitudinal distribution regarding the other two species (Perry, 1991; Farjon and Styles, 1997). For example, in Nuevo San Juan Parangaricutiro–Pico de Tancítaro region, at the Purepecha Plateau of Michoacán, México, *P. pseudostrobus* distributes between 2100 and 2800 m altitude (Sáenz-Romero et al., 2005), *P. montezumae* between 2300 and 3000 m, and *P. hartwegii* between 3000 and 3600 m (Niniz-Romero, 2006).

Note that in an altitudinal interval of only 1000 m (*e.g.* 2100–3100 m) it is possible to find at least those three species in the same region (in fact, several more distribute naturally in the same region: *P. devoniana*, *P. leiophylla* and *P. ayacahuite* distribute altitudinally). This makes the high species diversity evident that characterizes México, regarding *Pine* species, and the high degree of adaptational specialization of such species. It also contrasts with other latitudes northwards, like the Rockies Mountains, USA, where in a similar altitudinal range of 1000 m mostly provenances of the same species are found, like *Pinus contorta* (Rehfeldt, 1988) and *P. ponderosae* (Rehfeldt, 1991).

It would be expected that the altitudinal distribution of the three species would parallel an altitudinal pattern of adaptation to frost, where *P. pseudostrobus* were the most susceptible to frost damage, and *P. hartwegii* the most resistant, and *P. montezumae* had an intermediate resistance.

*P. montezumae* and *P. hartwegii* show grass stage during their early years of growth. It has been argued that grass stage is an adaptation both to occurrence of frosts and to wild fires (Perry, 1991; Rodríguez-Trejo and Fulé, 2003). *P. pseudostrobus* does not present grass stage.

The taxonomic existence of *P. pseudostrobus* var. *apulcensis* as distinguishable variety of typical *P. pseudostrobus* is supported by Martínez (1948) and Perry (1991), but is not recognized by Farjon and Styles (1997). Beyond the taxonomic discussion, it would be relevant to know if both putative varieties (typical and *apulcensis*) had different adaptational characteristics. If so, the recognition of such varieties would have management implications, in order to prevent plantation of one or the other variety in sites to which they would not be adapted (Stead and Styles, 1984; Favela, 1991).

There is also taxonomic controversy about the existence of *Pinus rudis* Endl., a putative species with an intermediate altitudinal distribution and morphological appearance with respect to *P. montezumae* and *P. hartwegii*, although it is closer to the later. *P. rudis* is recognized by Martínez (1948), Madrigal-Sánchez (1982) and Perry (1991), and not accepted by McVaugh (1992) and Farjon and Styles (1997), who consider that putative species as a phenotypic variation of *P. hartwegii*. A multivariate analysis comparing morphological traits of *P. rudis* and *P. hartwegii* made by Matos (1995), showed that *P. rudis* actually is *P. hartwegii*. For the purposes of this report, we assume that the provenance labeled as *P. hartwegii* belongs to that species, since we consider Matos's results, robust (1995).

The objective of this report is to explore the relationship between growth potential and frost damage, comparing the field performance during the first 2 years of age of four taxa of three species: typical *P. pseudostrobus*, *P. pseudostrobus* var. *apulcensis*, *P. montezumae* and *P. hartwegii*. We aim also at finding out if there are adaptational differences between typical *P. pseudostrobus* and *P. pseudostrobus* var. *apulcensis* that could help to support or not their taxonomical separation.

## 2. Materials and methods

### 2.1. Seed collection and nursery stage

Four taxa of three species (*P. pseudostrobus* typical, *P. pseudostrobus* var. *apulcensis*, *P. montezumae* and *P. hartwegii*) were represented in the tests by a total of nine provenances from several regions of the Mexican Neovolcanic Axis, where those species are ecologically and economically important (Fig. 1 and Table 1). Several provenances by taxon were included when possible, with the purpose to capture at least partially the variation among populations within taxon. However, limitation of resources, availability of seed, and the non-concurrence of all taxa in the same regions (for example, *P. pseudostrobus* var. *apulcensis* does not distribute in Michoacán) made the number of provenances by taxon and region unbalanced. Thus, typical *P. pseudostrobus* was represented by four provenances that represent three regions within Michoacán: Nuevo Parangaricutiro and Pátzcuaro (central-west of the state), Coalcomán (south of the state) and Ciudad Hidalgo (east of the state); the former two provenances were collected by the authors and the later two were kindly provided by CAMCORE (Central America and México Coniferous Resource Cooperative). *P. pseudostrobus* var. *apulcensis* were represented by two provenances from two distant regions: one from Zimapán, Hidalgo (collected by the authors) and another from Perote, Veracuz (provided by the Mexican Centro de Genética Forestal A.C.). *P. montezumae* was represented by two provenances from the northwestern State of Puebla (provided by the Sociedad de Pequeños Propietarios Silvícolas de Zacatlán, Puebla). *P. hartwegii* was the only taxon represented by a single provenance, also from the northwest of the State of Puebla (provided by the Unidad de Conservación y Desarrollo Forestal Número 3, near of Chignahuapan, Puebla) (Table 1 and Fig. 1). Provenances were originated from the collection of 11–30 individual trees.

Seedlings were produced in a nursery at the Instituto de Investigaciones Agropecuarias y Forestales, Universidad Michoacana de San Nicolás de Hidalgo, at Morelia, Michoacán, using 380 $cm^3$ rigid containers (Broadway Plastics of México®) and a commercial substrate (Creciroot®) during 9 months before transplanting to the field.

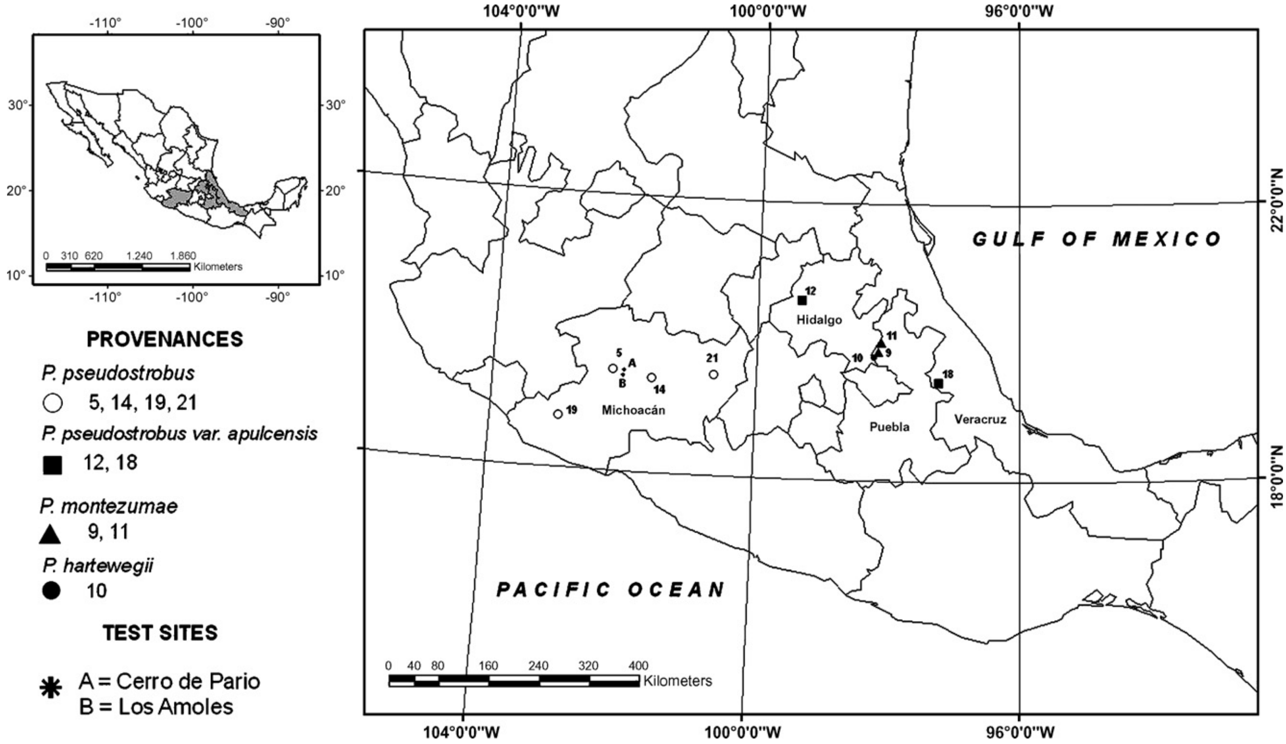

Fig. 1. Location of provenances of *Pinus pseudostrobus* (four provenances), *P. pseudostrobus* var. *apulcensis* (two provenances), *Pinus montezumae* (two provenances) and *Pinus hartwegii* (one provenance, number codes keyed to Table 1) tests at two sites (Cerro de Pario and Los Amoles) in the State of Michoacán, western México.

### 2.2. Experimental design and data collection

Two field tests were established in July 2002 at two contrasting altitudes within the forest of the Native Indian Community of Nuevo San Juan Parangaricutiro, Michoacán. One test was placed at one of the highest sites of the forest in that region, in the upper altitudinal limit of the altitudinal distribution of *P. pseudostrobus*, beside the peak of a mountain named Cerro de Pario (2800 m, 19°28′N, 102°11′W). The other test was established near the lowest altitudinal limit of *P. pseudostrobus*, at a site named Los Amoles (2200 m, 19°24′N, 102°13′W, Fig. 1). Each test had a randomized complete block design with 16 blocks and one single tree per plot.

Seedling height was measured at four ages (from sowing date in the nursery containers): 12 months (December 2002), 15 months (March 2003), 20 months (August 2003) and 24 months (December 2003).

Frost damage, evaluated at 15 months (March 2003), was determined with a 0–10 index, according to the percentage of frost damage in the plant, where 10% are equivalent to 1 and so on, up to a damage of 100%, equivalent to 10. To assess the damage value, each seedling was imaginarily divided in ten equivalent parts along its vertical axis, from the seedling collar to the tip of the leader bud; then, each tenth part of the seedling was scored for foliage (intense green needles = no damage = 0, brownish or light green needles and/or dehydrated appearance = severe damage = 1, intermediate aspect = 0.5) or for shoot (healthy light brown turgent shoot = no damage = 0, dark brown and/or dehydrated aspect and/or twisted shoot = severe damage = 1, intermediate aspect = 0.5); finally, scores of each

Table 1
Location of nine provenances from four *Pine* taxa tested at two sites at Nuevo San Juan Parangaricutiro, Michoacán, M,xico

| | Provenance (code, location, municipality, state) | Taxon | Coordinates | | Altitude (m) |
|---|---|---|---|---|---|
| | | | LN | LW | |
| 5 | Cerro de Tumbiscatillo, Parangaricutiro, Michoacan | *Pinus pseudostrobus* | 19°28′ | 102°10′ | 2400 |
| 14 | San Juan, Pátzcuaro, Michoacan | *P. pseudostrobus* | 19°25′ | 101°34′ | 2320 |
| 21 | Las Espinas, Cd. Hidalgo, Michoacan | *P. pseudostrobus* | 19°38′ | 100°38′ | 2390 |
| 19 | Varaloso, Coalcomán, Michoacan | *P. pseudostrobus* | 18°41′ | 102°57′ | 2450 |
| 12 | Comunidad Durango, Zimapán, Hidalgo | *P. pseudostrobus* var. *apulcensis* | 20°53′ | 99°14′ | 2300 |
| 18 | "Sitio 38", Perote, Veracruz | *P. pseudostrobus* var. *apulcensis* | 19°27′ | 97°13′ | 2850 |
| 9 | Cuatelolulco, Chignahuapan, Puebla | *Pinus montezumae* | 19°53′ | 98°08′ | 2700 |
| 11 | Las Lajas, Zacatlán, Puebla | *P. montezumae* | 20°01′ | 98° 06′ | 2650 |
| 10 | Piedra Ancha, Chignahuapan, Puebla | *Pinus hartwegii* | 19°48′ | 98°13′ | 2700 |

seedling part was added up to obtain the frost damage index (method based on Glerum, 1985).

Phenological stage of the bud was evaluated at 16 months (April 2003) and 27 months (March 2004), by means of a phenological index, representing the stage of development of the apical bud, with values from 0 to 6: 0 = bud in dormancy; 1 = bud initiating growth and swelling; 2 = intermediate elongation of the shoot; 3 = complete shoot elongation, but without evident fascicles; 4 = completely elongated shoot, with approximately 25% of its length covered by fascicles; 5 = well-developed shoot, entirely covered by fascicles. In individuals presenting a second growth cycle, this was evaluated using the same system as the first one (index from 0 to 6), but adding a value of 6; in other words, plants with a second cycle had values from 6 to 12. This method allows to make a rapid assessment of the relative development of the shoot (Jach and Ceulemans, 1999).

Basal diameter (cm) and total number of whorls was assessed at 24 months of age. Survival was quantified (0 = dead plants, 1 = live plants) in the final evaluation at 27 months of age (March 2004).

### 2.3. Statistical analysis

Frost damage scores were transformed to square root of each original value divided by 10, in order to normalize the data. This was the best transformation of several tested (Shapiro–Wilk test, $W = 0.508$).

An analysis of variance was made using the MIXED procedure of SAS (SAS Institute, 1998), considering the two plantation sites together, and then, separately, an analysis for each site. The analysis considered four taxa (*P. pseudostrobus* typical, *P. pseudostrobus* var. *apulcensis*, *P. montezumae* and *P. hartwegii*), and provenances nested in taxon. The statistical model in the combined analysis of the two sites was

$$Y_{ijkl} = \mu + S_i + B(S)_{ij} + T_k + P(T)_{kl} + \mathrm{ST}_{ik} + \mathrm{SP}(T)_{ikl} + \varepsilon_{ijkl} \tag{1}$$

where $Y_{ijkl}$ is the observation, $\mu$ the general mean, $S$ the site effect, $B(S)_{ij}$ the block within the site, $T_k$ the taxon, $P(T)_{kl}$ the provenance within taxon, $\mathrm{ST}_{ik}$ the site–taxon interaction, $\mathrm{SP}(T)_{ikl}$ the site–provenance interaction within taxon, and $\varepsilon_{ijkl}$ is the error. Site, taxon, and provenance were considered as fixed effects, and block as random effect.

In the analysis separate per site, the statistical model was

$$Y_{jkl} = \mu + B_j + T_k + P(T)_{kl} + \varepsilon_{jkl} \tag{2}$$

Seedling height values at the age of 12 months were used as covariate in the ANOVA analyses for seedling height at 15, 20 and 24 months of age, in order to subtract the effect of initial seedling height, which was very different among taxa, specially considering that *P. montezumae* and *P. hartwegii* present grass stage.

A cluster analysis was conducted using a matrix of Euclidian distances among provenances, using the CLUSTER procedure of SAS (SAS Institute, 1998) and the closest neighbor method (simple cluster). From this analysis, a dendogram was constructed using the option TREE of the CLUSTER procedure. Previous to the cluster analysis, seedling height at ages 15 and 20 months was eliminated, to avoid the inclusion of redundant variables. The procedure was to eliminate one by one the variables with the largest number of high correlation values ($r > 0.85$) with other variables.

## 3. Results and discussion

### 3.1. Differences among plantation sites

Plant height and bud development during the first months (ages 15 and 16 months, respectively) at the site of higher altitude (Cerro de Pario, 2800 m) was significantly superior than at Los Amoles (2200 m) (Table 2). This probably happened because (a) initial growth at the site of higher elevation occurred earlier and with greater initial vigor; (b) frosts that occurred only at the site of less elevation (contrary to expectations) apparently caused delayed growth, an average frost damage of 16.4% and significantly lower survival at Los Amoles (Table 3). Seedling height at 20 and 24 months and bud development at 27 months of age were not significantly different among sites (Table 2). Nevertheless, at the end of the evaluations, basal diameter was significantly superior at the lower site (Tables 2 and 3), according to the expectation that sites at lower altitudes allow for a better growth than sites at higher altitudes (Campbell, 1972; Arnold et al., 1994; Gwaze et al., 2001; Wei et al., 2001; Li et al., 2003).

Frost occurrence only at the low site (Los Amoles) might be explained by the fact that the site is a flat valley, at a foothill, and during the night the air cools off on the hill and then goes down and settles down at the valley; this type of cold air usually is the cause of frost damage (Castro-Zavala, 1993; Ayllón, 1996). However, the low survival at Los Amoles (33.6%, contrasting to 84.8% at Cerro de Pario) was also due to a severe attack of pocket gophers. It was not possible to determine with certainty, to what extent mortality at Los Amoles was caused by frost damage and by pocket gophers, even though in some cases it could be observed that plants had been uprooted by these animals.

### 3.2. Variation among taxa, and among provenances within taxon

Differences among taxa for almost all traits were highly significant ($p < 0.02$, Table 2) and very large (average contribution of taxon to total variance was 40.7% at Los Amoles and 49.7% at Cerro de Pario, Table 3), either on the combined analysis and on the separate analysis by site (except for survival on the combined analysis and on Los Amoles, which were non-significant, Table 2).

Typical *P. pseudostrobus* presented the largest seedling height at 24 months of age (67.5 cm, average between sites), but it had also the largest average percent of frost damage (31.5% at Los Amoles). In contrast, *P. hartwegii* had the least growth in seedling height (34.8 cm average between sites), and the lowest

Table 2
Significance level ($p\leq$) in the analysis of variance of growth characteristics in plants of *P. pseudostrobus*, *P. pseudostrobus* var. *apulcensis*, *P. montezumae* and *P. hartwegii* at two evaluation sites

| Trait | Combined analysis | | | | | Analysis by site | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Site | Taxon | $P(T)$ | $S \times T$ | $S \times P(T)$ | Cerro de Pario | | Los Amoles | |
| | | | | | | Taxon | $P(T)$ | Taxon | $P(T)$ |
| Height 15 months[a] | <0.0001 | 0.0084 | 0.6148 | 0.0142 | 0.9828 | 0.0012 | 0.7641 | 0.0181 | 0.8675 |
| Height 20 months[a] | 0.7150 | 0.0007 | 0.1652 | 0.2682 | 0.2318 | 0.0005 | 0.7761 | <0.0001 | 0.6321 |
| Height 24 months[a] | 0.6003 | <0.0001 | 0.1468 | 0.8348 | 0.2649 | 0.0007 | 0.9748 | <0.0001 | 0.6326 |
| Basal Diameter | 0.0044 | <0.0001 | 0.0344 | 0.2410 | 0.0368 | <0.0001 | 0.5680 | <0.0001 | 0.6068 |
| Whorls | 0.8421 | <0.0001 | 0.7326 | 0.9435 | 0.9714 | <0.0001 | 0.6117 | <0.0001 | 0.4362 |
| Bud phenology (16 months) | <0.0001 | <0.0001 | 0.0877 | 0.8732 | 0.2607 | 0.0008 | 0.5471 | <0.0001 | 0.5135 |
| Bud phenology (27 months) | 0.1182 | <0.0001 | 0.6251 | 0.2155 | 0.4314 | 0.0001 | 0.7846 | <0.0001 | 0.8033 |
| Frost damage | 0.0018 | <0.0001 | 0.1577 | <0.0001 | 0.1052 | – | – | 0.0042 | 0.9646 |
| Survival | <0.0001 | 0.3403 | 0.4167 | 0.0007 | 0.6912 | 0.0013 | 0.9978 | 0.4214 | 0.5833 |

Site analysis combined and separately. $P(T)$ = provenance nested in taxon, $S \times T$ = interaction site by taxon, $S \times P(T)$ = interaction site by provenance nested in taxon.

[a] Seedling height at age 12 months used as covariate (only for seedling height) was significant ($p \leq 0.02$) for all ages and for the site analysis combined and separately.

Table 3
Means, percentage of contribution to total variance (%) and total variance($\sigma^2_T$) per test site, for growth and adaptive characteristics of *P. pseudostrobus*, *P. pseudostrobus* var. *apulcensis*, *P. montezumae* and *P. hartwegii*

| Trait | Los Amoles | | | | | Cerro de Pario | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | % | | | $\sigma^2_T$ | Mean | % | | | $\sigma^2_T$ |
| | | Taxon | $P(T)$ | Error | | | Taxon | $P(T)$ | Error | |
| Height 15 months (cm) | 30.1 | 63.8 | 1.2 | 35.0 | 115.4 | 35.4 | 64.4 | 1.6 | 34.0 | 322.4 |
| Height 20 months (cm) | 47.0 | 60.3 | 24.3 | 15.4 | 738.2 | 45.5 | 65.6 | 0.0 | 34.4 | 664.3 |
| Height 24 months (cm) | 54.2 | 55.2 | 19.0 | 25.8 | 1034.9 | 51.9 | 67.0 | 0.0 | 33.0 | 943.5 |
| Basal Diameter (mm) | 194.0 | 0.0 | 7.1 | 92.9 | 7488.9 | 147.7 | 51.5 | 0.0 | 48.5 | 2652.6 |
| Whorls | 1.7 | 58.0 | 0.0 | 42.0 | 0.5 | 1.7 | 44.0 | 0.0 | 56.0 | 1.1 |
| Bud phenology (16 months) | 2.5 | 25.0 | 7.7 | 67.3 | 2.4 | 4.5 | 31.1 | 0.0 | 68.9 | 5.0 |
| Bud phenology (27 months) | 3.3 | 55.9 | 0.0 | 44.1 | 14.9 | 2.4 | 41.6 | 0.0 | 58.4 | 6.4 |
| Frost damage (%) | 16.4 | 44.7 | 0.0 | 55.3 | 0.1 | 0.0 | – | – | – | – |
| Survival (%) | 33.6 | 3.5 | 0.0 | 96.5 | 0.2 | 84.8 | 32.0 | 0.0 | 68.0 | 0.1 |
| Average | – | 40.7 | 6.6 | 52.7 | – | – | 49.7 | 0.2 | 50.1 | – |

$P(T)$ = provenance nested in taxon.

frost damage (0.0% at Los Amoles). *P. pseudostrobus* var. *apulcensis* and *P. montezumae* had intermediate values of growth and frost damage, with more growth the former and less frost damage the later taxon (Table 4).

The results indicate a highly significant differentiation among these taxa for adaptive traits. Significant differentiation among Mexican pine species has being found in growth traits at early ages among *Pinus greggii* Engelm., *P. patula* Schl. et Cham., *P. maximinoi* H.E. Moore and *P. tecunumanii* (Schw.) Eguiluz *et* Perry (Salazar et al., 1999), and among (*Pinus caribaea* var. *hondurensis* Morelet, *P. caribae* var. *bahamensis* Barr. & Golf and *P. pseudostrobus* (Das and Stephan, 1982).

There were no significant differences among provenances within taxon for almost all traits (Table 2). Contribution to total variance of provenances within taxon was only 6.6% at Los Amoles and 0.2% at Cerro de Pario (Table 3). Only basal

Table 4
Multiple mean comparison and Tukey test ($p \leq 0.05$) for 24-month-old seedling height (cm), frost damage (%) and survival (%) for four taxa: *P. pseudostrobus*, *P. pseudostrobus* var. *apulcensis*, *P. montezumae* and *P. hartwegii*

| Taxon | Height (average both sites) | | | | Frost damage (Los Amoles) | | | Survivorship (Cerro de Pario) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Tukey | | | Mean | Tukey | | Mean | Tukey | | |
| *P. pseudostrobus* | 67.5 | A | | | 31.5 | A | | 100.0 | A | | |
| *P. pseudostrobus* var. *apulcensis* | 57.8 | A | B | | 17.1 | | B | 98.9 | A | B | |
| *P. montezumae* | 52.2 | | B | | 4.6 | | B | 79.1 | | B | C |
| *P. hartwegii* | 34.8 | | | C | 0.0 | | B | 62.1 | | | C |

Test site is in parenthesis.

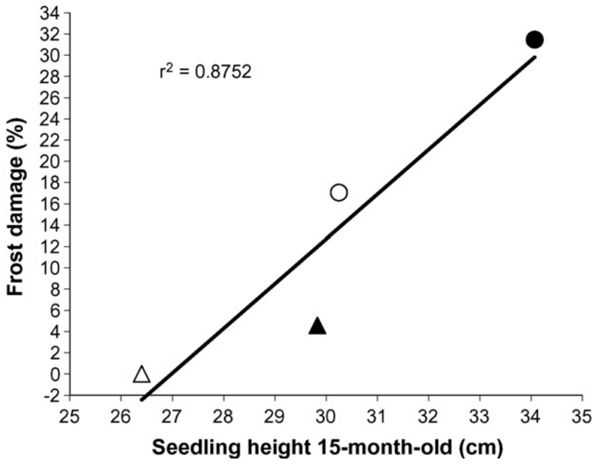

Fig. 2. Regression of average frost damage percentage by taxon with respect to average 15-month-old seedling height by taxon, for *P. pseudostrobus* (●), *P. pseudostrobus* var. *apulcensis* (○), *P. montezumae* (▲) and *P. hartwegii* (△).

diameter had significant differences among provenances in the combined analysis (Table 2).

### 3.3. Correlation between growth potential and frost damage

There is a positive correlation by taxon between 15-month-old seedling height and amount of frost damage ($r^2 = 0.8752$, $p = 0.0645$, $n = 4$). This indicates that those taxa having higher growth also had severer frost damage, and those taxa with less growth had less frost damage (Fig. 2). A similar pattern was found between 16-month-old bud phenology and frost damage, where taxa with greater shoot development had more intense frost damage, and taxa with less shoot development had less frost damage ($r = 0.76$, $p < 0.0001$, $n = 4$). These results are similar to the patterning of differentiation among *P. contorta* Dougl. population, where populations with higher growth potential also were more susceptible to frost damage (Rehfeldt, 1983, 1985; Jonsson et al., 1986).

### 3.4. Cluster analysis

The dendogram of the cluster analysis base clearly reveals a grouping of provenances in four groups that corresponds to the four putative taxa, when drawing a threshold at 0.76 of distance (Fig. 3). This analysis confirms the taxonomic identity of the provenances as they where identified in Table 1, and it is consistent with the mean multiple comparison using Tukey (Table 4).

The separate grouping of the two provenances of *P. pseudostrobus* var. *apulcensis* (Group II), and its intermediate position between typical *P. pseudostrobus* and *P. montezumae* but closer to the former, support the taxonomic classification made by Martínez (1948) and later by Perry (1991), who suggested that *P. psedostrobus* var. *apulcensis* is a variety distinguishable from typical *P. psedostrobus*.

### 3.5. Applications for management in reforestation programs

Considering that typical *P. pseudostrobus* had the best growing rates and the largest frost damage average values, we suggest using this species for reforestation in the studied region (Purépecha Plateau of Michoacán State, México) at sites with very low frost incidence. *P. montezumae* would be appropriate for reforestation of sites with important frost incidence, given its low average values of frost damage.

*P. hartwegii* should be discarded in this particular region for its very low growth rate and poor survival, although perhaps it should be tested at higher altitudes, considering

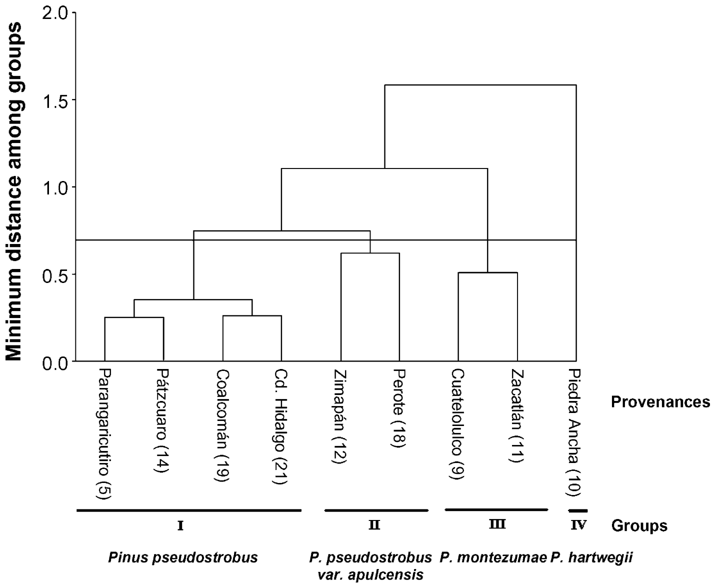

Fig. 3. Cluster for nine provenances of *P. pseudostrobus*, *P. pseudostrobus* var. *apulcensis*, *P. montezumae* and *P. hartwegii*, based on eight adaptive traits. Provenance number is keyed to Table 1.

that its natural altitudinal range is between 3000 and 3600 m at the nearby Pico de Tancítaro National Park (Niniz-Romero, 2006). Also *P. pseudostrobus* var. *apulcensis* should be discarded for having lower growth potential than typical *P. pseudostrobus* and higher susceptibility to frost damage than *P. montezumae*.

These recommendations are based on the tested provenances. It is possible that different provenances of the same taxa might have different performance.

### *3.6. Growth trends towards later ages*

Although the results presented here are based on data collected when individuals of *P. montezumae* and *P. hartwegii* still were at grass stage, there are indications that differences among taxa remained essentially the same at later ages, when *P. montezumae* and *P. hartwegii* had already broken their grass stage. Differences among taxa were significant at the age of 3 years, both in an analysis of the two sites together and in an analysis by site ($p < 0.0001$) (analysis not shown due to small sample size: four seedlings by provenance on average at the site Los Amoles – after the 24-month-old measurements, cattle walked in at Los Amoles test and destroyed a large part of it – although an acceptable 13 seedlings by provenance on average remained at Cero de Pario site).

## 4. Conclusions

There are large differences in growth potential between the four studied taxa. Typical *P. pseudostrobus* is the taxon with the largest growth potential. *P. pseudostrobus* var. *apulcensis* grew less than typical *P. pseudostrobus*, little more than the height reached by *P. montezumae* and almost twice the growth of *P. hartwegii*.

There is a strong association by taxon between growth potential and susceptibility to frost damage. Taxa with more growth potential had also more frost damage (*P. pseudostrobus* typical and *P. pseudostrobus* var. *apulcensis*, in this order), and taxa with less growth potential had less frost damage (*P. montezumae* and *P. hartwegii*, in this order).

The results suggest that for reforestation in the Purepecha Plateau of Michoacán, México, typical *P. pseudostrobus* is the best species at sites with low frost incidence, due to its higher growth potential. *P. montezumae* would be the appropriate species for sites with important frost incidence, due to its low susceptibility to frost damage. We do not recommend the use of *P. pseudostrobus* var. *apulcensis* for the region, for having less growth potential than typical *P. pseudostrobus* and high frost damage susceptibility. The use of *P. hartwegii*, is not recommendable either because of its very low growth rate and high mortality.

*P. pseudostrobus* var. *apulcensis* is a taxon distinguishable from typical *P. pseudostrobus* for its growth potential and frost damage susceptibility, whose taxonomic classification is supported by Martínez (1948) and Perry (1991), who recognize the existence of both taxa.

## Acknowledgements

The authors thank for financial support from CONACYT-SIMORELOS 20000306021, CONACYT-CONAFOR 2002-C01-4655, Coordinación de la Investigación Científica of the UMSNH (5.1) and USDA-Forest Service, Rocky Mountain Research Station 01-JV-11222063-183, granted to CSR. Thanks to Manuel Echeverría, Rafael Echeverría, Luis Toral, Felipe Aguilar and other personnel from the Forestry Office of the Native Indian Community of Nuevo San Juan Parangaricutiro, Michoacán, for their help with seed collection, establishment and maintenance of field tests. We are grateful for seed donation by the Central American and México Coniferous Resource Cooperative (CAMCORE, Raleigh, NC, USA, through Bill Dvorak), by the Sociedad de Pequeños Propietarios Silvícolas de Zacatlán, Pue., by the Unidad de Conservación y Desarrollo Forestal Número 3 (Chignahuapan, Pue), and the Centro de Genética Forestal, A.C. Thanks to Ernesto Moreno, Daniel Saldívar, Víctor Quiñónez and other personnel of the Michoacan State Forest Commission for their help with seed collection and field test establishment. We thank Soraya González and Guadalupe Hernández for their help during the nursery stage and for the valuable comments by Hans Nienstaedt. We thank Reyes Bonilla Beas and Ricardo Domínguez López for the taxonomic verification of the provenances. Jerry Rehfeldt and an anonymous reviewer helped to improve the manuscript.

## References

Alden, J., Hermann, R.K., 1971. Aspect of cold-hardiness mechanism in plants. Bot. Rev. 37, 37–141.

Anekonda, T.S., Adams, W.T., 2000. Cold hardiness testing for Douglas-fir tree improvement programs: guidelines for simple, robust and inexpensive screening methods. West. J. Appl. For. 15, 129–136.

Arnold, R.J., Jett, J.B., McKeand, S.E., 1994. Natural variation and genetic parameters in Fraser fir for growth and Christmas tree traits. Can. J. For. Res. 24, 1480–1486.

Ayllón, T., 1996. Elementos de meteorología y climatología. Trillas, México, D.F..

Bello-Lara, A., Cibrián-Tovar, J., 2000.In: Evaluación técnica de la reforestación 1998. 1er. Congreso Nacional de Reforestación. Montecillo, Texcoco, México (CD-Rom).

Campbell, R.K., 1972. Genetic variability in juvenile height-growth of Douglas-fir. Silvae Genet. 21, 126–129.

Castro-Zavala, R., 1993. Introducción a la meteorología. Universidad Autónoma Chapingo, Chapingo, Edo. de México.

Das, B.L., Stephan, B.R., 1982. Provenance trial with *Pinus caribaea* Morelet and *P. pseudostrobus* Lindl. in Orissa, India. Silvae Genet. 31, 203–208.

Farjon, A., Styles, B.T., 1997. *Pinus* (Pinaceae). Flora Neotropica Monograph, No. 75. The New York Botanical Garden, New York.

Favela, S., 1991. Taxonomía de *Pinus pseudostrobus* Lindl., *Pinus montezumae* Lamb. y *Pinus hartwegii* Endl. Reporte Científico No. 26. Universidad Autónoma de Nuevo León, Facultad de Ciencias Forestales, Linares, Nuevo León, México.

Glerum, C., 1985. Frost hardiness of coniferous seedlings: principles and applications. In: Duryea, M.L. (Ed.), Evaluating Seedling Quality: Principles, Procedures, and Predictive Abilities of Major Test, Workshop Held on October 16–18, 1984, Forest Research Laboratory, Oregon State University, Corvallis, OR, USA, pp. 107–135.

Gwaze, D.P., Williams, J.A., Kanwski, P.J., Bridgwater, F.E., 2001. Interactions genotype-site for height and stem straightness in *Pinus taeda* in Zimbabwe. Silvae Genet. 50, 135–140.

Jach, M.E., Ceulemans, R., 1999. Effects of elevated atmospheric $CO_2$ on phenology, growth and crown structure of Scots pine (*Pinus sylvestris*) seedlings after two years of exposure in field. Tree Physiol. 19, 289–300.

Jonsson, A., Eriksson, G., Franzen, A., 1986. Within-population variation in frost damage in *Pinus contorta* Dougl. seedlings after simulated autumn or late-winter conditions. Silvae Genet. 35, 96–102.

Li, M.H., Yang, J., Kräuchi, N., 2003. Growth response of *Picea abies* and *Larix decidua* to elevation in subalpine areas of Tyrol Austria. Can. J. For. Res. 33, 653–662.

Madrigal-Sánchez, X., 1982. Claves para la identificación de las coníferas silvestres del Estado de Michoacán. Boletín Divulgativo No. 58. Instituto Nacional de Investigaciones Forestales, SARH, México, D.F.

Martínez, M., 1948. Los pinos mexicanos. Ediciones Botas, México, D.F..

Matos, A., 1995. *Pinus hartwegii* and *P. rudis*: a critical assessment. Syst. Bot. 20, 6–21.

McVaugh, R., 1992. Flora Novo-Galiciana. A descriptive account of vascular plants of western México. Gymnosperms and Pteridophytes, vol. 17. University of Michigan Herbarium, Ann. Arbor.

Niniz-Romero, R., 2006. Variación morfológica de conos y semillas de Pinus hartwegii Lindley, a lo largo de un transecto altitudinal en Pico deTancítaro, Michoacán, México. Bachelor degree thesis in Biology, UMSNH.

Perry, P.J., 1991. Pines of Mexico and Central America. Timber Press, Portland, OR.

Rehfeldt, G.E., 1983. Adaptation of *Pinus contorta* populations to heterogeneous environments in northern Idaho. Can. J. For. Res. 13, 405–411.

Rehfeldt, G.E., 1985. Ecological genetics of *Pinus contorta* in the Wasatch and Uinta Mountains of Utah. Can. J. For. Res. 15, 524–530.

Rehfeldt, G.E., 1988. Ecological genetics of *Pinus contorta* from the Rocky Mountains (USA): a synthesis. Silvae Genet. 37, 131–135.

Rehfeldt, G.E., 1991. A model of genetic variation for *Pinus ponderosa* in the Inland Northwest (USA): applications in gene resource management. Can. J. For. Res. 21, 1491–1500.

Rodríguez-Trejo, D.A., Fulé, Z.P., 2003. Fire ecology of Mexican pines and a fire management proposal. Int. J Wildl. Fire 12, 23–37.

Salazar, J.G., Vargas-Hernández, J.J., Jasso-Mata, J., Molina, J.D., Ramírez, C., López-Upton, J., 1999. Variación en el patrón de crecimiento en altura de cuatro especies de *Pinus* en edades tempranas. Madera y Bosques 5, 19–34.

Sáenz-Romero, C., Snively, A., Lindig-Cisneros, R., 2003. Conservation and restoration of pine forest genetic resources in México. Silvae Genet. 52 (5–6), 233–237.

Sáenz-Romero, C., Lindig-Cisneros, R., 2004. Evaluación y propuestas para el programa de reforestación en Michoacán México. Ciencia Nicolaita 37, 107–122.

Sáenz-Romero, C., Rehfeldt, G.E., Soto-Correa, J.C., Aguilar-Aguilar, S., Zamarripa-Morales, V., López-Upton, J., 2005. Altitudinal genetic variation among *Pinus pseudostrobus* populations. Preliminary analysis from a two-location shadehouse test. In: Proceedings at Meeting VII of the Mexican Society of Forest Resources, Chihuahua, Chihuahua, México, October 26–29.

SAS Institute, 1998. SAS/STAT Guide for Personal Computers, Version 8.0. SAS Institute, Cary, NC, USA.

Stead, J.W., 1983. A study on variation and taxonomy of the *Pinus pseudostrobus* complex. Commonw. For. Rev. 62, 25–35.

Stead, J.W., Styles, B.T., 1984. Studies of Central American pines: a revision of the '*Pseudostrobus*' group. Bot. J. Linn. Soc. 89, 249–275.

Wei, R.P., Lindgren, K., Lindgren, D., 2001. Parental environment effects on cold acclimation and height growth in lodgepole pine seedlings. Silvae Genet. 50, 252–257.