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# A STAND GROWTH AND YIELD MODEL FOR NORTHERN REFORESTED STANDS OF MEXICO

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Abstract. The aim of this research was to develop a growth and yield model for predictions of the basal area and timber volume of reforested stands in degraded, arid, semi-arid and dry-temperate lands of northern Mexico. In total, 124 forest stands (chronosequences) were sampled for allometric features (basal and breast height diameter, canopy height and canopy cover); data from 75% of the stands were used for model fitting and data from the remaining 25% of the stands were used for the model validation. The potential timber volume and basal area growth were determined for each reforested species. The growth rates of reforested native coniferous species in the states of Durango (*P. durangensis* Martinez, *P. cooperi* C.E. Blanco, and *P. engelmannii* Carrière) and Nuevo Leon (*P. pseudostrobus* Lindl.) were higher than those of pine species not native to south Central Durango (*P. arizonica* Engelmann), eastern Nuevo Leon (*P. cembroides* Zucc., *P. pinceana* Gordon, and *P. nelsonii* Shaw) and Coahuila (*P. halepensis* Mill.). Because forest stands are often reforested at high seedling densities, the productivity is higher than that of pre-existing native forests communities. Therefore, this practice is recommended in order to increase timber stocks and the productivity of Mexico's degraded temperate and semi-arid forests.

**Keywords:** Growth and yield model, Chronosequences, Stand scale, Environmental services.

## 1 Introduction

Forest plantations covered 124 M ha or approximately 3.6% of the estimated global forest area in 1995 (FAO, 2007). However, it is estimated that there will be a need for an additional 130 to 235 M ha of forest plantations by the year 2050 to meet increasing demand for fiber (FAO, 2007). Around 20 M ha of the global forested area is covered by non-industrial reforested plantations aimed at restoring plant cover, halting or reducing land degradation processes and increasing soil productivity (UN, 2000).

Reforestation is common practice in northern upland sites in the Sierra Madre Occidental and Oriental mountain ranges in Mexico. The state governments of Durango, Coahuila, and Nuevo Leon, (Mexico) reforested an average of 10,000 ha of land per year in the period of 1993 - 2009 (SEMARNAT, 2010), and the country already has almost 3 M ha of forest plantations of which 90% are non-industrial reforestations. However, extensive areas of Mexico's northern coniferous forests have low plant densities and require additional silvicultural treatments. The standing timber volume in approximately 4 M ha of land in the states of Durango and Chihuahua is lower than 60 $m^3$ $ha^{-1}$ (INEGI, 2001), and planting at low, medium and high density is required to improve stocking. In particular, the eastern slopes of the Western Sierra Madre mountain range require prompt natural regeneration, and stocks are being further reduced by human-related disturbances such as overharvesting, overgrazing, forest wildfires and subtle climate changes (Návar et al., 2001; Návar-Cháidez and Lizárraga-Mendiola, 2013).

Scant attention has been given to developing growth and yield models for non-industrial forestations and reforestations. There is also a lack of flexible, user-friendly and practical models that can be used in a wide range of site conditions reforested with a diversity of tree species. Growth and yield models include individual tree, stand class and whole stand models (Clutter et al., 1983; Vanclay, 1994; Peng, 2000). Individual tree models are further subdivided into distance dependent and distance independent models. Examples of the application of these techniques for monospecific stands are reported elsewhere (Zepeda-Bautista and Dominguez, 1998; Návar-Cháidez and Domínguez-Calleros, 2013).

Contemporary growth and yield models used in forestry are usually empirical in nature (Peng, 2000). Although more process, mechanistic, and hybrid, models are currently being developed, these are still too scarce to be widely used in conventional forest management programs. Hence, most growth and yield models are local in nature and several examples have been developed for regular, monospecific stands. Stand class models for regular monospecific temperate forest stands are reported in the scientific literature (Aguirre-Bravo, 1987; Zepeda and Domínguez, 1998; De los Ríos et al., 2009). Examples of distance independent models and individual tree models have been reported by Návar-Cháidez and Domínguez-Calleros (2013). Most of these technologies are developed for local forests with limited spatial application, and there is shortage of growth and yield models that can be applied to more widespread forests, such as the Mexico's northern temperate forests. In this study, we developed a stand class growth and yield model that can be applied to upland reforested stands of the Sierra Madre Occidental and Oriental mountain ranges. In the model, we have included proven growth and yield methodologies, such as those reported by Clutter et al. (1983), Vanclay (1994) and Peng (2000).

Thus, the aim of this study were: a) to measure tree allometric features in reforested stands, and b) to develop a stand level growth and yield model for projecting standing basal area and timber volume of reforested stands in northern upland sites in Mexico.

## 2 Experimental Section

The study was conducted in reforested upland stands in the Sierra Madre Occidental and Oriental mountain ranges in northern Mexico (Fig. 1).

Mixed coniferous forests distributed in different climates were sampled: cold-temperate forests in the state of Durango, temperate forests in the state of Nuevo Leon and semi-arid forests in the state of Coahuila. The Table 1 has been added to depict means of the measured tree attributes.

Initial planting density and density at measurement (No. per ha), Age (years), Basal diameter (cm), Top height (m), Tree cover ($m^2$), Height dominant = height of dominant trees (m), Basal area ($m^2$ $ha^{-1}$), timber volume ($m^3$ $ha^{-1}$).

The species planted in Durango are native to the sites, with the exception of *P. arizonica*, a pine species that preferably colonizes upland sites farther north. The pinyon pines (*P. pinceana*, *P. nelsonii* and *P. cembroides*) are not naturally distributed in the reforested stands in Nuevo Leon, and the first two are listed in the rare and endangered species list (SEMARNAT, 1999). Moreover, although *Pinus pinceana* ("weeping piñon") is considered at lower risk thanspecies in the 'vulnerable' or 'endangered' categories of the IUCN Red List, it is threatened and is close to being categorized as 'vulnerable' because of its low area of occupancy and fragmented range (Perry, 1991; Farjon and Page 1999). *Pinus halepensis*, an exotic pinyon pine species, has been extensively planted in upland sites near Saltillo in the state of Coa-huila (Mexico).

### 2.1 Statistical analysis

We fitted a stand class model to standing timber volume data by using basal area, site index and age of reforestations as independent variables, following the methodology of Clutter et al. (1983). The growth and yield model projects basal area and timber volume in time, weighted by site productivity. Site productivity, which is indirectly estimated by the conventional site index approach, assumes that the top height of dominant trees is dependent on site productivity. This method uses an equation to project top height of dominant trees as a function of age. Following the methods proposed by Clutter *et al.* (1983), the full growth and yield model of Schumacher (1939) that works at stand scale is described below:

$$\ln(Vt) = B_0 + B_1 SI + B_2 \ln(BA) \quad (1)$$

Where site index (SI) is derived from model (2)

$$\begin{aligned} H_0 &= B_0 \times e^{(-B_1/t)} \\ SI &= H_0 \times e^{(-B_1/t_o - 1/t)} \end{aligned} \quad (2)$$

And BA is further developed by model (3)

$$\ln(BA) = B_0 + B_1 \ln(DBH) + B_2 \ln(SI) \quad (3)$$

Where DBH was predicted by model (4)

$$DBH = \frac{B_0}{1 + B_1 \times e^{(tB_2)}} \quad (4)$$

Where $t = age$ (years), $t_o$ = base age of 15 years for these reforested sites, $BA$ = basal area ($m^2$ $ha^{-1}$) using

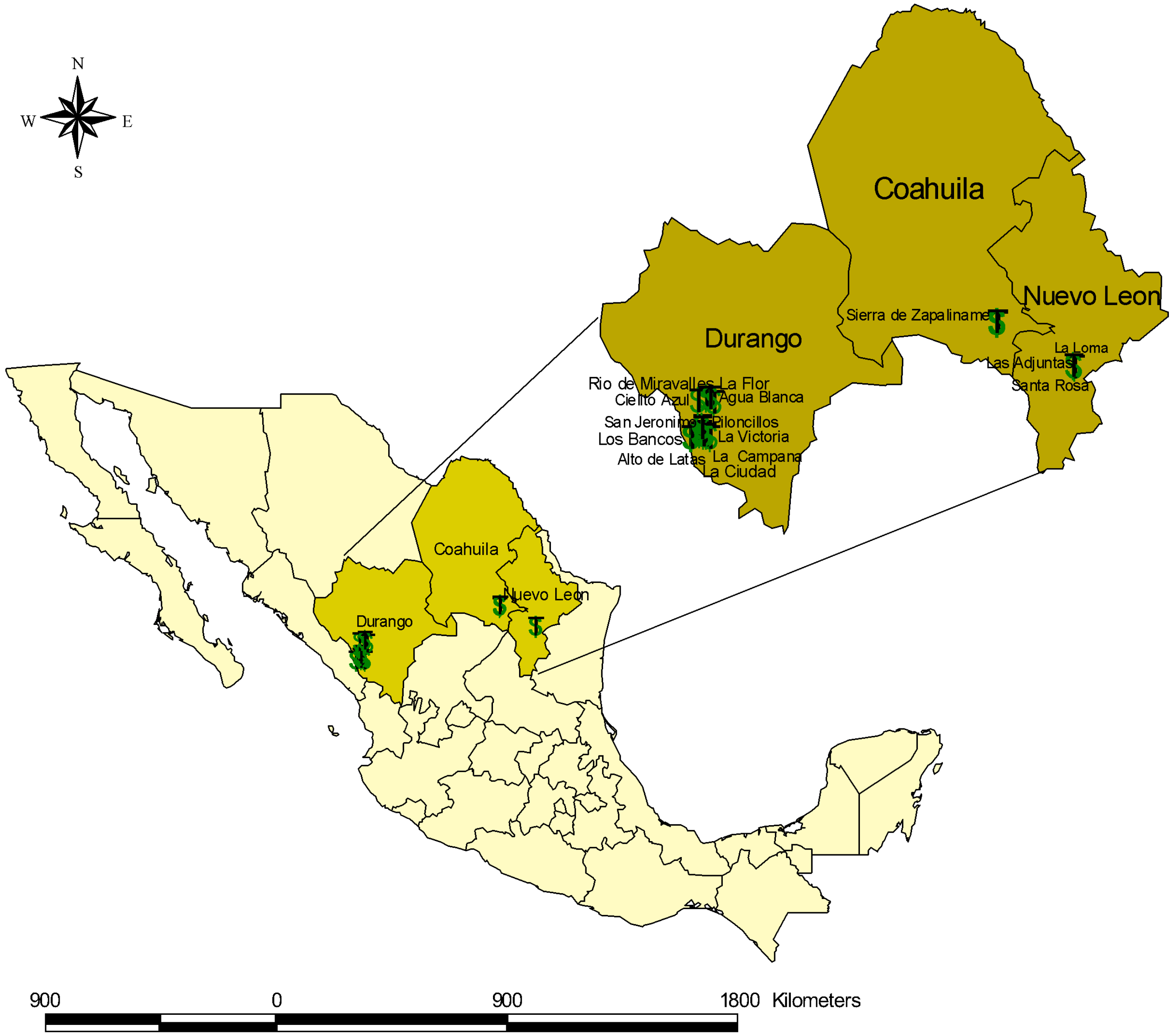


Figure 1: Map showing the reforested sites in the states of Durango, Coahuila and Nuevo Leon (Mexico).

basal diameter instead of diameter at breast height, $Vt$ = standing stem volume (m$^3$ ha$^{-1}$), $SI$ = site index, $B_0$, $B_1$, $B_2$, $B_3$ = statistical parameters to be estimated by regression techniques.

The basal area and timber volume models were fitted to 75% (93 plots) of the randomly selected data and the remaining 25% (31 plots) of the data were used to validate the models. The coefficient of determination, $r^2$, and standard error, Sx, provide the goodness-of-fit statistics for basal area, volume, biomass and carbon models.

## 3 Results and Discussion

The multivariate detrended canonical analysis of stand volume data yielded three individual clusters that indicated differences in site productivity of reforestations within each state (Durango, Nueva Leon and Coahuila). Hence, site index curves were developed for reforestations in each state. However, productivity models were constructed for all reforestations in northern Mexico. The timber volume stocks were largest in the Durango reforestations, although these were on average 18 years old and the final stand density was lower than in the Nuevo Leon reforestations. In Durango, the reforested sites were

Table 1: Mean values of measured tree and stand attributes in 124 Mexico's northern reforested stands.

| Species | Initial Planting Density | Stand Density at Measurement | Age | Basal Diameter | Top Height | Tree Cover | Dominant Height | Basal Area | Timber Volume |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Coahuila | | | | | |
| *P. halepensis* | 2319 | 439 | 32 | 17.41 | 4.95 | 3.86 | 7.84 | 15.25 | 18.86 |
| *P. halepensis* | 798 | 357 | 8 | 2.54 | 1.14 | 1.24 | 1.28 | 0.88 | 0.20 |
| | | | | Durango | | | | | |
| *P. cooperi* | 1990 | 1404 | 11 | 8.45 | 1.98 | 0.96 | 3.47 | 5.60 | 4.30 |
| *P. duranguensis* | 4358 | 2350 | 18 | 12.62 | 6.82 | 6.22 | 16.14 | 43.78 | 57.06 |
| *P. engelmani* | 2033 | 1558 | 14 | 14.65 | 4.48 | 8.01 | 5.44 | 24.00 | 32.17 |
| *P. arizonica* | 7500 | 1893 | 19 | 8.83 | 4.55 | 2.07 | 6.03 | 11.64 | 18.94 |
| *P. cooperi* | 4956 | 2449 | 19 | 14.46 | 7.95 | 8.61 | 18.62 | 59.57 | 79.51 |
| *P. duranguensis* | 1406 | 3733 | 13 | 12.40 | 4.48 | 8.45 | 5.59 | 45.05 | 63.98 |
| | | | | Nuevo León | | | | | |
| *Cupressus spp* | 10000 | 1225 | 21 | 5.43 | 3.86 | 5.43 | 11.87 | 21.92 | 0.52 |
| *P. cembroides* | 10000 | 8907 | 5 | 1.37 | 1.31 | 0.49 | 1.33 | 2.77 | 6.00 |
| *P. nelson* | 10000 | 6820 | 5 | 1.04 | 0.86 | 0.39 | 0.87 | 1.32 | 2.41 |
| *P. pinceana* | 10000 | 8601 | 5 | 0.89 | 0.95 | 0.52 | 1.78 | 2.09 | 2.31 |
| *P. pseudostrobus* | 10000 | 1583 | 11 | 7.77 | 2.51 | 1.17 | 4.27 | 8.98 | 9.97 |

Initial planting density and density at measurement (No. per ha), Age (years), Basal diameter (cm), Top height (m), Tree cover ($m^2$), Height dominant – height of dominant trees (m), Basal area ($m^2/ha$), timber volume ($m^3/ha$).

located in temperate areas and on Lithosols and Regosols, unlike the Coahuila reforestations, which were planted on semi-arid land predominated by Regosols. The Nuevo Leon reforestations are generally young and most of the pines are low growing pinyon pine species.

Site index curves projected by the Schumacher (1939) equation are shown in Figure 2.

For average site index, the mean top height of dominant trees at age 20 years was found to be respectively: 8.3, 6.2 and 6.4 meters, for the Durango, Nuevo Leon, and Coahuila reforestations. Native *P. cembroides* forests in Nuevo Leon attain a mean top height of 5.3 m at age 20 years for average site productivity stands and a maximum of 9 m in high productivity stands (Návar-Cháidez, 2010). According to a previously developed growth and yield model (Aguirre-Bravo, 1987), the native *P. cooperi* forests in Durango attain a mean height from 10.7 m to 15.9 m for site indexes of 16 m and 24 m, respectively at a base age of 50 years.

According to the site index relationship, site productivity is higher in stands reforested with temperate pine species in Durango (*P. cooperi*, *P. durangensis*, and *P. engelmannii*) than in the stands reforested with semi-arid pine species in Coahuila (*P. halepensis*) and Nuevo Leon (*P. cembroides*, *P. nelsonii*, *P. pinceana*, and *P. pseudostrobus*). The whole stand growth and yield model predicts higher productivity for native *P. cooperi* forests in Durango than for stands reforested with most temperate pine species. Conversely, the productivity of reforested *P. cembroides* stands in Nuevo Leon is higher than that of native *P. cembroides* stands in Nuevo Leon (De los Ríos et al., 2009; Návar-Cháidez, 2010).

Diameter at breast height, DBH, was satisfactorily predicted by a logistic (model 4: Fig. 3). At age 20 years, reforestations attained a mean DBH of 8, 9 and 14 cm in measured plots in Coahuila, Nuevo Leon, and Durango, respectively. The logistic model accounted for part of the large variation in basal area growth (Fig. 4). The model explained the least amount of variance in the Durango reforested stands. This can be attributed to the fact that the reforestation was carried out on degraded and semi-arid sites and on temperate sites where forest fires had occurred, as well as to the different initial stand densities. The large variation in basal area was explained by age and site index. However, for the Nuevo Leon and Coahuila reforestations, the reforested species accounted for a large part of this variance.

Standing timber volume, for average site index and a base age of 20 years, were approximately 40, 13, and 12 $m^3$ $ha^{-1}$, for reforestations in Durango, Nuevo Leon, and Coahuila, respectively (Fig. 5). At a mean stand age of 62 years, native *P. cembroides* stands in Nuevo Leon attained a mean (standard deviation) standing timber volume of 85 $m^3$ $ha^{-1}$ (56 $m^3$ $ha^{-1}$), in the 21 sites inventoried (Návar-Cháidez, 2010). Assuming that native regeneration is established 5 years after the final harvest (Návar et al. 2001), the native *P. cooperi* forests in Durango reach between 61 $m^3$ $ha^{-1}$ and 80 $m^3$ $ha^{-1}$,

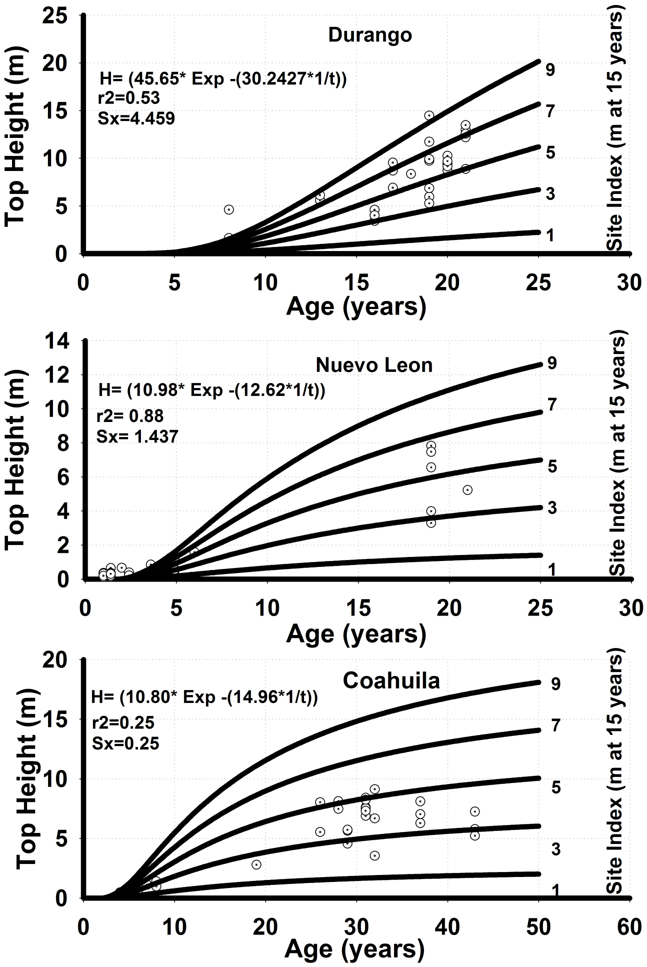


Figure 2: Site index curves for reforestations in the states of Durango, Nuevo Leon and Coahuila (Mexico).

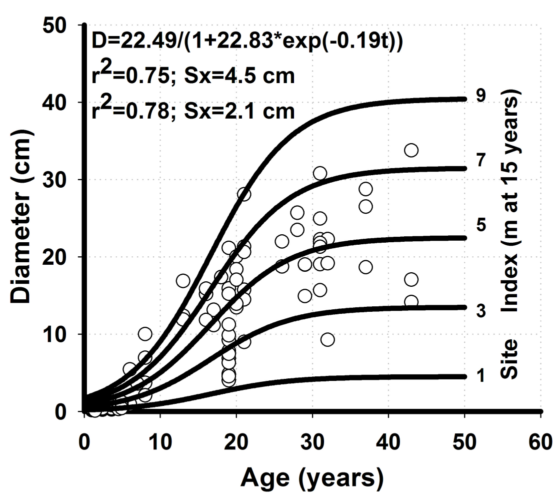


Figure 3: Diameter at breast height projections by age and site index for reforestations in the states of Durango, Nuevo Leon and Coahuila (Mexico).

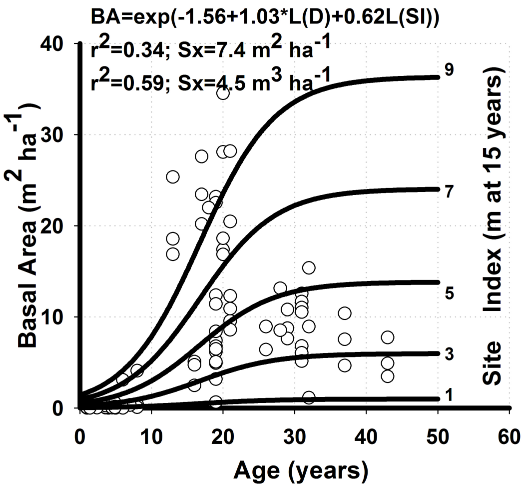


Figure 4: Basal area projections weighted by site index curves for reforestations in the states of Durango, Nuevo Leon and Coahuila (Mexico).

for site indexes of 16 and 24 m, respectively at a base age of 50 years (Aguirre-Bravo, 1987).

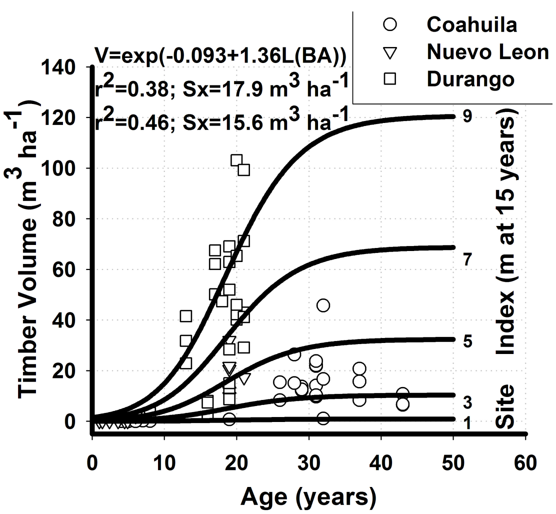


Figure 5: Standing volume weighted by site index curves for reforestations in the states of Durango, Nuevo Leon and Coahuila (Mexico).

The large variation in timber volume stock indicated by the scattered data explains the species diversity, variation in site features and large initial variation in stand density. At one site (La Escondida), *P. arizonica* accounted for the smallest and *P. cooperi* O. the largest stand volume stocks; and at another site (La Ciudad), *P. durangensis* accounted for the largest and *P. leiophylla* the smallest stand volume stocks. The smallest and largest stand volume stocks and productivities were obtained for *P. cooperi* B. (Piloncillos) and *P. cooperi* O.

(Las Adjuntas), respectively. Site features also explained part of the variation in volume stock. For example, at one site (Piloncillos) *P. cooperi* O. did not reach its full growth potential; the species are reforested in stands dominated by Lithosols and are located below the distribution range of this species. However, reforestations at another site (Alto de Latas) were located in stands in which *P. durangensis* is quickly responding by growing well in basal area and timber volume because of the combination of the most appropriate species for reforestation at the site. In general, the stand class growth and yield model fitted well to the measured data, with a large coefficient of determination and a small standard error. The fitting and validating parameters were also quite consistent (Tab. 2).

In general, the stand class growth and yield model fitted well to the measured data for both field campaigns (Figure 6). The fitting and validating parameters were also quite consistent.

Reforestations at the highest initial density (1 m x 1 m) yielded the largest standing volume stocks. Ford-Robertson (1996) and Specht and West (2003) noted that initial plant density also plays an important role in determining timber volume stocks in 20 year old *P. radiata* plantations in New Zealand. The effect of initial plant density on timber volume vanishes once intra-specific competition modulates stand density, which may occur at approximately 25 years in the Durango reforestations, although stand density dominated by competition is already taking place in several reforested sites in Nuevo Leon.

For Nuevo Leon pinyon pine reforestations planted on sites of average productivity, the model predicts timber volume stocks of 21 Mg $ha^{-1}$ for *Pinus nelsonii* (in Las Adjuntas) and *Pinus cembroides* (in La Loma) and up to 35 Mg $ha^{-1}$for *Pinus cembroides* and *Pinus pinceana* (in the Las Adjuntas site) at an age of 30 years. In 21 sites inventoried by Návar-Cháidez (2010), the mean (standard deviation) timber volume of 60 year old native *P. cembroides* forests in Nuevo Leon was 27 (38) $m^3$ $ha^{-1}$. This value is consistent with mean volume stocks of 27 $m^3$ $ha^{-1}$ for woodlands composed of *Pinus edulis – Juniperus monosperma* in Central Arizona (Grier et al., 1992).

The mean annual increment (MAI) of volume in the Durango reforestations is 6.0 $m^3$ $ha^{-1}$ $y^{-1}$. This value is similar to that reported by Birdsey (1996) for reforestations in USA (1.2 to 8.6 $m^3$ $ha^{-1}$ $y^{-1}$). Estimates for Durango are also in the range of values reported for reforestations in the tropics by Silver et al. (2000), ranging from 2.60 to 12.4 $m^3$ $ha^{-1}$ $y^{-1}$ for the first 20 years of the forest development.

In Nuevo Leon, the native pine species *P. pseudostrobus* (planted at Santa Rosa) and *P. cembroides* (planted at Las Adjuntas) accounted for the largest timber volume stocks, and pinyon pine species (planted at La Loma) accounted for the smallest timber volume stocks (Fig. 5). The native pine species, *P. pseudostrobus,* was planted in sites where it can grow at adequate rates, as the average timber volume growth rate is 2.0 $m^3$ $ha^{-1}$ $y^{-1}$. In contrast, the introduced pinyon pine species, *P. nelsonii*, *P. pinceana* and *P. cembroides* (planted at La Loma), have much lower mean timber volume growth rates, all less than 0.40 $m^3$ $ha^{-1}y^{-1}$. These pinyon pine species performed better in the Las Adjuntas site, where they grew at MAI of approximately 2.0 $m^3$ $ha^{-1}$ $y^{-1}$. Pinyon pine *P. edulis - Junniperus monosperma*, woodlands yielded MAI ranging from 2.0 to 3.0 $m^3$ $ha^{-1}$ $y^{-1}$ in the Colorado Plateau of Central Arizona (Grier et al., 1992). In the Las Adjuntas site (Nuevo Leon, present study), the mean stand timber volume growth rate reached a value of approximately 2.0 $m^3$ $ha^{-1}$ $y^{-1}$. Native *P. cembroides* forests in the state of Nuevo Leon grow at MAI of 3.0 $m^3$ $ha^{-1}$ $y^{-1}$, at a base age of 60 years (Návar-Cháidez, 2010). The latter pinyon pine species does not appear to be well adapted to these site conditions. However, high values were recorded for stand top height and density of these trees, although the basal and breast height diameters did not reach maximal values. Because of this, several of the reforested already require thinning.

In the state of Coahuila, the stands reforested with *P. halepensis* were highly variable, which was attributed to site conditions and potential human and climate-induced disturbances. The introduced *P. halepensis* species appears to have a wide tolerance to these variable environmental conditions. At some sites (this pine species can produce almost 60 $m^3$ $ha^{-1}$ in 30-year-old reforestations), the trees grew at an annual rate of slightly more than 2.0 $m^3$ $ha^{-1}$, but at other sites (lower triangles for Area 13 and Area 11) a mean timber volume stock of 10 $m^3$ $ha^{-1}$ was reached with growth at a MAI as low as 0.20 $m^3$ $ha^{-1}$. The semi-arid Greek *P. halepensis* forests grow at MAI of 0.6 and 0.8 $m^3$ $ha^{-1}$ $y^{-1}$ (Spanos and Feest, 2007). In the reforested sites studied here, most of the variation in volume stock can be attributed to variable initial seedling density, high seedling mortality during the early stages of development due to drought, pests and diseases, as well as other sources of tree mortality, such as trampling and grazing by a variety of grazing stocks.

Average stand timber volume stocks of *P. halepensis* reforestations are close to 26 $m^3$ $ha^{-1}$. Although this is lower than the stocks produced by other species, it is similar to the timber volume recorded in native forests of this species. Gracia et al. (2004) reported a mean stock volume of 40 $m^3$ $ha^{-1}$ for data from 2045 inventoried plots of Spanish *P. halepensis* stands. Maximum *P.*

Table 2: Statistics of model fitting and validation for predicting site index, basal diameter, basal area and timber volume of northern reforestations of Mexico.

| Model | Fitting the Model | | Validation of the Model | |
|---|---|---|---|---|
| | $R^2$ | Sx | $R^2$ | Sx |
| $SI(Dgo) = H = (45.65\exp(-30.24/t))$ | 0.53 | 4.5 m | 0.61 | 3.9 m |
| $SI(N.L) = H = (10.98\exp(-12.62/t))$ | 0.88 | 1.4 m | 0.87 | 1.5 m |
| $SI(Coah) = H = (10.8\exp(-14.96/t))$ | 0.25 | 8.2 m | 0.28 | 6.9 m |
| $Db = 23.27(1-\exp(-0.0656t))^{1.9}$ | 0.63 | 5.2 cm | 0.71 | 4.3 cm |
| $BA = \exp(-1.84 + 1.43\ln(Db) + 0.44\ln(SI))$ | 0.87 | 5.8 $m^2/ha$ | 0.9 | 5.6 $m^2/ha$ |
| $V = \exp(-0.35 + 1.32\ln(BA))$ | 0.96 | 15.1 $m^3/ha$ | 0.95 | 15.4 $m^3/ha$ |

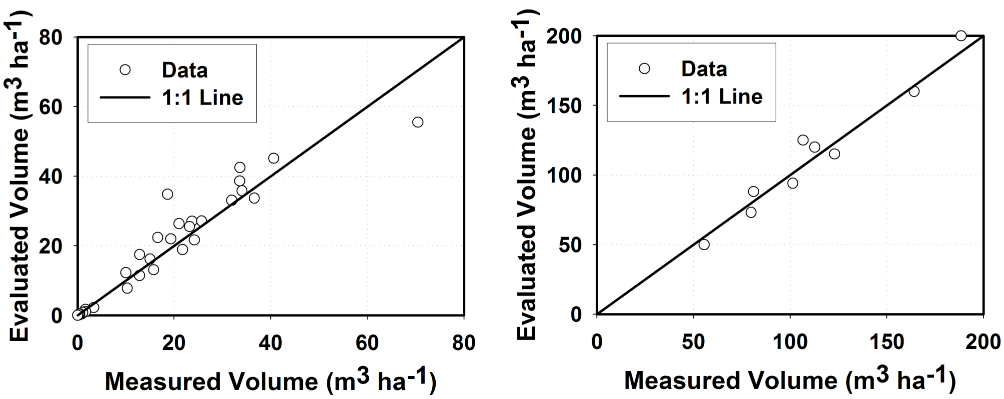


Figure 6: Measured and evaluated timber volume in Mexico's northern reforested stands in two field campaigns: 2002-2003 (6a) and 2014 (6b). The 1:1 line is depicted as well.

*halepensis* forest stocks in northern Greece reach a value of 36 $m^3\ ha^{-1}$ (Chatzianthanassiou, 2008).

Growth and yield models project timber volume stocks at a base age of 20 years for average site indexes of 37, 12, and 8 Mg $ha^{-1}$, for Durango, Nuevo Leon, and Coahuila reforestations, respectively. From these data, MAI of timber volume of 3.8, 1.20, and 0.84 $m^3\ ha^{-1}\ y^{-1}$ were calculated for Durango, Nuevo Leon, and Coahuila reforestations, respectively. These figures are similar to those reported for semi-arid forests throughout the Western US, which grow at rates of 0.50 to 5.0 $m^3\ ha^{-1}\ y^{-1}$ (Houghton et al., 2000).

The environmental characteristics and features unique to each pine species explain the different timber volume stocks and growth rates. Native coniferous species in Durango (*P. durangensis*, *P. cooperi*, and *P. engelmannii*) and Nuevo Leon (*P. pseudostrobus*) grow at higher rates than introduced pine species in south Central Durango (*P. arizonica*), Nuevo Leon (*P. cembroides*, *P. pinceana*, and *P. nelsonii*) and Coahuila (*P. halepensis*). However, the two pinyon pine species from Nuevo Leon are listed in the IUCN red book of biological conservation (Bubb et al., 2009). Mean total timber volume stock is higher in reforested stands in Durango, although the Coahuila reforestations are older. Productivity was highest in reforested stands in cold-temperate climates (mean annual temperature and precipitation of $11^0$C and 900 mm), with initially high stand density (4000 trees $ha^{-1}$), high tree survival rates and soils with high organic matter content (Lithosols, Regosols and Rendzins) (these sites were located in uplands of the Sierra Madre Occidental mountain range of Durango). Conversely, the reforested sites with the lowest recorded productivities were established in Coahuila and characterized by semi-arid climates, low stand densities, high seedling and tree mortality rates (on an average of 420 trees $ha^{-1}$) and soils with low organic matter content (Yermosols and Xerosols).

The reforested stands in Durango grew at a faster rate than pre-existing native coniferous forests. The stand class growth and yield model developed by Aguirre-Bravo (1987) predicts MAI of 1.62 $m^3\ ha^{-1}\ y^{-1}$ for low density stands of native coniferous forests with average site productivity, within the first 20 years following seedling establishment. The stand class growth and yield model developed for this report predict average productivity rates of 3.86 $m^3\ ha^{-1}\ y^{-1}$for reforestations at age 20 years. The additional timber volume growth rate is explained by the higher stand stocking in reforested stands than associated with natural regeneration.

When projecting timber volume stocks, by using both the growth and yield model proposed here and the growth and yield model developed by Aguirre-Bravo (1987), timber volume stock projections are quite similar for stands with medium to low productivity. However, in highly productive sites (> 10 m at 15 years of age) for time intervals of less than 30 years, reforestations yield larger timber volume stocks. In sites of intermediate productivity, reforestation yielded slightly more than 8 and 22 $m^3$ $ha^{-1}$ for site indexes of 10 and 12 m, respectively (Fig. 6). For site indexes below 10 m and ages under 25 years, the reforestations yielded timber volume stocks that are quite similar to those estimated for native coniferous forests.

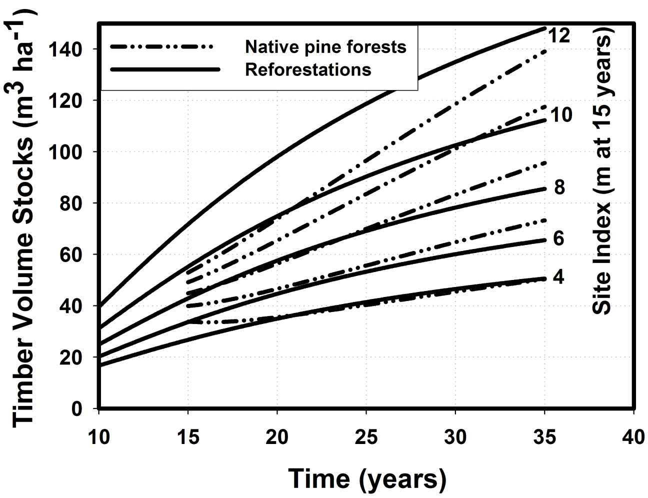


Figure 7: Projections of timber volume stocks for reforestations and native coniferous forests in the state of Durango (Mexico).

Reforested stands in Nuevo Leon and Coahuila provide additional forest and environmental benefits as the silvicultural practices were conducted in areas covered with grasslands or degraded scrublands. In other words, timber volume stocks in these plant communities were in the range of 10 to 20 $m^3$ $ha^{-1}$, while timber volume stocks in 20 year old reforested stands are currently in the range of 20 to 50 $m^3$ $ha^{-1}$ in Nuevo Leon and 20 $m^3$ $ha^{-1}$in Coahuila. Moreover, timber volume stocks are increasing steadily, at a current rate of 0.80 to 2.7 $m^3$ $ha^{-1}$ $y^{-1}$ in the reforested plots; this additional timber volume growth rate was not expected for the pre-existing grasslands and scrublands.

The full stand class growth and yield model that projects basal area and timber volume stocks in reforested stands for each of the Mexican states included in the study has the following strengths: a) it can forecast basal area and timber volume stocks and growth rates for several site productivities and for several native and some introduced pine species; b) the temporal scale of projections may double the time scale of measurements, in the ranges 0–40 years, 0–30 years, and 0–50 years for reforested sites of Durango, Nuevo Leon, and Coahuila, respectively; and c) the equations predict timber standing volume and silvicultural practices such as thinning and time of harvesting trees with e.g., sawable dimensions.

## 4 Conclusions

Measurements and modeling indicate a large amount of variation for each allometric parameters predicted; however, the models clearly show that stands reforested with local pine species grow at a faster rate than those planted with introduced pine species. Reforestations also outgrow pre-existing native plant cover, and they are therefore beneficial in forestry-related enterprises. These benefits may be increased by selecting the most appropriate pine species for reforestation of particular stands in future forestation or reforestation projects. In addition, the timber volume growth rates of desirable trees may be increased by applying suitable silvicultural practices. The stand class growth and yield model developed in this study may help foresters accomplish these objectives.


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