Tropical and Subtropical Agroecosystems

SHORT NOTE [NOTA CORTA]

ROOT ALLOMETRY OF TWO SUBTROPICAL PLANT COMMUNITIES OF NORTHEASTERN MEXICO

[ALOMETRIA DE RAICES DE DOS COMUNIDADES SUBTROPICALES DEL NORDESTE DE MEXICO]

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SUMMARY

This research work aimed at the study of the root allometry in sub-tropical Tamaulipan thornscrub and pine forest communities of Nuevo Leon, Mexico. By excavating each individual root of each of 20 trees per plant community, we developed root allometric equations for biomass, volume, total length and diameter. Covariance analysis, ancova, was employed to determine the statistical difference of these variables between plant communities. Results indicate that pine plant trees have larger root volumes, longer root systems and higher root basic densities than trees of Tamaulipan thornscrub forests. This piece of information is key to estimate root biomass, volume, total length and diameter of roots of trees of these plant communities at the stand scale.

Key words: Power equations; root biomass; volume; root length and diameter.

RESUMEN

Este trabajo de investigación se enfoca en el estudio de la alometría de raíces en el matorral subtropical Tamaulipeco y en pinos piñoneros de comunidades templado secas de Nuevo León, México. Mediante la excavación individual de las raíces de 20 arbustos de cada comunidad se desarrollaron ecuaciones alometricas para la biomasa, el volumen, la longitud y el diámetro de las raíces. Se utilizó el análisis de covarianza para determinar las diferencias estadísticas en las variables medidas entre comunidades. Los resultados indican que existe una mayor cantidad de raíces por unidad de diámetro basal, la longitud de las raíces es mayor y la densidad básica es también mayor en pinos que en matorrales. Esta información es clave en el cálculo de la biomasa, el volumen y la longitud total de raíces en estas dos comunidades a la escala del rodal.

Palabras clave: Ecuaciones de potencia; biomasa; volumen; longitud y diámetro de raíces.

INTRODUCTION

Root allometric equations are common in the scientific literature (Laclau, 2003; Rodriguez *et al.*, 2003; Guerra *et al.*, 2005; Cole and Elwell, 2006; Sierra *et al.*, 2007; Návar, 2009). This information is key in the estimation of stocks and fluxes of several biogeochemical elements in belowground biomass (Vogt *et al.*, 1999). The spatio-temporal variations of the root/aerial biomass indices have been the subject of recent investigation, as a form to explain the functioning of plant communities based on the environmental variation (Levy *et al.*, 2004; Leuschner *et al.*, 2006).

Nevertheless, the mathematical, allometric functions that describe biomass, volume, length or diameter of roots are hard to find in the scientific literature. In spite of their ecological importance (Návar, 1992; Li *et al.*, 2009), the calculations of volume, length and diameter of roots have not been described by researchers for the sustainable management of natural resources. This information is key in; i.e., understanding the soil volume that is exploited by each tree or the plant community, when this information is coupled with measurements of fine roots that emerge from the main roots systems.

Alive roots are preferential water flow paths within the soil (Návar, 1992; Li *et al.*, 2009). Decomposed roots form porous structures that convey water into deep soil profiles (Beven and Germann, 1982; Návar, 1992). Therefore, root dimensions are important in the estimation of macroporous structures that remain within the soil after the decomposition of these plant organs. The volume, length and diameter of root macropores are critical water flow pathways that facilitate the transport of biogeochemical and polluting elements within soils (Beven and German, 1982; Turton *et al.*, 1995; Návar *et al.*, 1995; 1996). Soil macropores (d > 0,3 cm) generate water fluxes beyond non-conventional, diffusion laws.

The objectives of this investigation were: a) to mathematically describe allometry of roots, b) to determine statistical differences associated between root allometric components and c) to try to explain the causes of possible differences in the allometric relations of two contrasting plant communities of the northeast of Mexico. The central hypothesis was that root allometry do not differ between plant communities.

MATERIAL AND METHODS

This study was conducted in the northeast of Mexico in two sub-tropical semi-arid plant communities: a) the Tamaulipan thornscrub of the area of Linares, N.L., Mexico and b) the semi-arid, dry-temperate pinyon pine species of Iturbide, N.L., Mexico.

The sub-tropical Tamaulipan thornscrub forest distributes in the coastal plain of the northern Gulf of Mexico, and covers an approximate area of 200.000 km^2, including close to 80% of the surface of the Mexican states Nuevo Leon and Tamaulipas (Jurado and Reid, 1989). Coarse roots (d<1.0 cm) of 20 trees of this plant community were excavated in the area of Linares, in a site located at an altitude above sea level of 360 m. Climate is sub-tropical, semi-arid, warm, with a mean annual precipitation and temperature of 750 mm and 22.3 ºC, respectively. The topography is gentle, with slopes generally of less than 20% and plateaus with smaller slopes. Soils are characterized by deep Vertisols highly homogeneous in dark-coloration and high fertility, although variations are often found that are affected primarily by their position in the slope, vegetation and geology.

The roots of 20 pinyon pine trees were also excavated in the area of Iturbide, N.L., Mexico. Pinyon pine seedlings were planted during the summer of 1983 in an experimental field near the town of Santa Rosa, Iturbide, about 40 km to the southwest of Linares, N.L. The site is typical of the eastern Sierra Madre mountain range landscape located at an altitude above sea level of 1400 m. Climate is dry temperate to semi-arid depending on the slope face with mean annual precipitation and temperature of 600 mm and 17°C, respectively. The geology of this part of the eastern Sierra Madre mountain range, consists of limestones of the Upper Cretacic Period, along with recent sedimentary deposits. Outcrops of the Jurasic and the Lower Cretacic are also typical of this place. The topography is very rough, with slopes generally of 30-70% and limestone crests with smaller slopes. Soils vary from shallow Litosols to Regosols with a wide diversity in coloration and fertility, affected primarily by their relation with the slope, vegetation and geology.

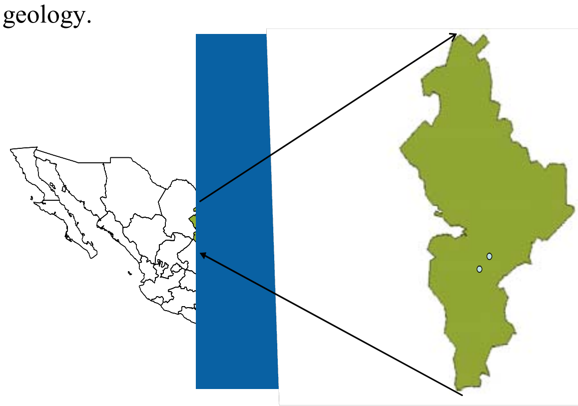

Figure 1. The location of the studied plant communities in the northeast of Mexico.

Procedure. First measurements of normal diameter and canopy cover were taken before trees were harvested for biomass measurements. Later, the soil beneath the stump was carefully removed taking care of not damaging main roots. The stump together with roots was gentle and gradually raised with a chain with pulleys inserted in a steel tripode while the process of excavating the main roots continued until it was not possible to keep unearthing these roots. In general roots with a diameter ≥ 1.0 cm were entirely excavated.

Root diameter was measured every 5 cm until attaining full length. Therefore, taper measurements were taken from the root base, where it joins the stump until the distal portion. Thereafter, roots were fresh weighed and samples were taken to the laboratory for oven dry weight with the aim to calculate total dry weight. The index dry weight/fresh weight of the samples multiplied by total fresh weight estimated the dry root biomass. Root volume was estimated using the typical equation of Smalian for each individual root (Clutter *et al.*, 1983). The volume of roots with small dimensions was calculated by dividing the dry weight between the root basic density. Basic density for larger roots was available since volume and dry weight were variables measured. Biomass and volume equations using the independent variable basal diameter of the stump as well as biomass and volume using the same basal diameter of roots were developed for each plant community. The central hypothesis of this study was proven for each measured variable with the use of covariance analysis (ancova). First the volume, V, or dry biomass, B, data and the stump basal diameter was transformed to the natural logarithm and later fitted to the mathematical function;

$$\mathrm{Ln}(B, V) = \mathrm{Ln}(b0) + b1\,\mathrm{Ln}(Db)$$

Where:
B = biomass, V = volume, Db = basal diameter of stump and b0, b1 are statistical parameters to be calculated using least squares techniques in linear regression analysis.

The ancova analysis tests for differences between plant communities in volume or biomass by using the covariable basal diameter of the stump. The covariable adjusts the variance analysis in such a manner that age of plants is implicitly considered since the stump basal diameter is a function of age.

Root diameter profiles were modeled using classic taper equations. An ample diversity of these equations is reported in the scientific Literature (Cao *et al.*, 1980; Max-Burkhart, 1976; Parresol and Thomas, 1996; Newnham, 1990). The existence of this wide variety of mathematical functions obeys to the fact that taper changes between trees of the same stand and between trees of different stands, in addition to the way in which this mathematical function is mathematically described (Gregoire and Schabenberger, 1996; Tassisa and Burkhart, 1998; Eerikäinen, 2001). In this research the equation of Newnham (1990, 1992) (Model [1]) was used; because it has proven to be useful in the description of the diameter profiles of trees in the north of Mexico (Návar, 2009).

$$\left[\frac{d}{D}\right]^2 = b_0 \cdot \left(\frac{H-h}{H}\right)^{b_1} \qquad [1]$$

Where:
d = diameter i to the length i of root i; h = length i, D = root basal diameter, H = total root length, b0 and b1 are statistical parameters to be calculated by regression analysis with the use of empirical data.

Changes in the diameter profiles between communities could be determined by estimating variation of parameters b0 and b1, with the calculation of the confidence intervals. Figures of diameter profiles also show places were major differences in root profiles can be found.

This information is critical in the calculation of the root allometry individually and in collective form for each pine trees or shrubs. By example, for the biomass or volume calculation of an individual roots it is enough to know the root basal diameter of interest. It is possible to directly excavate each root at the stump base, measure its diameter and then calculate its length, volume or biomass employing equations developed in this study. That is, it is not necessary to excavate the root entirely. The root length is calculated with the use of the power equation that relates length to root basal diameter. It is recommended to use each equation separately per plant community. The mathematical procedure for the calculation of volume, biomass, or root length is by applying the conventional techniques of analytical or numerical integration of the taper model [1], fed with given parameters in this report. If the root mass is required then the resulting volume from integration of the taper equation has to be multiplied by the root basic density for each community. Extrapolations at the level of the stand must be cautiously taken since plant communities are composed of a mixture of species that may have different root features.

Aboveground biomass data reported by Návar *et al.*, (2002) for 37 quadrats of 5x5 m placed in the full distribution range of the Tamaulipan thornscrub in northern Mexico and 23 sites inventoried within the framework of the Mexican Forest Inventory 2004-2006 for pinyon pines of Nuevo Leon, Mexico were available for the calculation of root biomass and volume of these native forest communities. Calculations in Tamaulipan thornscrub forests included all shrubs of all species and all dimensions, db> 0.5 cm, while in pinyon pine forests only trees with diameter at breast height, dbh > 7.5 cm were inventoried.

RESULTS

The allometric equations that describe root biomass as a function of the stump basal diameter for both communities are reported in Figure 2. These mathematical functions are different from those reported by De Los Ríos-Carrasco and Návar (2009) because they do not include the belowground portion of the stump, where roots are inserted.

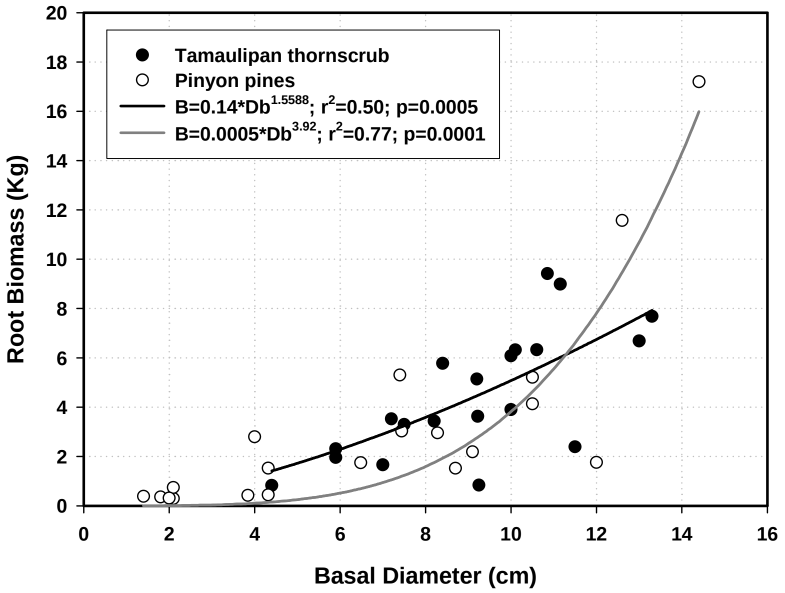

Figure 2. Allometric equations that describe the root biomass as a function of the stump basal diameter for two forest communities of the northeast of Mexico.

The power equations (transformation to the natural logarithm of both variables) suitably describe the relation between root biomass and the stump basal diameter for pinyon pine and Tamaulipan thornscrub forests (p=0.0001). The coefficients of determination of this relation are 77 and 50%, respectively. It is important to observe that in this rank of trees with low diameters, the allometric equation for thornscrub trees has a smaller slope (1.55) whereas for pinyon pines, the slope is greater (3.92). Nevertheless, ancova showed that plant communities have similar amounts of root biomass per unit of stump basal diameter (p=0.49), due to the high variation that shows the slope of both relations. It is important to note, that when the belowground part of the stump, where roots are inserted, is included in the root biomass component, the ancova separate these equations and they enter within the statistical significance (De Los Ríos-Carrasco and Návar, 2009). The slopes of the two plant communities seem to be a little slanted in contrast to those reported in the scientific literature. For example, for temperate pines of the north of Mexico, Návar (2009) reported the following equation to estimate root biomass [$0.0051D^{2.6680}$]. Guerra *et al.*, (2005) reported a slope figure of 2.48 for *P. radiata* plantations of southern Chile. Sierra *et al.*, (2007) calculated a slope value of 2.69 for primary and secondary tropical forests of Colombia. Giraldo *et al.*, (2007) estimated a slope figure of 2.12 for acacia trees of the Colombian Cauca region. Therefore, extrapolations of equations reported in this study must be cautiously conducted for trees of larger basal diameters or for other tree species.

The equations that describe the root volume allometry as a function of the stump basal diameter are reported in Figure 3.

The power equations (both variables transformed to the natural logarithm) fit well empirical data because the statistical significance of the models has a very low probability of rejecting the null hypothesis (p=0.0001). Ancova analysis showed that the plant communities have different volume amounts (p=0.0025), as well as different volume amounts per unit of stump basal diameter (p=0.023). That is, root volume of plant communities and the slopes of the equations are significantly different.

The relation between root biomass and root volume for two plant communities is displayed in Figure 4. The linear equation fits well the relation between root biomass and root volume for both plant communities (p=0.0001). Tree communities display different amounts of biomass per unit volume of roots. That is, the basic density (Mass / Volume), explained by the model slopes, is significantly different; with a mean (standard error) value of 0.7322 g cm^{-3} (0.026) for the thornscrub species and 0.8960 g cm^{-3} (0.044) for the pinyon pine species. These root basic densities are larger than the basic wood densities reported for the softwood and hardwood components of many forest species.

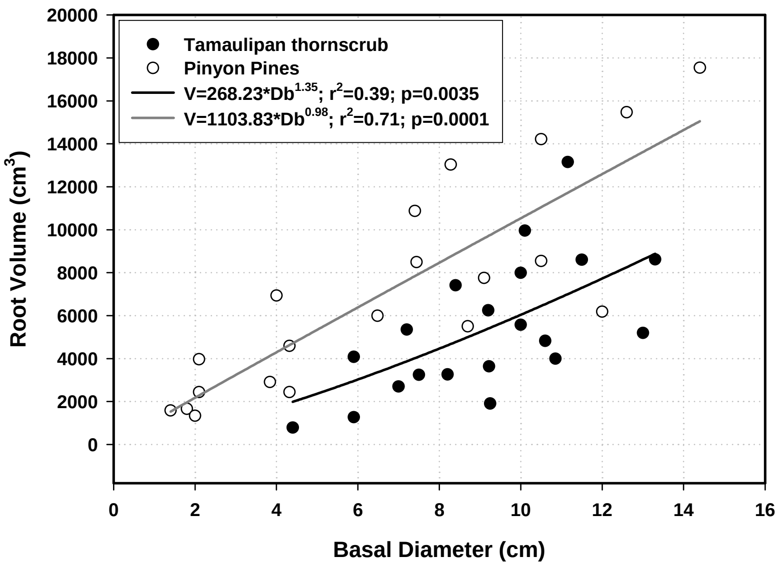

Figure 3. Root volume allometry for two forest communities of the northeast of Mexico.

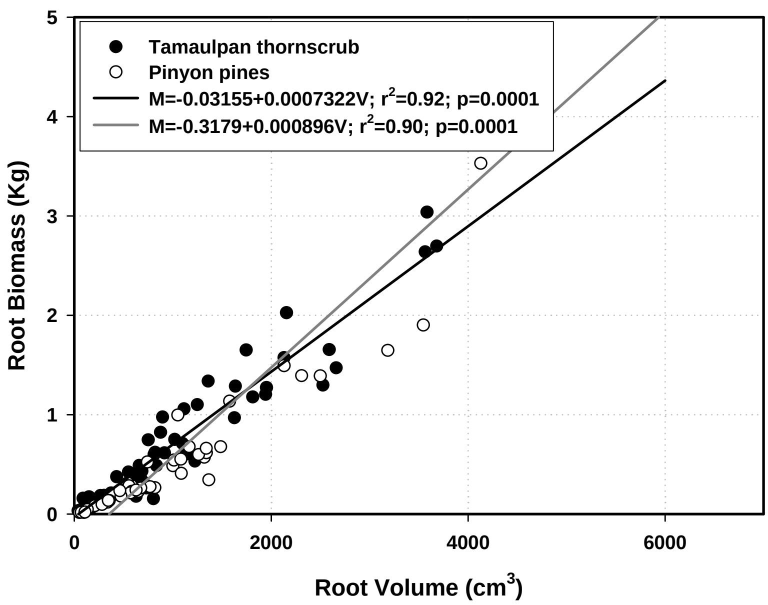

Figure 4. Allometric equations that describe to the relation between root biomass and root volume for two forest communities of the northeast of Mexico.

The relation top height as a function of the stump basal diameter appears in Figure 5. The ancova analysis describes that the power equation suitably fits the relation top height and stump basal diameter for both communities (p=0.0001). The slopes of this relation turned out to be statistically different (p=0.027), in contrast to the intercept (p=0.68). The mean slope (standard error) value for the Tamaulipan thornscrub community was 0.3588 (0.12) and that for the pinyon pine community was 0.89 (0.17).

The relation that describes root length as a function of the root basal diameter for selected measured roots fitted well with a power function (Figure 5).

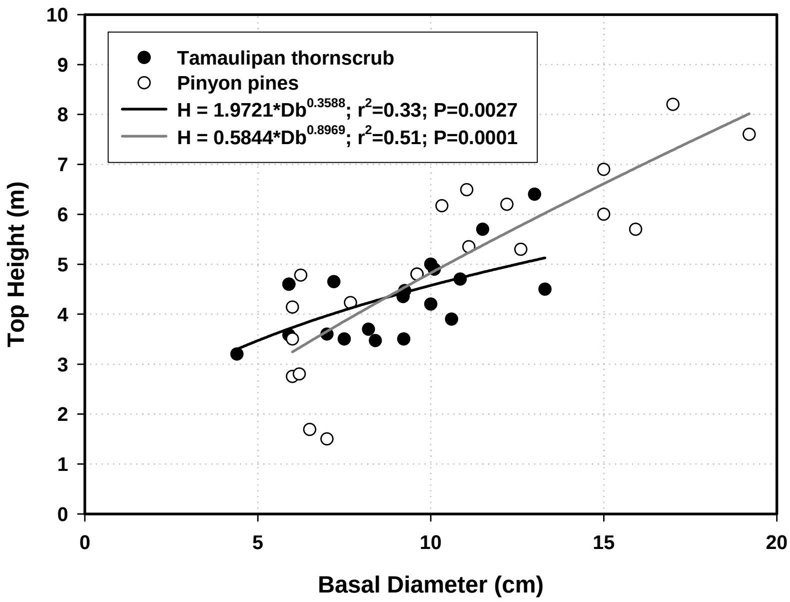

Figure 4. Allometric equations that describe the relation between top height and stump basal diameter of two forest communities of northeastern Mexico.

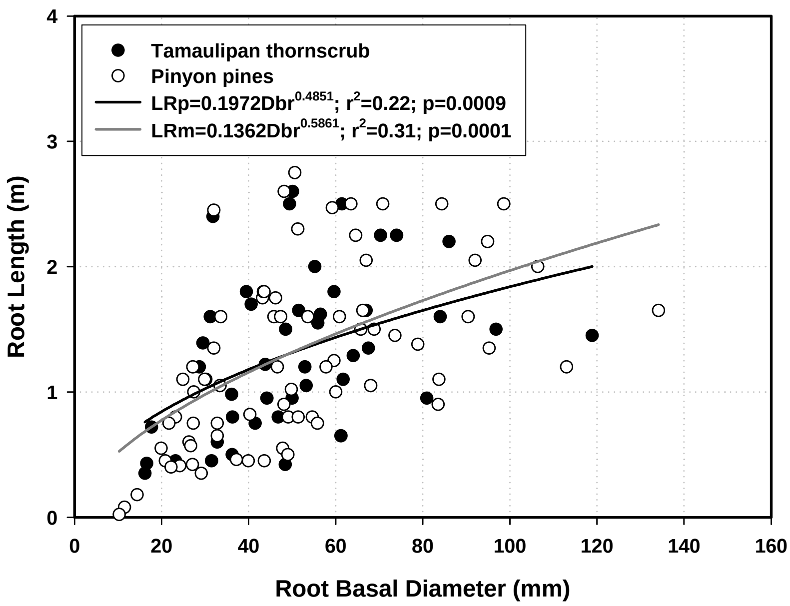

Figure 5. Allometric equations that describe the relation between the root basal diameter and root length for two forest communities of the northeast of Mexico.

The power equation statistically fitted well this relation, in agreement with the ancova analysis (p=0.0001). The root length is not different (p=0.31) nor is the slope between plant communities (p=0.077).

The root biomass and its relation with the root basal diameter for each individual root are reported in Figure 6. Root biomass is significantly different between plant communities (p=0.0069) and so is the slope of this mathematical relation between tree communities (p=0.0023).

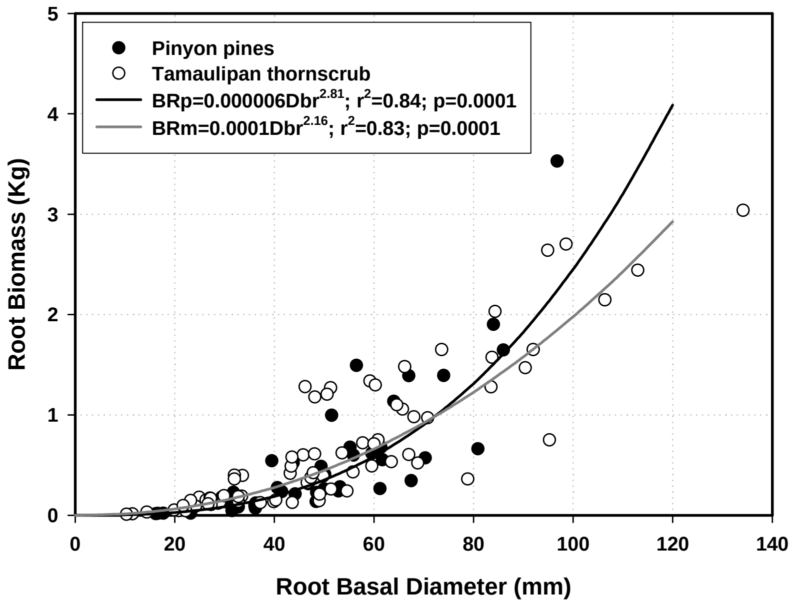

Figure 6. Allometric equations that describe the relation between the root basal diameter and the root biomass for two forest communities of the northeast of Mexico.

The slope of this relation for the Tamaulipan thornscrub was of 2.1481 (standard error = 0.1144) and the one for pinyon pines was 2.8055 (0.1816), showing that by each unit of basal diameter, the root biomass is greater in pinyon pine species. This finding is consistent with the greater calculated basic root density.

The relation between the root volume and the root basal diameter appears in Figure 7. Plant communities did not show significant differences in root volume when it is not weighed by root basal diameter (p=0.15) nor existed significant differences between the slopes of this relation (p=0.28).

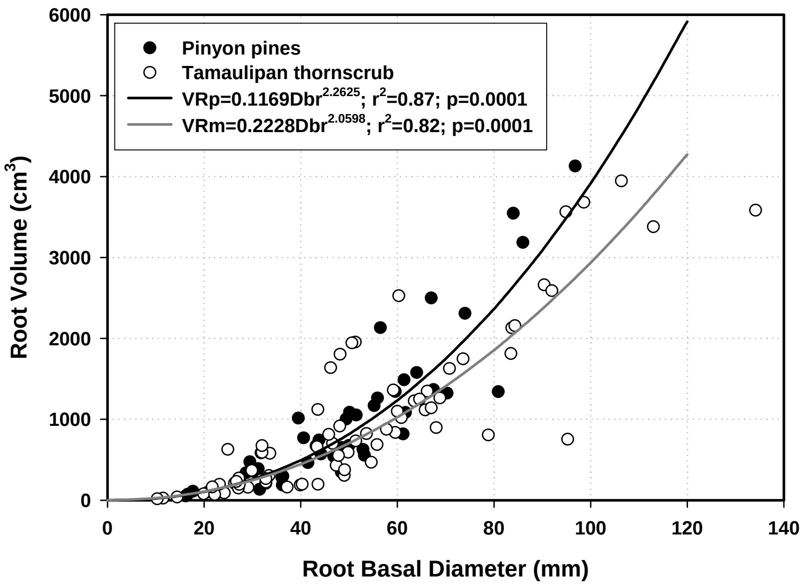

Figure 7. Allometric equations that describe the relation between root basal diameter and root volume for two forest communities of the northeast of Mexico.

The diameter profiles of roots turned out to be different between plant communities (Figures 8 and 9). For the Tamaulipan thornscrub species, roots are shorter for similar basal diameters, in proportion of almost 40% in relation to roots of pinyon pine forests. Whereas roots of the Tamaulipan thornscrub species reach 2.0 m with basal diameters of 1.75 cm, pine roots attain 3.25 m for similar root basal diameters.

The statistical parameters of the Newnham (1990) taper models indicate that the intercept (B0) is significantly different between plant communities. Nevertheless, the slopes (B1) for the lateral roots are significantly similar (Table 1). Most pinyon pine species did not display differentiated anchorage root systems and henceforth taper equations for this type of roots are not reported.

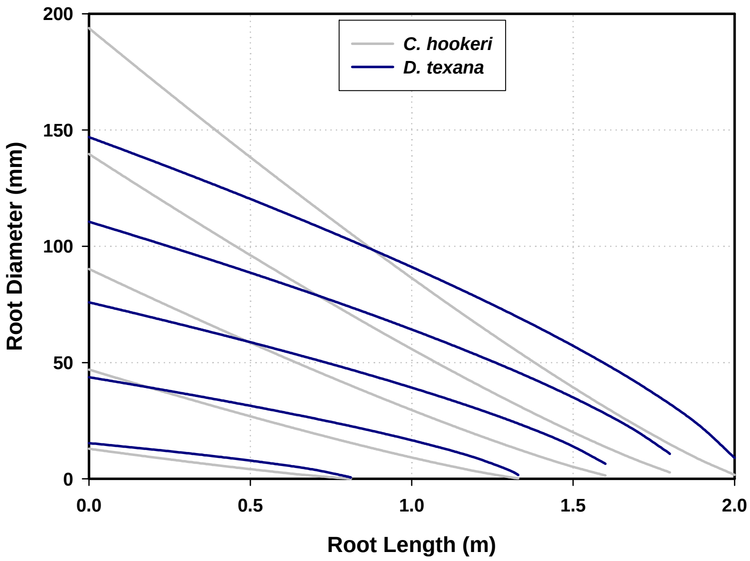

Figure 8. Modeled diameter root profiles for Tamaulipan thornscrub species of the northeast of Mexico.

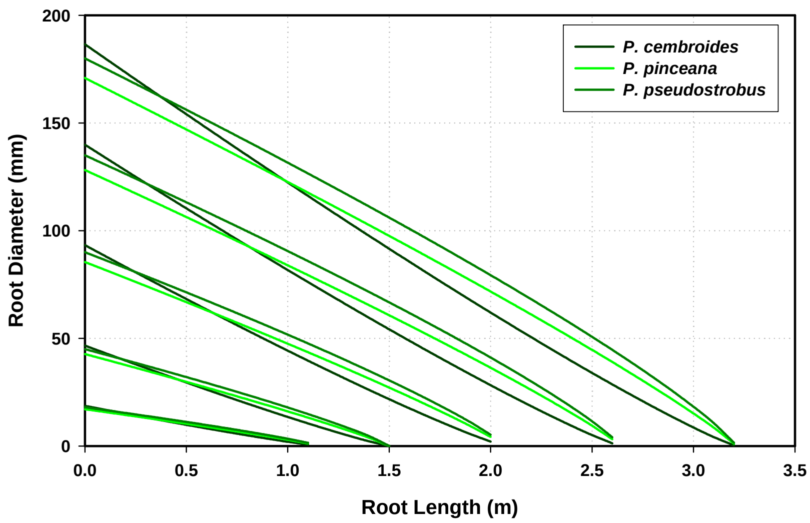

Figure 9. Modeled diameter root profiles for pinyon pine species of the northeast of Mexico.

Table 1. Statistical parameters of the Newnham (1990) taper model for Tamaulipan thornscrub species and for pinyon pine species of the northeast of Mexico.

	B0	CI	B1	CI	R2	Sx	N
C. hookeri	0.6786	0.04	2.40	0.25	0.78	0.14	596
Anchorage roots	0.6019	0.10	1.24	0.40	0.85	0.14	58
D. texana	0.7847	0.039	1.42	0.13	0.86	0.17	572
Anchorage roots	0.9478	0.070	1.13	0.19	0.95	0.12	52
P. cembroides	0.87	0.05	2.26	0.22	0.87	0.16	382
P. pinceana	0.73	0.04	1.78	0.17	0.86	0.14	407
P. pseudostrobus	0.81	0.03	1.68	0.10	0.88	0.15	835

Where: B0 and B1 are statistical parameter of the Newnham (1990) taper model, CI are the confidence intervals (α = 0,05), r2 = coefficient of determination, Sx = standard error of the estimator and N = number of observations.

DISCUSSION

Root allometry was developed for both plant communities. In general, power, linear and the non linear taper equations fitted measured data well. The ancova analysis showed that plant communities exhibited differences in root systems. A greater amount of roots per unit of basal diameter was found in dry pinyon pines that in sub-tropical Tamaulipan thornscrub species. For roots with similar basal diameters, the length of the root systems is greater also in pinyon pines than in thornscrub trees. The root basic density is greater in pines than in scrubs and as consequence root biomass per unit of basal diameter is greater in pinyon pines than in thornscrub trees. The root biomass is greater in scrubs of low stature in contrast to the pinyon pines, but as trees reach greater dimensions, the root biomass is greater in pines than in scrubs.

In addition to the tree age, resource availability in the environment, light, water and nutrients and the ecological relations such as competition, symbiosis, etc., modulate the dimensions of the root systems in plant communities. The area where Tamaulipan thornscrub distributes has a more negative water balance (745 mm of annual precipitation and close to 2000 mm of pan evaporation), in contrast to the area where the pinyon pines were reforested (640 mm of annual precipitation and 800 mm of pan evaporation). Therefore, the environmental variation given by the more negative water balances causes a substantial modification in the root systems i.e., the presence of anchorage roots that exploits deep soil profiles, as well as most lateral roots distributing close to the soil surface. Only the distal part, between the 15 and 25% of its final length is inserted more deeply into the soil. These root features allow subtropical shrubs to take advantage of both source of soil water; the superficial and underground soil water.

Considering that the water balance is more benign in pinyon pine communities, in the early stages of development, these have minor amounts of root biomass but greater amounts of root volumes. These results are consistent with observations made in other ecosystems. Barton and Montagu (2006), Zegada-Lizarazu *et al.* (2007) and Woods *et al.* (2007) observed in eucalyptus plantations of Australia, in semi-arid shrubs in the USA and seedlings of the Chihuahuense Desert, respectively that the root biomass was reduced by half in sites continuously irrigated in contrast to sites without irrigation.

The smaller volumes and length of roots in the subtropical Tamaulipan thornscrub obey partially to the so narrow competition that exists by soil water. This community have a stand density of between 5,000-20,000 shrubs per hectare (Návar *et al.*, 2002), with the presence of an important shrub diversity (15 species in sites of 1000 m^2) (Manzano and Návar, 2000). Therefore there exists inter and intra-specific competition by soil water. During the excavations root overlap was not observed, which partly explains the competition by the limiting site resources. Mahall and Callaway (1998) were able to monitor the inhibition of root growth of some species by the presence of others in semi-arid landscapes. The inter-specific competition by soil water occurs because it seems that there are more shrub species than adaptations to this water-deficit environment (Návar and González-Elizondo, 2009).

Preliminary root estimates of native *Pinus cembroides* communities of the northeast of Mexico, with the use of 23 sites sampled within the Mexican Forest Inventory framework, have (roots with d $\geq$1.0 cm) a mean (confidence interval) of 7.48 m^3 ha^{-1} (2.04 m^3 ha^{-1}). The total tree volume for bole, branches and roots is on average 74.74 m^3 ha^{-1} (23.24 m^3 ha^{-1}). Hence, the root volume represents 10% of the total tree volume at the stand level. Considering that the largest portion of roots is in the top 30 cm of soil, the root volume represents only 0.25% of the total soil volume. With the use of the basic density, the root biomass has an average (confidence interval) of 6.70 Mg ha^{-1} (1.83 Mg ha^{-1}). This value represents between 20 and 30% of the total tree biomass at the stand level, and it is consistent with estimates conducted by Murphy and Lugo, (1986); Castellanos et al, (1991) and Návar (2009), who recorded belowground biomass values between 20 and 36% of the total biomass.

Aboveground biomass estimates for data reported by Návar *et al*., (2002) for 37 quadrats of 5x5 m placed on the Mexican Tamaulipan thornscrub forests indicate that the root biomass has a mean (confidence interval) of 13.11 Mg ha^{-1} (1.42 Mg ha^{-1}) and this represents 24.70% (1.44%) of the total shrubby biomass (bole, branch, follage, and root) of this community. The estimated root volume averages (confidence interval) 15.76 m^3 ha^{-1} (1.70 m^3 ha^{-1}).

These estimates appear to indicate that the sub-tropical Tamaulipan thornscrub community displays greater root biomass and volume stocks in contrast to the pinyon pine community of the Central Plateau of northeastern Mexico. However, stand density and basal area of the sub-tropical thornscrub are greater than in the pinyon pine community. For Tamaulipan thornscrub forests, mean (confidence interval) stand density is 4160 shrubs ha^{-1} (543) with a mean basal area of 14.5 m^2 ha^{-1} (1.8 m^2 ha^{-1}). The dry-temperate forests of *P. cembroides* have a mean density and basal area (confidence interval) of 364 trees ha^{-1} (85 trees ha^{-1}) and 10.22 m^2 ha^{-1} (2.5 m^2 ha^{-1}), respectively. These convincing root system differences between plant communities were previously justified in terms of how they adapt to the environmental variation.

CONCLUSIONS

This research report emphasizes the development and use of root allometry of two contrasting plant communities of northeastern Mexico. Through modeling biomass, volume, length, and diameter of roots with d > 1.0 cm and statistically analyzing data by ancova tests, we observed that shrubs of the sub-tropical Tamaulipan thornscrub have minor volumetric amounts, shorter, and roots with smaller basal diameters than those of the pinyon pines of temperate-dry communities. Root allometry reported in this study provides the necessary information for the calculation of biomass, volume, length or the diameter profile of roots per individual tree or at the stand scale of these communities. Preliminary calculations in natural pinyon pine communities and Tamaulipan sub-tropical thornscrub forests show that the latter plant community could have the double of root biomass and volume than the former one. Higher stand density and larger basal area of Tamaulipan thornscrub plant communities explain these differences.

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