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BIOMASS ALLOMETRY FOR TREE SPECIES OF NORTHWESTERN MEXICO

[ALOMETRÍA PARA BIOMASA EN ESPECIES ARBÓREAS DEL NOROESTE DE MÉXICO]

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RESUMEN

La biomasa juega un papel importante en el manejo forestal sustentable. Esta variable es la base de la estimación de los almacenes y flujos de varios elementos biogeoquímicos, la cantidad de energía contenida y de otros bienes y servicios convencionales. El modelo matemático mas común en estudios de biomasa toma la forma de la función lineal logarítmica donde la biomasa se estima en función del diámetro a 1.3 m y de dos coeficientes escalares *a* y *B*. En este estudio se contestaron las siguientes preguntas relacionadas con el modelo alométrico: a) ¿Qué tan importante es desarrollar ecuaciones generalistas a la escala de la especie en contraste con ecuaciones locales a la escala de la especie-sitio; b) ¿Cual es el número adecuado de datos para ajustar una ecuación alométrica?; y c) ¿Es posible desarrollar ecuaciones con un número menor o nulo de datos sin perder confiabilidad en la estimación de la biomasa? Con el uso de una fuente de datos de biomasa colectados en el noroeste de México para nueve diferentes especies, medidos en seis diferentes sitios desde el sur de Chihuahua hasta el sur de Durango, México se encontraron respuestas a estas preguntas. Se observa que se obtiene una ganancia de cerca del 5% en el coeficiente de determinación y del 20% en el error estándar cuando se ajustan ecuaciones al niveles de la especie para cada sitio específico. El número de datos mínimo necesarios es de 60 para ajustar estas ecuaciones con coeficientes escalares con la menor varianza y mas consistentes. Se presentan dos modelos: a) restrictivo en el bajo número de árboles derribados a tres para ajustar ecuaciones alométricas disponibles y b) un modelo no-destructivo para ajustar ecuaciones con el nivel de confiabilidad que presentan las ecuaciones alométricas convencionales. Ambos métodos proveen estimaciones de biomasa dentro de los límites impuestos en la pendiente del coeficiente escalar *B* de la ecuación convencional.

Palabras clave: Modelos alométricos convencionales; restrictivos y no destructivos; biomasa arbórea total; relaciones dimensionales y de forma; noroeste de México.

ABSTRACT

Tree biomass plays a key role in sustainable forest management since it is the basis for estimating stocks and fluxes of several biogeochemical elements, the amount of energy stored in biomass, and other conventional goods and services. The most common mathematical model takes the form of the logarithmic equation where biomass is estimated as a function of diameter at breast height, dbh, with the scaling coefficients *a* and *B*. In this study, I answered the following questions related with the allometric model: a) Is it important to develop biomass equations at the species scale or at the site-specific scale?; b) What is the least number of data required for fitting an allometric equation?; and c) Is it possible to develop allometric equations with few or null biomass data without loosing accuracy in biomass estimation? I employed a biomass data source collected in northwestern Mexico for nine different forest species, collected in six different sites from southern Chihuahua to southern Durango, Mexico to answer these questions. Results showed that by fitting site-specific biomass equations there is a net gain of 5% in the coefficient of determination and close to 20% in the standard error in contrast to fitting an equation at the species level. The minimum number of observations needed is 60 harvested trees to calculate parameters with the least variance and with high consistency. I present two alternate restrictive methods of biomass estimation: a) restricting the number of harvested trees to three to fit equations available in the scientific literature and b) a non-destructive model to fit equations with the same level of accuracy that display conventional allometric models. Both methods estimate biomass within the confidence bounds imposed on the *B* coefficient of the conventional allometric model.

Keywords: Allometric conventional; restrictive and non-destructive models; Total Aboveground biomass; size-shape relations; northwestern Mexico.

INTRODUCTION

The estimation of tree biomass is necessary in the evaluation of: a) the carbon stocks and fluxes (Brown, 1997; Návar, 2009a); b) the amount of primary energy that is obtained from forests as an alternative to fossil fuels (Richardson et al., 2002); c) the stocks and fluxes of other biogeochemical elements such as nitrogen (Hughes et al., 1999) and other conventional goods and holistic services. Biomass is a fundamental state variable of several ecological and eco-physiological models (Zianis and Mencuccini, 2004).

The development and application of allometric equations are the standard methodology for the estimation of tree and stand biomass (Brown et al., 1989; Chavé et al., 2001; 2003; Návar, 2009a). The logarithmic equation that relates biomass, M, with diameter at breast height, D, is classic in this type of studies (model [1]).

$$\text{Ln}(M) = \text{Ln}(a) + B\,\text{Ln}(D) \qquad [1]$$

Where: *a* and *B* are scalar coefficients that are estimated by least square techniques in linear regression.

The estimation of bole volume and the multiplication by its wood basic density value is another procedure of biomass estimation (Mohren and Klein Goldewijkt, 1990). The expansion factors of bole volume to biomass at the tree or stand scale are now common in the scientific literature (Gracia et al., 2004; Návar-Cháidez, 2009; Silva-Arredondo and Návar-Cháidez, 2009), which are calculated by employing volume and biomass equations. Zianis and Mencuccini (2004) introduced a reductionist model, which harvest only a few trees of the stand to fit and validate already known biomass equations.

An allometric non-destructive model based on the fractal theory developed by West et al., (1999), where the main assumption is that the D is related to biomass, M, by $M < D^{3/8}$ indicates that the exponent *B* equals to 2.67 (Enquist et al., 1998). This approach requires further refinement to be used in biomass estimation and discussions on the search and application of this non-destructive of biomass estimation technique are ongoing (Zianis and Mencuccini, 2004, Pilli et al., 2006; Návar, 2009b). In spite of the current discussion, the methodology of fractals has not been fully explored in estimating biomass of trees and forests as a non-destructive alternative. Návar (2010) proposed a new non-destructive method of biomass estimation that uses the fractal theory in conjunction with size-shape relations of trees. However, this technique requires further assessment to evaluate its feasibility in other tree communities.

Regardless of the wide range of allometric equations reported (see the compilations conducted by Ter Mikaelian and Korzukhin, 1997; Zianis and Mencuccini, 2004; Návar, 2009b), there are still renewed efforts to estimate biomass more precisely at the local, regional or national scales. Then several questions arise when sampling trees to improve efficiency at developing and using biomass allometry. There is currently a tendency to fit allometric equations for complex forests with the inclusion of wood basic density parameters (Chavé et al., 2003; Návar, 2009a) or a parameter that describes plant community diversity (Návar et al., 2002) as an aid to improve precision or to reduce unexplained biomass variation.

Therefore, the objective of this study was to answer three basic questions related to sampling in the development and use of biomass equations: a) What is the precision involved when developing equations at the species level in contrast to at the site species-specific models?; b) What is the minimum number of data necessary to fit an allometric equation with scalar coefficients that are consistent and have least variance?; and c) Is it possible to develop allometric equations with a small or null number of harvested trees without losing confidence in the estimation of this parameter? These questions were answered using a biomass data sample of 794 trees of the species *Pinus*, *Quercus* and species of the tropical dry forests of northwestern Mexico.

MATERIALS AND METHODS

Allometric data

A list of 794 trees data consisting on total aerial biomass, diameter, top height, and bole volume distributed from southern Chihuahua to southern Durango was used in answering questions raised previously. Equation parameters, goodness of fit statistics and diameter range values are reported in Table 1. This data source was originally reported by Návar (2009a) and Návar-Cháidez (2009) as allometric equations with estimated scalar coefficients by non linear regression at the species level and biomass data of young pines was reported in Návar et al. (2004) as seemingly unrelated equations. None of these equations were reported following the conventional log transformed M-D data; i.e. $\text{Ln}(M) = \text{Ln}(a) + B\text{Ln}(D)$. The list of trees comprised 40 trees of tropical dry forests of eastern Sinaloa; 104 trees of the species *Quercus* spp of Durango and Southern Chihuahua and 594 trees of the species *Pinus* (*P. durangensis* (199), *P. cooperi* (48), *P. ayacahuite* (60), *P. arizonica* (128), *P. leiophylla* (31), and other pine trees (72)). In addition data on 56 young pine trees (*P. durangensis*, *P. cooperi*, *P. engelmannii*, *P. teocote*) of south Central Durango was used to test hypotheses implicitly described in all three questions. This source of data was collected in reforested stands with ages < 20 years in the Sierra Madre Occidental mountain range of Durango, Mexico. For the development of conventional biomass equations for several pine and oak species (*P. arizonica*, *P. leiophylla*, *P. durangensis*, *Quercus spp*), trees were harvested from Guachochi in southern Chihuahua to southern Durango in Mezquital, Mexico; with six major centers of data collection: southern Chihuahua (Guachochi, Papajichi and Caborachi); northern Durango (El Tule, La Soledad and El Tarahumar); Central Durango (Altares, El Negro and Topia); south Central Durango (Tambores, San Bartolo, San Manuel, El Salto) to southern Durango (Santiago Teneraca). This wide spatial distribution range caused the data to exhibit a large biomass variation, in all but of paramount importance in the branch component because trees were collected on a diversity of forest types, with different management systems and as a result from different levels of stand stocking.

Table 1. Scalar coefficients and goodness of fit parameters for the conventional allometric equation [1] at the site-specific scale for 22 allometric studies of northwestern Mexico.

		Coefficients and Parameters of Model [1]					Diameter Range		
Site	Species/Genus (n)	*a*	*B*	S_B	r^2	MSE	Min	Max	Mean
1. S. Chihuahua	*P.arizonica* (n=30)	-1.482	2.129	0.1697	0.84	0.026	16.20	32.90	25.70
2. S. Chihuahua	*P.durangensis* (n=30)	-3.532	2.731	0.1478	0.92	0.054	12.10	46.00	27.40
3. S. Chihuahua	*Qurcus spp* (n=45)	-2.144	2.403	0.1275	0.89	0.060	15.40	48.70	29.10
4. El Salto, Dgo	*P.cooperi* (n=20)	-1.922	2.321	0.1596	0.93	0.068	12.50	57.40	31.70
5. El Salto, Dgo	*Q.sideroxylla* (n=30)	-2.592	2.585	0.1093	0.95	0.061	9.80	62.50	27.80
6. Tepehuanes, Dgo.	*P.arizonica* (n=36)	-3.573	2.746	0.0897	0.96	0.038	10.00	45.00	22.60
7. Tepehuanes, Dgo.	*P.durangensis* (n=15)	-3.416	2.715	0.1405	0.96	0.039	11.80	57.20	24.30
8. Tepehuanes, Dgo.	*P.leiophylla* (n=12)	-3.039	2.523	0.2237	0.92	0.058	13.90	34.80	21.30
9. Altares, Dgo	*P.arizonica* (n=60)	-0.877	1.980	0.0560	0.81	0.094	9.90	45.00	25.70
10. San Dimas, Dgo	*P.ayacahuite* (45)	-3.066	2.646	0.0690	0.97	0.044	5.70	30.30	15.40
11. San Dimas, Dgo	*P.cooperi* (n=12)	-3.264	2.707	0.1100	0.90	0.274	8.20	38.10	18.40
12. San Dimas, Dgo	*P.durangensis* (n=71)	-2.084	2.323	0.0680	0.94	0.074	6.20	48.50	18.70
13. San Dimas, Dgo	*P.leiophylla* (n=15)	-3.549	2.787	0.1020	0.94	0.065	9.60	29.00	20.20
14. Mezquital, Dgo	*P.oocarpa* (31)	-3.065	2.625	0.1030	0.93	0.061	12.20	44.80	25.20
15. Mezquital, Dgo	*P.pseudostrobus* (n=24)	-2.611	2.531	0.2700	0.88	0.047	12.00	32.00	19.60
16. Mezquital, Dgo	*P.teocote* (n=49)	-3.182	2.702	0.0690	0.96	0.050	7.30	43.30	21.90
17. Mezquital, Dgo	*Quercus spp* (n=17)	-2.754	2.574	0.0700	0.94	0.089	7.30	41.20	21.10
18. Topia, Dgo	*P.durangensis* (n=60)	-2.108	2.373	0.0606	0.96	0.019	11.80	48.40	26.00
19. E. Sinaloa	*Tropical Dry trees* (n=40)	-2.523	2.437	0.1993	0.80	0.443	5.20	32.60	14.80
20. Durango-S. Chihuahua	*Pinus spp* (n=520)	-2.818	2.574	0.0260	0.94	0.076	5.70	57.40	23.50
21. Durango-S. Chihuahua	*Quercus spp* (n=106)	-2.874	2.631	0.0807	0.93	0.078	7.30	62.50	26.80
22. El Salto, Dgo	*Young pine trees* (n=56)	-3.139	2.585	0.1576	0.83	0.165	3.8	16.0	9.7

Where: Dgo. = Durango, *a* and *B* scalar coefficients of the conventional allometric biomass model, S_B = standard error of *B*; r2 = coefficient of determination; MSE = Mean square error; Min = Minimum Max = Maximum. The coefficients r2 and MSE were calculated from the logarithmic model.

Allometric equations estimate total aerial biomass including bole and bark and branches and leaves. The first two and the last two biomass components were jointly weighted. For all 22 case studies, three major plant communities were studied: *Quercus* spp, *Pinus* spp and species of tropical dry forest; seven tree species: *P. arizonica*, *P. durangensis*, *P. leiophylla*, *P. cooperi*, *P. ayacahuite*, *Quercus* spp and species of tropical dry forest. In the 22 case studies, the interval in diameter ranged from 3.8 to 62.5 cm with an average 20.0 cm. This source of data represents an un-biased sample of the relation *M–D* for species found in forest communities of northwestern Mexico. The diameter structure of sampled trees resembles the diameter structure of the standing trees inventoried in forests of the South Central portion of the western Sierra Madre mountain range of Durango, Mexico (Figure 1).

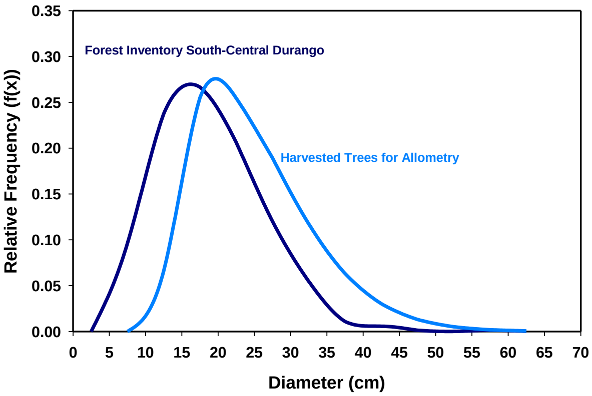

Figure 1. Diameter structures of trees harvested of the species *Pinus* and of the forest inventoried in the South Central portion of Durango, Mexico.

The questions previously raised were answered with this source of biomass data as it is described next. Question a) (what is the precision involved when developing equations at the specific in contrast to at the site-specific scale?) was answered by developing allometric equations at the species and at the site-specific scales. The minimum number of data for fitting model (1) for each species of each site was 12. The goodness of fit statistics of the transformed allometric model at both scales was obtained from the SAS proc Reg procedure. A coefficient of gain in precision was obtained, according to model [2]:

$$CG = \frac{\left[CA_{ee} - CA_{ee-s}\right]}{CA_{ee}} x100 \qquad [2]$$

Where: CAee = Goodness of fit coefficient at the species level; CAee-s = Goodness of fit coefficient at the level of the species for each site.

The coefficient of determination, r^2, the standard error, Sx, and the coefficient of variation, C.V. were employed in calculating the gain coefficient.

The second question raised was; b) what is the minimum number of data necessary to fit the conventional equation with scalar coefficients that are consistent and have least variance? In order to answer this question, 594 pairs of M-D data of *Pinus* spp were ranked by diameter and samples were selected proportionally per diameter class. Samples consisted on randomly selecting the 2, 5, 8, 10, 15, 20, 25, 30, 40, 50, 60 and 70% of the data proportionally per diameter class for fitting the allometric model [1]. The scalar coefficients, *B* and *a*, were graphed as a function of the percentage of data used in calculating these parameters. The standard error of *B*, S_B, was also graphed in order to understand their oscillating behavior or tendency as a function of a theoric population mean. It is preliminarily predicted that the scalar coefficients *a* and *B* for each sample would randomly oscillate around the *a* and *B* scalar coefficients obtained from the 594 M-D pairs of data. The oscillation diminishes as the sample size increase and eventually converges within the intervals of standard error, S_B. The point of convergence is taken in here as the minimum number of data to use in estimating *a* and *B* that are consistent with the population mean and have a theoric population variation.

The third question establishes; c) is it possible to develop allometric equations with a small or null number of harvested trees without losing confidence in biomass estimation? Two methodologies were used: a) the restrictive model proposed by Zianis and Mencuccini (2004) and b) the non-destructive model proposed by Návar (2010). The restrictive approach theoretically harvested only 3 trees of the smallest diameter classes to measure total aboveground biomass, since trees with small diameter dimensions exert an important control on the direction and tendency of the allometric equation (Chavé et al., 2003). Already derived allometric equations are employed to estimate TAB for these theoric harvested trees as well as for the remaining trees in each sample. Once one equation or a mixture of equations is selected based on the least variance between measured and estimated TAB for trees with small diameter, biomass is estimated for the rest of trees that were theoretically harvested. In general, an average of published equations estimated better TAB.

In the non-destructive model proposed by Návar (2010) uses the fractal theory in conjunction with the size and shape relations to estimate *B* with the use of the allometric functions of bole volume, V, and H-D by fitting the classic equation of Schumacher and Hall

(1933) in a logarithmic fashion, and a power relation equation for the estimation of *a* is implemented with the independent variable *B* for the already reported allometric equations in the region. The details of the fractal theory and the size-shape relations to calculate *B* is more explicitly explained in Návar (2010) and Zianis and Mencuccini (2004), respectively.

Nine biomass studies at the species level were used to calculate TAB with calculated *a* and *B* scalar coefficients by the conventional, the restrictive and non-destructive models. Allometric equations were developed following model [1] for *P. arizonica* (n=126), *P. durangensis* (n=197), *P. cooperi* (n=46), *Quercus* spp (n=103), *P. ayacahuite* (n=58), *Pinus leiophylla* (n=31), *Pinus* spp (n=594), young Pines of Durango (n=56) and trees of tropical dry forests of Sinaloa (n=40). The conventional procedure estimates the scalar coefficients *a* and *B* by least square techniques in linear regression with transformed M-D data to the natural logarithm. The restrictive method used for pine species several equations reported by Ter Mikaelian and Korzukhin (1997) for *P. taeda* of North Carolina; *P. contorta* for Idaho and Montana, *P. ponderosa* for Arizona, *P. monticola* for Idaho and Montana and *P. albicaulis* for Idaho and Montana, in addition to the equation of *P. pseudostrobus* for Nuevo Leon, Mexico developed by Rodriguez-Laguna et al. (2007). For the genus *Quercus* spp, the equations developed for *Q. laceyi*, *Q. rizophylla* and *Q. cambyi* by Rodriguez-Laguna et al., (2007) for the Mexican State of Nuevo Leon were used to estimate total aboveground biomass. For tropical dry trees the equations reported by Brown (1997) for tropical dry forests of the world and by Martinez-Yrizar et al. (1992) for tropical dry forests of Jalisco, Mexico were employed. The non-destructive method calculates the scalar coefficient *B* by using the power coefficients of that describes H as a function of D. An empirical the bole volume equation of V= f(D-H); i.e., Ln(V) = Ln(a) + b1Ln(D) + b2Ln(H); and the power equations of H=f(D); i.e., Ln(H) = Ln(a) + b3Ln(D); i.e. *B*=b1+b2*b3. The following empirical equation for the calculation of *a* was developed for this study by using *B* as independent variable; $a = 160.16B^{-8.3875}$; r2=0.96, following the consistency of these equations reported in Zianis and Mencuccini (2004); Pilli et al. (2006); Návar (2009a; 2009b).

Total aboveground biomass was estimated by model [1] with scalar coefficients estimated by all three independent procedures; the conventional, the restrictive and the non-destructive approaches. Measured and estimated TAB in original units provided enough data for the calculation of the goodness of fit parameters r2, Sx and CV. Finally, measured and estimated TAB data were graphed as a function of D. For the conventional model the confidence bounds on the standard error of *B*, S_B, were also graphed with the objective to observe if estimated biomass by the other two procedures fall within the intervals of the conventional model.

RESULTS

Allometric equations at the level of the species or the species by site

Biomass equations at the site-specific level provide better goodness of fit statistics in contrast to the equations at the species level (Table 2). That is, it is more accurate to develop local than regional biomass equations. When increasing the number of M-D data of trees collected in other areas, the variation in total biomass increased.

Table 2. Goodness of fit statistics for the conventional allometric model fitted at the species scale.

	Conventional allometric model				Gain (%)		
Species	n	C.V.	r^2	Sx (kg)	C.V.	r^2	Sx (kg)
P. arizonica	126	18.35	0.94	45.38	1.94	**3.63**	8.29
P. durangensis	197	47.58	0.83	135.11	5.62	4.06	23.72
P. cooperi	46	28.93	0.91	142.97	10.54	4.66	28.89
P. ayacahuite	58	31.72	0.96	61.73			
P. leiophylla	31	32.21	0.87	46.65	35.81	3.35	9.90
Pinus spp	594	43.62	0.86	125.10	27.43	2.66	41.07
Young *pines*	56	48.65	0.69	9.71	21.33	11.90	12.00
Quercus spp	103	30.48	0.91	127.46	2.98	**1.25**	3.46
Average					15.09	5.327	18.19

The best goodness of fit statistics is noted when fitting allometric equations at the site-specific level, since the standard error is reduced on the average by 20%, with range values from 3 to 41%. The coefficient of variation also diminishes, on average by 15%, with minimum and maximum values of 2 and 36%. The coefficient of determination records the smallest gain, with an average of 5% and minimum and maximum values from 2.6% in *Pinus spp* up to 11.9% in young pine trees. It can be stand out that in two species; *P. arizonica* and *Quercus spp*, the coefficient of determination in reality diminished when the equations were fitted at the level of the species by site. The largest gain is noted when site-specific equations are fitted, in contrast to when one equation is fitted for all trees for *Pinus* spp, because variation in model fitting diminishes by close to 27% and the r2 increases by 3%. That is, as the number of observations increases so does the biomass variation for *Pinus* spp, as well.

The minimum number of data to fit allometric equations

The minimum number of data pairs to fit allometric equations with the smallest variation in the scalar coefficients *a* and *B* is defined between 60 and 90 and equitably distributed by diameter class of trees recorded in the forest inventory (Figure 2).

The scalar coefficients *a* and *B* exhibit a large variation with a few M-D data pairs (n < 15%) and tend to converge on the average into the variation of the population parameter when n > 15%. The standard error in *B*, S_B, also diminishes as a function of D with a power tendency (Figure 3). Therefore, it is recommended to use between (594x0.10 or 594x0.15) 60 to 90 M-D data pairs to estimate scalar coefficients with the least variation, within the standard error of *B*, with small *B* variation, and that are consistent with the population parameters.

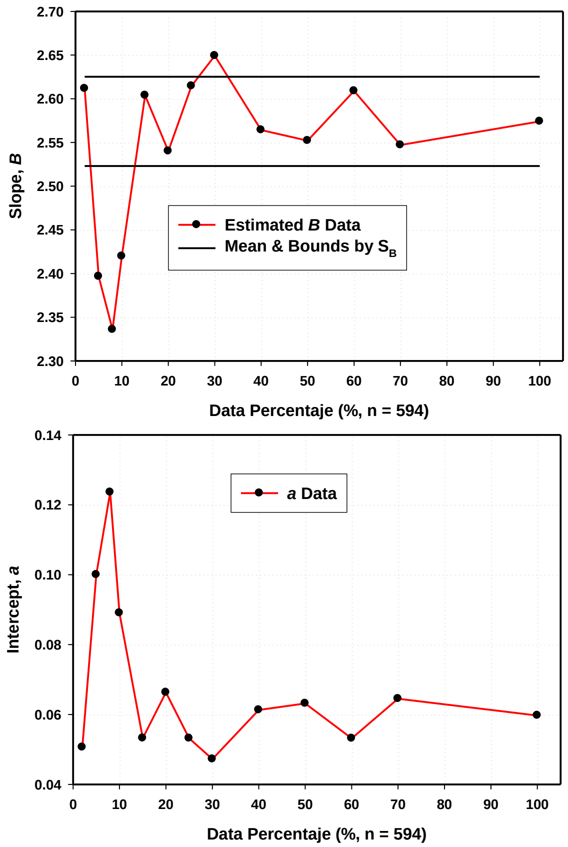

Figure 2. Tendency of the scalar coefficients *a* and *B* as function of the percentage of data used in fitting the conventional allometric model [1] for 594 pine trees of northwestern Mexico.

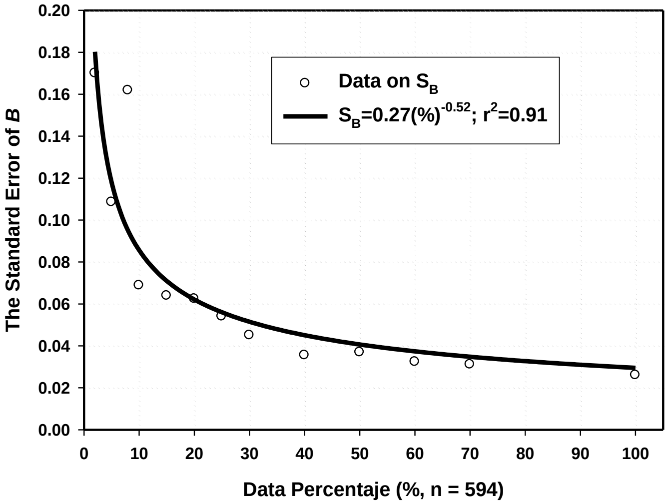

Figure 3. Tendency of the standard error of the *B*- scalar exponent based on the percentage of data used in fitting the conventional allometric model to 594 pine trees of northwestern Mexico.

Allometric equations developed with a small or null M-D data pairs.

The scalar coefficients of the conventional, restrictive and non-destructive model appear in Table 3. The mean *B* coefficient is significantly equal for all three procedures of estimation because the averages and intervals of confidence overlap for the non-destructive (2.4388 ± 0.112), restrictive (2.5326 ± 0.0931) and conventional (2.5498 ± 0.0541) models.

The maximum values that reach with the sum of the mean and confidence intervals are 2.55, 2.62 and 2.60, respectively. That is, these figures are significantly different (p=0.05) from the value of 2.67 proposed by West et al. (1999) and by Enquist et al. (1998). These authors using the theory of fractals came up with the constant 8/3 as the standard slope for the allometric equations of any species. The intercept, *a*, values do not significantly differ either between models, since the non-destructive has an average (confidence interval) of 0.105 (± 0.0347), the restrictive of 0.0614 (± 0.0277) and the conventional model of 0.0634 (± 0.0098). The *a* values and their variations are similar between the restrictive and conventional models.

The scalar coefficients for the conventional and the restrictive models, like the relationship that uses the non-destructive model, are related by a negative power function (Figure 4). That is, *a* decays in power fashion with an increase of *B* for all models. High values of *B* are related to small and less-variable values of *a*. The coefficients of this relation are similar to those reported by Návar (2009a) whose models are also reported in Fig. 4 and that was used in this study for the estimation of *a* in the non destructive method.

The evaluation of the allometric model [1] with three procedures of parameter estimation as a function of the measured biomass data is reported in Table 4 for each one of the studied species.

The non-destructive and restrictive methods of coefficients estimation have similar average parameters of goodness of fit and they show less precise goodness of fit statistics than those recorded by the conventional method (Table 4). The upper and lower values calculated by the average ± the confidence interval show that these parameters are not statistically different to each other. These values are smaller than those calculated by nonlinear regression by Návar (2009a) partially because they were not weighted by the typical correction factor determined by Bekersville (1972).

The restrictive method provides suitable biomass estimates because it is in general within the confidence intervals of the conventional equation (Figure 5). It results in good TAB estimations for *Quercus* spp, trees of tropical dry forests, *P. leiophyla* and young pine trees. Only in three (*Pinus* spp, *P. cooperi* and *P. ayacahuite*) out of nine cases the restrictive model provides estimations outside the limits of the standard error of *B*. Aboveground estimates by the non-destructive method fall within the intervals of confidence of the conventional model for all reported cases. For *Pinus* spp, *P. arizonica*, *P. durangensis*, and *P. ayacahuite* the non - destructive model estimate TAB values that are least skewed. In general, the restrictive and non-destructive methods provide TAB estimates within the confidence bounds given by diverse biomass equations fitted for the same plant community (i.e., Návar, 2010).

Table 3. Scalar coefficients of the conventional allometric biomass model estimated by three independent procedures for tree species of the northwest of Mexico.

	Parameters of Biomass Models: Ln (M) =Ln (a)+BLn (D) =aD^B						
	Non-destructive		Restrictive		Conventional		
Species	a	B	a	B	a	B(S_B)	CF
P. arizonica	0.1588	2.2810	0.0403	2.6062	0.0572	2.5569 (0.055)	1.0186
P. durangensis	0.0787	2.4800	0.0409	2.6025	0.0880	2.4540 (0.042)	1.0368
P. cooperi	0.0686	2.5210	0.0405	2.6064	0.0666	2.5804 (0.069)	1.0297
Quercus spp	0.1912	2.2310	0.0975	2.4477	0.0632	2.5852 (0.081)	1.0526
P. ayacahuite	0.0332	2.7490	0.0423	2.5915	0.0428	2.6991 (0.061)	1.0302
P. leiophylla	0.0487	2.6260	0.0416	2.5960	0.0708	2.4874 (0.152)	1.0463
Pinus spp	0.1353	2.3250	0.0410	2.6019	0.0597	2.5741 (0.026)	1.0390
Young pines	0.0987	2.4140	0.0452	2.5635	0.0433	2.5851 (0.158)	1.0862
Tropical dry forests	0.1367	2.3220	0.1633	2.1775	0.0789	2.4260 (0.199)	1.2534
Average	0.1056	2.4388	0.0614	2.5326	0.0634	2.5498	1.0659
Standard deviation	0.0532	0.1714	0.0425	0.1424	0.0150	0.0827	0.0729
Interval of Confidence	0.0347	0.1120	0.0277	0.0931	0.0098	0.0541	0.0476

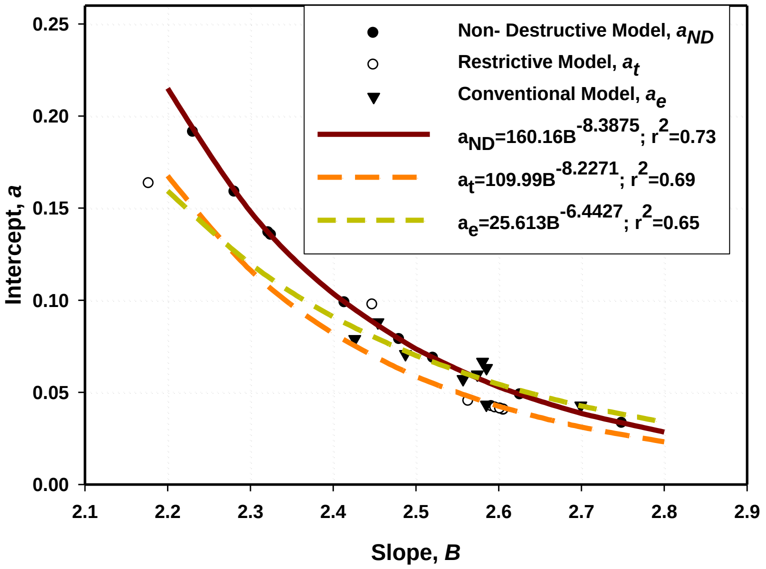

Figure 4. Relations between the scalar coefficients of the restrictive, non-destructive and conventional methods of parameter estimation for species reported in Table 4.

Table 4. Parameters of goodness of fit by evaluating allometric model [1] to the measured biomass data of with scalar coefficients estimated by the conventional, restrictive and non-destructive procedures.

	Conventional			Restrictive			Non-Destructive		
Species	R^2	S_X	C.V (%)	R^2	S_X	C.V (%)	R^2	S_X	C.V (%)
P. arizonica	94	45.38	18.35	88	61.64	24.92	92	50.47	20.40
P. durangensis	83	135.11	47.58	76	162.33	57.17	84	168.64	59.39
P. cooperi	91	142.97	28.93	73	243.02	49.17	90	148.86	30.12
Quercus spp	91	127.46	30.48	99	52.88	12.65	82	183.17	43.81
P. ayacahuite	96	61.73	31.72	80	132.04	67.85	96	61.60	31.65
P. leiophylla	87	46.65	32.21	81	55.38	38.24	76	62.46	43.13
Pinus spp	86	125.10	43.62	75	168.84	58.87	86	127.74	44.54
Young pine trees	69	9.71	48.65	69	9.78	48.96	45	12.94	64.78
Tropical dry forests	73	55.61	64.17	73	54.87	63.32	65	62.60	72.24
Average	85	83.30	38.41	79	104.53	46.80	79	97.61	45.56
Standard deviation	9.09	49.21	13.78	9.09	75.65	18.36	15.65	60.26	17.13
Interval of Confidence	5.94	32.15	9.00	5.94	49.42	12.00	10.22	39.37	11.19

DISCUSSION

In this study, I solved three questions related to sampling for developing and using biomass allometry. It is recommended to conduct allometric studies for local species rather than by single tree species harvested on a broad, ample area and that between 60 to 90 trees proportionally distributed by diameter class are required to obtain scalar coefficients *a* and *B* that are consistent with population parameters and that have least variance. Finally, two restrictive methods are proposed that computes TAB within the confidence bounds of the conventional allometric model and the variation expected when fitting multiple biomass equations for one plant community or forest type. Of these, the non-destructive method is a viable alternative when preliminary developing projects of TAB estimation. Allometric equations developed off site estimates biased TAB values (Figure 6). Therefore, when using a single reported equation, it is recommended to employ the restrictive methods to have two other independent allometric models and a mean of these equations would probably improve TAB estimates. The site-specific equations for restricted sites are useful in the development of sustainable management of local forest resources. Its application to other species or the same species for other areas must be cautiously carried out. If possible they could be combined with proven restrictive methods as those reported in this study to improve TAB estimates.

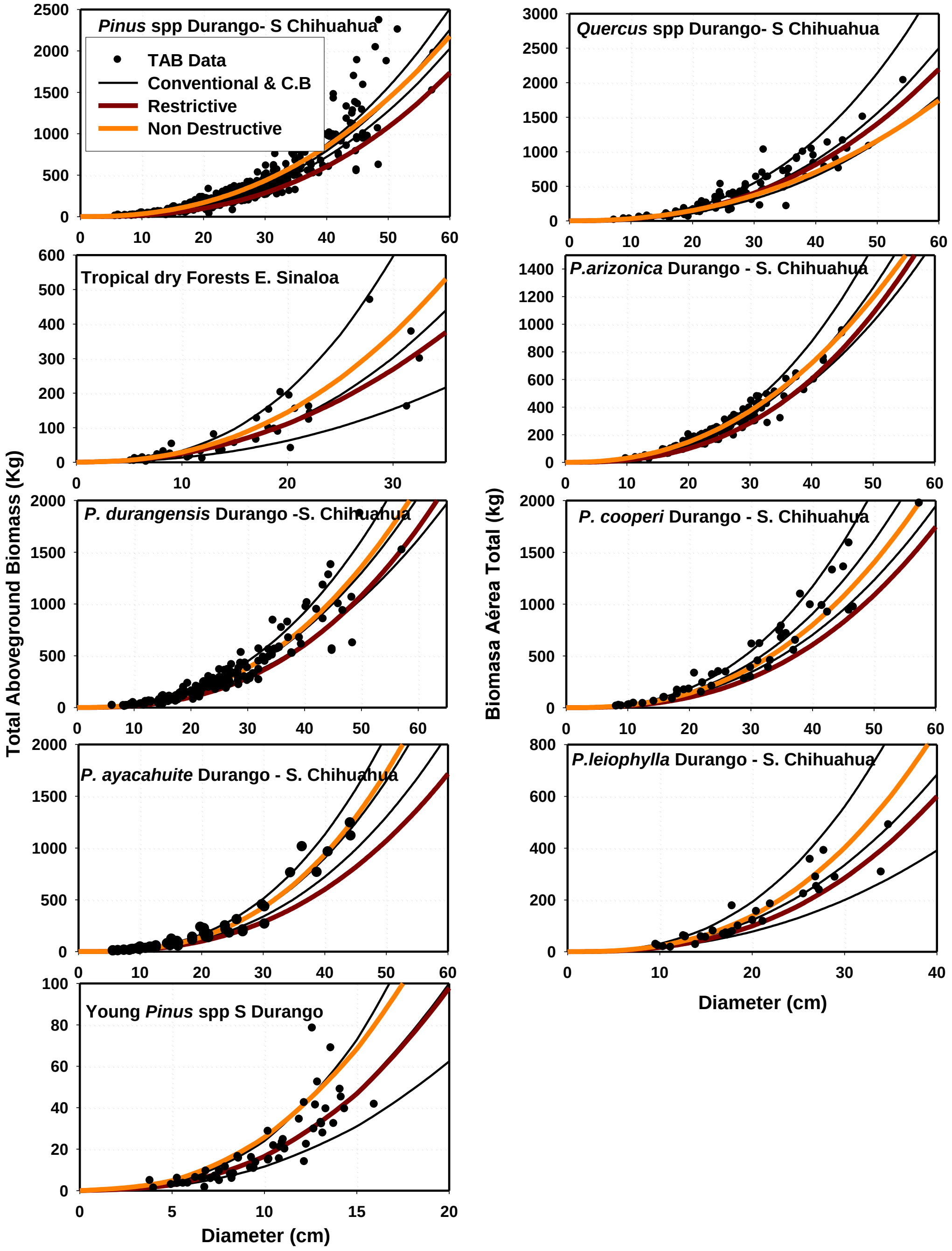

Figure 5. The allometric biomass model [1] with coefficient estimates by the conventional, restrictive and non-destructive methods for nine species or groups of species of the northwest of Mexico.

The scalar coefficients calculated by the restrictive methods are good estimators since they are statistically similar to those estimated by the conventional method. The *B* coefficients reported by all three independent methods are significantly similar but they are significantly different than the theoric *B* value (2.67) proposed by West et al. (1999) and by Enquist et al. (1998). This observation has been additionally corroborated in extensive studies lead by Zianis and Mencuccini (2004); Pilli et al. (2006); Návar (2009a; 2009b). This information leads to preliminary reject the hypothesis that the fractal theory put forward by West et al. (1999) and by Enquist et al. (1998) would have to be further reviewed in order to come up with another non-destructive approach of TAB estimation. The scalar coefficient *a*, is significantly similar between all three methods of estimation, as well.

The mean (standard deviation) scalar coefficients for pines and oaks of the Sierra Madre Occidental Mountain Range of Durango and Chihuahua, Mexico and for tropical dry trees of eastern Sinaloa, Mexico, would be 0.06391 (0.03299) and 2.5476 (0.111); 0.1173 (0.066) and 2.4213 (0.1786); and 0.1263 (0.04315) and 2.3085 (0.1247), respectively. Values outside these ranks anticipated by the averages ± the standard deviation are probabilistically possible. However values outside the limits imposed on these confidence interval values could be hard to find in the study region. The likelihood of finding biomass equations in worldwide tropical dry forests is high, since in Figure 6, four out of eight equations fall beyond the confidence bounds. That is, harvested trees in tropical dry forests are not sufficient to calculate scalar coefficients that are consistent with population means and that have a small variance. In addition the diameter range from harvested trees was limited, from 5 to 32 cm with only five tree species represented in this sample.

The statistical relation between the scalar coefficients *a* and *B* is consistent for several reports that have previously defined mathematically this equation (Figure 7).

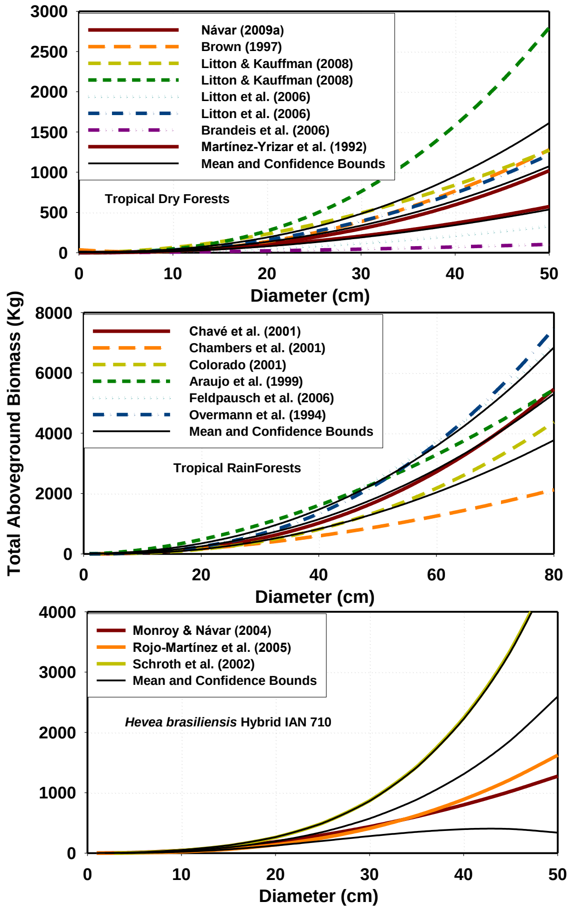

Figure 6. Allometric biomass equations for three major forest types with mean and confidence interval bounds.

The tendency is to consistently reduce *a* with increasing *B* figures. The eco-physiological explanation of this function for several allometric studies is not absolutely clear. However, its consistency motivates the use of the equation to empirically calculate *a*. Although it is a procedure that is statistically suitable, its spatial application could be limited. Henceforth, other independent procedures are required to calculate *a*. Pilli et al. (2006) related *a* with the basic wood density, *p*, with a good level of precision. Unfortunately, *p* data are hard to find at the site-specific scale to develop this empirical equation and to continue searching for better and independent intercept estimators. The non-destructive method can be used as long as there is information on the bole volume, diameter at breast height and top height for the estimation of *B*. The calculation of the *a* coefficient can be conducted by plotting *B* and *a* values for world-wide forests with the use of the compiled biomass equations by Zianis and Mencuccini

(2004) or for American North forests by Ter Mikaelian and Korzukhin (1997) or for the northwestern tree species of Mexico by the equations used in this report. This procedure will result in estimates given within the limits of the standard error of *B*, as it was emphasized in this report and as it was reported for an independent M-D data source (Návar 2009a). TAB deviations smaller than 23% are expected when comparing estimates by the non-destructive approach and the measured ones. The restrictive method provides biomass estimates that deviated by less than 40% (Zianis and Mencuccini, 2004). The non-destructive methodology is also useful in the preliminary TAB estimation for forests where there is usually information on stem volume and where there are restrictions for harvesting trees. It is of paramount importance for forests under some state of conservation, since surface tends to increase at local and global scales. Therefore this approach is important in the development of sustainable forest management plans.

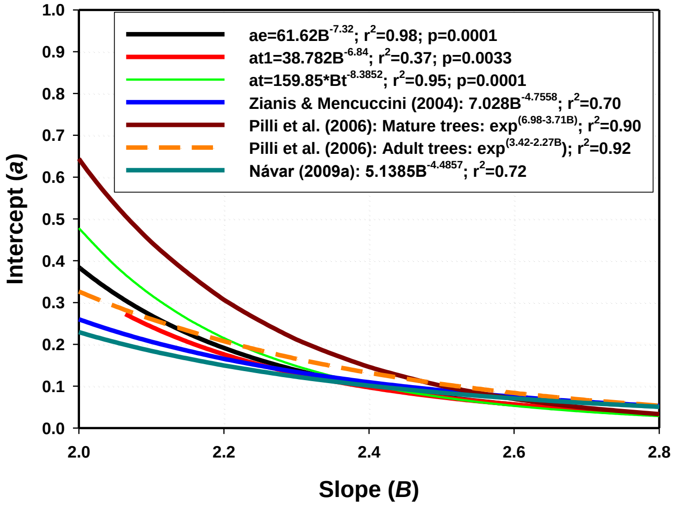

Figure 7. Relations to project *a* as a function of *B* for several biomass studies.

CONCLUSIONS

In this study, three questions on sampling for the development and application of biomass allometry were answered with good level of precision. Results showed that biomass equations must be fitted at the site-specific scale with at least 60 trees harvested that must be proportionally distributed according to the present diameter structures. In the absence of resources, the restrictive and the non-destructive methods are available to develop biomass allometry. The former approach requires harvesting only a few trees for biomass measurements and it is fed with biomass equations already reported for specific tree species. The latter approach requires information on the bole volume equations for the estimation of *B* and the use of an already developed empirical model to estimate *a* as a function of *B*. These techniques calculate TAB within the confidence bounds given by the standard error of *B* as well as within the confidence intervals when several biomass equations estimate TAB for a single forest type.

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