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Article

Ecuaciones alométricas para estimar carbono en brinzales de *Pinus hartwegii* Lindl.

Allometric equations to estimate carbon in seedlings of *Pinus hartwegii* Lindl.

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Resumen

Los bosques de alta montaña ofrecen importantes servicios ecosistémicos de los cuales destaca el almacenamiento de bióxido de carbono (CO_2), uno de los principales gases de efecto invernadero causantes del calentamiento global. Cuantificar el CO_2 en este tipo de ecosistemas ayudaría a entender cómo funcionan y cómo contribuyen a la mitigación del cambio climático. El objetivo de este trabajo fue ajustar las ecuaciones alométricas para *Pinus hartwegii* en plantaciones de reforestación en el Parque Nacional Izta-Popo Zoquiapan. Las variables utilizadas fueron diámetro de la base, altura total y altura a la primera rama viva para relacionarlas con la biomasa. Se seleccionaron 90 brinzales y se calculó la biomasa de cada uno, así como la biomasa por componente: follaje, ramas, tallo y raíz. Se estimó el contenido de carbono para determinar la cantidad de este elemento capturado en los propios brinzales. Las ecuaciones resultantes para el diámetro a la base fue $B=0.0092*DB^{2.7226}$, con un coeficiente de determinación de $R^2= 0.9521$; y para la altura total fue de $B=0.7546*h_T^{2.5819}$, con un coeficiente de determinación de $R^2= 0.8644$. La variable de altura a la primera rama viva obtuvo un coeficiente de determinación bajo, $R^2= 0.3203$. El contenido de carbono promedio para los brinzales fue de 50.81 %.

Palabras clave: Altura total, carbono, CO_2, diámetro de la base, *Pinus hartwegii* Lindl., plantaciones.

Abstract

High mountain forests provide essential ecosystem services, the most important of which is the storage of carbon dioxide (CO_2), one of the leading greenhouse gases (GHG) which cause global warming. Quantifying CO_2 in this kind of ecosystems would help to understand how they work and how they help to mitigate climate change. The aim of this study was to adjust the allometric equations for *Pinus hartwegii* in reforestation plantations in the *Izta-Popo* National Park using variables of easy measurement to relate them to biomass; these variables were base diameter, total height and height to the first live branch. For this, 90 seedlings were selected and the biomass of each one was calculated, as well as the biomass of each component: foliage, branches, stem and root. Carbon content was calculated to determine the amount of this element captured in the seedlings. The resulting equation for the diameter at the base was $B=0.0092*DB^{2.7226}$, with a coefficient of determination of $R^2=0.9521$. The equation for the total height was $B=0.7546*h_T^{2.5819}$, with a coefficient of determination of $R^2 = 0.8644$. The height variable at the first live branch obtained a low coefficient of determination, $R^2=0.3203$. The average accumulated carbon for the seedlings of this study was 50.81 %.

Key words: Total height, carbon, CO_2, base diameter, *Pinus hartwegii* Lindl., plantations.

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Introduction

The greenhouse gas emissions (GGE) to the atmosphere, mainly CO_2, have been one of the most important causes of climate change (Montes *et al*., 2008). This gas comes, mostly, from fossil fuel consumption for the generation of energy of domestic, and transportation use (Cruz, 2016). The effects of climate change become apparent in desertification, temperature increase, plagues and diseases, and gradual loss of glaciers. At the *Pico de Orizaba* and *Izta-Popo Zoquiapan* National Parks in Mexico, forest phytosanitary diseases have been observed (Semarnat, 2016).

The negative impacts of climate change may be reduced through the conservation and management of forest ecosystems and their environmental services, among other actions. Vegetation absorbs, assimilates and retains CO_2 and transforms it into structural tissue through photosynthesis (Ordóñez and Masera, 2001; Zamora-Martínez, 2015; Romero, 2016). To assess the captured carbon in forests, allows to qualify and quantify its contribution to mitigate the effects of climate modifications, and thus, to direct and execute management practices that increase the captured carbon in its biomass (Barrionuevo *et al*., 2013).

In this regard, the allometric equations are a basic tool for biomass and carbon quantification within ecosystems. Estimations are obtained through variables easy to measure, such as diameter or height, in order to relate them to the accumulated biomass or carbon in broader stands and plant communities (Schlegel, 2001; Acosta, 2003; Flores *et al*., 2011; Díaz *et al*., 2016).

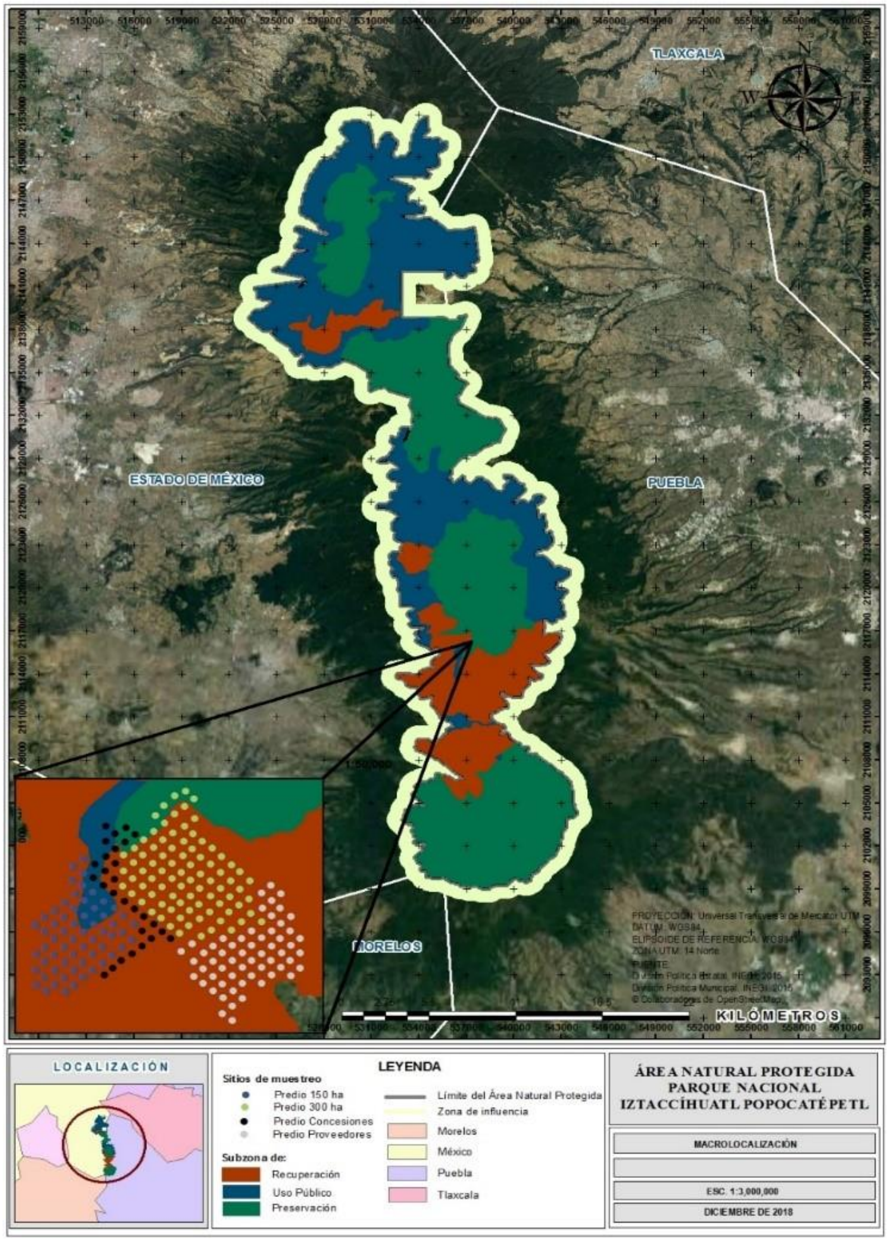
At the *Iztaccíhuatl Popocatépetl* National Park (PN *Izta-Popo*), The "Restauration, Protection and Conservation of Natural Resources of the *Iztaccíhuatl Popocatépetl* National Park Program" is carried out. This integral project is a joint initiative of the social, public and private sectors, oriented to the conservation of the natural heritage and the sustainable development of the park and its influence area, at the short, medium and long term (Semarnat, 2013).

Volkswagen de México S. A. de C. V. has sponsored reforestation works at the park over 750 ha with *Pinus hartwegii* Lindl. Since 2008, the initial year, such effort focused on the maintenance of 300 ha under the "adoption" scheme; later, in 2010, with the support of several additional collaborators 200 ha were added, 100 ha more in 2012 and recently, 150 ha more. One of the aims of the program is to assess carbon sequestration in the 750 ha where restoration and reforestation activities have been done. From the interest of knowing the value of reforestation on the carbon capture in its different growth stages, the objective of the present study was to generate an adjusted allometric equation to estimate the biomass and carbon accumulated in *Pinus hartwegii* plantations in the seedling stage at the *Izta-Popo Zoquiapan* National Park.

Materials and Methods

Study area

The study was performed in the *Iztaccíhuatl-Popocatépetl* National Park, which is located at the *Eje Neovolcánico Transversal*, between 21°11'58'' North and 53°60'14.83'' West, whose average altitude is 3 770 m in a range between 3 000 and 5 480 m (Semarnat, 2013). It comprises 39 819.086 ha divided into the states of *Estado de México*, with 28 307.48 ha (71.09 %); *Puebla* with 11 072.91 ha (27.81 %) and *Morelos* with 438.68 ha (1.10 %) (Figure 1).



Source: Semarnat, 2013.

Figure 1. Location of the *Iztaccíhuatl Popocatépetl* National Park Natural Protected Area.

Its geoforms (mountain chains, volcanic cones and hillsides) have a volcanic origin, in which the basaltic rocks and andesites prevail. According to FAO's classification (FAO, 2015), the present soil units are: Lithosols, Regosols, Andosols, Cambisols and Fluvisols.

The average annual temperature fluctuates from 3 to 5 °C, with an annual variation less than 3 °C, but with enough daytime oscillation for frosts to occur throughout the year. The average annual rainfall is between 600 and 800 mm, and although a considerable percentage falls as snow, it does not remain for long periods on the ground. Sunlight and wind are intense, thus favoring a high evaporation (Rzedowski, 2006).

The PN Izta-Popo Management Program (Semarnat, 2013) is divided into three sub-zones: Restauration, Public Use and Conservation, among the present study was established, mainly on the first one (Figure 1).

Obtaining of biomass

The methodology that was used was similar to that proposed by several scientists (Acosta, 2003; Avendaño *et al*., 2009; Carrillo *et al.,* 2014; Carrillo *et al*., 2016), but it was different since instead of using normal diameter (*DN*) as an independent variable, the base diameter, the hight up to the first branch and total height were used, as most of the seedlings had not fully developed a *DN*.

Based on the cost of its extraction, a sample size of 90 seedlings was used to obtain an allometric equation for biomass and carbon. The selection criterion was that seedlings had been planted through reforestation projects since 2008, and were 10 years-old as maximum age, in order to include most of the available categories to increase the range of variability.

Before the extraction of the seedlings from the root, the diameter at the base, total height and height at the first live branch were measured. Later, they were stored in bags with their respective identification number, after which they were transferred to the greenhouse of the *Valle de México* Experimental Field of *Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias* (INIFAP) in *Coatlinchán, Texcoco de Mora, Estado de* México. There they were kept inside the bags for five weeks so that they lost as much moisture as possible before putting them in a Blue M 0v-490A2 drying kiln.

The foliage, branches, stem and root were separated and weighed on a Tecnocor 20-CHIS digital scale, for minimum weights of 200 g and maximum weights of 30 kg to get the dry weight. Samples weighing less than 200 g were weighed on a Scout®Pro precision scale. When the samples were weighed, aliquots were obtained to be introduced into the drying kiln for 48 h at 70 °C and obtain the 4-component dry weight per 90 seedlings, for a total of 360 samples. Once the moisture percentage after passing through the drying kiln was recorded, it was added to the fresh weight of each component, with which the total and section biomass were calculated.

With the biomass data, the predictive models were adjusted for each one of the variables of interest: the base diameter, total height and the height up to the first living branch. The equation in its potential form was used for the base diameter and total height:

$$B = \beta_0 * X^{\beta_1}$$

For practical matters, *DB* was used for base diameter and h_T as total height.

The equation in its second degree polynomial linear form was used for the height to the first living branch:

$$B = \beta_0 * X^{\beta_1} - \beta_2 * X + \beta_3$$

Where:

B = Biomass (kg)

X's = Independent variables

β's = Adjustment coefficients

All the statistical analyses were performed in the free R software (The R Team, 2013).

Categories of the variables of interest

Four diametric categories were defined for the base diameter and 10 for total height; both were used to construct a biomass table that allows predicting such variable by using these two measurements.

Carbon determination

For the calculation of the carbon contained in the saplings, 13 specimens were selected, in order to include the widest range of size intervals, with their respective components; some, subsamples were taken, and carried to the Soil Fertility and Environmental Chemistry Laboratory of the *Colegio de Postgraduados, Montecillo* campus. The dry combustion method was applied to them on the Shimadzu TOC 5050A carbon analyzer.

Once the results of the analysis were obtained, the coefficient of carbon content per component was applied to the 90 seedlings.

Results and Discussion

Fresh weight and dry weight

As the seedlings were small, it was not necessary to determine fresh weight directly at the field as suggested by several authors (Acosta, 2003; Avendaño *et al*., 2009; Bonilla, 2009; Carrillo *et al*., 2016). The average numbers of moisture loss for each component were 8. 3% for leaves, 11.1 % for branches, 16.2 % for the stem and 15.6 % for the root.

Biomass distribution

The distribution of biomass in the seedlings was 30 % for foliage, 8 % for branches, 24 % for the stem and 37 % for the root. Several authors (Díaz *et al.,* 2007; Avendaño *et al*., 2009; Carrillo *et al*., 2014; Carrillo *et al*., 2016) suggest different distributions, even though they do not take into account the root. Castañeda *et al*. (2012) proposes between 15 and 20 % as a per cent of biomass of the root for adult trees, which is also far from the actual results of this study.

Chávez *et al.* (2016) mention that age directly affects the distribution of biomass in trees. In the early stages of a stand, this distribution will be conditioned by the physiological functions required by the species. In *Pinus*, the first stages focus on the high demand for carbohydrates advocated to the stem that will provide support and can be maintained at a constant rate during its growth. The root must constantly supply water to the leaves, which, in turn, will need great physiological capacity by increasing the leaf area to capture and use solar energy, which will increase photosynthetic rates and biomass production. Vose and Ryan (1994), Van and Franklin (2000), Wang *et al.* (2007) and Pretzsch (2014) mention that the leaf biomass and crown structure of different forest species are crucial for tree growth and development.

Equation fit

For *DB* a coefficient of determination was obtained as R^2=0.9521 and a potential equation $B=0.0092*DB^{2.7226}$. For h_T, R^2=0.8644 and the equation $B=0.7546*h_T^{2.5819}$. For the height up to the first living branch, R^2=0.3203, making it unnecessary to show the equation as such coefficient was under what was considered a good fit. The DB graph is shown in Figure 2 and h_T in Figure 3.

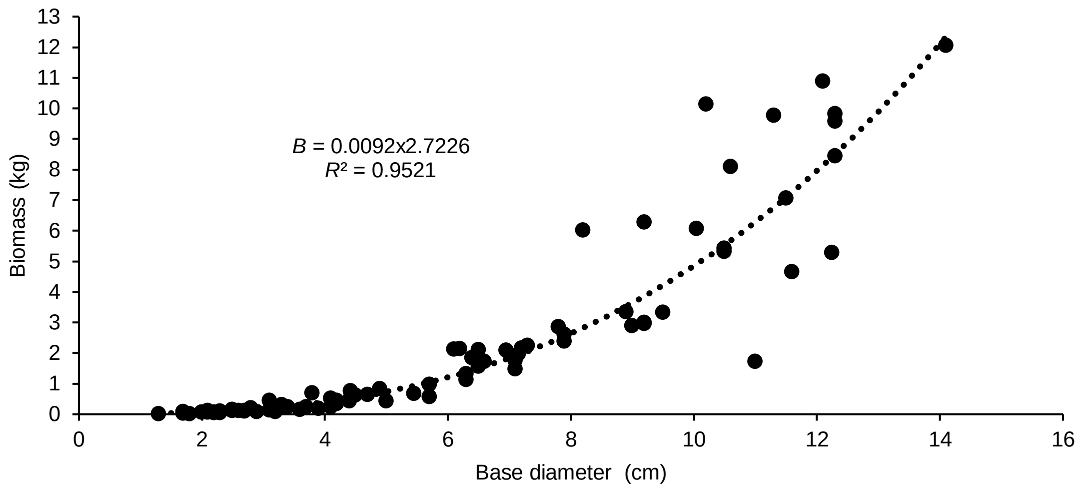


Figure 2. Trend line of the biomass values related to the base diameter.

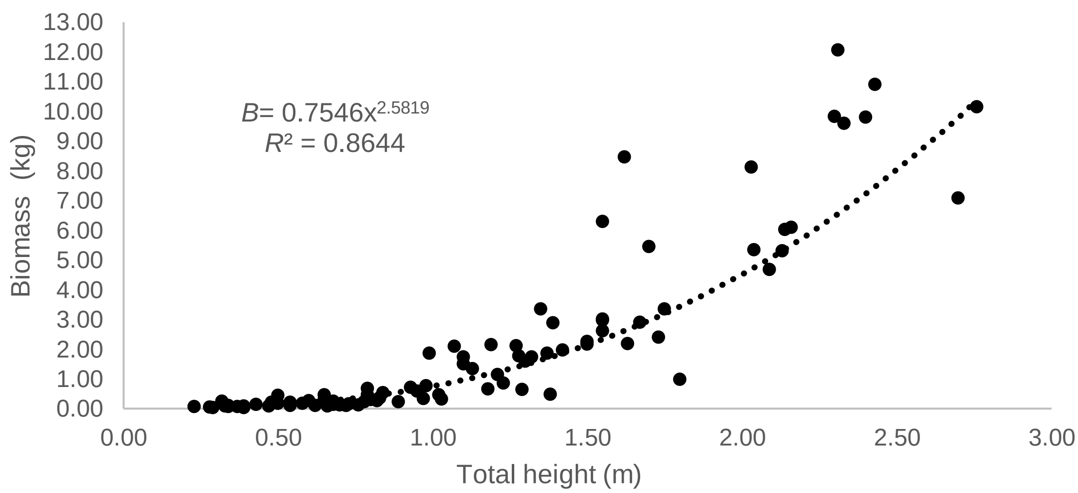


Figure 3. Data dispersal and trend line of the biomass values related with total height.

Brown *et al.* (1989) believes that it is better not always to include the total height of the trees in the biomass estimation procedures due to the complexity of taking the height by closed canopies and because ecological inventories have not included these data in the case of tropical forests.

With the previous results, it was observed that height itself is a significant variable to estimate the biomass in seedlings because this type of vegetation does not have closed canopies, in addition to the fact that the distances between *Pinus hartwegii* trees are very wide (in some cases up to 15 or 20 m from tree to tree), probably from an innate characteristic of the species.

Biomass tables

Table 1 shows the biomass tables generated from the *DB* and h_T equations (with the highest coefficient of determination), with the categories defined for these variables.

Table 1. Biomass tables from the equations and the categories of the *DB* and h_T variables.

Base diameter category (*DB*) (cm)	**Biomass (kg)** $B=0.0092(DB)^{2.7226}$ $R^2=0.9521$	**Total height category (h_T) (m)**	**Biomass (kg)** $B=0.7546(h_T)^{2.5819}$ $R^2=0.8644$
1	0.009	0.01	0.000
5	0.736	0.25	0.021
10	4.857	0.50	0.126
15	14.649	0.75	0.359
20	32.061	1.00	0.755
-	-	1.25	1.343
-	-	1.50	2.150
-	-	1.75	3.200
-	-	2.00	4.518
-	-	2.25	6.124
-	-	2.50	8.038
-	-	2.75	10.281
-	-	3.00	12.871

The table above represents a tool that can facilitate in the field the calculation of biomass for a specific tree or set of trees, such as a stand, through the categories of base diameter or total height.

Obtaining of carbon content

Table 2 shows the results of carbon content by component of the seedlings.

Table 2. Average and standard deviation of carbon content in foliage, branches, stem and root components.

	Foliage	**Branches**	**Stem**	**Root**
Average	50.57	50.79	51.67	50.21
Standard deviation	0.67	1.09	2.62	1.36
Total average	50.81			

The percentage of carbon found in the present study was similar (50 %) to that proposed by the International Panel for Climate Change (IPCC, 1996) Some authors calculated percentages not so far for mild-temperate species. For example, Carrillo *et al.* (2016) obtained 48.5 % for *Pinus hartwegii*; Avendaño *et al.* (2009) 46.48 % for *Abies religiosa* (Kunth) Schltdl. *et* Cham., and Carrillo *et al.* (2013) 48 % for *Quercus*. For *Pinus patula* Schiede ex Schltdl. & Cham., Carrillo *et al*. (2016) determined 48.55 % and Díaz *et al.* (2007), 50.31 % for the same species.

With the obtained coefficient, the carbon content was calculated by applying the value of 0.5081 to the total biomass or by component of each seedling.

Conclusions

The equations to estimate the total biomass are reliable when the base diameter *DB* and the total height h_T are used, because the coefficients of determination were R^2 = 0.9521 and 0.8644, respectively. On the other hand, when the height to the first living branch was used, the determination coefficient was low: R^2 = 0.3203, so its use is not reliable.

By applying a coefficient of 50.81 % to the biomass calculated with the allometric equations for the base diameter or the total height, it is enough to know the carbon content in *a Pinus hartwegii* tree, stand or seedling plantation so it can be used satisfactorily.

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Conflict of interests

The authors declare no conflict of interest.

Contribution by author

José Efraín Martínez Luna: planning and carrying out of field work, structure and review of the document; Fernando Carrillo Anzures and Miguel Acosta Mireles: planning of the research study, development, analysis, data processing, structuring and writing of the document; Martin Enrique Romero Sánchez and Ramiro Pérez Miranda: structure and review of the document.

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