BOSQUE 38(2): 381-386, 2017 DOI: 10.4067/S0717-92002017000200015

Within-tree carbon concentration variation in three Mexican pine species

Variación de la concentración de carbono en tres especies mexicanas de pino

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SUMMARY

Assessing carbon content in forest species is considered essential for programs designed to mitigate global warming. A value of 50 % has been assumed as a generic percentage. However, recent research indicates that there are substantial variations in carbon concentration even within a tree or tissues. The aim of this study was to assess the variations of carbon concentration along the longitudinal profile of *Pinus durangensis*, *P. engelmannii* and *P. leiophylla* in northern Mexico, including its components: root, bark, stem, branches, twigs, leaves and fruits. Using a selective sampling design, dominant and well-shaped trees were selected, whose samples were processed by chemical analyses. Results indicated significant differences in the mean concentration of carbon along the longitudinal profile, with the maximum value always at the base of the tree. Variations at the species level were also recorded. *Pinus engelmannii* had the lowest percentage with 49.31 %, followed by *P. leiophylla* (50.18 %) and *P. durangensis* (50.36 %). In the components of all species, the carbon concentration in the bark was higher than in the rest (52.48 %). A wide range of variation was observed in the carbon coefficients of the components of the species, from 47.39 % in the root of *P. engelmannii* to 53.49 % in the bark of *P. leiophylla*. It is therefore appropriate to consider these variations when making more accurate estimates of carbon stocks in forest ecosystems.

Key words: *Pinus durangensis*, *Pinus engelmannii*, *Pinus leiophylla*, components, trees.

RESUMEN

Evaluar el contenido de carbono se considera esencial para programas diseñados a mitigar el calentamiento global. Se ha asumido un valor de 50 % como porcentaje genérico. Sin embargo, investigaciones recientes indican que existen variaciones substanciales en concentraciones de carbono incluso entre árboles y tejidos. El objetivo de este estudio fue evaluar las variaciones de la concentración de carbono a lo largo del perfil longitudinal de *Pinus durangensis*, *P. engelmannii*, y *P. leiophylla* en el norte de México, incluyendo sus componentes: raíz, corteza, tallo, ramas, ramillas, hojas y frutos. Los resultados indican diferencias significativas en la concentración media de carbono a lo largo del perfil longitudinal, con máximos valores siempre en la base del árbol. También se registraron variaciones al nivel de especie. *Pinus engelmannii* tuvo el más bajo porcentaje con 49,31 %, seguido por *P. leiophylla* (50,18 %) y *P. durangensis* (50,36 %). En los componentes de todas las especies, la concentración de carbono en la corteza fue más alta que en el resto (52,48 %). Un amplio rango de variación se observó en los coeficientes de carbono de los componentes de las especies, desde 47,39 % en la raíz de *P. engelmannii* a 53,49 % en la corteza de *P. leiophylla*. Es por tanto apropiado considerar estas variaciones cuando se hagan estimaciones más precisas de almacenes de carbono en los ecosistemas forestales.

Palabras clave: *Pinus durangensis*, *Pinus engelmannii*, *Pinus leiophylla*, componentes, árboles.

INTRODUCTION

Global averages of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) reached their maximum levels in 2014. In 2015 the National Oceanic and Atmospheric Administration (NOAA) found an unprecedented increase (+3.01 parts per million) in CO_2. Climate change is mainly attributed to greenhouse gasses (GHG). In the period 1990-2014, the annual GHG index increased by 36 %, of which 80 % was CO_2 (OMM 2016).

Forests are terrestrial ecosystems that capture and store most carbon (Martin and Thomas 2011) and play an important role in the carbon cycle (Wang *et al.* 2015). Carbon capture and storage give to forests additional value since they contribute to the absorption of GHGs (Aguirre-Calderón and Jiménez-Pérez 2011). For instance, environmental services offer very valuable indirect benefits (Pagiola *et al.* 2005).

Several studies have demonstrated the best yields obtained by ecosystem services compared to timber uses

(Martin-Ortega 2013, Álvarez and Rubio 2013). In some cases, environmental services (*e.g.* carbon sequestration) have an average value 1.47 times higher than that of wood (Álvarez and Rubio 2013). Therefore, knowing the variation of carbon in the different compartments of the tree will help to improve the estimates of the commercial value of the forest for the carbon bonds, and to contribute to the knowledge of carbon flows. Knowing the concentration of carbon in different compartments of the tree provides precise and useful information in generating strategies and actions to counteract climate change, forest productivity and anthropogenic impact (Aguirre-Calderón and Jiménez-Pérez 2011, Wang *et al.* 2015).

The procedures for estimating carbon content are based on biomass estimation, assuming a 50 % carbon concentration for practical purposes (Lamlom and Savidge 2006). This operational methodology leads to inaccurate results, due to variation of the carbon concentration between arboreal components (Pompa and Yerena 2014) and within tree components (Bert and Danjon 2006, Martin *et al.* 2015). The stem is the aerial component with the highest biomass and consequently stores significant amounts of carbon, thus knowing longitudinal carbon variation is a priority issue. This specific problem has rarely been studied given the difficulties involved (Castaño-Santamaría and Bravo 2012), although dissimilarities of carbon at different tree heights are well known (Bert and Danjon 2006, Herrero *et al.* 2011). In Mexico, no study has presented vertical variations of carbon despite the high abundance of Pinaceae (González-Elizondo *et al.* 2012). The species *Pinus durangensis* Martínez, *P. engelmannii* Carrière and *P. leiophylla* Schiede ex Schltdl. *et* Cham., have huge ecological and economic interest and they are widely distributed in Northern Mexico (González-Elizondo *et al.* 2012), therefore they constitute an ideal group of species to contribute to the knowledge of the variations of carbon.

Although recent studies have reduced the uncertainty of carbon calculation around the world (Thomas and Martin 2012, Durkaya *et al.* 2013), there is a current concern to determine the flow of carbon, which allows having precise indicators for future tradable projects of carbon. The most frequent studies aim at determining the concentrations of carbon in different tree components, finding variations that do not coincide with that of 50 % (Pompa and Yerena 2014). For instance, in Mexican forest many studies use a constant value for carbon concentration (often 50 %) to model carbon flux in different ecosystems, providing a limited understanding of the role of trees as a carbon sink. Knowing within-tree carbon concentration variation in representative pine species could reduce biases of such estimates. In addition, for this species, to our knowledge, no such effort has been made to date.

By hypothesizing that concentrations of carbon differ from 50 % conventionally assumed, the aim of this study is to assess the variations in carbon concentration along the stem of three species of Pinaceae, including other structures such as root, bark, branches, twigs, leaves and fruits.

METHODS

Study area. The present study was carried out in the cooperative Sierra del Nayar (2,350 m a.s.l.), which forms part of the municipalities of Durango and Pueblo Nuevo located in the southwest of the state of Durango (northwest of Mexico), within the Occidental Sierra Madre (figure 1). From the study area, a population of three commercial

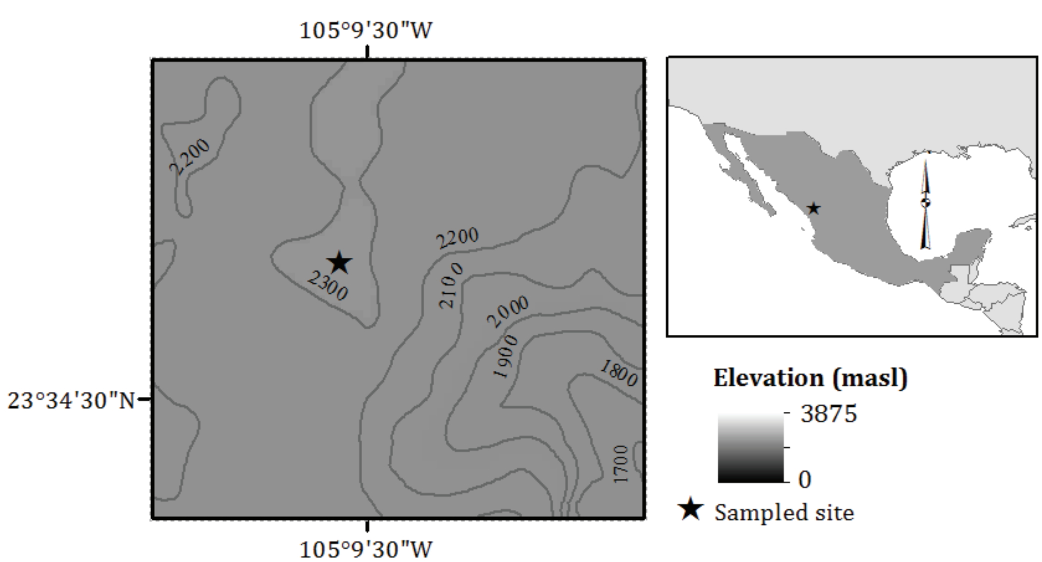

Figure 1. Location of the study area.

Localización del área de estudio.

pine species was selected: *Pinus durangensis, P. engelmannii* and *P. leiophylla.*

The climate of the area is temperate. The dominant vegetation types are Pine and Pine – Oak forests. These mixed forests include *P. durangensis*, *P. leiophylla*, *P. strobiformis* and *P. pseudostrobus*, which are often associated with *Quercus* and *Arbutus* species (González-Elizondo *et al.* 2012). The forest has an irregular structure, an average site quality, with real stocks per weighted hectare of 78.6 m^3 ha^{-1}, density of 520 trees ha^{-1}, and a current annual increment of 1.6 m^3 per year (CCMSS 2002).

Data. We used a selective sampling design from the extraction forest stands. A total of well-shaped 12 trees of each species were selected. Trees were of dominant heights and had no signs of damage, had diameters > 35 cm and were older than 70 years. From each tree, samples of 50 g of leaves, branches, twigs (diameter < 5 cm), bark, root and fruit were collected without any pattern of sampling. Radial cores of each tree were collected using a Pressler increment borer, at different heights: core 1 at 0.30 m, core 2 at 2.74 m, core 3 at 5.18 m, core 4 at 7.62 m and core 5 at 8.28 m, following the length of commercially sawn timber. The samples were taken to the laboratory following the procedures of Karlik and Chojnacky (2013), and immediately placed in paper bags to minimize the loss of volatile carbon (Lamlom and Savidge 2003, Martin and Thomas 2011). Samples were dried at room temperature until reaching a constant weight. Following the procedure of Lamlon and Savidge (2003), the samples were ground using a pulverizing mill (Fritsch pulverisette 2), which produces fractions smaller than 10 µg. Total carbon concentration (TCC) was obtained using the Solids TOC Analyzer (1020A from O I Analytical, USA), which analyzes solid samples of 30 mg by complete combustion at a temperature of 900 °C. The resulting gases were measured through a non-dispersive infrared detector that counts the carbon molecules (Yerena *et al.* 2012).

Statistical analyses. After the verification of the statistical assumptions of normality, homoscedasticity and independence, the data were subjected to an analysis of variance (ANOVA) using the statistical program SAS (Statistical Analysis System 2004) to determine if there were significant differences ($P \geq 0.05$) in the carbon concentration among the averages of the different heights of the stems, species and their components. We tested two factors (treatments): species, which were divided into three levels (*P. engelmannii*, *P. leiophylla* and *P. durangensis*) and components, where seven levels were determined (root, stem, branch, leaves, twig, fruit and bark). Thus, a 3 x 7 factorial experimental design with 21 interactions between treatments was analyzed. Whenever significance was observed between factor levels –component groups and species groups–, a totally randomized ANOVA ($P \leq 0.05$) was performed for the components. Similarly, we performed an ANOVA to test if there were significant differences along the stem profile of tree species. We determined two factors: species (three levels) and heights (five levels: 0.30, 2.74, 5.18, 7.62 and 8.28 m), with 15 interactions (3 x 5). When significance was found, we used a totally randomized ANOVA design for stem heights. When statistical differences were detected, we compared the means with a Tukey test ($P = 0.05$).

RESULTS

There was more carbon in the two lowest heights of the stems ($P = 0.002$, table 1). *Pinus engelmannii* with 49.31 % had the lowest carbon concentration, while *P. leiophylla* and *P. durangensis* (50.18 % and 50.36 %, respectively) had higher concentrations ($P = 0.005$, table 2).

There were differences among the components across species ($P < 0.0001$). Across species, carbon concentration was higher for bark (52.48 %) than for other components, and was similar for the groups formed by root-stem-branch-leaves and stem-branch-leaves-twigs-fruits (table 3).

The range of variation of carbon concentration among the components of the species was 6.1 percentage points, from 47.39 % in the *P. engelmannii* root to 53.49 % in the bark of *P. leiophylla* ($P = 0.006$). The Tukey test

Table 1. Carbon concentration of different heights along the stem.

Concentraciones de carbono de las diferentes alturas en el perfil longitudinal.

Tree cores at different heights (m)	Mean ± SE	Tukey[1] grouping
1 - 0.30	49.08 ± 0.40	A
2 - 2.74	49.14± 0.36	A
3 - 5.18	48.14 ± 0.34	B
4 - 7.62	47.40 ± 0.42	B
5 - 8.28	47.86 ± 0.32	B

[1]Means with different letters are statistically different (Tukey $P = 0.05$).

Table 2. Carbon concentration of species (%).

Concentración de carbono de las especies (%).

Species	Mean ± SE
Pinus engelmannii	49.31 ± 0.22a
Pinus leiophylla	50.18 ± 0.27b
Pinus durangensis	50.36 ± 0.18b

Means with different letters are statistically different (Tukey $P = 0.05$).
EE = standard error of the sample.

(P = 0.05) showed six groups of means. The roots and stems of the three species together with branches of *P. leiophylla* and *P. engelmannii*, leaves of *P. engelmannii* and *P. durangensis* had lower values (from 47.39 to 49.57 %); in contrast, bark of the species had the highest carbon concentration of all components of the species, with values ranging from 51.47 to 53.49 % (table 4).

DISCUSSION

This is the first study that shows differences in the concentration of carbon along heights of the stems and tissues in Mexican pine species. This study has evidenced that even in the same stem there are variations that should be considered to improve the estimates of the assimilation capacity of carbon in the forest. As with Bert and Danjon (2006), the results showed differences in the concentration of carbon that were found in each sample obtained from the longitudinal cut of the stem and the maximum value was always found at the base of the tree. A possible explanation for these values found is attributed to the geometric effect and age at the base. This is explained by the fact that, at an older age, rings with a higher percentage of latewood are formed and this increases the density of the wood (Bert and Danjon 2006). It is also well known that, comparatively, late wood has more carbon than that found in early wood (Pallardy 2008). In contrast, the amount of early wood increases as the height of the tree grows. Consequently, the chemical composition of the base gradually differentiates along the vertical profile. This implies that, if the concentration of carbon along the stem varies, sampling should be carried out by weighting this aspect. Recent studies have shown that variations in biomass and hence carbon, depend on the height of the stem (Jones and O'Hara 2012). Although this analysis goes beyond the objectives of the present study, a representative stem height should be considered. Until now, considering 1.3 m as a source of information could produce biased values, despite the advantage of non-destructive methods (*e.g.*, tree core extraction using Pressler borer).

Our results showed significant differences in mean carbon concentration among species, with two groups of differentiated means: on the one hand, *P. engelmannii* that is a species of wide ecological distribution, varying from 1,800 to 2,600 m a.s.l. (González-Elizondo *et al.* 2012), therefore their low concentrations of carbon could be attributed to the minimum nutrition requirements. The other group consists of *P. leiophylla* and *P. durangensis*, with higher values. According to Sáenz-Esqueda *et al.* (2010) these species are rich in volatiles and carbohydrates that contribute to increase the concentrations of carbon.

Significant differences of carbon concentration among components were evident (see table 4). The high concentration value of carbon in the bark agrees with Zhang *et al.* (2014), who found that bark contains high concentrations of carbon. Similarly, in the study by Bert and Danjon

Table 3. Carbon concentration per component of all species (%).
Concentración de carbono por componente de todas las especies (%).

Component	Mean ± SE
Root	48.72 ± 0.31a
Stem	49.23 ± 0.36ab
Branch	49.32 ± 0.41ab
Leaves	49.59 ± 0.15ab
Twig	50.24 ± 0.15b
Fruit	50.47 ± 0.29b
Bark	52.48 ± 0.17c

Means with different letters are statistically different (Tukey P = 0.05).
SE = standard error of the sample.

Table 4. Average concentration of carbon per component per species.
Concentración promedio de carbono por componente por especies.

Pinus engelmannii		*Pinus leiophylla*		*Pinus durangensis*	
Component	Mean ± SE	Component	Mean ± SE	Component	Mean ± SE
Root	47.39 ± 0.65a	Branch	48.34 ± 1.14ab	Root	49.19 ± 0.33abcd
Leaves	48.71 ± 0.13abc	Stem	49.06 ± 0.51abc	Leaves	49.44 ± 0.19abcd
Stem	49.08 ± 0.75abc	Root	49.57 ± 0.35abcd	Stem	49.54 ± 0.67abcd
Branch	49.15 ± 0.25abc	Fruit	49.91 ± 0.17bcd	Branch	50.48 ± 0.29bcde
Twig	49.83 ± 0.23bcd	Twig	50.05 ± 0.18bcd	Fruit	50.72 ± 0.52bcde
Fruit	50.57 ± 0.08bcde	Leaves	50.61 ± 0.11bcde	Twig	50.82 ± 0.29cde
Bark	51.47 ± 0.14def	Bark	53.49 ± 0.23f	Bark	52.49 ± 0.18ef

Means with different letters are statistically different (Tukey P = 0.05).
SE = standard error of the sample.

(2006), bark was the part of the tree with the highest concentration of carbon. In contrast, roots and stems had low values of carbon across species, which has been attributed to the chemical composition of cellulose and lignin, the primary components of wood (Fonseca *et al.* 2012).

Usually the most conventional method to determine the amount of stored carbon is by multiplying the total dry weight of trees by a coefficient of 0.5 (Durkaya *et al.* 2013). In the case of the average concentration of carbon in the components of the three species, the variation was between 47 % and 53 %. This result is consistent with those found by other authors (Thomas and Martin 2012, Durkaya *et al.* 2013, Pompa and Yerena 2014) and would be helpful to improve carbon estimations in Mexican forests (Carrillo *et al*. 2016).

CONCLUSIONS

Carbon concentration for three Mexican pines differed among species, stem height and tissues. Results for this study show that the generalized 50 % of carbon concentration assumption may produce consistently misleading estimates. Therefore, variations in compartments should at least be considered when attempting to define the most appropriate carbon fraction used to estimate carbon stocks in Mexican pine species. These multi-species data contribute to improve precision on estimates of carbon balance in terrestrial ecosystems, to yield superior insights into the carbon inventories. Additional comparative analyses of inter- and intraspecific variations are needed to reduce uncertainty of carbon variation in forest ecosystem.

ACKNOWLEDGEMENTS

We recognize financial support from CONACyT (CB-2013/222522) in Mexico. Also, we thank the editor for an early review of this manuscript and two anonymous reviewers that helped to improve the article.

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Recibido: 21.03.17
Aceptado: 15.05.17