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Director: DrC. Marta Bonilla Vichot
Email: mbon@upr.edu.cu

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Translated from the original in spanish **Original article**

Estimation of carbon stored value based on two sampling methods in pine forests of the state of Chihuahua, Mexico

Estimación del valor de carbono almacenado en función de dos métodos de muestreo en bosques de pino del estado de Chihuahua, México

Estimativa do valor do carbono armazenado com base em dois métodos de amostragem em florestas de pinheiros do estado de Chihuahua, México

Viridiana Sugey Galván-Moreno[1], Oscar A. Aguirre-Calderón[1]*, Eduardo Alanís-Rodríguez[1], Javier Jiménez-Pérez[2], Luis Gerardo Cuellar-Rodríguez[1], Gerónimo Quiñonez-Barraza[2], Joel Rascón-Solano[3]

[1] Autonomous University of Nuevo Leon, Mexico.

[2] National Institute of Forestry and Agricultural Research, Guadiana Valley Experimental Field (INIFAP-CEVAG), Km 4.5 Durango-Mezquital Highway, 34170, Durango, Durango, Mexico.

[3] Autonomous University of Chihuahua, Faculty of Agricultural and Forestry Sciences, Km 2.5 Delicias-Rosales Highway, 33000, Delicias, Chihuahua, Mexico.

*Corresponding author: oscar.aguirrecl@uanl.edu.mx

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ABSTRACT

The study was carried out on the private property "La Lobera", located in the municipality of Guachochi in the southwest of the state of Chihuahua, Mexico, with the aim of contrasting the estimates of the carbon content stored in an irregular forest in relation to two sampling methods used. Fifty sites of fixed dimension and 50 of variable dimension were made with Bitterlich angular sampling at coincident sample points. The carbon equivalent estimate differs by 66.42 metric tons per hectare, where the Bitterlich method presents the highest value. Regarding the current annual increment, expressed as a percentage, there were no differences between methods; however, the ICA of carbon equivalent differs by 4.40 metric tons per hectare, where the Bitterlich method presents the highest value, overestimating the values.

Keywords: carbon credits, Bitterlich, fixed area, sampling methods.

RESUMEN

El estudio se realizó en el predio particular "La Lobera", localizado en el municipio de Guachochi al suroeste del estado de Chihuahua, México, con el objetivo de contrastar las estimaciones del contenido de carbono almacenado en un bosque irregular en relación a dos métodos de muestreo empleados, se realizaron 50 sitios de dimensión fija y 50 de variable con el muestreo angular de Bitterlich en puntos muestrales coincidentes. La estimación de carbono equivalente difiere en 66,42 toneladas métricas por hectárea, donde el método de Bitterlich presenta el valor más alto. En cuanto al incremento corriente anual, expresado en porcentaje, no se presentaron diferencias entre métodos; sin embargo, el ICA de carbono equivalente difiere en 4,40 toneladas métricas por hectárea, donde el método de Bitterlich presenta el valor más alto, sobreestimando los valores.

Palabras clave: bonos de carbono, Bitterlich, área fija, métodos de muestreo.

RESUMO

The study was carried out on the private property "La Lobera", located in the municipality of Guachochi, in the southwest of the state of Chihuahua, Mexico, with the aim of contrasting the estimates of the carbon content stored in an irregular forest with respect to two sampling methods used in 50 fixed-dimension sites and 50 variable-dimension sites, with Bitterlich angular sampling at the coincident sampling points. The estimate of the carbon equivalent differs by 66.42 metric tons per hectare, where the Bitterlich method presents the highest value. Regarding the current annual increase, expressed as a percentage, there were no differences between the methods; however, the ICA of the carbon equivalent differs by 4.40 metric tons per hectare, where the Bitterlich method presents the highest value, overestimating the values.

Palavras-chave: créditos de carbono, Bitterlich, área fixa, métodos de amostragem.

INTRODUCTION

In the world, the total area of forests in 2020 was 4.06 billion hectares (ha), which corresponds to 31% of the total surface of the Earth (FAO, 2020). These forests are great generators of oxygen and capturing carbon dioxide (CO_2) by fixing it in the soil and eliminating it from the atmosphere, so forest lands capture 188 million tons of CO_2 (CONAFOR, 2019).

The growing international concern about the harmful consequences of climate change has encouraged organizations and institutions to deepen their knowledge of greenhouse gases and their dynamics. Knowing the carbon footprint allows us to control, reduce or mitigate emissions and their effects, and its scope for trade in goods and services is increasingly recognized, especially at an international level and among participating countries, to reduce emissions that signed the Kyoto Protocol (Schneider and Samaniego, 2010).

According to Vazquez (2011), Castillo-Elias *et al.* (2018), According to Frelich (2020) and Hilmers *et al.* (2020), "carbon bonds" is the generic name given to a series of economic and market instruments created to reduce greenhouse gas (GHG) emissions. López-Toache *et al.* (2016) mention that the carbon bond market is one of the mechanisms used by environmental economics to try to mitigate GHG emissions worldwide.

Mexico began to play a role since 1998, but it was not until October 23, 2008, when the approved energy reform gave the country importance in the carbon bond market. Vázquez (2011) mentions that, since that year, Mexico has occupied 4th place worldwide, with a 3% share. The Kyoto Protocol opened up opportunities for the Mexican industry that emits GHG into the atmosphere by reducing pollution with a smaller investment, while also being efficient by modernizing production processes. The stored tons are purchased by companies in industrialized countries through carbon credits, which allows companies in developed countries to offset their GHG emissions in such a way that they avoid economic sanctions, and developing countries obtain resources to modernize their industrial processes. Nowadays in Mexico, the sale of carbon credits is an increasingly common practice in the business sector. The country has various projects to reduce greenhouse gas emissions, which generate carbon credits that can be sold on the international market.

Net storage of organic carbon in forests depends on management, age, size distribution, structure and composition of vegetation. An adequate assessment of forest biomass is a very important factor because it allows determining the carbon potential that can be stored in the surface of natural vegetation (forests and jungles) and following strategies or institutional commitments for mitigation (Rincón-Ruíz, *et al*., 2014).

Obtaining a correct estimate of forest biomass, and therefore of the amount of carbon sequestered, is of utmost importance in order to determine the amount of this element that could be released into the atmosphere in the form of carbon dioxide, thus contributing to increasing the amount of greenhouse gases; or, on the contrary, to know the amount that is stored when the forest is sought to mitigate the effects of these gases (Schlegel 2001; López-Toache *et al*., 2016).

In this sense, forest inventory attributes are an important source of information for a variety of strategic and tactical forest management purposes (Brosofske *et al.,* 2013; Goodbody *et al.,* 2017; Vandendaele *et al.,* 2021). However, methods for estimating carbon content have been limited to fixed-area sampling, which tend to be expensive and involve considerable time for the total recording of data. For this reason, methods for processing data for carbon storage estimates must be easy to execute and applicable to different types of ecosystems, in such a way that they allow comparisons with each other. Therefore, the objective of the study was to contrast the estimates of carbon stored in an irregular forest in relation to two sampling methods used on a property in northwestern Mexico in the municipality of Guachochi, Chihuahua.

MATERIALS AND METHODS

Area of study

The present study was carried out on the private property "La Lobera", which has an area of 200 ha, of which 145 ha are wooded and under timber production, the property is located in the municipality of Guachochi in the southwest of the state of Chihuahua, in the region of the Sierra Madre Occidental, its extreme geographic coordinates are 26°36' - 27°42' North latitude and 106°49' - 107°51' West longitude (Figure 1).

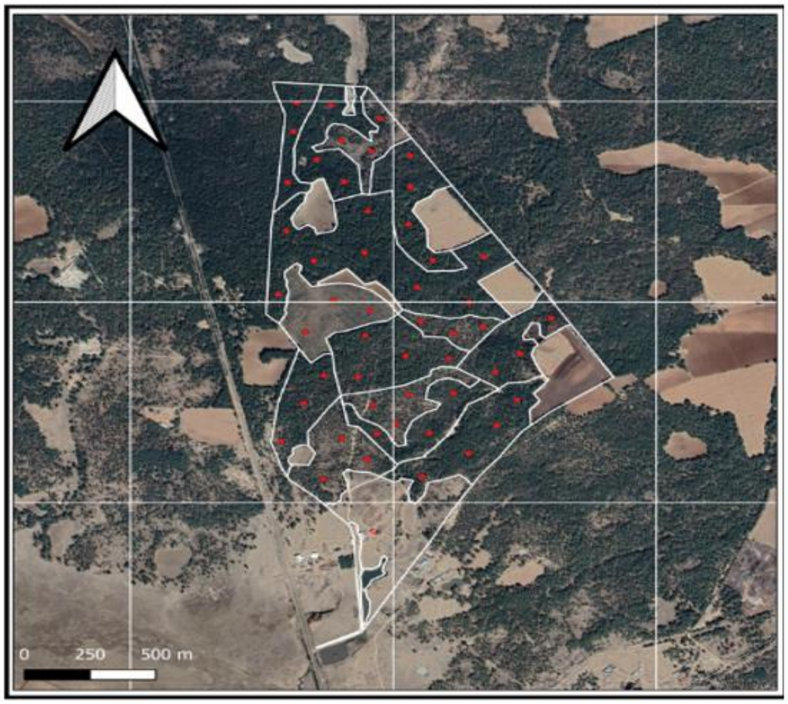

Figure 1. *- Geographic location of the study area*

Forest sampling methods

a) Bitterlich method

The method is based on Bitterlich's postulate which, according to (1984) (Finger, 1992), the number of trees in a stand whose diameters at breast height (D1.30m) from a fixed point are greater than a constant angular value alpha is proportional to the basal area in square meters per hectare. According to Pardé (1956), referring to a small or large number of trees becomes a source of error in the estimation of the basal area per hectare. Biterlich (1984) mentions that the appropriate factor is one that counts 20 to 30 trees per sampling unit (360° rotation).

b) Fixed Area Method.

In this method, the selection of individuals is carried out in proportion to the surface area of the minimum management unit and, in turn, by the frequency of the individuals found within it. The shape and size of the sampling unit constitute the fundamental variables to evaluate the practical application of this method (Péllico-Netto and Brena, 1997) . The shape and size of the sampling units are generally defined by the practicality and difficulty of operation for determining the floristic composition, density, delimitation and location in the field, rather than by any other argument.

Methodological procedures

In the study area, 50 Bitterlich sites of variable dimensions and 50 circular sites of 1,000 m ^{2} were established using a systematic sampling method with a sampling intensity of 3.45 %, a reliability of 95% and a sampling error of 5%. The dasometric data of the species, normal diameter and total height of each of the individuals were recorded; in the variable dimension sites, the factor of four was used with the Bitterlich relascope. These data were collected to determine biomass and from it derive the value of stored carbon, as well as the statistical precision of each sampling method based on the actual stock; the estimate of the number of trees per hectare (N arb ha $^{-1)}$, basal area per hectare (G) and volume per hectare (Vol m ^{3} ha $^{-1)}$ was compared.

$^{-1}$) was calculated for circular sites with the following relationship Equation 1:

$$\text{N arb ha}^{-1} = \frac{\sum Narb_I}{\text{M}} * 10 \quad (1)$$

Where:

N arb ha $^{-1}$ = Number of trees per hectare.

N arb $_i$ = Number of trees at site $_{i.}$

M = Number of sites.

The estimation of basal area per hectare (G) was carried out with the following procedure Equation 2:

$$\text{G} = \frac{\sum \text{g}_\text{i}\,(\text{m}^2)}{\text{M}} * 10 \quad (2)$$

Where:

G = Basal area in square meters per hectare.

g $_i$ (m ^{2}) = Basal area of site $_i$ expressed in square meters.

M = Number of sites.

The individual volume (m^3) was determined using the equation developed by the biometric model of UMAFOR-0807 (CONAFOR - Government of Chihuahua - UMAFOR 0807, 2014), which is presented below Equation 3:

$$\text{VTA} = \beta_0 * (d_{1,30}\ \hat{}\beta_1) * (\text{H}\hat{}\beta_2) + \beta_3 * (d_{1,30}\ \hat{}2) \quad (3)$$

Where:

VTA $m^3 ha^{-1}$ = Total Volume in m^3 per hectare.

VTA $_i$ = Total Tree Volume of site $_{i.}$

â = Volume estimation parameter.

D $_{1.30m}$ = Diameter.

The estimation of biomass and carbon content was obtained with the following equation Equation 4:

$$B = exp\,(x)\,(d_{1,30})^y \quad (4)$$

Where:

x = Dependent Variable Parameter

y = Parameter Independent variable

D $_{1.30m}$ = Normal diameter

Carbon content was obtained by multiplying the biomass value by the IPCC (1996) suggested conversion factor of 0.50. Each tonne of stored carbon was multiplied by the IPCC carbon expansion factor of 3.67.

Materials and equipment used

The dasometric data for the study were taken from each individual; the database consists of the trees whose diameter ($D_{1.30m}$) ≥ 7.6 cm was measured with a 90 cm Haglöf® caliper and the total height with a Suunto® PM5-1520 hypsometer. Additionally, the species to which each individual belongs was recorded. To estimate the basal area in sites of variable dimensions, the Bitterlich Relascope was used.

Statistical procedures

The statistical package IBM-SPSS® version 25 was used to detect statistical differences in the estimates of both sampling methods. Equality of variance was assessed with the F test ($P<0.05$). Parametric and non-parametric analyses of variance ($P<0.05$) were performed to determine the differences between methods with respect to the variables number of trees per hectare, basal area per hectare, total volume per hectare and carbon equivalent per hectare. Duncan's mean separation test was used to identify sub-stands that showed similarity in relation to the sampling method.

RESULTS AND DISCUSSION

The difference in the number of trees per hectare estimated by the methods is significant in two sub-stands, 14 and 23, according to the results of the fifty sample units established. These values indicate that although in the other sub-stands the estimates are similar in terms of the estimated number of trees per hectare, the irregular distribution of the trees may have an effect on the precise calculation of density (Figure 2a).

Figure 2b shows that tree distribution, tree diameter and stand density generate variability in the estimation of basal area per hectare between sampling sites with significant differences in sub-stands 8, 14 and 23. Studies have been conducted to determine which is the best basal area factor in *Pinus spp.* plantations, where Gorenstein (2002) indicates that he found no significant differences between basal area factors (BAF) 1, 2 and 4 tested in that study. By using a small basal area factor at a specific sampling point, a large number of trees will be counted, whose normal diameter will be greater than the projected angle, which complicates field work. Banyard (1976) recommends using a large BAF to count few trees per variable area plot; however, this implies less precision in the estimate. Brack and Wood (1998) recommend counting between 7 and 12 trees per variable plot point. Once the appropriate FAB has been selected, the same value should be used in each variable area plot (Biterlich, 1984).

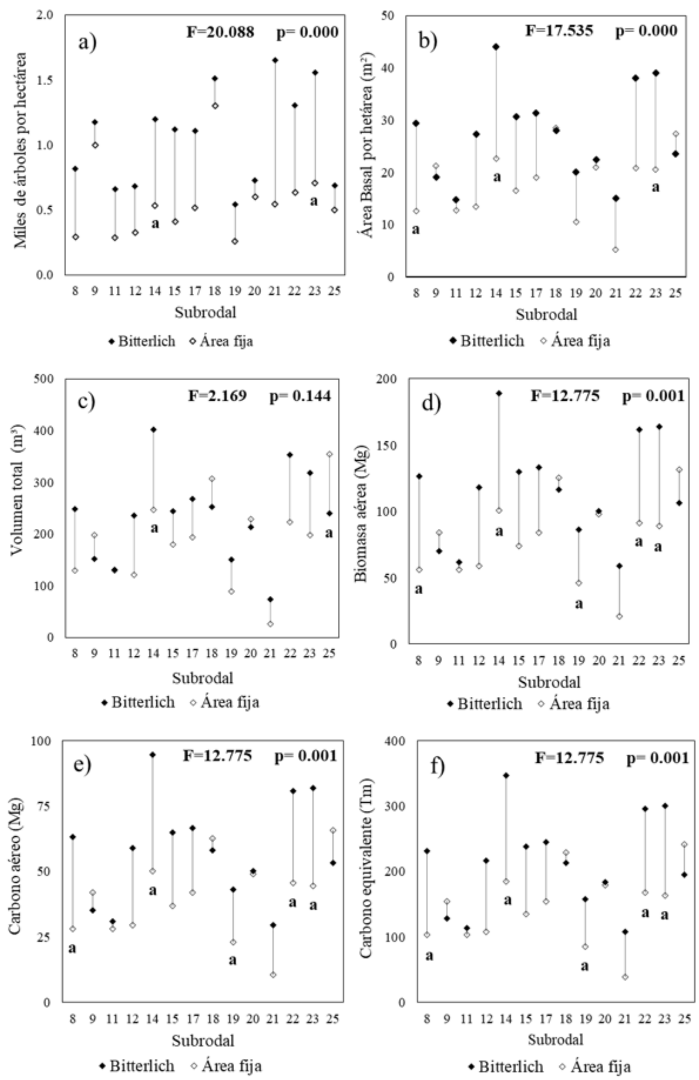

***Figure 2.** - Contrast of results of the sampling methods of the sub-stands analyzed*

The difference in total tree volume per hectare estimated using the fixed dimension method is not significant (P = 0.144) as shown in Figure 2c; due in part to the fact that at variable dimension sites a reference tree with dasometric characteristics representative of the sampling point is taken; and for its part, the fixed dimension sites take into account the individual volume of the trees present in the sample area, in this sense the dimensions of the representative tree at the variable dimension site were very close to the dimensions of the sampled trees at the fixed dimension sites. Figure 2d, on the other hand, shows significant differences in the estimates of aboveground biomass in relation to the sampling methods used. The main statistical differences are related to the sampling sites that presented inequality in terms of basal area and volume. This is mainly due to the fact that the biomass estimate is made from an estimate of normal diameter, a variable that presents significant differences between the sampling methods. Figures 2e and 2f, on the other hand, present significant differences between sampling methods because they are estimates derived from aerial biomass.

As shown in Figure 3a, the ICA (%) does not present a significant difference between methods, only two sites showed statistical differences (p = 0.663), which is mainly due to the differences found in the age and increment of the selected trees. On the other hand, the ICA (Volume) does show significant differences, this result is derived from the volume estimates made in the study (Figure 3b), when there are differences between methods in the volume per hectare, inequalities will occur in the ICA (Volume) estimates. On the other hand, Figures 3c and 3d show that there are significant differences in the estimates of stored carbon and equivalent carbon respectively. As mentioned above, these estimates are highly related to the average diameter and the diameter distribution recorded at the sampling sites.

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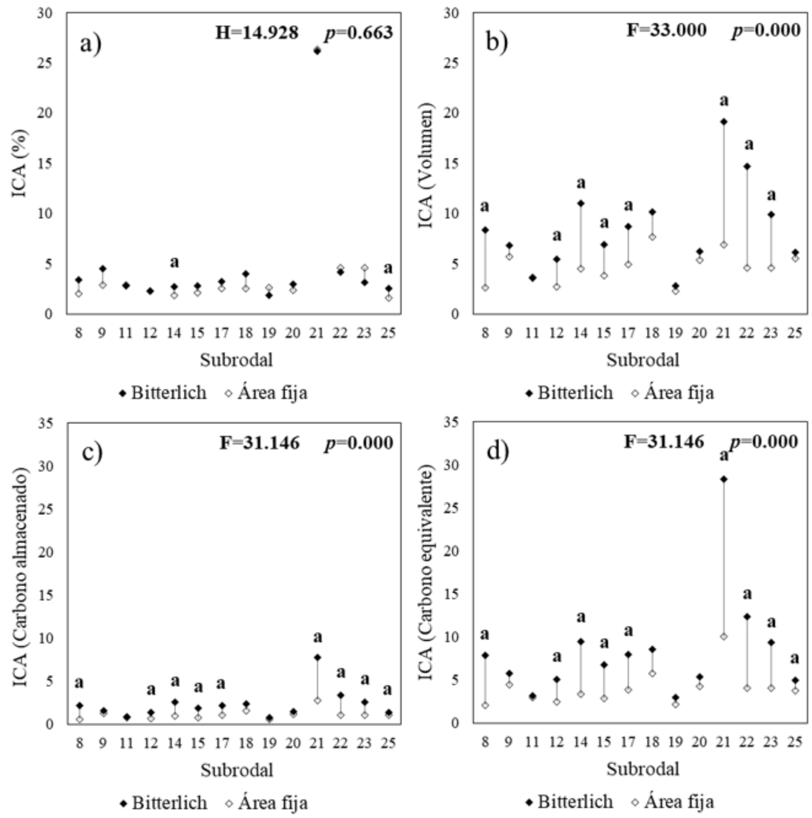

Figure 3. *- Estimates and contrast of volume increase and carbon stored per subrodal*

Regarding carbon credits, it was found that the variable dimension sampling method presents incomes from 348.24 to 3,614.64 dollars per year, in relation to the estimated current annual increase and the surface of the stands as shown in Table 1. In this sense, the incomes are mainly related to the growth capacity and density of the forest, for example, stand number 21 is made up of a pure stand of *Pinus arizonica* Engelm. planted in 2009 (13 years old at the time of sampling) with a density of 1,111 trees ha$^{-1,}$ due to being a young stand the increases tend to be greater in relation to mature stands. Finally, the income received from the sale of carbon credits using this sampling method is estimated at 14,800.80 dollars annually with respect to the wooded surface of the property.

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Table 1. *- Estimated carbon value for the La Lobera property. The first section of the table refers to the results of the variable dimension method and the second part of the table refers to the results of the fixed dimension method. ICA: Annual Current Increase; ICAcareq: Carbon equivalent ICA; dlls: American dollars; MN: National Currency of Mexico*

Stand	Surface (ha)	ICA (%)	ICAcareq (ton)	ICAcareq/rod (ton)	Value dlls ($)	Value MN ($)
8	3.90	3.37	7.82	30.49	365.88	6.951.72
9	5.34	4.49	5.78	30.87	370.44	7.038.36
11	6.08	2.76	3.13	19.06	228.72	4.345.68
12	7.01	2.31	5.02	35.20	422.40	8.025.60
14	8.13	2.73	9.48	77.07	924.84	17.571.96
15	8.44	2.82	6.72	56.69	680.28	12.925.32
17	8.96	3.24	7.92	70.95	851.40	16.176.60
18	9.69	4.01	8.57	83.01	996.12	18.926.28
19	9.97	1.84	2.91	29.02	348.24	6.616.56
20	10.32	2.92	5.37	55.42	665.04	12.635.76
21	10.65	26.13	28.28	301.22	3.614.64	68.678.16
22	13.16	4.17	12.36	162.65	1.951.80	37.084.20
23	13.97	3.11	9.35	130.64	1.567.68	29.785.92
25	30.30	2.55	4.99	151.11	1.813.32	34.453.08
Total	145.92	4.75	8.41	1.233.40	14.800.80	281.215.20
8	3.90	2.02	2.08	8.12	97.44	1.851.36
9	5.34	2.89	4.46	23.82	285.84	5.430.96
11	6.08	2.83	2.93	17.78	213.36	4.053.84
12	7.01	2.26	2.45	17.15	205.80	3.910.20
14	8.13	1.82	3.35	27.23	326.76	6.208.44
15	8.44	2.13	2.89	24.38	292.56	5.558.64
17	8.96	2.53	3.89	34.89	418.68	7.954.92

18	9.69	2.50	5.75	55.69	668.28	12.697.32
19	9.97	2.58	2.19	21.82	261.84	4.974.96
20	10.32	2.34	4.22	43.50	522.00	9.918.00
21	10.65	26.30	10.05	107.50	1.290.00	24.510.00
22	13.16	4.56	4.02	100.86	1.210.32	22.996.08
23	13.97	4.56	4.02	104.13	1.249.56	23.741.64
25	30.30	1.56	3.78	114.39	1.372.68	26.080.92
Total	145.92	4.35	4.01	701.26	8.415.12	159.887.28

The fixed area sampling method indicates that the minimum income to be received is US$ 97.44, while the highest expected income is US$1,372.68 per year. The above results are mainly related to the density of the stands and the estimates of realized biomass. The stands with the lowest density and lowest biomass values are those with the lowest income. Additionally, it was found that in this method the surface area of the stand is significantly important, because the largest stands are also those that represent the highest income. According to the estimates made; by using this sampling method it would be possible to receive an annual income of US$ 8,415.12 from the sale of carbon credits.

Although reports by Kenning *et al.* (2005), Kiani *et al.* (2013), Kuliešis *et al.* (2016), Mirzaei and Bonyad (2016), Vidal *et al.* (2016), Lupi *et al.* (2017), Basiri et al. (2018), Mora-Espinoza *et al.* (2020), Pucher *et al.* (2022), Galván-Moreno *et al.* (2023) and Leiter and Hasenauer (2023) state that both sampling methods are reliable for estimating density, basal area and volume, more robust analyses are needed to define the efficiency of applying these methods in even-aged and heterogeneous forests to make dasometric, ecological and carbon estimates. These analyses must use an absolute reference element, such as a census or forestry monitoring plots, so that it is possible to compare their precision and adaptability to the diverse conditions of Mexican forests in timber production.

CONCLUSIONS

There are significant differences in relation to the estimates of the stored carbon content, in the La Lobera property, between two sampling methods used.

The carbon equivalent estimate differs by 66.42 metric tons per hectare, where the Bitterlich method presents the highest value.

The current annual increment did not differ between methods; however, the carbon equivalent ICA differed by 4.40 metric tons per hectare for the Bitterlich method.

Using the Bitterlich method would overestimate the revenues obtained from the sale of carbon credits for irregular forests.

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