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Original article

Carbon removal in Pinus caribaea of the Management Unit Agroforestal Viñales, La Palma

Remoción de carbono en Pinus caribaea de la Unidad de Base Empresarial Agroforestal Viñales, La Palma

Remoção de carbono em Pinus caribaea da Unidade de Base de Negócios Agroforestal Viñales, La Palma

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ABSTRACT

Pinus caribaea plantations in Cuba store a large amount of carbon because they play a very active role in the exchange of carbon dioxide between the biosphere and the atmosphere, contributing to the reduction of greenhouse gas concentrations. This study was conducted at the Viñales Agroforestry Unit, part of the La Palma Agroforestry Company, to determine the carbon removed by *Pinus caribaea* plantations of different ages: 10, 15, and 25 years old. Samples measuring 2.5 cm in width and length were taken, in which the percentage of moisture, volatile matter, ash percentage, and consequently, the carbon removed were determined. There are significant differences between the variables volatile matter, ash percentage, and carbon removed with respect to the age of the plantation. The greatest amount of carbon removed is found in the 25-year-old stands of 299.47 tCa ha^{-1}.

Keywords: carbon removal, *Pinus caribaea*, age.

RESUMEN

Las plantaciones de *Pinus caribaea* var. *caribaea* en Cuba almacenan una gran cantidad de carbono pues tienen un papel muy activo en el intercambio de dióxido de carbono entre la biosfera y la atmósfera, participando en la reducción de las concentraciones de gases de efecto invernadero. El presente estudio se realizó en la Unidad Agroforestal Viñales, perteneciente a la Empresa Agroforestal La Palma, con el propósito de determinar el carbono removido por plantaciones de *Pinus caribaea* de diferentes edades diez, 15 y 25 años de edad. Se tomaron probetas de 2,5 cm de ancho y largo, donde se determinó el porcentaje de humedad, materiales volátiles, porcentaje de cenizas y por consiguiente, el carbono removido. Existen diferencias significativas entre las variables materiales volátiles, porcentaje de cenizas y carbono removido con respecto a la edad de la plantación. La mayor cantidad de carbono removido se encuentra en los rodales de 25 años de 299,47 tCa ha^{-1}

Palabras clave: remoción de carbono, *Pinus caribaea*, edad.

RESUMO

As plantações de Pinus caribaea var. caribaea em Cuba armazenam uma grande quantidade de carbono porque desempenham um papel muito ativo na troca de dióxido de carbono entre a biosfera e a atmosfera, participando da redução das concentrações de gases de efeito estufa. Este estudo foi realizado na Unidade Agroflorestal de Viñales, parte da Empresa Agroflorestal La Palma, com o objetivo de determinar o carbono removido por plantações de Pinus caribaea de diferentes idades: dez, 15 e 25 anos. Foram utilizados tubos de ensaio com dimensões de 2,5 cm de largura e comprimento, onde foram determinados o percentual de umidade, materiais voláteis, percentual de cinzas e, consequentemente, o carbono removido. Existem diferenças significativas entre as variáveis materiais voláteis, porcentagem de cinzas e carbono removido em relação à idade da plantação. A maior quantidade de carbono removido é encontrada nos povoamentos de 25 anos de 299,47 tCa ha^{-1}.

Keywords: remoção de carbono, *Pinus caribaea*, idade.

INTRODUCTION

The current climate crisis is unquestionably a product of the accumulation of greenhouse gases in the atmosphere, emitted by human activities. Greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane, and nitrous oxide, trap heat from the Earth's atmosphere, causing global warming and climate change. The greater the concentration of GHGs in the atmosphere, the hotter the planet becomes, and the more severe the impacts and consequences of climate change become for people and natural ecosystems around the world.

These gases can remain in the atmosphere for a long time; some, like CO_2, for hundreds or even thousands of years. This means that even if humanity achieves zero emissions today, the gases already released into the atmosphere will continue to trap heat and warm the Earth for a long time, demonstrating that climate change is irreversible (IPCC, 2022).

Through the National Plan for Adaptation and Mitigation to Climate Change, some carbon dioxide removal measures (RDC) are proposed, in order to achieve the mitigation goal in 2030 (MAyDS, 2022). Although the DRC is not explicitly addressed in the Plan, the main measures that would contribute to carbon sequestration include ecosystem restoration and conservation, crop rotation (none of which are quantified), and a greater push for forestation. This last measure plans to increase the area covered with conifers, eucalyptus, and other trees that year and other species (native and exotic).

The Intergovernmental Panel on Climate Change (IPCC) defines carbon dioxide removal as any "anthropogenic activity by which $CO_2$is removed from the atmosphere and stored permanently in geological, terrestrial or oceanic reservoirs, or in products" (IPCC, 2019).

Carbon dioxide removal (CDR) emerges as an approach to sequester this gas on a large scale through new technologies or through biological methods such as afforestation, ecosystem restoration and carbon sequestration in soils (Gonda, 2023) .

Quinto (2024) states that forests, due to their high rates of carbon capture and storage, in addition to their role as sinks and reservoirs of atmospheric CO_2, have a fundamental role in the carbon balance and in the mitigation of global climate change.

Furthermore, it suggests that carbon capture and stocks in forests depend on various ecological factors, such as temperature, precipitation, humidity, solar radiation, soil nutrient type and content, disturbance regime, successional state, plant species, topographic position, and human impacts in each area, among others.

Forest management activities aimed at increasing carbon density *in situ* and at the field level are common practices that are technically feasible. In this regard, as a further step toward protecting biodiversity, reducing air pollution, and mitigating climate change, Cuba implemented incentive payments for forest carbon removal for the first time.

According to the document, in force since February 21, forest carbon is understood to be the organic carbon accumulated in any of the three reservoirs of the forested area (in tree biomass, aboveground and underground), in necromass (dead trees and leaf litter), and in the soil up to 30 centimeters deep.

The IPCC defines carbon dioxide removal (CDR) as any anthropogenic activity by which CO_2 is removed from the atmosphere and stored permanently in geological, terrestrial or oceanic reservoirs, or in products (IPCC, 2019).

Moisture content represents the amount of water in biomass, expressed as a percentage by weight of the material. Ash content represents the amount of solid residue remaining after the biomass sample is completely burned; the main components of ash are silica, aluminum, iron, calcium, magnesium, titanium, sodium, and potassium oxide. Condensable vapor and incondensable gases released during the thermal decomposition of biomass constitute volatile matter (excluding water vapor). Fixed carbon is the solid combustible residue remaining after heating the biomass and removing volatile matter (Pérez *et al*., 2021).

Pinus caribaea Morelet var. *caribaea* Barret and Golfari is one of the most important forest species in western Cuba, due to the uses made of its wood, being one of those prioritized in reforestation plans until 2030 (Castillo *et al*., 2018) .

Various investigations have been developed regarding carbon removal in Cuba, Mercadet *et al*. (2022); Álvarez & Mercadet (2023) and Gonda (2023), however, there are few studies developed with the purpose of determining the influence of tree age on carbon removal in different forest species.

This research is developed as a result of the international project "Municipal climate governance and sustainable agroforestry food production with low emissions and adapted to climate change in Cienfuegos and Pinar del Río, Cuba" and has the purpose of determine the carbon removed by *P. caribaea* plantations of different ages in the Unit of Agroforestal Viñales of the “La Palma” Agroforestry Company.

MATERIALS AND METHODS

General characteristics of the study area

The research was conducted at the "Agroforestal Viñales" Base Business Unit, located in the municipality of Viñales and belonging to the "La Palma" Agroforestry Company. It

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has a forest heritage of 41,550.6 ha, of which 40,950.3 ha are forested, 600.3 ha are non-forested and the young plantations represent 496.0 ha.

The mountainous relief predominates, reaching 71% of its total surface, according to the data provided by the State Forestry Service in the Province obtained from the Forest Dynamics with a closing date of December 2023 (Figure 1).

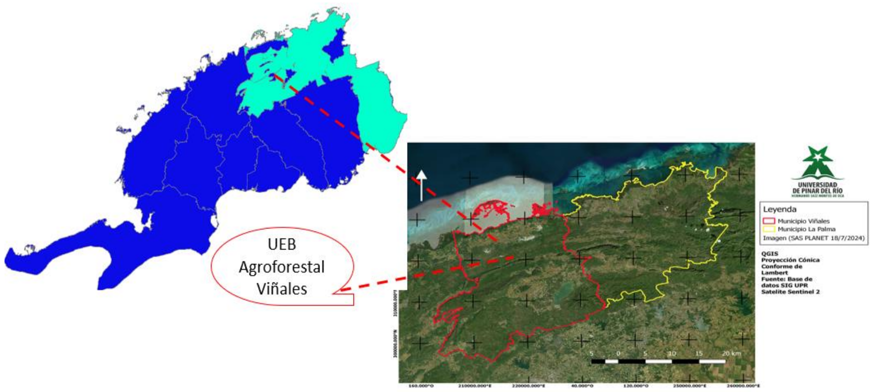

Figure 1. *- Geographic location of the study area. Source: UPR GIS Database, Sentinel 2 Satellite*

According to a report from the State Forestry Service of Pinar del Río (2023), the main forest formations are mainly represented by pine forests that cover an area of 8,790.9 hectares, approximately 70% of the surface of Viñales is forested, covering more than 48,000 hectares. 71.8% of the soils are occupied by forests distributed in the four existing forest ecosystems (pine forests, holm oak forests, mangroves and xerophytic mogotes).

Each species plays an important role within the forest. Their presence, abundance, and combination with other species give each forest its own unique type and beauty. Vegetation is found primarily in the coastal zone, the Pizarra Heights, and the mogotes.

The main forest formations are represented mainly by pine forests, which cover an area of 8,790.9 hectares and constitute the only indigenous formation in Cuba where the tree layer is made up of only one or at most two species.

The existence of this formation is primarily due to edaphic factors, because pine species thrive in acidic soils with a low water retention capacity. Although these areas are located within climatic regimes corresponding to semi-deciduous forests, the species typical of these forests cannot exist in pine forests due to the severe water shortage in times of drought, while pines, with their extremely xeromorphic leaves, can survive.

Edaphoclimatic characteristics

Viñales' climate is tropical in nature. During the winter season, precipitation levels decrease significantly compared to the summer months. The Köppen climate classification is Aw. The average annual temperature in Viñales is 25.5°C, and the annual rainfall is 782 mm (Figure 2).

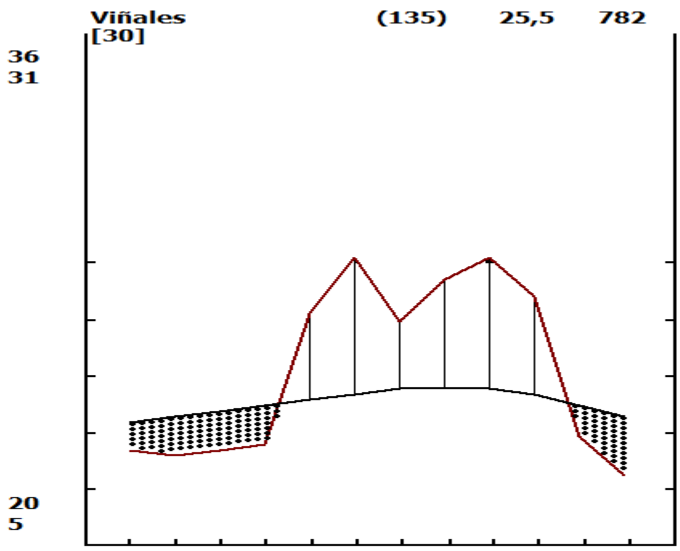

Figure 2. *- Climatic characteristics of the study area*

The Viñales region is characterized by a temperate climate, and the summer season presents some challenges in terms of precise categorization. The month with the lowest precipitation levels is February, with a mere 28 mm of rainfall. September experiences the highest rainfall, with an average of 190 mm.

Skeletal soils predominate in most of the territory, determined by geological and geomorphological characteristics. The presence of elevated areas of both carbonate and sandy-clayey materials, along with the influence of erosion, prevent the accumulation of an effective substrate for soil formation.

Brown soils with carbonates are found on the outer slopes of the calcareous heights, while on the heights composed of slates, schists, phyllites, and highly cracked and friable quartzites, the soils are easily weathered. Residual materials from the slate heights accumulate at the bottom of the valleys, giving rise to yellowish-red ferralitic soils with varying degrees of leaching. In the river valleys, there are alluvial deposits with patches of sandy-quartzite soils. On the limestone elevations connected to river caves, yellowish-red ferralitic soils appear with varying degrees of leaching (Jaimez, 2006), (Figure 3).

Materials used

Figure 3. *- Laboratory materials and equipment. a- crucibles, b- desiccator, c- muffle*

To obtain the wood samples (test tubes), the following procedure was applied:

a) *Pinus caribaea* species was selected as the most representative of the company, the experiment was carried out in plantations of different ages, as recommended by INEN Standards (2012), 20 wood samples were taken from a 10-year-old plantation, 20 from a 15-year-old plantation and 20 samples from a 25-year-old stand measuring 2.5 * 2.5 * 2.5 cm in length, width and height respectively. These dimensions were based on the.

b) The samples were placed in airtight containers until weighed; in this case, bags were used for each sample, with the respective enumerations.

c) Sample analysis and testing methods were performed in the chemistry research laboratory at the University of Pinar del Río.

d) The carbon retained in the stem was determined by analyzing the percentage of ash, volatile material and moisture content.

Procedure for obtaining the moisture content of wood samples

The procedure performed was done using the standard technique for coal and coke analysis established in the standard (ASTM D 3173-11).

a) The process began by taring the crucibles. To do this, they were first weighed on a technical scale and then incubated at a temperature of 105°C to 110°C for 24 hours. This process continued until the samples were completed.
b) After this time, they were removed from the oven to the desiccator for 20 to 30 minutes and weighed again. The process was repeated for up to 48 hours, at which point the crucible data on the technical scale was maintained.
c) The crucible was weighed with the wood sample, obtaining the first moisture content data, then it was placed in the oven at a temperature between 105 °C -110 °C as established in the INEN standard for a period of 24 hours, it was removed from the oven and placed in the desiccator for 20 to 30 minutes until it had cooled completely, the same procedure is repeated for another 24 hours, until a constant weight is obtained.

The formula stipulated by INEN Standard 1160 was applied, fulfilling the first objective. The moisture content is obtained using the following equation (Equation 1):

$$CH = P - Psh * 100\% / Psh \quad [1]$$

Where: CH = moisture content, in percentage. P = original mass of the sample, in grams. *Psh = mass of the anhydrous sample, in grams*

Procedure for obtaining percentages of volatile material from samples

a) The crucible with the dry wood sample was weighed on the scale and then placed in the muffle furnace at a temperature between 750 and 800 °C, avoiding contact with air for approximately 3 to 5 minutes.
b) At the end of this time, the samples were removed to the desiccator and allowed to cool for 30 minutes. After this time, they were weighed and the data obtained were recorded. These data were applied using the equation in ASTM Standard D3175-89(02).

The samples were placed in the muffle furnace and heated at a temperature of 900 ° C without contact with air for seven minutes. Once the mass was heated, gaseous and liquid products were released, mainly gaseous components such as: water, hydrogen, carbon dioxide, carbon monoxide, methane, etc. In general, rapid heating increases the proportion of volatiles, so the analysis of volatiles is standardized.

Volatiles are calculated by the following formula: Equation 2):

$$\%MV = \left[C - D\frac{}{C} \times 100\right] - \%Humedad \quad [2]$$

Where:

C= Initial weight, g samples used

D=Final weight, g of sample after heating

Procedure for obtaining ashes (ASTM D3174-00 standard)

For coal ash measurement, the furnace must have adequate air circulation and be able to control the temperature between 700 and 750°C. The furnace must be equipped with a temperature gauge and means to control it within limits. The coal samples must be heated for two hours and so on until they turn to ash (Vásquez, 2006).

Although the four-hour burning time described is sufficient for most coals to achieve complete combustion, some unreacted bituminous coals may require additional time. If unburned coal particles are observed, or if duplicate results are suspected, samples should be returned to the furnace long enough to achieve a constant mass (± 0.001 g).

In this way, the sulfur in pyrite oxidizes and decomposes, eliminating calcite. An adequate nozzle air supply, "two to four changes per minute," must be ensured at all times to ensure complete oxidation of the sulfur pyrite and the elimination of the sulfur dioxide formed. The 4-hour delay can be reduced if the sample reaches a constant weight at 700–750°C in less than 4 hours. (Vásquez, 2006)

a) The crucibles with the already volatilized samples were weighed and then placed in the muffle in a cold state until reaching a temperature of 450°C within a period of four hours.
b) After this, it was removed from the oven to the desiccator, where each crucible was covered until it cooled and could be weighed.
c) Once the final weighing data was obtained, the respective calculations were made by applying the following formula established by the ASTM D-3174-00 standard (Equation 3)

$$Ceniza\ en\ la\ muestra\ de\ análisis\% = A - B \times 100\%/C \quad [3]$$

Where:

A= Weight of crucible, lid, and ash residue, in grams.

B= Weight of the empty crucible and lid in grams.

C= Weight of the sample used in the analysis, in grams.

Procedure for calculating carbon removed (3172 - 89(02))

Carbon removed is used as an indicator of coke production from wood or coal and is a measure of the combustible materials remaining after the evaporation of light compounds. This is the non-volatile portion and burns in a solid state. It is the difference between the total residual moisture, ash and solid matter (Vásquez, 2006).

To determine the carbon removed from the wood samples, data on moisture content, ash content, and volatile matter were used. Carbon removal was calculated by differences according to ASTM D3172-13.

- The data were processed in Excel and in InfoStat to check the normality of the data, a Kolmogorov-Smirnov test was applied.
- The moisture content of the sample was then calculated.

The formula stipulated by INEN Standard 1160 was applied, fulfilling the first objective. The moisture content is obtained using the following equation (Equation 4):

$$CF = 100 - (\%humedad + \%Ceniza + \%Material\ volátil) \quad [4]$$

RESULTS AND DISCUSSION

The statistics show the results of the determination of volatile materials, percentage of ash and carbon removed in plantations of different ages (Table 1).

Table 1. *- Results of the non-parametric Kruskall-Wallis test for comparison of variables*

Variables	age (years)			*H*	P
	10	15	25		
Volatile Material	$213{,}68^{A}$	$228{,}66^{B}$	$240{,}37^{C}$	49,97	≤ 0,05*
ashes	$0{,}12^{A}$	$0{,}30^{B}$	$0{,}50^{C}$	42,71	≤ 0,05*
Carbon removal	$41{,}04^{A}$	$280{,}53^{B}$	$299{,}47^{C}$	52,46	≤ 0,05*

Note: * significative differences at P ≤ 0,05

The Normality test showed that the data did not follow a normal distribution, for this reason non-parametric Kruskal-Wallis tests were applied for the variables volatile materials, percentage of ash and carbon removed, comparing them with each other, to determine if there were significant differences between the variables in terms of the age of the stands.

The results are consistent with those obtained by Álvarez *et al*. (2020) and Mosquera (2023). Mature trees tend to have a greater carbon absorption capacity, since larger trees accumulate more biomass throughout their lives. Therefore, their protection and conservation is essential to maximize their role in mitigating climate change.

Table 1 shows the results of the statistical analysis, demonstrating significant differences between the variables volatile matter, ash percentage, and carbon content removed in categories A, B, and C. Therefore, the null hypothesis is rejected and the alternative hypothesis is accepted. This is due to the soil and climate conditions of the site, where the trees' capacity to absorb carbon depends on their state of conservation and age.

This is due to the soil and climate conditions of the site, where the trees' ability to absorb carbon depends on their state of conservation and age.

The variable "moisture content" was not taken into account for the statistical analysis; it is necessary to determine the carbon retained in the wood of the different plantations, but there is variation, as it depends on soil and climate conditions.

Determination of volatile material

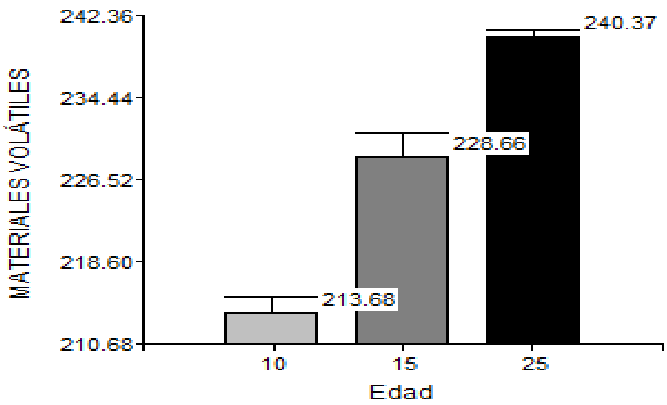

Figure 4. *- Volatile material in plantations*

Figure 4 shows the behavior of volatile matter with respect to age, which showed significant differences between the 10, 15, and 25-year-old plantations. The 25-year-old plantations contributed the highest volatile matter content, with an average value of 240.37, demonstrating that the older the plantation, the higher the volatile matter content in *Pinus caribaea.*

Similar results have been published by Bilen (2019) and Malucelli *et al*. (2024) that report as volatile material decreases, which is quite high in forest biomass, according to Ruiz *et al*. (2019). In this sense, its presence is necessary, since it facilitates the development of the porous surface during the carbon activation process.

De la Cruz *et al*. (2020) obtained results similar to those of the research in question due to the rapid ignition, presence of flame and high spark production of volatile materials, producing excessive smoke during combustion and generating more soot at the age of 25 years.

The samples from the 25-year-old plantation had the highest volatile matter content. They contained the lowest amount of binder and the highest water content. It can be said that the higher the amount of binder, the lower the volatile matter in the samples, and the water content present in the different experiments had minimal influence on the determination of this parameter (Figure 5).

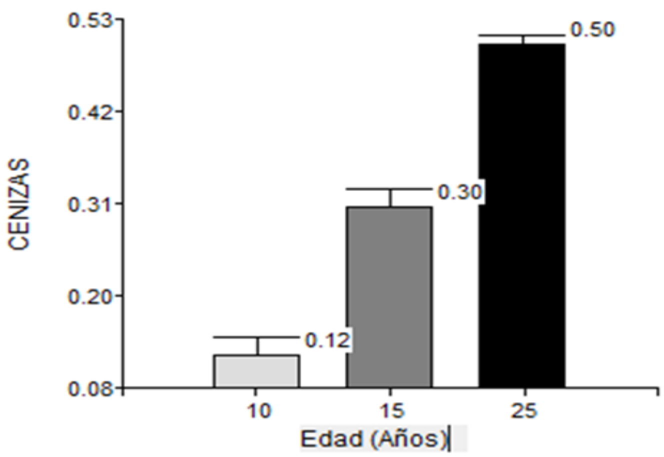

Figure 5. *- Percentage of ash in Pinus caribaea plantations*

The percentage of ash in the plantation is greater at the age of 25 years of the stand with a value of 0.50%, it can be seen that the concentration of ash is lower at ten years and increases with the age of the plantation, which shows that the concentration of ash is directly proportional to the age in *P. caribaea,* as shown in Figure 5.

The results obtained are consistent with the ranges reported in the literature for conifers or softwoods, with pine having ash levels between 0.02% and 1.1%.

González (2017) obtained similar results, due to the fact that the 25-year-old specimens have a greater binder content. In other words, the resin influences the amount of material used, leaving a greater amount of ash (Figure 6).

Pinus caribaea plantations

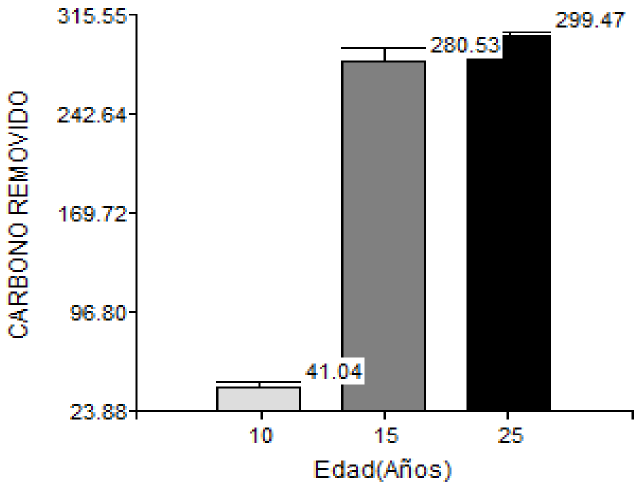

Figure 6. *- Carbon removed at different ages of the plantation*

Significant differences were found between volatile matter, ash percentage, and carbon removed (P <0.05), demonstrating that the species behaves differently at each age. It is assumed that older forests accumulate more carbon than younger ones. Their proximity to the felling stage influences carbon retention, taking into account their growth and the soil and climate conditions in which the stand develops. These results are higher than those reported by Mercadet (2020) in *Pinus caribaea* plantations, that obtained a carbon retention of 761.21 t in 4,040.90 ha.

The first values of the IMA (Average Annual Increment) of carbon recorded by the forests corresponding to the pine groves were reported by Álvarez *et al.* (2014) with values lower than 8.51, however, the extension of the evaluations to other areas of the Forest patrimony allowed them to be modified and those reported by Mercadet *et al.* (2015) are in use.

The ten-year-old plantation has a carbon retention of 41%, showing a lower percentage than the other plantations, since it has the lowest amount of binder, influencing the process of utilizing the combustion of the matter. In this sense, the research by González (2017) shows that the removed carbon obtained because of the release of volatile matter and ash had a low percentage, since both the volatile content and the removed carbon content are the two forms in which the chemical energy of biomass is stored.

On the other hand, De la Cruz *et al.* (2020) stated that the removed carbon is considered one of the most important characteristics of combustible materials, because it determines the quality and quantity of embers that form during combustion.

CONCLUSIONS

Pinus caribaea plantations from the Unit Agroforestal Viñales remove a greater quantity of carbon at 25 years with a value of 299.47 tCa ha^{-1} with 240.37 % of volatile material and a percentage of 0.50% ash.

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The authors declare not to have any interest conflicts.

***Contribution of the authors*:**

The authors have participated in the writing of the work and analysis of the documents.