

Potential of the native bamboo *Guadua aculeata* Rupr. for the carbon credit market

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ABSTRACT

Objective: To estimate biomass production, quantify carbon sequestration in natural stands of the native bamboo *Guadua aculeata* Rupr. at the “Las Margaritas” Experimental Station, and assess the economic value in a voluntary carbon credit market.

Design/methodology/approach: A forest biomass and carbon inventory was conducted in stands of *G. aculeata* in Puebla, Mexico. Using a simple random sampling design, 12 square plots of 100 m² each were established, and the diameter at breast height (Dbh) was measured in each bamboo individual. Aboveground dry biomass for structural components (culm, branches and leaves) and total biomass per individual were estimated with a system of additive equations; the carbon (C) concentration was obtained with C fractions of 0.46, 0.44 and 0.42 for culm, branches and leaves, respectively.

Results: On average, the stands contained 263.14 Mg·ha⁻¹ of biomass; distributed in 91% for culm, 5% in branches and 4% in the leaves. The average carbon stock was 120.34 Mg·ha⁻¹. At the farm level, the carbon inventory and storage amounted to 7,701.73 Mg in 64 ha of bamboo stands forest. Annual carbon sequestration was estimated at 23.72 Mg·ha⁻¹ per year, equivalent to mitigating 87.05 Mg·ha⁻¹ of CO_{2e} per year, representing an economic value of \$3,133.8 MXN.

Limitations on study/implications: Biomass, carbon, and CO₂ in mulch and soil were not quantified.

Findings/conclusions: *G. aculeata* demonstrates high potential for inclusion in the carbon credit market.

Keywords: Giant native bamboo, carbon storage, biomass, voluntary market, carbon offsets.

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INTRODUCTION

In recent years, significant changes in climatic conditions have been recorded in Mexico, primarily associated with global climate change caused by the increase in greenhouse gases (GHG). Some of its adverse effects have been reported by Flores-Campaña *et al.* (2012) and Cuervo-Robayo *et al.* (2020). Environmental changes are of the highest interest to governments, as they directly affect agricultural, livestock, and forestry production (Gómez-Pineda *et al.*, 2020). To address this critical issue, the United Nations signed the Kyoto Protocol in 1997, which directly tackled the problem of climate

change. A total of 192 countries committed to adopting policies aimed at reducing GHG emissions by 5.2% compared to 1990 levels. Subsequently, an Intergovernmental Panel of Experts on Climate Change (IPCC) was established. In 2015, the Paris Agreement was signed, establishing concrete and realistic goals on how to achieve the reduction and mitigation of GHG emissions. In this context, Mexico, with mitigation and compensation goals and actions, committed to: a) achieving zero deforestation by 2030; b) reforesting upper, middle, and lower watersheds with native species; c) increasing ecological connectivity and carbon sequestration through conservation and restoration; d) enhancing carbon capture and coastal protection through the conservation of coastal ecosystems; e) implementing REDD+ (Reducing Emissions from Deforestation and Forest Degradation) synergies; and f) ensuring integrated water management across its different uses (agricultural, ecological, urban, industrial, and domestic).

In this scenario, bamboo forests can provide environmental services as well as tangible and intangible benefits to humanity (Ordóñez-Prado *et al.*, 2024).

Among its ecological functions, bamboo stands out for its rapid growth, soil recovery, maintenance and recharge of water bodies, and carbon sequestration (Cecon and Gómez-Ruiz, 2019; Ordóñez-Prado *et al.*, 2023). Research on bamboo carbon stocks remains relevant both nationally and internationally, as establishing climate change mitigation strategies requires baseline information on fast-growing species with high carbon capture potential.

Studies on this topic report that natural forests and plantations with giant bamboo are capable of producing biomass quantities comparable to those of tropical broadleaf plantations, reaching up to 429 Mg·ha⁻¹ (Ziccardi *et al.*, 2019). Darabant *et al.* (2014) report a total aboveground biomass production of 307 Mg·ha⁻¹ in bamboo plantations established in India. Carbon sequestration is closely linked to biomass production, which can reach up to 392 Mg·ha⁻¹ when considering necromass and roots (Yuen *et al.*, 2017). For bamboo taxa in natural forests, biomass estimates may be lower (Ziccardi *et al.*, 2019).

Many bamboo species are recognized for their potential to capture carbon (Yuen *et al.*, 2017). Their rapid growth and continuous production of shoots foster a high dynamic in various carbon stocks (Liu *et al.*, 2018). The genus *Guadua*, classified as giant bamboo, can reach heights exceeding 20 meters and diameter at breast height greater than 10 centimeters (Clark and Ely, 2011). *Guadua aculeata* Rupr. (carrizo, caña brava) is the most robust native species in Mexico.

Bamboos have the potential to provide economic benefits by being considered in carbon credit markets, which are aimed at offsetting greenhouse gas emissions. In this regard, Pizarro (2021) notes that carbon credits are an alternative for countries implementing them, as they can obtain economic resources by reducing GHG emissions into the atmosphere. For bamboo to be included in carbon markets, research is needed to document its growth, biomass production, carbon sequestration, silviculture, and the development of long-life bamboo products that store carbon over extended periods (Kaam *et al.*, 2023; Ordóñez-Prado *et al.*, 2024).

In Mexico, the state of Puebla is a pioneer in bamboo cultivation, with various plantations established for commercial and restoration purposes (Ordóñez-Prado *et al.*, 2023). In this region, *G. aculeata* is used in local housing construction, the production of artisanal furniture, fences, and supports for agricultural crops (Hernández-Santiago and Torres-Hoyos, 2020). Additionally, its physical-mechanical properties make it ideal for construction (Ordóñez-Candelaria *et al.*, 2014). Despite the importance of bamboo, studies on its carbon sequestration potential are scarce, highlighting the need for information on the capacity of bamboo stands forest to capture and store carbon as a viable alternative for carbon credit markets. Based on the aforementioned context, the objective was to estimate biomass production, quantify carbon sequestration in natural stands forest of the native bamboo *G. aculeata* in the Hueytamalco region, Puebla, Mexico, and assess its economic value in a voluntary carbon credit market.

MATERIALS AND METHODS

Study Area

The study was conducted in natural stands forest of *G. aculeata* bamboo at the “Las Margaritas” Experimental Station (SEMAR, acronym in Spanish) belonging to the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), located in Hueytamalco, Puebla, Mexico, between the extreme coordinates 20° 02' 35" and 19° 58' 50" N and 95° 21' 27" and 97° 16' 40" W, at an altitude of 450 to 500 meters. SEMAR is one of the best-preserved areas in the region, primarily composed of species representative of the medium-sized evergreen forest. Its orography of small hills and its annual precipitation of 3,000 mm support an abundant water network, providing ideal conditions for the growth of native bamboo *G. aculeata* (Figure 1).

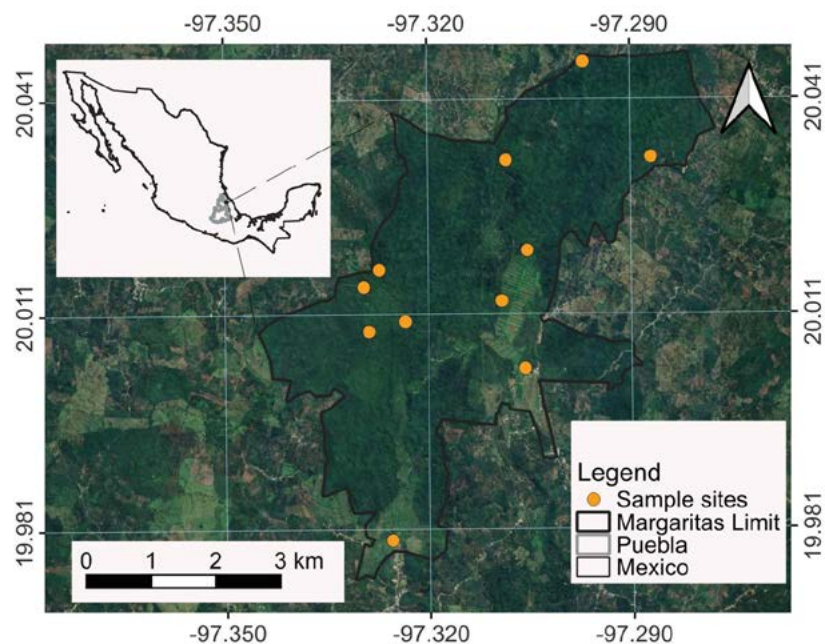


Figure 1. Distribution of bamboo stands at the Experimental Station, Puebla, Mexico.

Field Data

A zoning of the distribution of *G. aculeata* stands forest was carried out using a satellite image (image ©2019 Maxar Technologies) from the online server Google® Earth®, verified through field surveys. A total of 39 natural areas covered by the studied bamboo were identified. The coverage of these stands ranged from 0.5 to 4 hectares (Figure 1). Based on this zoning, a random sampling design was created to establish 12 square plots of 10×10 meters, where the diameter at breast height (Dbh) was measured at 1.3 meters above ground level for each bamboo culm (Figure 2). The Dbh was used to estimate the total aboveground dry biomass per individual, for which the additive equations system proposed by Ordóñez-Prado *et al.* (2024) was applied. The mathematical structure and parameters are shown in equations 1 to 4. Subsequently, the biomass estimated for each structural component of each bamboo was multiplied by the carbon concentration: 46%, 44%, and 42% for culms, branches, and foliage, respectively. This resulted in the stored carbon, scaled to the hectare level.

$$B_c = \exp(-2.44613) Dbh^{2.446172} \quad (R_{adj}^2 = 0.93, RMSE = 4.2849) \quad 1$$

$$B_r = \exp(-5.4065) Dbh^{2.494163} \quad (R_{adj}^2 = 0.63, RMSE = 0.7115) \quad 2$$

$$B_f = \exp(-8.82811) Dbh^{3.7639121} \quad (R_{adj}^2 = 0.42, RMSE = 0.9904) \quad 3$$

$$B_T = Y_c + Y_r + Y_f \quad 4$$

Where: B_c , B_r , B_f y B_T correspond to the estimated dry base biomass weight of the culm, branches, leaves, and total aboveground biomass, respectively.



Figure 2. Natural stands forest of *Guadua aculeata* and fieldwork conducted for biomass and carbon quantification in the study area.

Statistical Analysis

A forest inventory of biomass and carbon in the bamboo stands of the study area was conducted using simple random sampling estimators (Tamarit-Urias *et al.*, 2021). The average biomass per hectare, standard deviation, and 95% confidence intervals were estimated, as well as the sampling error. The biomass inventory was conducted for an area of 64 ha. For the carbon inventory, the biomass of each structural component of the bamboo was multiplied by the respective proportion of fixed carbon expressed in Mg ha^{-1} .

Stored Carbon Value

The annual biomass production of bamboo for mature stands forest with commercial culm production was estimated using seven culms with an average DBH of 10 cm. Based on observations, it was assumed that for this species, on average, seven culms are produced annually in each clump, and the average DBH is 10 cm. A density of 280 plants $\text{clump}^{-1} \text{ha}^{-1}$ was considered. Based on Barnabas *et al.* (2020), to estimate the amount of carbon dioxide equivalent (CO_2e) per hectare fixed by a bamboo species, Equation 5 was applied.

$$\text{CO}_2\text{e} = Bt \cdot CC \cdot FP \quad 5$$

Where: *Bt* is the total aboveground biomass, *CC* is the carbon content proportion in the *Bt*, and *FP* is the proportionality factor, which takes the value of 3.67.

After the annual estimation of the stored CO_2e , the economic value was estimated based on the World Bank report (2024), which indicates that the price range is between US\$0.46 to US\$16 ($\text{Mg} \cdot \text{CO}_2\text{e}$). For Mexico, a value of <US\$20 is estimated (Figure 3). Based on this information, for the purposes of this research, a conservative price of US\$2 (\$36 MXN at the exchange rate) per ton of CO_2e was established.

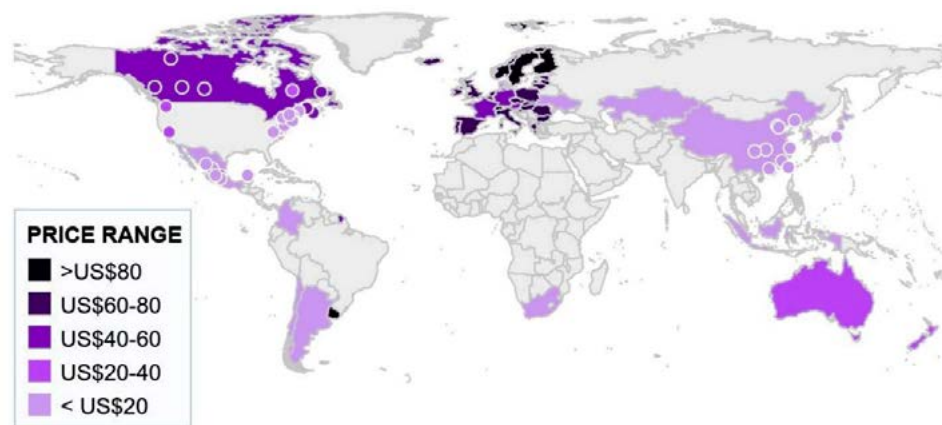


Figure 3. Carbon price around the world for 2024 (The World Bank, 2024).

RESULTS AND DISCUSSION

Carbon stored in bamboo groves

It was determined that the natural stands forest of *Guadua aculeata* store an average of $263.14 \pm 10.13 \text{ Mg ha}^{-1}$ of total aboveground dry biomass; with 91%, the culms are the structural component of bamboo that stores the most biomass, while the branches hold only 5%, and the remaining 4% is found in the foliage. In Table 1, the carbon reservoirs per unit area for the structural components culms, branches, and foliage are shown. The results obtained are higher than those reported for commercial plantations of *B. oldhamii* Munro and *G. angustifolia* Kunth, established in the same study region (Aguirre *et al.*, 2018), which indicates that the *G. aculeata* stands are located in areas with physiographic characteristics ideal for their development. Furthermore, the results are higher than those reported by López-Martell *et al.* (2008), who reported an average of $70.9 \text{ Mg} \cdot \text{ha}^{-1}$ for *B. vulgaris* Schrader ex Wendland in the Granma province, Cuba.

Regarding the stored carbon, an average of $120.34 \pm 6.81 \text{ Mg} \cdot \text{ha}^{-1}$ was estimated in the aboveground biomass, with proportions for each structural component similar to the biomass distribution. Table 1 presents the average values of stored carbon in the structural components and the total. The estimates of carbon content further reinforce and confirm the high potential of bamboo forests to capture and store carbon. Although carbon fixation is slightly lower than in tree species, their rapid growth and constant shoot production rate are strengths that these ecosystems possess for carbon capture. The results obtained are lower than those reported by Fonseca-González and Rojas (2016), who estimated $186.73 \text{ Mg} \cdot \text{ha}^{-1}$ for *D. latiflorus* plantations, while for *G. angustifolia* Kunth and *G. aculeata* Rupr. plantations, they report $117.74 \text{ Mg} \cdot \text{ha}^{-1}$, a value lower than that determined in the present study. These results are also similar to those reported by García-Soria and Del Castillo (2015), who recorded a carbon storage of $121.86 \text{ Mg ha}^{-1}$ for natural bamboo forests of *G. sarcocarpa* Londoño & Peterson in Peru.

Carbon stored value in bamboo forests

It was estimated that the carbon capture in the aboveground biomass of the studied bamboo forests is $23.72 \text{ Mg} \cdot \text{ha}^{-1}$ of carbon per year. This equates to the mitigation of $87.05 \text{ Mg} \cdot \text{ha}^{-1}$ of CO_2e per year. This means that each hectare covered with bamboo is generating 87 carbon credits or carbon offset credits per year. These carbon credits have a value of \$3,133.8 MXN, considering an average cost of US\$ 2.0 per $\text{Mg} \cdot \text{ha}^{-1}$ of CO_2e per year.

Table 1. Biomass and carbon stored in natural *Guadua aculeata* bamboo forests in Huey tamalco, Pue., Mexico.

Component	Dry base biomass (Mg ha^{-1})	Total biomass inventory on the property (Mg)	Carbon content (Mg ha^{-1})	Total carbon inventory on the property (Mg)
Culmo	238.57 ± 8.92	$15,268.41 \pm 570.72$	109.74 ± 6.05	$7,023.47 \pm 387.08$
Ramas	13.91 ± 2.15	890.15 ± 137.80	6.12 ± 1.43	391.66 ± 91.41
Follaje	10.66 ± 1.89	682.38 ± 120.65	4.48 ± 1.22	286.60 ± 78.19
Total	263.14 ± 10.13	$16,840.94 \pm 61.87$	120.34 ± 6.81	$7,701.73 \pm 435.78$

By estimating an average mitigation of $87.05 \text{ Mg}\cdot\text{ha}^{-1}$ of CO_{2e} , this represents an annual value of \$200,448.00 MXN for CO_{2e} capture in *G. aculeata* bamboo forests growing naturally on the “Las Margaritas” Experimental Station and land. The results obtained are conservative compared to those reported by Pathak *et al.* (2015), who estimated that the production of culms is between 11 to 20 per bamboo clump per year. With a density of 124 clumps per hectare, the biomass production calculated by these authors can reach $104.7 \text{ Mg}\cdot\text{ha}^{-1}$ per year (Table 2).

Table 2. Biomass accumulation potential in different bamboo species.

Specie bamboo	Culms produced by clump per year	Clump per hectare	Aboveground biomass tons per hectare
<i>Bamboosa tulda</i>	15	124	70.40
<i>Bamboosa bambos</i>	15	124	75.69
<i>Bamboosa nutan</i>	15	124	41.82
<i>Bamboosa asper</i>	20	124	7.12
<i>Dendrocalamus strictus</i>	11	124	12.94
<i>Bamboosa vulgaris</i>	12	124	53.42
<i>Bamboosa balcoa</i>	15	124	104.70

The annual carbon capture of *G. aculeata* bamboo demonstrates the potential of this highly lignified grass to be considered in voluntary carbon markets. This would allow companies to make their services and products carbon-neutral by acquiring carbon credits from natural forests or bamboo plantations, with 1 carbon credit equivalent to 1 Mg of CO_{2e} . Additionally, it could serve as a source of income for rural community families, contributing to improving their quality of life. In this regard, Pan *et al.* (2023) and Kaam *et al.* (2023) mention that the role of bamboo in climate change mitigation occurs in three dimensions: as a carbon sink in the form of biomass, as carbon storage in bamboo products, and as a contributor to carbon credit projects. However, bamboo species, like many other forest species, face limitations in their incorporation into carbon credit markets due to the absence of internationally accepted methodologies for the precise quantification of carbon reservoirs and the debate on whether bamboo should be considered a tree species or a highly lignified giant grass (as it is currently recognized) (Wu *et al.*, 2015). The estimated potential for annual carbon capture in this study indicates that *Guadua aculeata* is feasible for establishing promising ecological projects as a nature-based strategy and solution (NbS).

CONCLUSIONS

The biomass inventory of *Guadua aculeata* bamboo forests allowed the quantification of the amount of carbon and CO_{2e} stored in this little-studied ecosystem. The study provides basic information about the carbon storage potential of this fast-growing species. A total of 7,701.73 Mg of carbon were quantified as stored in the natural bamboo stands, making them a potential alternative that could help mitigate the effects of climate change. The

estimated annual carbon capture potential and CO_{2e} fixation indicate that the native giant bamboo *Guadua aculeata* is feasible for establishing promising environmental projects as a nature-based solution (NbS), thereby generating additional income for bamboo producers.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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