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Capture and Storage of Carbon in the Dry Forests of Pomac (Lambayeque, Peru) to Improve the Focus of Reforestation on new Ecosystem Services

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The estimation of aerial forest carbon storage and capacity (CCS) is a fundamental instrument to evaluate the application of forest management measures and soil recovery under the approach of use in new ecosystem services (CCUS). The research has aimed to evaluate the capture and storage of carbon in the dry forests of Pomac (Lambayeque, Peru) to improve the approach of reforestation in new ecosystem services. For this, the non-destructive method was used, 15 random plots were selected, the tree species were identified, counted and measured, taking into account the diameter at breast height (DBH), the results indicated a total accumulation of aerial biomass (dry) of 75.09 t/ha and a mass of stored carbon of 37,545 t/ha. The highest contribution of aerial biomass was dominated by three species: *Prosopis pallida* H.B.K. for Arnata ferreyra (carob tree) (90.99%) > *Capparis ovalifolia* (Vichayo) (6.13 %) > *Capparis scabrida* (Sapote) (2.02 %). The quadratic models to estimate the aerial biomass (AGB) of each species and of the plots studied based on the DBH were robust (R2>0.7) and significant and demonstrated a great payment potential in relation to the carbon credit in the Voluntary Market of Carbon. These results can be used to improve forest management and the recovery of degraded soils under the approach of new ecosystem uses that include the CCUS approach.

1. Introduction

Dry forests are the ecosystems that represent the second largest type of tropical forests in Latin America, but various human activities make them the most threatened ecosystems on the planet (Quijas et al. 2019; Ocampo-Ariza et al. 2022, Marcelo- Peña et al 2020; Guzmán et al. 2021). Tropical forests bear great risks from human and natural factors, as they are subject to severe disturbances and play an important role in climate change adaptation and mitigation because they contribute significantly to the regulation of various ecosystem services and global carbon storage (Siyum 2020). The carbon neutrality approach that leads to zero CO_2 emissions offers a good opportunity to fight against climate change and the capture and storage of carbon by the forest is a technology that deserves special attention for a good integrated management of forests that also could supply energy with zero CO_2 emissions (Michaga et al. 2022). Peru is aware of the need to take coordinated actions to reduce climate risks on the population and ecosystems; it has laid the regulatory foundations to implement concrete actions towards carbon neutrality to reduce GHG emissions and has prioritized measures to strengthen the governance of forests (MINAM 2021a). Control of deforestation must be reduced by up to 30% by 2030 and implement the phases for the Reduction of Emissions from Deforestation and Forest Degradation (REDD+). In this context, it also promotes the generation of renewable energy from biomass, however, the potential energy value of forests that could lay the foundations for reforestation processes in deforested areas that could provide new ecosystem services has not yet been analysed. In Peru, dry forests form an ecosystem of semi-dense vegetation, its main characteristic is a dry climate with short rainy seasons, with arid areas being the most vulnerable (Morales and Tullume 2015). According to MINAM (2021b), the seasonal dry forests of Lambayeque

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in northern Peru, in 2018 had an area of 505,209 ha of the 2,376,055 ha of dry forests in the north of the country, equivalent to 21.26 % of the total dry forests. The great diversity is concentrated in forest species, such as ceibo, carob, faique, willow, and palo verde, which have the ability to retain rainwater and survive in periods of drought. In the case of the carob tree, its adaptability, resistance to stress and life in dormant conditions stand out. Thus, the dry forest controls the advance of deserts and provides services to agricultural activity (Morales and Tullume 2015). The quantification of the accumulated carbon in a forest or a certain forest species is carried out by estimating the biomass, knowing as such the amount of living organic matter in the aerial part of the tree species, expressed in tons of dry mass per area unit. Said estimation can be made by the non-destructive method, which estimates the biomass through regression analysis (Riofrío et al., 2013). In tropical forests with a rich and wide diversity of species where not all are used commercially, harvesting is very extensive when destructive methods are used, in which case it is more practical to apply accurate models; to provide highly reliable estimates of growing stock, biomass, carbon sequestration, according to species, genera and sites (De Cauwer et al. 2020). On the other hand, part of the uncertainty in the estimates of the quantity and spatial variation of biomass in forests can be overcome by developing allometric equations, in order to improve the precision in the non-destructive estimation of above-ground tree biomass (AGB). The allometric relationships incorporate dasometric variables, such as the diameter and total height of the tree, as predictor variables, since they present a high correlation with biomass. The most important variables are the diameter of the breast height (DBH), the estimation of the aerial biomass (AGB) and the expressed carbon content (C_{mass}).
The Pómac Historic Sanctuary Forest (SHBP), is a protected natural area (Nolazco and Sánchez 2020) in charge of the National Service of Protected Natural Areas of Peru (SERNANP), it is located in Ferreñafe (Lambayeque) in northern Peru (Chávez et al. 2022). This Peruvian equatorial-tropical dry forest is part of the group of tropical forests, it is known for its high diversity and endemism (Cueva et al. 2019). It is located on the western slope of the Andes Mountains and protects the largest carob tree forest (Prosopis pallida) (H. et Bonpl. ex Willd.) H.B.K. of the world. The forest extends in 5887.38 hectares (Chávez et al. 2022). Due to its final state of conservation, it has been considered an endangered ecosystem; and they have been given the highest conservation priority, since they are severely threatened ecosystems at a global level, due to the high degree of loss of cover with respect to their original distribution (MINAM 2021b). The objective of the research was to evaluate the capture and storage of carbon in the dry forests of Pomac to improve the approach of reforestation in new ecosystem services under different scenarios (Michaga, et al. 2022).

2. Materials and Methods

2.1 Study Area and Inventory of tree cover

A first inventory of the trees of the aerial dry forest of Pómac, Lambayeque Region, located in the northern region of Peru (2015-2016). For this, the number of trees was quantified and coded by plots. The study applied the stratified sampling design because it was a population of woody and shrubby species. Fifteen (15) plots totaling an area of 15,000 m2 were evaluated, using the non-destructive indirect method. The plots formed rectangular shapes and the forest inventory of all the individuals that formed the forest within each randomly selected plot was carried out. Then, the amount of dry biomass in the study area was determined, as well as the biomass and carbon at the species level. In addition, the allometric models for the Pómac forest and the allometric models for five (05) forest species were applied.

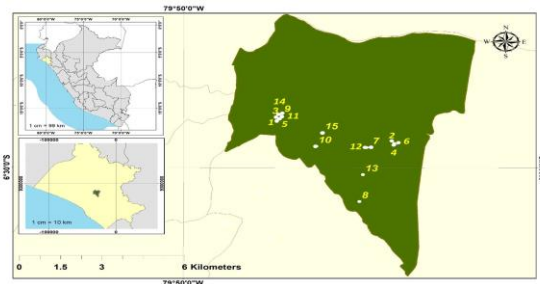

Figure 1. Sampling positions of the Forest in the Pomac Sanctuary 2015-2016. Ferrenafe, Lambayeque Peru.

2.2 Tree Height and Diameter at Breast Height (DBH)- Estimation of Above Ground Biomass (AGB) and Carbon Content

In this research, the biomass estimate was quantified using a non-destructive method whereby tree height and diameter at breast height (DBH) were measured for each individual tree. The quantification of the amount of carbon mass included the carbon contained in any plant species equivalent to 50% of its biomass (Sharma et al 2020):

Carbon mass = 0.5 × total biomass

While the CO_2 equivalent was calculated using the following equation:

CO_2 (eq.) = (Carbon mass × 44)/12

3. Results

The estimation of the total accumulation capacity of aerial (dry) biomass of the fifteen (15) plots studied was equal to 75.09 t/ha. The result of the extrapolation of the biomass of each plot with respect to its surface, confirming the existence of a considerable biomass in this type of tropical forest, likewise the calculation of the carbon mass registered 37,545 t/ha. Table 1, details the scientific and common names of the species found, the diameter at breast height (DBH), the aerial dry biomass and the recorded carbon mass. The first three species contribute a higher biomass and carbon content in the dry forest, according to the following order: *Prosopis pallida* H.B.K. for Armata ferreyra (90.99%) (algarrobo) > *Capparis ovalifolia* (Vichayo) (6.13 %) > Capparis scabrida (Sapote) (2.02 %). The high biomass of "algarrobo" is due to its high average basic density of 0.88 g/cm^3.

Table 1. Species, diameter at breast height, aerial dry biomass and carbon mass

Common name	Species	DBH (cm)	AGB (T/Ha)	Cmass (T/Ha)	% Cmass
Algarrobo	*Prosopis pallida*	(0.37-95.49)	68.33	34.16	90.99
Vichayo	*Capparis ovalifolia*	(0.32-42.97)	4.6	2.3	6.13
Sapote	*Caparis scabrida*	(0.95-22.28)	1.53	0.76	2.02
Canutillo	*Graboswskia boerhaaviaefolia*	(0.95-35.01)	0.32	0.17	0.45
Faique	*Acacia macracantha*	(2.86-14.64)	0.19	0.09	0.24
Cuncuno	*Vallesia glabra Cav.*	(2.86-6.84)	0.05	0.02	0.05
Palo verde	*Cercidium praecox*	(5.09-15.28)	0.1	0.01	0.03
	Total		75.09	37.545	100

Table 2. Allometric equations of the total dry biomass (AGB_T) and the dry stem biomass (DSB) for each species

	Alometric equations	R^2
Total dry aerial biomass	AGB_T = 79.25-14.24 (DBH)+ 0.81(DBH)^2	0.93
Stem dry biomass	DSB =39.66-7.27(DBH)+0.46(DBH)^2	0.9
Species:		
Prosopis pallida	AGB_T = -6.01-1.49 (DBH) + 0.61 (DBH)^2	0.92
	DSB =20.57-3.54 (DBH)+0.43 (DBH)^2	0.93
Capparis ovalifolia	AGB_T = 0.123 (DBH)$^{2.01}$	0.92
	DSB =1.75-2.51 (DBH)+0.70 (DBH)^2	0.94
	DSB = -21.23+2.27 (DBH)+5.86 (FH)	0.86
Capparis scabrida	AGB_T = 0.06 (DBH)$^{2.52}$	0.91
	AGB_T = 0.48 (DBH)$^{2.44}$	0.88
	AGB_T = -45.44+4.44 (DBH)+ 5.16 (SH)+3.2 (CD)^2	0.71
Graboswskia boerhaaviaefolia	AGB_T = 0.066 (DBH)^{2,167}	0.95
	DSB = 0.5 (DBH)$^{2.13}$	0.94
Acacia macracantha	AGB_T = 0.386 (DBH)$^{2.75}$	0.9
	DSB = -12.75+ 5 (DBH)-1.32 (DBH)^2	0.88

Table 2 shows the results of the non-linear regression analysis based on the diameter at breast height (DBH), which turns out to be an adequate variable to predict the values of total biomass and of the total biomass of the stem of the trees in the plots studied. Fisher's test confirmed the significance level of p-value <0.05. In addition, the coefficients of determination (R^2) of the total variation observed in the aerial biomass are observed, explained in a high percentage by the diameter at breast height (DBH) calculated for each species evaluated in the dry forest of Pómac (Table 3). The coefficients of determination (R^2) of the total variation observed in the dry aerial biomass (AGB) is explained in a high percentage by the diameter at breast height (DBH), crown diameter (CD) and stem height (SH).Figure 2 shows correlations between estimated stem dry biomass (AGB) vs diameter at breast height (DBH) for the entire forest and species; with determination coefficients greater than 0.71 using the SPSS v25 software.

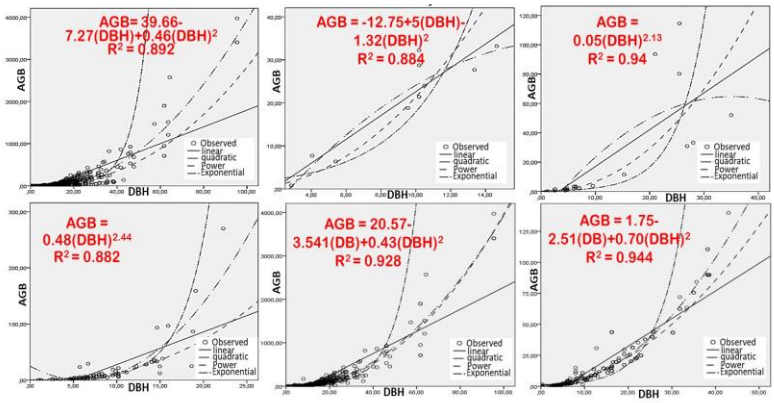

Figure 2. Correlation between Dry biomass (AGB) vs. diameter at breast height (DBH): a) forest species in the dry forest (total); b)_Faique (Acacia macracantha); c) Canutillo (Graboswskia boerhaaviaefolia);d) Sapote (Capparis scabrida);e) Algarrobo (Prosopis pallida H.B.K. for Arnata ferreyra); e) Vichayo (Capparis ovalifolia)

The Table 3, presents the analysis of variance (ANOVA) of the significant ($p<0.05$) and most robust models (R^2: 0.88-0.95) related to the estimation of the total aerial biomass (AGB_T and AGB) for the total forest and for each species.

Table 3. ANOVA models for the dry biomass (AGB_T/AGB)-DBH in the forest and species

Models: AGB_T vs DBH	Model Summary					Parameter estimates		
	R^2	F	gl1	gl2	Sig.	Constant	b1	b2
Forest-Quadratic	0.93	5,547	2	801	0	79.25	-14.24	0.81
Algarrobo-Quadratic	0.92	2,603	2	454	0	-6.01	-1.50	0.61
Vichayo-Power	0.92	2,207	1	206	0	0.12	2.01	
Sapote-Power	0.91	924	1	91	0	0.06	2.52	
Canutillo-Power	0.95	444	1	23	0	0.07	2.17	
Faique-Power	0.90	74	1	8	0	0.39	1.75	
Models: AGB vs DBH								
Forest- Quadratic	0.90	3,425	2	801	0	39.66	-7.27	0.46
Algarrobo-Quadratic	0.93	2,908	2	454	0	20.57	-3.54	0.43
Vichayo- Quadratic	0.94	1,697	2	201	0	1.75	-0.25	0.07
Sapote- Power	0.88	681	1	91	0	0.05	2.44	
Canutillo- Power	0.94	358	1	23	0	0.05	2.13	
Faique- Quadratic	0.88	27	2	7	0	-12.75	5.00	-0.13

4. Discussion

The total amount of aerial biomass on average in the dry forest of the present study reports 75.09 t/ha, similar to what was recorded by López (2014) in the sectors of Pítipo (87.24 t/ha), Salas (72.82 t/ha) and Olmos (68.92 t/ha), the average of these forests was equal to 76.32 t/ha of aerial biomass. Accumulation estimates could correspond to site quality, period of forest development, degree or intensity of intervention or disturbance, and age. Carbon storage gradually decreases in advanced stages of forest age due to biophysical limitations of vegetation growth (Mora et al., 2018, Cortés-Calderón et al. 2021; Petersson, et al. 2022). The average amount of carbon accumulated in the Pómac dry forest was 37,545 t/ha, close to that reported by López (2014) (C*mass*: 38,163 t/ha). According to the conversion stoichiometry of one ton of carbon equivalent to 3.67 tons of CO_2 and considering 5,887.38 ha, the amount of CO_2 equivalent amounts to 811,222.97 t CO_2. On the other hand, human society payments for environmental services are part of a relatively new and straightforward conservation paradigm. The need to agree between the interests of the landowners and/or the State and the users of the services is recognized as an extremely attractive alternative because it encourages landowners to maintain, restore and improve ecosystem services (Moros, et al. 2022). In Peru, the carbon credit in the Voluntary Carbon

Market differs in price from each other depending on the negotiation, which varies from 8 dollars to 10 US dollars per ton (Lock 2021). This means that the amount of CO_2 calculated for the Pómac plots studied represents the CO_2 not emitted into the atmosphere, which represents in terms of payment for environmental services an approximate amount between 1,768,333.44 and 2,210,410.68 US dollars.

Table 4. Carbon mass, Pómac forest area, amount of carbon, carbon dioxide and payment for environmental services.

Carbon mass (t/ha)	**Area (Ha)**	**Total carbon stored in the Pómac forest (t)**	**Total CO_2 in the Pómac forest (t)**	**Payment for environmental carbon service (US$)**
37545	5887.38	221041.68	811222.97	1,768,333.4 - 2210410.68

The greater amount of carbon was related to a higher population density, the distribution of aerial biomass and carbon is dominated by few species that concentrate a large amount of carbon. However, the distribution of diameter classes and the population density have a fundamental role in the accumulation of carbon and in the stages of the growth process to become dominant trees. Likewise, the interaction of tree age and site quality and conditions such as El Niño events also significantly influence the proportion of stem biomass (Deng, et al. 2023; Pécastaing and Chávez 2020). In this investigation, species with higher basic density were evidenced, due to an anatomical structure with thicker cell walls and a small lumen. For example, the species *Prossopis pallida* presented a mean basic density of 0.88 g/cm^3, while other species with lower densities showed an anatomical structure of wood with thin cell walls and a large lumen, such as the species Vallesia glabra (basic density : 0.50 g/cm^3). The use of allometric models developed in different regions for the estimation of biomass presents limitations due to the variability of environmental conditions that govern tree growth, genetics, local subpopulations, climate and soils (Kellomäki 2022). These factors are determinant in the increase in biomass and therefore in the fixation of CO_2 (Srinivas et al. 2019). In general, the quadratic and exponential regression fits were highly significant ($P < 0.0001$). It should be noted that the study will generate the necessary information for subsequent studies related to the restoration of degraded soils (Fremout et al. 2022) with a view to holistic management that includes the energy use of forest biomass.

5. Conclusions

The forest composition with the highest potential for carbon storage was evaluated to improve the management of the tropical dry forest of Pómac, Lambayeque, in northern Peru. The plots studied registered a significant average biomass of 75.09 t/ha, although it presents high amounts of biomass, it constitutes carbon sinks, which accumulate in their anatomical structures of forest species in this type of dry forest. The mean amount of carbon accumulated (37,545 t/ha) can provide a significant environmental service payment that in turn generates socio-economic value for the region. The largest amount of aerial biomass was made up of three species: *Prosopis pallida* H.B.K. for Armata ferreyra, *Capparis ovalifolia* and *Capparis scabrida*, which guarantee a greater accumulation of carbon, due to their anatomical characteristics. The allometric models developed for each species presented high coefficients of determination ($R^2 > 0.71$), indicating their high degree of reliability.
This basic and referential information can be used for the purpose of promoting the reforestation of degraded areas with future energy security applications.

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