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A Bioenergetic Carbon Capture and Storage (BECCS) Approach in the Secondary Montane Humid Forest-Oxapampa, Peru

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Forests are capable of sequestering carbon through tree biomass and it is important to predict their storage potential given the increase in CO_2 from deforestation and illegal mining. The objective of this research was to evaluate the storage of carbon and calorific value based on the aerial biomass of the forest diversity located between 2358 to 2450 masl of the Montane Humid Forest (Bh mo) in the buffer zone of San Alberto-Quilla in the Biosphere Reserve. The forest was located on the eastern Andean flank of Oxapampa in Cerro de Pasco (Peru). Four forest plots with an area of 900 m^2 each were evaluated, using the destructive method for trees with a diameter at breast height (DBH) equal to or greater than 10 cm. Species richness, density, diameter at breast height, and aerial biomass (AGB) were determined. Twenty-six species were identified, the dominant being *Miconia sp.* (12%), *Cyathea sp.* (9%), *Weinmannia sp.* (9%), *Ocotea sp.* (7%). The dry aerial biomass varied between 1.15 and 40.07 (t/ha), the highest values corresponded to *Miconia, Clusia, Hasseltia and Ocotea sp.*, and the evaluated plots followed the descending order: $AGB_{cresta-II}$ (86.93 t/ha) > AGB_{Ribera} (47.74 t/ha) > $AGB_{Cresta-I}$ (42.27 t/ha) > AGB_{Ladera} (34.13 t/ha); and a significant calorific value (CP_{total}= 26190 Gj/ha). The regression analysis and allometric model, was based on the diameter at breast height (DBH) of the tree species, and it proved to be the appropriate variable to predict the carbon mass and its energetic value. The results can be used as a reference to optimize the management of carbon storage and energy value in the montane humid forest in the BECCS context.

1. Introduction

Carbon capture and utilization (CCU) is a way of converting carbon emissions into valuable fuels and chemicals (Ioannou et al., 2023). One route is Bioenergy Carbon Capture and Storage (BECCS), which combines bioenergy with CO_2 capture and storage to control GHG emissions and uses plant photosynthesis to transform atmospheric CO_2 into organic matter (Wang et al., 2021; Migo-Sumagang et al., 2021). Forests are essential units in the continental ecosystem because they constitute forest carbon sinks (Xu et al., 2019 ; Ramírez et al., 2022). Carbon sequestration is carried out in biomass and forest soil, in amounts greater than those captured in crops or pastures; which generates a greater stock of carbon sequestration in forest areas, improving hydraulic properties and soil quality (Lopes et al., 2020 ; Rengifo et al., 2021). Stored CO_2 can be burned directly producing heat and power; and important socio-economic values can be provided, so natural restoration is recommended, as ecological carbon storage capacity can be improved (Wang et al., 2021). It is important to estimate forest carbon stocks based on accurate above-ground biomass data (AGB), due to a greater storage capacity of aerial components (Xu et al., 2019). Destructive allometric estimates require at least knowing the biomass of the branches, to then scale towards the total biomass (Ho and Park, 2020), this measure is known as aboveground biomass (AGB). The total aerial biomass and the carbon mass (Cm) can be estimated by means of allometric models that use the Breast Height Diameter (DBH) as the only regression variable. Arreaga, (2002), estimated the carbon stored in forests with forest management in El Petén, Guatemala, using linear

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models based on regression variables such as the DBH. Peru is located on the central and western coast of South America, it faces the loss of forests, due to deforestation, illegal mining, among others, with the commitment to reduce GHG emissions before the UNFCCC. In Oxapampa located in Cerro de Pasco (Peru) (450-4338 masl), there are very humid montane secondary forests with an unaltered floristic structure, as an economic asset for timber extraction (Acosta, 2019). The objective of this research was to evaluate the carbon storage capacity in forest species distributed in the humid montane forests of the buffer zone of the "Biosphere" Reserve (Oxapampa) and; analyze the energy potential (BECCS) to strengthen policies to reduce GHG emissions within the REDD framework (United Nations, n.d.).

2. Materials and methods

The study area was located in the secondary forests of the Biosphere Reserve in the Quilla-San Alberto basin in Oxapampa (Peru), on the eastern Andean flank between 2358 and 2450 masl (75°20' - 75º23' W and 10º31 ' - 11º34 ' S). Four plots were evaluated in an area of 900 m^2 called "Cresta I" with a mean slope of 25% (2450 masl); "Cresta II" with a mean slope of 45% (2430 masl); "Ladera" with a mean slope of 45% (2355 masl); and "Ribera" with a mean slope of 85% (2328 masl). The plots were square, 15x15 m (225 m^2). The forest inventory was carried out for trees with a diameter at breast height equal to or greater than 10 cm. The trees were felled, cut and weighed. Botanical identification was carried out and the fresh weight, dry weight, moisture content, fresh volume and density of branches, leaves and trunk were analyzed. Subsequently, the amount of dry biomass for the study area was calculated, the carbon content at the genus level was calculated using allometric models based on the DBH. Based on previous reports(Coronado Silva & Prato Sarmiento, 2019 ; Fernández & Oliver-, 2014), a factor equal to 17 Mj/K has been proposed for calculating the calorific value per hectare.

3. Results and discussion

Figure 1 shows the location of the studied area and the distribution of the 26 genera found. The forest vegetation is dense and is distributed in three strata; the upper stratum is made up of trees that reach heights greater than 20 m, the second and third stratum are made up of trees of 15 m and 10 m respectively. Twenty-six species were recorded in the four plots studied, the amount of dry aerial biomass found followed the following order: $AGB_{Cresta-II}$ (86.93 t/ha) > AGB_{Ribera} (47.74 t/ha) > $AGB_{Cresta-I}$ (42.27 t/ha) > AGB_{Ladera} (34.13 t/ha).

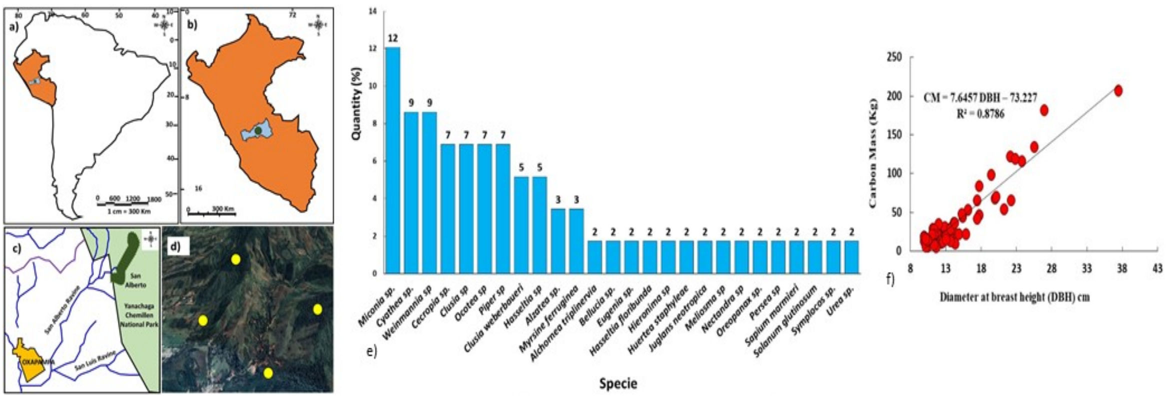

Figure 1. Forest distribution: a) Location of Peru; b) Location of the forest reserve in Oxapampa in Cerro de Pasco (Peru); c) Location of the Biosphere Reserve in Oxapampa; d) Location of plots studied in the buffer zone of the Reserve; e) Distribution of genera of the evaluated forest; f) Dispersion and allometric equation to estimate the dry mass of coal in the plots studied. https://earth.google.com/web/@0,0,0a,22251752.77375655d,35y,0h,0t,0r

This indicates that there is a large amount of aboveground dry biomass in this type of aboveground secondary forest in the Quilla-San Alberto basin. Table 1 reflects a high variability (44.44%) due to the variety of different organs of plant and tree species, site quality, environmental factors in tropical forests, and population density (Klock et al., 2022; Geng et al., 2021). The biomass depends on the life zone; site quality; state of development of the species; plant management; the terrain and intensity of the intervention (Morrison et al., 2021; Torres et al., 2020; Nunes et al., 2021). In this research, only that biomass whose DBH fluctuated between 10 and 37.5 cm (DBH_{mean}: 20 cm) and the density varied between 0.36 and 0.7 g/cm^3 (mean 0.56 g/cm^3) was considered due to the heterogeneity of the forest. The highest amount of dry aerial biomass was recorded in the "Cresta II" plot (AGB: 86.93 t/ha), which doubled that recorded in "Cresta I" (AGB: 42.27 t/ha).

Table 1. Storage of dry aerial biomass in the four plots and in the different components of an aerial secondary forest in the Quilla-San Alberto basin.

Parcel	Biomass Stem (t/ha)	Biomass Branches (t/ha)	Biomass Leaves (t/ha)	Total biomass (AGB)(t/ha)
Cresta I	27	12.72	2.54	42.27
Cresta II	48.36	36.23	2.34	86.93
Ladera	21.14	11.59	1.4	34.13
Ribera	31.85	13.31	2.58	47.74
mean	32.09	18.46	2.22	52.77
Sample variance	136.85	140.83	0.31	549.97
Standard deviation	11.7	11.87	0.55	23.45
C.V.%	36.46	64.28	24.96	44.44

Likewise, the "Ribera" plot developed a higher aerial biomass storage (AGB: 47.27 t/ha) compared to "Ladera" (AGB: 34.13 t/ha). The total aerial biomass (dry) for the plots studied (AGB mean: 52.77 t/ha) was higher than that reported by (Jones et al., 2019), in secondary tropical forests with 20 years of regeneration (34.53 t/ha); but lower than that reported by (Chacón et al., 2007), for secondary forests under 20 years old (96 t/ha). The highest percentage of biomass in the plots corresponded to the stem component, which increased with the age of the trees, while the branches and leaves of the crown decreased, coinciding with other reports (Le Goff & Ottorini, 2022; Ménard et al., 2022). This reflects the efficiency in the stem growth frequency; its biomass will depend on its age and social status in the forest (Huang et al., 2021; Sillett et al., 2021; Pretzsch et al., 2018 ; Wambsganss et al., 2021; Wieruszewski et al., 2022).

Table 2. Dry biomass at genus level, diameter at breast height (DBH), dry aerial biomass, carbon mass and basal density.

Genus	**DBH (cm)**	**AGB (t/ha)**	**C_m (t/ha)**	**BD (g/cm^3)**	**Genus**	**DBH (cm)**	**AGB (t/ha)**	**C_m (t/ha)**	**BD (g/cm^3)**
Weinmannia	(16.2-23.8)	40.07	20.04	(0,58-0,65)	*Cecropia*	(12.7-15.9)	5.23	2.62	(0,22-0,25)
Clusia	(10-27)	29.91	14.95	(0,55-0,64)	*Solanum*	17.8	4.08	2.04	0.36
Ocotea	(12-37.5)	28.53	14.26	(0,39-0,49)	*Juglans*	17.5	3.7	1.35	0.34
Hasseltia	(12-25.6)	17.42	8.71	(0,39-0,40)	*Cyathea*	(10.5-14.4)	3.11	1.56	(0.20-0.21)
Miconia	(10-14.2)	14.26	7.13	(0,50-0,57)	*eugenia*	12.9	2.71	1.36	0,66
Meliosma	22.2	10.85	5.43	0,45	*Urera*	13.7	2.62	1.31	0.4
jerónimo	17.8	7.39	3.7	0,62	*Oreopanax*	13.7	2.56	1.28	0.48
Alzatea	(14-21.3)	7.33	3.67	(0,62-0,66)	*Huertea*	11.1	1.83	0,92	0.41
simplocos	20.2	6.21	3.11	0,56	*persea*	14.9	1.94	0.97	0.44
Nectandra	22.3	5.8	2.9	0.58	*Bellucia*	13.6	1.72	0.86	0.2
Flautista	(10-14.2)	5.7	2.85	(0,53-0,56)	*sapio*	10.2	1.36	0,68	0.42
Mirsina	10.3-15.3	5.61	2.81	(0,59-0,63)	*Alchornea*	10.5	1.15	0.75	0.39

DBH: diameter chest height (cm); AGB: Aerial dry biomass; C_m: carbon mass; BD: basic density

The biomass in the "Cresta I" plot, presented trees with lower DBH (mean: 14 cm) and densities between 0.56 and 0.54 g/cm^3; while in the "Ladera" plot, the trees were young with lower DBH (mean: 13 cm) and basic densities of 0.52 to 0.60g/cm^3 (mean: 0.46 g/cm^3). "Ribera" is the plot with the highest biomass production, it ranked second among the four plots, and it presented a greater number of trees (19 trees) compared to the other plots (13 trees); higher DBH (mean 14 cm) and higher basic density (0.2 and 0.5 g/cm^3; mean: 0.41 g/cm^3). This plot is characterized by the presence of fast-growing softwoods, there is competition between the trees for being close to the rivers, and generally, the trunks are light in color, like the genus *Cecropia*, which has low density. However, it develops a higher population density, reflected in the greater number of trees, which translates into a greater biomass. The forest ecosystem retains high amounts of carbon per unit area compared to other types of vegetation (Dar and Parthasarathy, 2022).Table 1 shows the following AGB percentage order for each forest component: AGB_{fuste} (60.81%) > $AGB_{branches}$ (34.99%) > AGB_{leaves} (3.4%), also previously reported by Winckler et al. (2001).Table 2 shows the description of the aerial biomass for each genus found in the plots studied. This type of forest has shown a wide genetic variability, defined by species, site quality, altitude, slope, age, edaphoclimatic conditions, and population density (Zhao et al., 2022).Table 2 shows the first five (05) genera with the highest percentages in the distribution of dry biomass and carbon, being those responsible for the highest aerial accumulation of carbon in this secondary forest. From the table, the percentage contribution of carbon storage is calculated in the following order: *Weinmannia* (22.38%) > *Clussia* (16.7%) > *Ocotea* (15.93%) > *Hasseltia* (9.7%) > *Miconia* (7.96%).

The classification of tree genus per hectare according to the total dry aerial mass resulted in three tree groups. The tree genera *Weinmannia (Cunnoniaceae), Miconia (Melastomataceae), Clusia (Clussiaceae), Hasseltia (Flacourticaceae) and Ocotea (Lauraceae), Meliosma (Sabiaceae)* made up 66.81%, the second group represented 25.66% of the total weight: *Hieronyma (Euphorbiaceae), Alzatea (Alzateaceae), Symplocos (Simplocaceae), Nectandra (Lauraceae), Piper (Piperaceae), Myrsine (Myrsinaceae), Cecropia (Cecropiaceae), Solanum (Urticaceae), Juglans (Juglandaceae), Cyathea (Cyatheaceae).* The third group is made up of the genera *Eugenia (Myrtaceae), Urera (urticaceae), Oreopanax (Arealiaceae), Huertea (Staphylaceae), Persea (Lauraceae), Bellucia (Melastomataceae), Sapium (Euphorbiaceae) and Alchornea (Euphorbiaceae),* which represent 7.53 % of total biomass. This distribution of aerial biomass and carbon responds to the potential of the forest in the process of growth and some units will be the dominant trees. The presence of species at the genus level that present a higher basic density is due to its timber anatomical structure, since it presents thicker cell walls and a small lumen, such as the genus *Weinmania* (density: 0.58 and 0.65 gr/cm^3). However, other species also show low densities because their wooden anatomical structure has thin cell walls and a large lumen. The genus *Cecropia* stands out with a basic density between 0.22 and 0.25 gr/cm^3.

The linear regression and correlation analysis (Table 3) gave significant adjustments (p< 0.05) to predict the mass of carbon stored by the total aerial biomass and the calorific value as a function of DBH.

Table 3. Linear regression equations between carbon mass and diameter at breast height.

Parcel	Regression equation	R ^{2}	r	Calorific power (CP) equation
Cresta I	$C_{m\ (t/ha)}$ =8.302 DBH – 76.773	0.929	1	CP (Gj/ha) =141.13 DBH -1305.14
Cresta II	$C_{m\ (t/ha)}$ =7.8956 DBH – 79.881	0.878	0.9	CP (Gj/ha) =134.22 DBH -13578
Ladera	$C_{m\ (t/ha)}$= 8.3457 DBH – 81.009	0.828	0.9	CP (Gj/ha) =141.88 DBH-1377.15
Ribera	$C_{m\ (t/ha)}$ =6.0072 DBH – 54.249	0.715	0.9	CP (Gj/ha) =102.12 DBH -922.2
Total	$C_{m\ (t/ha)}$ =7.6457 DBH – 73.227	0.879	0.9	CP (Gj/ha) =129.98 DBH -1244.9

The values of the Pearson correlation coefficient (r) were close to one, indicating a high fit, that is, a high degree of association that agrees with the classification given by Padmakumar et al. (2018).Said correlation is positive, between the dry mass of coal and the diameter at breast height. Figure 1f shows the general linear regression with significant and robust determining factors (R^2 > 0.70; p < 0.05). The coefficients of determination of the total variation observed in the mass of carbon, is explained in a high percentage by the diameter at breast height (DBH). Regarding biomass and carbon accumulation at the genus level, there is no bibliographic information at the national level and neither is there any value of potential calorific value. In this study, this value was calculated using the approximation of the equation in Table 3 (CP_{total}= 26190 Gj/ha). However, these findings constitute a baseline that can be used in subsequent studies to directly assess the efficiency of managing aerial secondary forests. The F test for the estimation of total biomass through linear models was sufficient to demonstrate that the r and R^2 statistics are significant; using the DBH.The level of development of individual trees is reflected in the diameter, which directly influences the accumulation of biomass; plots with higher number of species tend to store more biomass and carbon (Yang et al., 2019; Brancalion et al., 2019; Jagodziński et al., 2018). Therefore it is important to note that these realms may differ significantly in productivity, biomass and energy (Muller et al., 2021). This information can be used as a reference base for the application of the BECCS approach that can help to develop different objectives to mitigate climate change, ensure the supply of energy in vulnerable areas that have a limited supply of energy and, above all, to reduce the GHG contribution. Likewise, it opens up new research routes in the use of secondary mountain forests.

4. Conclusions

Potential aboveground dry biomass, carbon storage, and an approximation of calorific value were investigated in four montane secondary forest plots in the buffer zone of the Oxapampa Biosphere Reserve (Peru) using the carbon capture and storage approach. bioenergetic (BECCS). These forests present a group of predominant arboreal genera in which Weinmannia, Miconia, Clusia, Hasseltia and Ocotea stand out. The anatomical shapes of this forest guarantee greater carbon storage and have a calorific value that could be applied as BECCS. Likewise, the unique conditions of the humid montane forest favor the following decreasing order in carbon storage: Cm stem > Cm branches > Cm leaves. The Quilla-San Alberto secondary forest constitutes a carbon sink in the recovery and growth phase, the linear regression analysis indicated that the diameter at breast height (DBH) of the tree species is an adequate variable to predict the carbon mass in the trees of the evaluated plots. Allometric models represent a very useful tool to estimate tree biomass and the simple linear model offered the best fit for the prediction of total tree biomass; carbon mass and calorific power. These forests capture carbon dioxide and store it in their anatomical structures, showing a key role in the carbon cycle and an alternative to face climate change.

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