Modern Environmental Science and Engineering (ISSN 2333-2581)
November 2017, Volume 3, No. 11, pp. 811-821
Doi: 10.15341/mese(2333-2581)/11.03.2017/009
Academic Star Publishing Company, 2017
www.academicstar.us

Enhancement and Potential Carbon Capture in a Hyper-Arid River Basin — Case Study: Central Coast of Peru

Alexis Dueñas Dávila[1, 2]

1. Pontifical Catholic University of Peru

2. Federico Villarreal National University

Abstract: Climate change, as a global-scaled problem, has a direct relationship with the economic process and, in particular, with the use of natural resources. This situation was discussed with particular interest in the Lima and Paris Climate Change Conferences; with the objective to design new production and demographic levels policies. In that context, the carbon capture plays an important role in sustainable development. The methodological approach in this paper considers the selection of a non-probabilistic sample, which was made taking into account the extent of each of the river basins to be studied, establishing the distinction between its vertical components (upper, middle and lower catchment area), as well as its both riverbanks (right and left). Six blocks of study were established and, in total, 18 units of analysis.

The objective of the present research is to estimate the carbon capture capacity of three river basins of central Peru, through the calculation of the interrelation between the production of primary biomass and the effective rate of carbon sequestered. Results showed an aggregated maximum capacity of 65,171 t CO_2/year for the three studied basin areas. Moreover, the calculated economic value of the environmental service (carbon capture), for the three studied river basin areas, were US$357,136, in current conditions without improvement, and US$365,127, if they included projects with Clean development mechanisms.

Key words: vegetal biomas, carbon capture, allometric equations

1. Introduction

Global climate change is one of the most important environmental problems facing the world, creating drastic impacts as a result of variations in the average temperature of the surface of the Earth [1]. Moreover, climate change, as a problem of global scale, has a direct relationship with economics and, in particular, with the appropriation of the natural resources [2-6], a situation that has been analyzed with particular attention at conferences in Lima (in 2015) and Paris (2016); designing policies in the production and demographic level [2, 7-10].

Part of this problem is due to technological progress that has developed since the eighteenth century. The result has been a steady increase of CO_2 concentration in the atmosphere [1, 11-13]. This has been due to such factors as biomass burning associated with deforestation, emissions from cement production and changes in the land use [14-18]. Consequently, as McCarthy (2001) [19] notes, global warming could affect the population and distribution of organisms, species composition, and the structure and functioning of ecosystems. All of this could have consequences for primary productivity and photosynthetic rate [19, 20-27].

The renewed interest in carbon captured is one of the consequences of the Kyoto Protocol, in particular the

Corresponding author: Alexis Dueñas Dávila, Ph.D.; research areas/interests: environment impact assessment, eco-efficiency, sustainable development. E-mail: fduenas@pucp.edu.pe.

Clean Development Mechanism (CDM) and Emissions and Credits (IEC) mechanisms, which have created a monetary value to carbon [28]. Countries with important forest areas and silvo-pastoral associations, such as Peru, have strategies to market “carbon units” and contribute directly to the development of rural local economies [29].

Peru presents important forest and pasture areas made up of agro-ecosystems that provide non-valued environmental services, providing an opportunity for the conservation of soil biodiversity, aquifer recharge and carbon capture [29-31]. In this context, the estimation of the carbon capture capacity in three river basin areas of the central coast of Peru, through the interrelation between the production of primary biomass and the effective rate of CO_2, storage, as well as an estimate of its economic value, is a contribution to the economic feasibility of new and clean development strategies.

One way to reduce CO_2 emissions is to increase capture and fixation levels. In this context, not only the Amazon area of Peru, but all the country’s plant systems, including agro-ecosystems, the forests and plant associations that thrive along the coast, are important for the transformation of CO_2 into biomass; they act as carbon sinks, regulating CO_2 concentration in the atmosphere [32, 33].

For this global approach about the carbon capture is necessary to know field conditions, the real capabilities of captures of carbon in different forest associations [14, 31]. The literature indicates three options to estimate carbon sequestration. The first relates to measurements from random samples of plant species, with destructive analysis of specimens, to generate laboratory estimates of carbon concentration. A second option is to measure different biometric parameters of a reasonable sample of specimens, using allometric equations to determine primary production and approach to carbon capture [34-37]. A third requires the support of remote sensing and digital photographs to determine the content of carbon in a plant association.

2. Material and Methods

One aspect to be taken into consideration is biomass [38, 39], which can be calculated using remote sensing [40]. However, estimation of primary biomass is only a first step, other aspects are required: the fixation rate and the CO_2 content itself, also referred in the literature as “stored content” or “sequestered”. Carbon capture considers different forms of carbon with the following equation [41, 42]:

$$c_t = c_v + c_d + c_s + c_p + c_f \quad (1)$$

where c_v is the carbon contained in the vegetation; c_d, the carbon contained in decomposing organic matter; c_s, carbon contained in soils; c_p, carbon contained in products used in the area and c_f, the carbon saved by not using fossil fuels. From Eq. (1), it is possible to calculate the total fixed carbon (in tonne/ha):

$$c_t = \frac{c_v + c_d + c_s + c_p}{T} + \sum_{i=1}^{n} cf_i \quad (2)$$

where, T is time.

For these considerations, the study is based on a simple methodology, based on a carbon capture estimation model, which applies to both natural ecosystems and agro-ecosystems by correlating primary production with the storage rate or carbon content in the biomass. In addition, it offers the possibility of knowing the CO_2 level of storage and CO_2 fixation of the biomass in vegetal associations.

The Peruvian coast is known for presenting isolated and low-density plant associations. They have only been studied from botanical and ecological perspectives, without calculating their environmental importance or, in particular, the environmental services provided. One such service is the capture of carbon. However, its capacity to do so has not been quantified; most such studies have focused on the Amazon basin.

This study was carried out on the central coast of the Peruvian department of Lima, in the Chancay, Lurín and Mala river basins, which has economic and environmental importance (forests, hydrographic network and life zones) in the Lima region (Fig. 1).

The selection of the non-probabilistic sample took into account the extent of each catchment area to be studied, establishing the distinction between its vertical components (upper, middle and lower catchment area), as well as its horizontal structure (right and left). This established 6 block accounts and, in total, 18 units of analysis.

The zoning proposed by Holdridge was used in order to establish the units of analysis in such a way that each life zone presented in the basin area was subject to stocktaking, as long as its vegetation cover was greater 40% [43]. The methodological recommendations proposed by Castañeda and colleagues (2005) [44], with adaptations to the objectives of the present investigation, were followed to determine the stocktaking in each unit of analysis and are summarized in the following steps:

(a) Forestry map of the river basins of the department of Lima.

Basin level	Lurin River	Chancay River	Mala River
Zonal level	Upper zone	Middle zone	Lower zone
Side level	Right side	Left side	

(b) Distribution of units of analysis in the field of study

Fig. 1 Basic characteristics of the basins area of the department of Lima.

(1) Measurement of the diameter of twelve randomly selected specimens (trees, shrubs or plants), to determine the average diametric.

(2) Selection of specimens to be collected during destructive sampling. The diameter, average height and density for each category (tree, shrub and canopy plants) are determined.

(3) Compilation of fresh weight of stems, branches and foliage The samples are dried in an electric oven at 74°C until reaching a constant weight.

(4) The data permits calculation of the dry weight/fresh weight ratio of each sample to obtain the values of dry matter (ms) for each component of the specimens to analyze.

(5) The total aerial dry weight of each specimen is obtained by adding the dry weight of the components (branches, stem, and leaves).

With the values of total aerial biomass, regression coefficients are estimated for the model using the following equation:

$$Y = \alpha D^{\beta} \quad (3)$$

where Y is the total biomass (ms) in g, D is the diameter of the specimen (cm), and α and β are the parameters to be estimated. Typically, the logarithmic transformation of the variables is applied to estimate the parameters using a simple linear regression model:

$$Ln(Y) = \ln(\alpha) + \beta \ln(D) \quad (4)$$

Castañeda et al. recommended for biomass calculation applying the adjustment proposed by Baskerville, in order to eliminate the bias associated with the logarithmic transformation of the model, which is expressed in the Wiant and Harner arithmetic scale [44].

$$Y_{ci} = e^{(\alpha + \beta \ln(D) + CME/2)} \quad (5)$$

where Y_{ci}, is the calculated biomass of the ith component, e is the basis of the natural logarithm and CME, is the square of the error calculated for each component and age.

In this study, various data collection instruments were applied. The first was used for the block that are located in each of the plant formations (annual, transitory and shrub or forest) to extract samples and perform the specimen counting. The other instrument was landscape mapping, developed with the help of satellite images and a panel of photographs in order to determine each of the landscape units (units of analysis) and in that way delimit the areas where the transects are installed, distinguishing both the vertical and horizontal structure of each basin.

The extraction of samples of plant specimens or destructive inventory is carried out for specimens that have reached maturity to show that the biomass formed are the highest possible. In addition, each specimen comprising the sample was weighed and its dimensions measured, in order to take an inventory of individuals. Then, the observation guides applied to each landscape unit were used to determine their composition, extent and characteristics of vegetal biomass, among other variables.

The data obtained, at the level of each unit of analysis, have been treated statistically by means of techniques related to the numerical summary of data; then established associations between variables with coefficients of correlation, and on this basis, causality, with techniques of regression models were built (alometric equations).

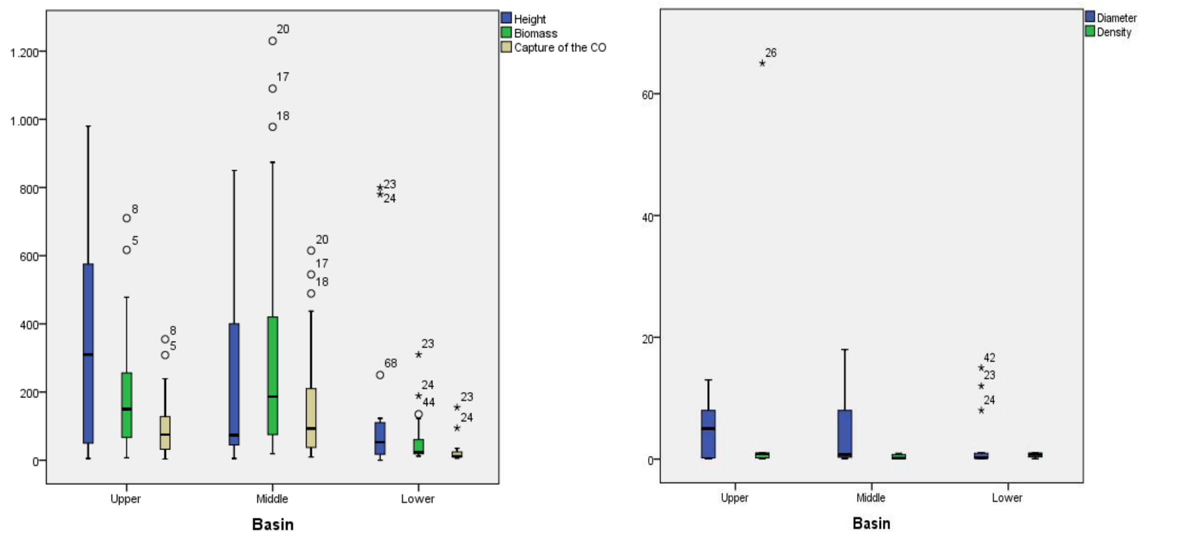
3. Results and Discussion

3.1 The Environmental Conditions of Study Area

In total, 75 plots were located, and 2×5 m (Table 1). In general terms, there is a notable dispersion of values for height, biomass and potential CO_2 capture. The heterogeneity involves, the upper, middle or low basins area (Fig. 2).

Table 1 Descriptive statistics of the variables studied.

	N	Minimum	Maximum	Average	standard error	standard deviation	Variance	Asymmetry	standard error	Kurtosis	standard error
Height	75	0.00	980.0	236.2	33.1	287.0	82381.3	1.1	0.27	-0.10	0.54
Diameter	75	0.01	18.0	3.05	0.5	4.9	24.3	1.2	0.27	0.31	0.54
Biomass	75	7.00	1230.0	217.6	31.9	276.8	76618.5	1.9	0.27	3.41	0.54
Density	75	0.02	65.0	1.3	0.8	7.4	55.6	8.6	0.27	74.59	0.54
CO_2 capture	75	3.50	615.0	107.4	16.0	138.9	19319.4	1.9	0-27	3.38	0.54
N valid (for list)	75										



(a) Box diagram for the variables height, biomass and potential CO_2 capture.

(b) Diagram of boxes for the variables diameter and density.

Fig. 2 Variance and distribution of the diameter, density and potential CO_2 capture.

The descriptive statistics offered cover three aspects. The first refers to the distribution of the data according to variable and area of study; for example, the variables height, biomass formation and potential CO_2 capture tend to become more homogeneous from upstream to downstream of the studied basins. Diameter and density present a similar pattern. Secondly, the distribution of these random variables are essentially asymmetric (sk $\neq$ 0). Third, with respect to its kurtosis, it has the leptokurtic type (biomass, density and potential capture of CO_2), platikurtic (height) and proximal to mesokurtic (diameter).

3.2 Carbon Capture, Biomass and Vegetal Biometry

It is assumed that certain biometric values of plants are associated between them, and is expected to have an influence on the formation of biomass, which would also influence in potential carbon capture. It can be assumed that the plots with high densities present smaller plant height and of narrower diameters. Also, the average composition of these plots are differentiated according to strata or components (arboreal, shrub or canopy).

Fig. 3 illustrates these causalities with notable differences, since it is only possible to consider associations, i.e., significant correlations, between plant height, diameter, biomass and potential CO_2 capture. There were no significant relationships between height and density, nor of that variable with any other. A highly significant relationship was found between biomass formation and CO_2 capture.

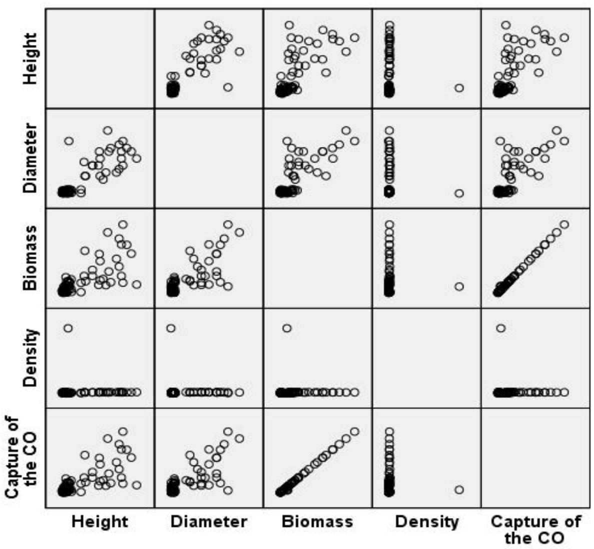


Fig. 3 Matrix scatter plot for the studied variables.

3.3 Allometric Equations and Causation in Carbon Sequestration

A frequently used method to determine the formation of primary biomass and/or net primary productivity is the application of allometric equations, as described in Formulaes (3), (4) and (5), above. From all of these, the most frequent model is the biomass-diameter [44], with which a multi-variable linear regression was estimated, summarized in Table 1. However, it may be the case that other models would better explain the behavior of the variables height and density.

This proposed model has the one variable explaining the causality between biomass formation and the studied variables. Therefore, this model is valid not only to explain the causality between the independent variables and the dependent variable, but also to predict the new values of the biomass as a function of the pool of variables studied. The value (1.395) of the Durbin-Watson statistic indicates that the residues are not correlated each other.

Table 2 (in the Appendix) shows the coefficients and error values and collinearity statistics. In the first case, the β corresponding to the diameter is significant for its Student's t-distribution, an aspect that differs substantially from the height and density variables. In addition, the diameter explains, on average 57.1%, of the variance, followed by height (25.5%). With regard to the analysis of collinearity (Table 3), it affects the height and diameter and the density; while with respect to the condition index, collinearity is relative, having a determined value (5.061) less than the Belsley limit (20).

Comparing both results, the classical allometric equation, (Eq. (1)), with the allometric Eq. (2), the biomass-diameter equation is more robust, as can be seen in the results of the estimated curvilinear estimation with different levels of adjustment (Table 4). From the results obtained, the linear and cubic expressions present the best adjustment levels, according to their coefficient of determination, which range from 0.785 and 0.788. These adjustment levels are more accurate than the classical logarithmic model, explained in expression (3).

Table 2 Coefficients of allometric regression (1).

Model[a]		Unstandardized coefficients		Standardized coefficients	t	Sig.	95.0% confidence interval for B		Collinearity analysis	
		B	Standard error	Beta			Lower limit	Upper limit	Tolerance	VIF
1	(Constant)	44.54	25.9		1.71	0.09	-7.28	96.3		
	Height	0.24	0.1	0.25	1.89	0.06	-0.01	0.5	0.28	3.5
	Diameter	32.04	7.5	0.57	4.25	0.00	17.01	47.0	0.28	3.5
	Density	0.79	2.6	0.02	0.29	0.76	-4.52	6.1	0.99	1.0
a. Dependent variable: Biomass										

Table 3 Diagnosis of colinearity of the allometric Eq. (1).

Model[a]	Dimension	eigenvalue	condition index	Proportions of variance			
				(Constant)	Height	Diameter	Density
1	1	2.4	1.0	0.06	0.03	0.03	0.01
	2	0.9	1.5	0.01	0.00	0.01	0.92
	3	0.4	2.3	0.90	0.03	0.07	0.08
	4	0.0	5.0	0.03	0.94	0.90	0.00
a. Dependent variable: Biomass							

Table 4 Summary of various models of the allometric Eq. (1)

Model	R	R squared	Error	F	Sig.
Linear	0.785	0.616	172.66	117.18	0.000
Logarithmic	0.687	0.472	202.51	65.24	0.000
Reverse	0.180	0.032	274.12	2.45	0.122
Quadratic	0.788	0.620	172.94	58.78	0.000
Cubic	0.797	0.635	170.78	41.13	0.000
Compound	0.713	0.508	0.93	75.31	0.000
Power	0.695	0.483	0.95	68.15	0.000
S	0.152	0.023	1.31	1.71	0.194
Increase	0.713	0.508	0.93	75.31	0.000
Exponential	0.713	0.508	0.93	75.31	0.000

In this way, the following allometric equations would be:

$$B_i = 60.93 + 44.056d \quad (6.1)$$

$$B_i = 70.465 + 32.024d + 0.908d^2 \quad (6.2)$$

$$B_i = 47.347 + 85.568d - 8.296d^2 + 0.379d^3 \quad (6.3)$$

3.4 Capturing Carbon in the Basin Area

Based on what is demonstrated in Fig. 2, which indicates that there is a clear relationship between biomass formation and carbon capture, it can be concluded that both allometric Eqs. (1) and (2) could be useful for estimating potential capture, taking into account the assumption that at least 50% of the cellular tissue contains carbon [32, 44, 45].

Fig. 4 shows the distribution of the carbon capture according to the location in the basin area. The highest

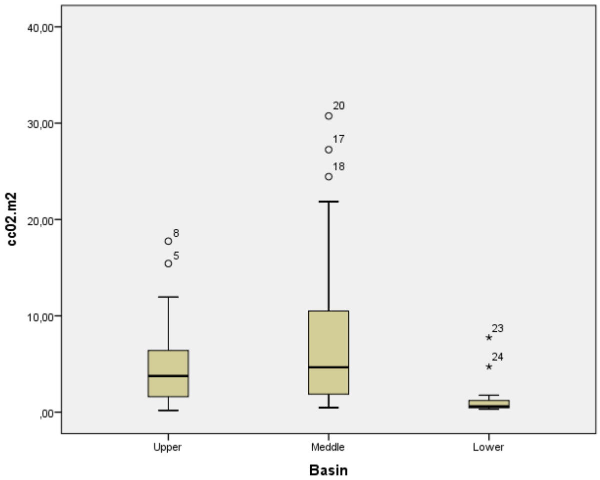


Fig. 4 Distribution of CO_2 capture according to basin area location.

dispersion is observed in the upper and middle areas, where there are complex compositions of three strata (arboreal, shrub and canopy) with predominance of the first two. Also, in the lower area, which basically shows herbaceous associations and annual plants (crops) the dispersion in carbon capture is also lower.

Table 5 presents the summary of the allometric equation model 1 which, unlike its counterpart (Eq. (1)), has as its dependent variable CO_2 capture. This multi-variable linear model has a suitable fit (R^2 = 0.792), with Fisher's F significant and no correlation of residues. Let's consider the important influence of the variable "diameter" which is presented as the main source of explanation for the variance in CO_2 capture, which also has a significant Student t. Finally, the collinearity analysis repeats what is detailed in the allometric Eq. (2).

The best fit expressions for the CO_2-diameter capture model (Table 6), which indicates the various estimated models; this also occurs in the linear, quadratic, and cubic models. The worst settings are presented in the inverse model and type "S". It can be pointed out that the logarithmic model is less recommendable than the linear and exponential model.

Table 5 Summary of the allometric equation model 2.

Model	R	R square	R square adjusted	Standard error of the estimation	Statistical parameters					Durbin-Watson
					Change in the R square	Change in the F	df1	df2	Sig. Change in the F	
1	0.792[a]	0.628	0.612	86.56	0.628	39.9	3	71	0.000	1.3975
a. Predictors: (Constant), Density, Height, Diameter										
b. Dependent variable: CO capture										

Table 6 Summary of various models of allometric Eq. (2).

Model	R	R squared	Error	F	Sig.
Linear	0.778	0.605	87.94	111.85	0.000
Logarithmic	0.688	0.473	101.56	65.60	0.000
Reverse	0.200	0.040	137.50	3.05	0.085
Quadratic	0.780	0.608	86.23	55.83	0.000
Cubic	0.790	0.623	87.08	39.18	0.000
Compound	0.700	0.490	0.951	70.20	0.000
Power	0.701	0.491	0.950	70.33	0.000
S	0.200	0.040	1.305	3.04	0.085
Increase	0.700	0.490	0.951	70.20	0.000
Exponential	0.700	0.490	0.951	70.20	0.000

The allometric Eq. (2) estimates the carbon capture per unit area, in this case per square meter. In the following expression, CO_2, is the potential catch per unit area and d the diameter of the specimen plant, the purpose is to establish the catch contained in the vegetation, which is a variant of expression (1).

$$CO_2 = 29.513 + 21.923d \quad (7)$$

Considering that each plot had an area of 20 m^2, the estimated values for the different components of the clump vary according the component and location of the basin area. As expected, the components of the trees contribute to capture more carbon than the shrub or canopy component. To simplify the subsequent calculations, two values of potential CO_2 capture were obtained in t/ha: 0.24 t/ha. Corresponding to the tree component, and 0.05 t/ha for the other components.

Finally, Table 7 presents the results of the estimation of carbon capture and the components based on the basin area average. The potential capture in the Lurín River Basin is 32,932.1 t CO_2/year; for the Chancay River Basin, 14,037.8 t CO_2/year and Mala River Basin is 18200.8 t CO_2/year. Combining the three would provide a capture of 65,170.8 t CO_2/year, with a monetary value, calculated at the end of October 2016, of US$5.48 per tone [46], i.e., US$357,135.9 per year.

Table 3 Estimation of potential carbon sequestration by basin area and plant components.

River basin	Area (hectares)				Capture of CO_2(in t CO_2/year)					
	Cultivated area	Meadow	Forests	Other	Cultivated area	Meadow	Forests	Subtotal (global)	Others (MIC)	Total (global+MIC)
Lurín	13,783.0	285,467.0	133.0	4,626.0	1,516.1	31,401.3	14.63	32,932.1	508.8	33,440.9
Chancay	26,749.0	100,707.0	161.0	6,129.0	2,942.3	11,077.7	17.71	14,037.8	674.1	14,712.0
Mala	12,826.0	152,559.0	77.0	2,503.0	1,410.8	16,781.4	8.47	18,200.8	275.3	18,476.1
Total	**53,358.0**	**538,733.0**	**371.0**	**13,258.0**	**5,869.3**	**59,260.6**	**40.81**	**65,170.8**	**1,458.3**	**66,629.2**

Table 8 Coefficients of allometric regression (2).

Model[a]		Unstandardized coefficients		Standardized coefficients	t	Sig.	95.0% confidence interval for B		Collinearity diagnosis	
		B	Standard error	Beta			Lower limit	Upper limit	Tolerance	VIF
1	(Constant)	21.18	13.16		1.6	0.11	-5.0	47.4		
	Height	0.13	0.06	0.28	2.0	0.04	0.0	0.2	0.28	3.5
	Diameter	1.19	3.82	0.53	3.9	0.00	7.5	22.8	0.28	3.5
	Density	-0.03	1.35	0.00	-0.,0	0.98	-2.7	2.6	0.99	1.0

a. Dependent variable: Capture of CO

To this last value, the potential capture can be augmented by arboreal-shrub reforestation of approximately 13,258 ha, with an additional potential catch of 1,458.3 t CO_2/year, which would yield an additional US$7,991.40.

4. Conclusion

The results demonstrate that carbon capture is not exclusively from the tree component, it is also possible to obtain important catchment rates from other components of plant associations, including herbaceous and shrub. This is contrary to the usually conclusions included in scientific studies about CO_2 capture in the arboreal stratum [42, 47-49]. Agriculture is also a sector that provides the collection and sequestration of carbon in a complex way. Cropping techniques, choice of species to cultivate and, above all, the management of crop residues has a direct impact on the amount of benefit [50]. Today this would be of special interest due to the welfares would have for small producers [51].

Several studies show the importance of secondary and secondary forest complex in carbon capture, although their average catchment is only half of the forest or tree complex [52]. The results obtained in this study indicate that even the natural degraded and secondary ecosystems, (such as the catchment areas studied in the central coast of Peru), can be provide attractive levels of carbon capture per unit area. For example, the herbaceous components of both transitional and natural pastures can provide capture levels of 0.05 t CO_2/ha (found in this study) to 0.188 t CO_2/ha [45]. In this case, the lower catchment rates found are related to the conservation status of the natural prairie, the density of the specimens, and the biomass that can be formed due to the conditions of high cattle pressure.

We refer to the importance of fragile or degraded ecosystems in carbon capture, a central aspect for climate change mitigation, as referred to by Biello (2016) [53], associated with the methods with which it is possible to estimate carbon capacity: destructive [54], non-destructive [55], remote sensing and use of allometric equations [56, 57].

The allometric equations proposed yield two consequences for discussion. First, given the insufficient cases studied in the specialized literature at the level of shrub and herbaceous components (meta-analysis), it would be include in the modeling components other than forest, as there are at least 44 kinds of shrubs, and these are mostly considered with diameter as the central parameter [56], and there is little scientific data for grasslands and arable crops in the literature [45]. It should coincide with the posture of uncertainty that involves modeling and then validating new allometric equations [58-60].

Second, the logarithmic allometric models based on the diameter of the specimen are adequate to estimate the biomass in the arboreal components but less efficient for herbaceous shrubs and specimens. Therefore, new equations, such as those presented in this paper, involving variables of plant, height and density of individuals per unit area, as well as the structure of the plant association, better estimate the biomass as a function of this potential carbon capture [61].

Acknowledgments

Thanks to Ian Vasquez, RamzyKahhat, José Livia and Milagros Defilippi for their valuable comments and suggestions, and to Vanessa García for being an excellent research assistant A special thanks to the Institute Research and Innovation of the Industrial Engineer Faculty of the Federico Villarreal University and the Pontifical Catholic University of Peru, Engineering Department, for supporting the workshops from which this paper emerged.

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