Introduction

One of the environmental problems arising from human development is the increase in greenhouse gas emissions. Specifically, CO$_2$ emissions have prompted research related to climate change so as to contribute with knowledge that will help mitigate such emissions (Pérez et al. 2009; Fonseca et al. 2011; Aguilar-Arias et al. 2012). According to the United Nations Framework Convention on Climate Change (UNFCCC), adopted in New York in May 1992, natural climate variability observed over comparable time periods are attributed directly or indirectly to human activity (land-use change, use of fossil fuels, use of agrochemicals, among others), which cause an increase in “greenhouse gas” concentrations in the atmosphere, affecting the increase in the average global temperature.

In view of this, the IPCC (2007) warns that, in the future, gases such as nitrous oxide (N$_2$O), carbon dioxide (CO$_2$), methane (CH$_4$), and ozone (O$_3$) would produce a global temperature increase between 3°C and 5°C, which would affect current precipitation patterns due to its impact on the land-ocean-atmosphere system. Of these, carbon dioxide (CO$_2$) is the most significant because of the large quantities produced as a result of human activity. In addition, about 20% of CO$_2$ emissions result from degradation or removal of natural ecosystems such as forests (Schimel et al. 2001; Schlegel et al. 2001). However, and in order to gather information regarding mitigation and adaptation options, the premise is that it is possible to capture carbon dioxide from the atmosphere and store it in the ecosystems themselves, preventing them from accumulating in the atmosphere.

In this context, several studies point out the potential of forests in terms of carbon storage, including studies carried out by Yatskov (2016), Jew et al. (2016), Fonseca et al. (2015, 2011, 2009), De Britez (2007), Mutuo et al. (2005), Oelbermann et al. (2004), Schimel et al. (2001), Ávila et al. (2001), among others. This is how forest
ecosystems appear as large carbon sinks containing more than 80% of all above-ground carbon.

Nevertheless, carbon storage capacity can vary markedly depending on the structure and composition of a forest. It could be therefore assumed that rainforests, because of their diversity and the size of the individuals living in them, have greater carbon storage capacity than dry forests. The latter are some of the least known and most threatened terrestrial ecosystems (Murphy and Lugo 1986); they are characterized by seasonal ecological and production processes, and, when compared to rainforests, are of lower stature and basal area (Gentry et al. 1995; Linares-Palomino 2004a,b).

In general, Ecuador’s dry forests are scarcely known, highly threatened, and economically important for large segments of the rural population, as they provide timber and nontimber products for subsistence and sometimes for sale. Several researches have been carried out on this type of forest, but it was not until only a few years ago that, after an intense and successful project, Ecuador managed to obtain important data at the country level, thanks to the so-called National Forest Assessment.

This type of (dry) forest can be found along the Ecuadorian coastline, the most diverse of which are located in the province of Loja (219 species), Guayas (169 species), and Manabi (143 species; Aguirre et al. 2006). In Manabi, dry forests are little known and highly threatened because of the economic importance they represent for certain rural sectors for whom they provide timber and consumer products.

In this sense, and as research progresses, a significant number of methodologies and guidelines have been established. Often, inventories use permanent plots of measurement to obtain statistically reliable data and reduce monitoring costs. In this regard, there are two commonly used methods to estimate biomass: the direct and the indirect methods.

The direct or destructive method consists in cutting down trees and determining their biomass by directly weighing each component. However, in this case, an indirect method was used given that this research was carried out in a reserve area.1 First, the above-ground biomass was estimated followed by the carbon stored in said biomass.

This indirect method consists in the use of models based on mathematical equations that relate biomass to tree variables (DBH, total height, wood density, crown diameter, among others). Above-ground biomass may be calculated using allometric equations provided that a statistically representative sampling is designed to measure the independent variables of the selected allometric equation.

The purpose of this study is to estimate the carbon stocks of the above-ground biomass expressed in megagrams (Mg) of oven-dry weight/unit area, in addition to the carbon stored in the soils of three plant formations in dry forests along the Ecuadorian coastline.

Materials and Methods

The research was carried out in an area located along the center of the Ecuadorian coast, consisting of the eastern and western slopes of the Pacoche, Los Lugos, Agua Fria, and Monte Oscuro mountains, which form part of the discontinuous massif of the coastal mountain range in Manabi. Politically, the area is part of the parishes of San Lorenzo and Montecristi, belonging to the cantons of Manta and Montecristi, respectively, and within micro-region 4 of the province of Manabi. Specifically, the area under study was the terrestrial part of the Refugio de Vida Silvestre Marino Costero Pacoche (Pacoche Marine and Coastal Wildlife Refuge; RVSMC-Pacoche), which occupies around 5096.41 ha (MAE, 2009).

The area stretches from sea level to 363 m above sea level. It is crossed longitudinally by the E15 or Marginal Way of the Coast, which connects Manabi with provinces Peninsula de Santa Elena, to the South, and Esmeraldas, to the North. The southern boundary is located 30 km from Puerto Cayo, a small town with tourist importance in the area. To the north, and 25 km from the boundary, lies the city of Manta, the closest city with tourism potential.

Even though the Ecuadorian State, through the National Forest Assessment developed by the Ministry of the Environment, has established a methodology for carbon studies, such methodology considers many other parameters that are not included in the scope of this research. However, both the methodology developed by the Ministry of the Environment and that of this paper use the same allometric equation to estimate carbon in above-ground live biomass.

Determining plot type and number

Determining the type and number of plots was subject to the type of coverage, the precision required, the availability of resources for the development of field activities, and laboratory analyses (Rügnitz et al. 2009), and the objectives of the research (IDEAM, 2010; Yepes and Duque 2011). Given the exploratory purpose, the number of plots and sampling intensity is based on minimum sampling for carbon estimation investigations in areas with low tree density and small diameters (Rügnitz et al. 2009). However, the calculations to determine the number of plots were verified using the Winrock Sample Plot
Carbon pools

The carbon pools of the various forest formations were selected based on logistic factors (ease to transport samples to laboratories, and technical aspects for REDD projects). In this context, two of the five pools that can be measured (Brown 2002; Rügnitz et al. 2009; IDEAM, 2010; Yepes and Duque 2011) were selected: above-ground live biomass and soil carbon.

Carbon stored in above-ground biomass

Compared to the destructive method, the indirect method is less expensive, and requires less time and less resources, which is why the latter was used to determine the carbon stores in above-ground biomass. In any case, destructive methods would not have been possible given that the area of study is a protected area. Thus, the allometric equation for mixed dry forests proposed by Chave et al. (2005) was used, requiring to measure variables in trees within the plots, to be entered into the following model:

\[
AGB_{est} = \exp \left( -2.187 + 0.916 \times \ln (\rho D^2 H) \right) \equiv 0.0112 \times (\rho D^2 H) 0.916,
\]

where \( AGB_{est} \) = Estimated above-ground biomass (kg DM/tree); \( \rho \) = Wood density (g/cm\(^3\)); \( D \) = Diameter at chest height (cm); \( H \) = Total height of the tree (m).

Measurement of dasometric variables

Once the sampling plots were installed, the required measurements were taken to apply to the allometric model. Such model includes measurements of the total height (m), DBH (cm), and wood density (g/cm\(^3\)). Only trees with diameter at chest height > 5 cm were measured.

With regard to wood density, species were identified in each sampling plot and the “Global Wood Density Database was used (Zanne et al. 2009). The objective set was to obtain the wood density for each species. However, in cases where there were no data in the database or in other bibliographic sources, the density of the genus or family was used. (Honorio and Baker 2010).

Calculation of carbon stock in above-ground biomass per hectare

After calculating the above-ground biomass (kg dry matter/tree), the total biomass is calculated in megagrams per hectare (Mg/ha), and this value is extrapolated to the hectare, as follows:

\[
AGB = \left( \sum AU / 1000 \right) \times (10,000 / \text{plot area}),
\]

where \( AGB \) = Above-ground tree biomass (Mg DM/ha); \( \Sigma AU \) = Sum of the tree biomass of all trees in the plot (kg DM/plot area); Factor 1000 = Conversion of sample units of kg DM/Mg; DM Factor 10,000 = Conversion of the area (m\(^2\)) to hectare.

Above-ground biomass to carbon conversions were performed pursuant to the guidelines established in the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (Penman et al. 2003), which assumes carbon content to be 50% of the above-ground biomass of each living tree (Barrett and Christensen 2011; Barrett 2014; Hetland et al. 2016; Jew et al. 2016; Rajput 2016; Tashi et al. 2016; Vijayakumar et al. 2016; Yatskov 2016).

\[
\Delta AGB = (AGB \times CF),
\]

where \( \Delta AGB \) = Carbon amount in above-ground biomass (Mg C/ha); \( AGB \) = Above-ground tree biomass (Mg DM/ha); \( CF \) = Carbon Fraction (Mg C/t DM). The default value is 0.50.

Soil carbon

The total amount of carbon in soil (%) was measured in each layer of the profile at depths of 0–10 cm, 10–20 cm, and 20–30 cm. Bulk density (g/cc) was measured at each depth using the cylinder method in undisturbed soils. Wet and dry soils were measured to calculate the dry soil in the cylinder and percentage of soil moisture using the following formula:

\[
D_w = \frac{WS}{Vol},
\]

where BD = Bulk Density; DS\(_w\) = Dry Soil weight; WS\(_w\) = Wet Soil weight; Vol\(_w\) = Volume of the Sampling Cylinder.

In the meantime, three soil samples were taken to determine organic carbon by applying the Walkley–Black method (wet oxidation method; Bazan 1996). The
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estimation of soil carbon stocks per unit area on a plot is calculated using the following formula (Eggleston et al. 2006; Rügnitz et al. 2009):

\[
\text{COS}_i = \sum_{\text{horizon}} \left( \left( \frac{\text{BD}_i \times \text{TH}_i \times \left( 1 - \frac{\text{CR}_i}{100} \right)}{100} \right) \times \text{C}_i \right) \times 100,
\]

where \( \text{COS}_i \) = Full profile organic carbon (Mg/ha); BD\(_i\) = Bulk density of horizon \( i \) (g/cm\(^3\)); TH\(_i\) = Thickness of horizon \( i \) (m); CR\(_i\) = Volume of thick fragments of the horizon \( i \) (vol. %); C\(_i\) = % of organic carbon in \( i \) horizon (%).

**Carbon stored in each plant formation**

The total carbon stored in each plant formation will be given by the sum of the components as follows:

\[
\text{C}_T = \text{C}_S + \text{C}_{BA},
\]

where: \( \text{C}_T \) = Total Carbon; \( \text{C}_S \) = Carbon in soil; \( \text{C}_{BA} \) = Total carbon stored biomass (Mg C/ha).

**Results and Discussion**

The variability in the biophysical characteristics in the different forest formations in the study area (microclimate, land cover, use or conservation status) causes differences in the carbon stored inside each formation (IDEAM, 2010; Phillips et al. 2011; Yepes and Duque 2011).

Total carbon stored in the above-ground biomass was higher in the Dry Semideciduous Forest (DSF), decreasing in the dry deciduous forest and dry scrubland (DS; Table 1). This situation responds to the fact that in the DSF there are trees of larger size and diameter and more diversity. Moreover, MS forests are characterized by shrub vegetation and are more threatened by human activity.

The results obtained are in agreement with the research carried out on this type of plant formation where carbon storage in above-ground biomass in dry forests could be between 25 and 60 Mg C/ha (Brown et al. 1989; Brown and Lugo 1992; Sánchez and Méndez 2003). Similarly, the Ministry of Environment of Ecuador (MAE), in its publication “Estadísticas de Patrimonio Natural” (Natural Heritage Statistics; MAE 2015) reports a mean dry forest carbon data of 37 Mg/ha which is in line with what was found in this study.

Furthermore, soil is an important carbon sink, containing more carbon than the sum in vegetation and the atmosphere (Swift 2001). This is why the IPCC recommends that it be considered as one of the compartments that should be evaluated in greenhouse gas inventories, for which the estimation is suggested to a depth of 30 cm (Eggleston et al. 2006; Solomon 2007). Accordingly, the results of the estimation of carbon stored in the study area are shown in Table 2.

In general terms, the results show low bulk densities at different depths and were not significantly different; they fluctuated between 0.95 and 1.15 g/cm\(^3\), which indicate that DDF and DSF organic soils are rich in humus, approaching the characteristics of loam soils; these being a little more clayey. These values tend to increase with depth, due to the greater biological activity in the horizon A and in DS.

The organic matter content for DS showed values ranging from 1.50% to 0.90%. Because many of these areas are intended for livestock, organic matter in the first horizon could increase. However, the values found do not show significant differences. Similarly, DDF results range from 1.00% to 3.30%, with the highest value corresponding to the first 10 cm of soil. In DSF, the highest organic matter value in the soil (2.00–5.40%) was found in the first 10 cm of the soil profile. This could be explained by the greater littering and biological activity in horizon A.

Therefore, based on the recommendation issued by the United States Department of Agriculture (USDA)’s Soil Survey Laboratory (SSL), the Van Bemmelen correction factor (1.724) was used to calculate the total carbon stored, assuming that the organic matter has 58% of organic carbon, yielding the following values: 26.83, 31.13, and 63.28 Mg C/ha for DS, DDF, and DSF, respectively.

**Table 1.** Above-ground biomass carbon (Mg/ha) stored in the plant formations present in the study area.

| Plant formations | Carbon stored (Mg C/ha) | SD |
|------------------|------------------------|----|
| DS               | 33.47                  | 13.26 |
| DDF              | 38.49                  | 24.43 |
| DSF              | 59.77                  | 25.93 |

| Plant formations | Organic matter (%) | Bulk density (cm) | Carbon stored (Mg C/ha) | Total carbon (Mg C/ha) |
|------------------|--------------------|------------------|------------------------|----------------------|
| DS               | 1.50               | 0–10             | 1.08                   | 15.66                | 26.83               |
|                  | 0.90               | 10–20            | 1.05                   | 5.48                 |                     |
|                  | 0.90               | 20–30            | 1.09                   | 5.69                 |                     |
| DDF              | 3.30               | 0–10             | 0.95                   | 18.18                | 31.13               |
|                  | 1.00               | 10–20            | 1.01                   | 5.86                 |                     |
|                  | 1.10               | 20–30            | 1.11                   | 7.08                 |                     |
| DSF              | 5.40               | 0–10             | 1.11                   | 34.77                | 63.28               |
|                  | 2.40               | 10–20            | 1.09                   | 15.17                |                     |
|                  | 2.00               | 20–30            | 1.15                   | 13.34                |                     |

DS, Dry Scrubland; DDF, Dry Deciduous Forest; DSF, Dry Semideciduous Forest; SD, standard deviation.
Moreover, the estimated values of soil carbon storage in the study area are in agreement with Balesdent and Arrouays (1999) and Trumbmore et al. (1995) who reported stocks between 60 and 70 Mg C/ha in forest soils. Along with evidence of soil carbon storage, it should also be considered that the change in soil carbon content due to land use does not exceed 20 Mg C/ha (IPCC, 2007).

Figure 1 shows the estimated data of carbon stored in biomass, carbon stored in soil, and total carbon for each of the plant formations under study. Thus, it can be observed that DSF contains more carbon in the above-ground biomass (59.77 Mg/ha) than DDF and DS (38.49 and 33.47 Mg/ha, respectively). Carbon stored in soil followed this trend with 63.28 Mg C/ha of carbon stock in DSF, followed by DDF with 31.13 and 26.83 Mg/ha for DS. The total carbon stored in each plant formation was represented by the sum of carbon in above-ground live biomass and soil carbon, yielding values of 60.30, 69.62, and 123.05 Mg of Carbon per hectare for DS, DDF, and DSF, respectively.

Conclusions
The carbon stored in live above-ground biomass was higher in Dry Semideciduous Forest (59.77 Mg C/ha) followed by the formation of Dry Deciduous Forest (38.49 Mg C/ha) and Dry Scrubland (33.47 Mg C/ha).

The soils of the Dry Semideciduous Forest formation have more stored carbon (63.28 Mg C/ha) than the Dry Deciduous Forest (31.13 Mg C/ha) and Dry Scrubland (26.83 Mg C/ha).

The formation of dry semi-deciduous forest contains more total carbon stocks (123.05 Mg C/ha) than the formations of Dry Deciduous Forest (69.62 Mg C/ha) and Dry Scrubland (60.30 Mg C/ha).

For this case, the carbon stock was related to altitude; at higher altitude, higher carbon stocks.

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Conflict of Interest
None declared.

Notes
1 Declared as a wildlife refuge by Ministerial Agreement No. 131, dated September 2, 2008.
2 Usually, for forest projects, a precision level (sampling error) of ±10% of the average carbon value is used at a 95% confidence level. However, in the case of small-scale CDM projects, a level of accuracy of ±20% is used (Pearson et al. 2005; Emmer 2007).
3 In carbon projects, it is essential to include above-ground biomass as a sink, as it is the pool that is most affected by deforestation/degradation of forests (BioCarbonFund, 2008).

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