

Article

Impact of Shrimp Ponds on Mangrove Blue Carbon Stocks in Ecuador

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Abstract: Mangrove forests play an important role in mitigating climate change but are threatened by aquaculture expansion. The inclusion of mangroves in climate change mitigation strategies requires measuring of carbon stocks and the emissions caused by land use change over time. This study provides a synthesis of carbon stocks in mangrove and shrimp ponds in the Gulf of Guayaquil. In this study area, we identified 134,064 ha of mangrove forest and 153,950 ha of shrimp farms. Two mangrove strata were identified according to their height and basal area: medium-statured mangrove (lower height and basal area) and tall mangrove (greater height and basal area). These strata showed statistical differences in aboveground carbon stocks. In both strata, the most abundant mangrove species was *Rhizophora mangle*. For both strata, trees had a maximum height (>30 m), and their density was greater than 827 ha⁻¹. Total ecosystem level carbon stocks (measured to 1 m soil depth) were 320.9 Mg C ha⁻¹ in medium-statured mangroves and 419.4 Mg C ha⁻¹ in tall mangroves. The differences are attributable to higher basal area, soil organic carbon concentrations and salinity, tidal range, origin of allochthonous material, and herbivory patterns. Mangrove soils represented >80% of the total ecosystem carbon. Ecosystem carbon stocks were lower (81.9 Mg C ha⁻¹) in the shrimp farms, 50% less than in undisturbed mangroves. Our results highlight mangroves as tropical ecosystems with extremely high carbon storage; therefore, they play an important role in mitigating climate change. This research provides a better understanding of how carbon stocks in this gulf are found and can be used for design strategies to protect global natural carbon sinks.

Keywords: carbon stocks; climate change; mangrove strata; shrimp ponds; soil carbon; vegetated coastal ecosystem



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1. Introduction

Mangrove forests have an area of 152,361 km² worldwide [1], with 15.7% of that surface in South America (23,882 km²) [2]. Currently, mangrove forests in Ecuador occupy 1906 km² [3]. These ecosystems are wildlife refuges with high natural, cultural, and scientific value, as well as the largest artisanal and industrial fishing area in Ecuador [4].

Mangrove forests play an important role in the global carbon cycle because they are highly productive ecosystems [5]. Currently, coastal ecosystems such as mangroves present burial rates of 353 gm⁻² y⁻¹ [6]. Although they occupy only a small fraction of the coastal area globally (0.5%), mangroves store 10%–15% of carbon (C) present in coastal sediments (at a rate of 24 Tg C y⁻¹) and export 10%–11% of terrestrial carbon particles to the ocean [7]. In addition, they contribute 55% of air–sea exchange and 14% of organic carbon burial, and export 28% of dissolved inorganic carbon (DIC) and 13% of dissolved organic carbon (DOC) plus particulate organic matter (POC) from the coastline and estuaries [8].

In these ecosystems, soils are the largest carbon sinks due to high contents of organic matter (OM) [5] and deep soil horizons. Soil C accumulation depends on several factors such as organic matter inputs, root turnover, necromass, algae and benthic organisms, the slow decomposition of refractory material, the magnitude and frequency of waves, the activity of micro- and macro-organisms, tree species and the composition of litter, and high humidity and temperature [9]. Average soil stocks are more than 1023 Mg C ha⁻¹, representing between 48 and 98% of carbon stored at depths from 0.5 to more than 3 m [10]. These values double and even triple carbon stocks in terrestrial tropical forest soils; one example is the terrestrial forest of Sumatra with 180 Mg C ha⁻¹ [11,12]. However, accelerated deforestation threatens the stability of mangrove carbon sinks. Global CO₂ emissions caused by the loss of mangrove forests have been estimated to be ~ 7.0 Tg CO_{2e} y⁻¹. Countries with the highest CO₂ emissions due to mangrove loss are Indonesia (3410 Gg CO_{2e} y⁻¹) and Malaysia (1288 Gg CO_{2e} y⁻¹) [13].

Land use change in mangrove forests results in mineralization of C that has been stored for decades or millennia. From 1982 to 2002, the loss of 35% of the world's mangroves resulted in the release of 3.8×10^{14} g C stored in the aboveground biomass of these forests [14,15]. It is estimated that 10,600 Mg CO₂ km⁻² will be emitted in the first year after mangrove cover changes to other land uses, and 20 years later, 3000 Mg CO₂ km⁻² y⁻¹ [16]. Globally, the estimates of emissions vary between 0.02 and 0.12 Pg C y⁻¹, equivalent to 10% of global emissions caused by deforestation [10,17,18]. In this sense, international agreements such as the mechanism for reducing emissions from deforestation and degradation (REED+), whose main strategy is to maintain C stored through economic incentives to forest conservation, are a cost-effective option to mitigate climate change [10]. In addition, there are other programs from the United Nations Framework Convention on Climate Change (UNFCCC), which require rigorous monitoring of carbon sinks and emissions.

To generate information about carbon stocks in mangroves, we chose the Gulf of Guayaquil because it covers approximately 80% of mangrove forest in Ecuador and has presented annual loss rates between 0.42% (Guayas province) and 2.69% (Manabí province) from 1969 to 1984 [19]. We estimated carbon stocks in two mangrove strata dominated by *Rizophora mangle*. These are the result of number of trees, age, and environmental conditions and are differenced mainly by their dominant tree height. Additionally, we compared soil carbon stocks in mangroves and shrimp ponds. Low carbon stocks in shrimp ponds relative to the mangrove forests are a measure of potential losses from land use change.

2. Materials and Methods

2.1. Study Region

This study was carried out in the mangrove forests and shrimp farms belonging to the tropical forest life zone of the Gulf of Guayaquil, located in Guayas and El Oro provinces in Ecuador, at 81°00'00" W and 03°23'34" S. The area has a tropical climate with two seasons: a rainy season influenced by El Niño warm ocean current, which runs from December to May, and a dry season influenced by the Humboldt cold ocean current, from June to November [20]. The average annual precipitation is 680 mm, and the mean annual temperature fluctuates between 20 and 32 °C. The average humidity is 48.7%, and tides vary between 1.8 and 3 m in amplitude [21]. Mangrove ecosystems within the gulf are characterized by developing on muddy soils, are poorly consolidated, are poor in oxygen, and are subject to periodic flooding and saline intrusion that occurs within the intertidal zone [22].

2.2. Forest Stratification and Transects Selection

We visually identified a priori two mangrove strata (medium-statured mangrove and tall mangrove) and shrimp farms using Google Earth (Figure 1). The medium-statured mangrove stratum had trees with smaller basal area than the tall mangrove stratum. Their structure was heterogeneous compared to inland channels. This stratum was located along

coastal lines where elevation is greater than the average height of waves. There is also greater saline intrusion, and it is flooded by the tide for 12 h daily. In addition, these forests have a highly developed root system that serves as a substrate anchor and an organic matter trap. The medium-mangrove stratum was identified in seven islands across the gulf (Bellavista, Canoa, Chupadores chico, Chupadores maduro, Tortuga, Bocana, and San Ignacio).

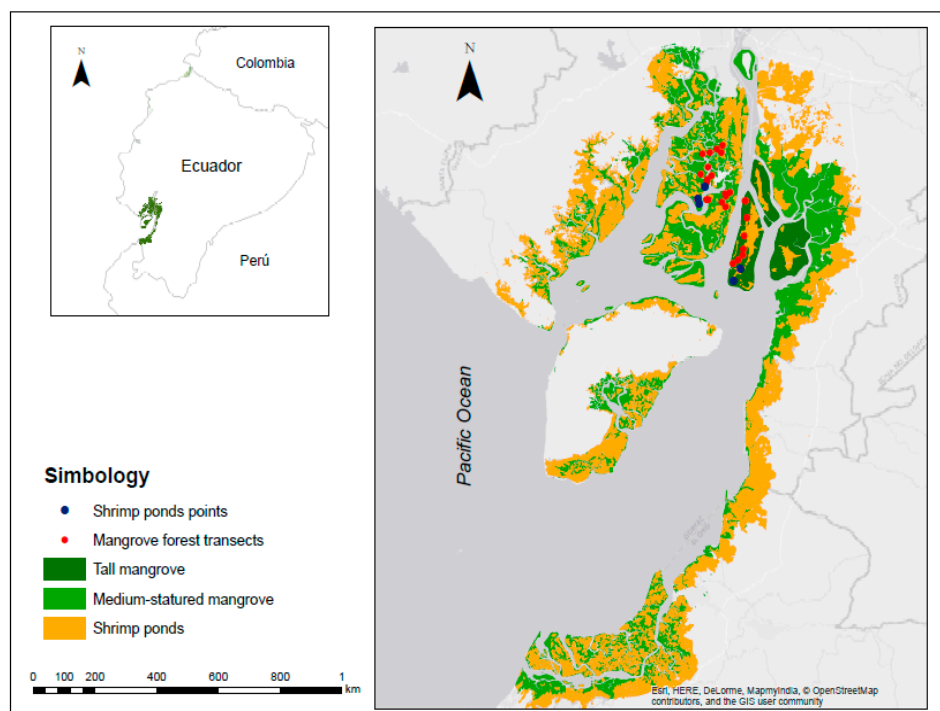


Figure 1. Location of study sites in Guayaquil Gulf, Ecuador.

On the other hand, the tall mangrove stratum grows mainly as riparian forests on riverbanks. These forests are dominated by *Rhizophora mangle*, with small areas of *Avicennia germinans* [23]. In this environment, fresh water and nutrient discharge are high, producing forests with well-developed dasometric and structural characteristics. The tides do not completely flood the tall mangroves due to a higher surface elevation [22,23]. The tall mangrove stratum was identified only on Mondragón island. Finally, shrimp farms were identified by their rectangular or triangular shape and by their proximity to the mangroves.

We delimited transects using geographic information systems tools (ArcGIS 10.5) and available satellite image servers (Earth Explorer). To visualize the mangrove coverage, we used land use maps from 2016, on which a grid and a layer of points (1000×1000 m) was applied to ensure that the transects were adequately separated from each other and to minimize spatial autocorrelation. A total of 29 points were chosen randomly according to their accessibility: 17 points in medium-statured mangrove, 7 for tall mangroves, and 5 for shrimp farms.

2.3. Aboveground Carbon

We used Kauffman et al.'s methodology [24], which consists of establishing 150 m linear transects located perpendicular to the coastline. Along the transect, six circular plots of 7 m radius (153.9 m^2) were located every 25 m (Figure 2). This design makes it possible to determine the composition, structure, and carbon stocks of mangroves, encompassing the variability in mean surface elevation and tidal flooding [24].

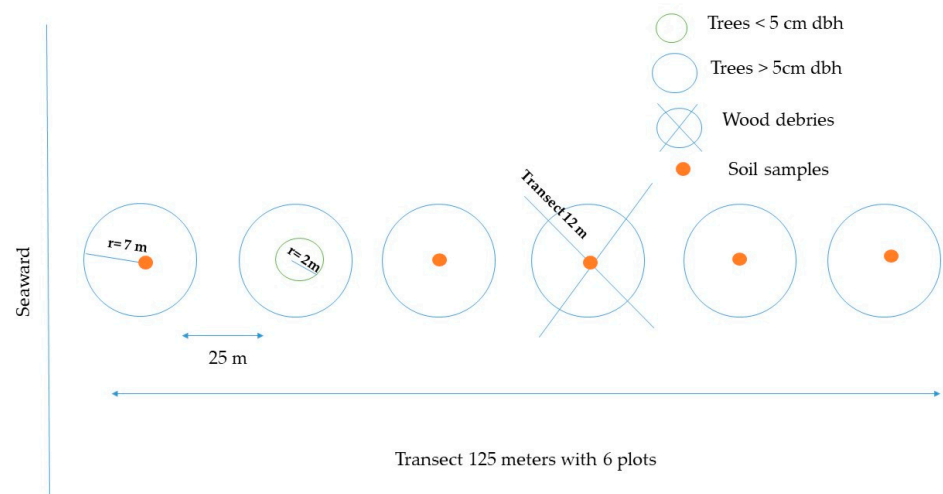


Figure 2. Schematic of plot layout for mangroves sampled in the Gulf of Guayaquil Mangroves, Ecuador. This graphic has been adapted from [24].

We measured tree diameter (DBH) and height for trees (alive and dead) with dbh > 5 cm. DBH was measured at 1.30 m in height or 30 cm above the last aerial root with a fiberglass diametric tape. Additionally, in plots of 2 m radius (12.6 m²), height and dbh were measured for trees with stem diameters < 5 cm. Samples of mangrove leaves and flowers were taken for species identification [24,25].

Aboveground biomass was determined with allometric equations using the following criteria: (i) equations for mangrove forests of the same region or the same continent, and (ii) equations for the species identified in the field. Since there are no allometric equations to measure aboveground in Ecuador, we used equations from French Guiana (*Rhizophora mangle* and *Laguncularia racemosa* var. *glabriflora*) [26] (Table 1). We used a factor of 0.47 to convert mangrove living biomass to C [24,27].

Table 1. Allometric equations used for aboveground biomass estimation in Ecuadorian mangrove forests.

Species	Aboveground Biomass	Root Biomass	n	r ²
<i>Rhizophora mangle</i>	$0.128 \times (\text{dbh})^{2.6}$	$= 0.199 \times (\rho)^{0.899} \times (\text{dbh})^{2.22}$	9	0.92
<i>Laguncularia racemosa</i>	$0.1023 \times (\text{dbh})^{2.5}$		70	0.97

Note: n: number of trees used for doing equation, r²: correlation coefficient of biomass y dbh, ρ: specific wood gravity.

To measure downed wood biomass, we used the planar intersect method [28,29]. This entails counting and measuring the diameter of all the downed wood ≥ 2.5 cm that intersected 4 transects of 12 m in length, running perpendicularly from each other and bisecting the main circular plot. Each piece of wood was assigned a category according to its decomposition status (hard or rotten) [27]. In total, five wood samples were collected by diameter and by decomposition status to determine their specific gravity. We used the water volume displacement method to measure the specific gravity of these samples. Herbaceous and litter biomass samples were collected and weighed in the field using 0.50 × 0.50 m (0.25 m²) micro-plots, which were randomly placed within the plots. A subsample of approximately 250–500 g was taken and dried at 60 °C for 48 h or until constant weight [24].

To calculate downed wood density biomass, we used specific gravity values of 0.89 g cm⁻³ for *R. mangle* and 0.620 g cm⁻³ for *L. racemosa* [30]. Biomass of downed wood resulted from the product between its volume (Equation (1)) and the corresponding specific gravity [29]. For estimating downed carbon, we used a factor conversion of 0.47. Litter carbon stocks were calculated from dry weight and conversion factor of 0.45 [24].

$$\text{Volume} \quad (\text{m}^3 \text{ ha}^{-1}) = ((\pi^2 \times \sum d^2)) / (8 \times L) \quad (1)$$

where: d = density of wood; L = transect length

2.4. Soil Carbon

At the center of each sampling plot, soil samples were collected at 0–15, 15–30, 30–50, 50–100, and >100 cm depth. The samples were extracted with an open face auger, specifically designed for unconsolidated soils. Undisturbed soil samples from corresponding depths were also taken to determine bulk density. For determining soil carbon concentration, we used composite samples for each depth along each transect, obtaining five samples per transect. We took soil samples from working shrimp farms following a similar approach. Soil carbon concentration was determined by the total dry combustion method. This method consisted of drying, sifting (sieve 2 mm), and subjecting the soil samples to high temperatures (> 1500 °C) using an automated total C analyzer [31]. The soil carbon (Mg ha^{-1}) was calculated using Equation (2) [24,32]

$$\text{Soil carbon} \quad (\text{Mg ha}^{-1}) = \text{bulk density (g cm}^{-3}) \times \text{soil depth interval (cm)} \times \text{Carbon (\%)} \quad (2)$$

Total carbon at the ecosystem level was calculated by adding the aboveground and belowground carbon stocks. Carbon stocks at the landscape level were calculated by multiplying the ecosystem C values by the area of corresponding land use strata (mangrove forest and shrimp ponds).

2.5. Statistical Analysis

We used general linear models (GLM) to evaluate the fixed effect or strata (medium-statured, tall mangrove cover, and shrimp farms) on carbon stocks. In the case of soil C, we also considered the fixed effect of depth and its interaction with strata. The assumption of normality and equal variances was analyzed by graphical inspection of model residuals [33]. We used Fisher's LSD to find differences among strata. The means comparison was made for (i) total carbon between mangrove strata, (ii) aboveground and belowground carbon for mangrove strata, (iii) aboveground carbon mangrove strata with respect to channel distance, and (iv) carbon concentrations at different soil depths in mangrove strata and shrimp farms. Pearson correlation coefficient was calculated for the relationship between aboveground and belowground carbon for the two mangrove strata. All these analyses were performed with InfoStat software version 2017 and using a significance level of 0.05.

3. Results

3.1. Mangrove Forest Strata and Shrimp Ponds

In the Gulf of Guayaquil, we identified 117,746 ha of medium-statured mangroves, 16,317 ha of tall mangroves, and 163,950 ha of shrimp farms (Figure 1). Due to the homogeneity in the composition of species present in the sampled transects, it was not possible to differentiate forest community types. However, basal area allowed us to differentiate the structure of the trees present in the two strata (Figure 3). The structure of both mangrove strata also differs, with a large presence of trees with 5–20 cm diameters and a low presence of trees of 36–50 cm in diameter in medium-statured mangrove. In contrast, tall mangroves showed a diameter distribution biased towards larger trees, exceeding the dbh > 50 cm category and reaching up to > 65 cm (Figure 4).

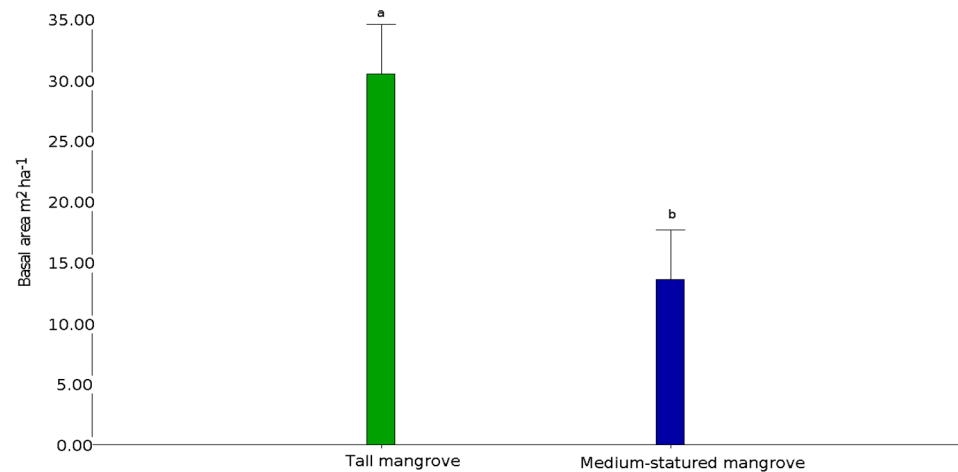


Figure 3. Differences in basal area between medium-statured and tall mangrove forests in the gulf of Guayaquil, Ecuador (different letters denote statistically significant differences).

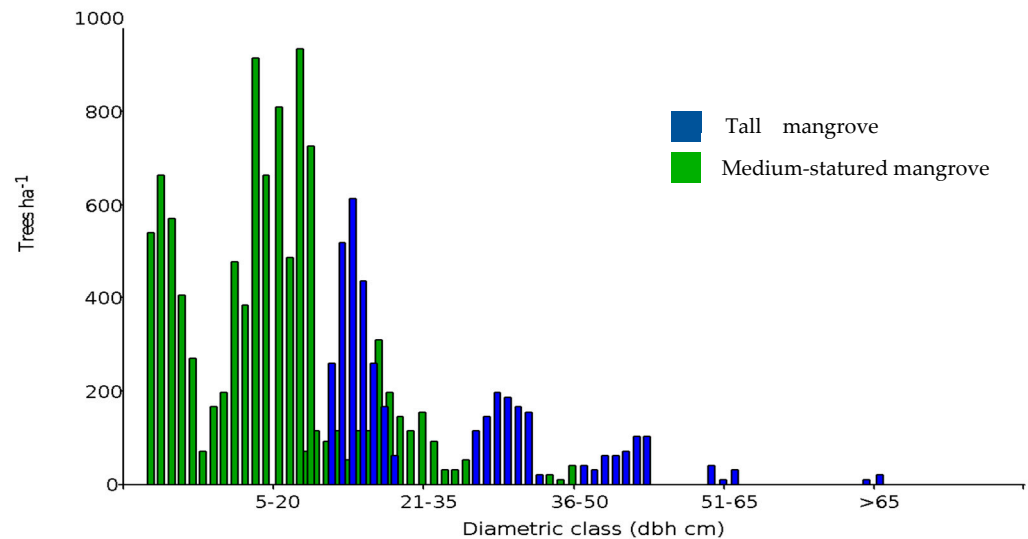


Figure 4. Number of trees (per ha⁻¹) by diameter class (cm) in medium-statured and tall mangrove forests in the gulf of Guayaquil, Ecuador.

Rhizophora mangle (red mangrove) and *Laguncularia racemosa* var. *glabriflora* (white mangrove) were present in both mangrove strata. We found red mangrove relative abundances of 99.6% and of 0.3% for white mangroves in medium-statured mangroves, respectively, while their relative dominances were 91.1% and 8.8%, respectively. The average height for these strata was 17 ± 4 m, with a maximum height of 34 m. The average basal area was 15.4 ± 6.5 m² ha⁻¹, and tree density reached 834 ± 410 ha. For tall mangroves, we found relative abundances of 96.2 and 3.7% and relative dominances of 95.2% and 5% for red and white mangroves, respectively. The average tall mangrove strata height was 17.9 ± 4.1 m, with a maximum height of 38 m. The average basal area was 30.8 ± 6.7 m² ha⁻¹ and the tree density reached 827 ± 388 ha (Table 2). Although similar in density, tall mangroves had twice the basal area as the medium-statured mangroves.

Table 2. Mangrove forest height (m), basal area ($\text{m}^2 \text{ha}^{-1}$), and tree density (trees ha^{-1}) by island in the gulf of Guayaquil, Ecuador.

Mangrove Stratum	Transect	Island	Species	Height	Basal Area	Tree Density
Medium-statured	T11	San Ignacio	Rhiz	18.0 ± 2.4	10.5 ± 4.3	671 ± 281
Medium-statured	T12	Canoa	Rhiz	18.2 ± 1.5	16.2 ± 6.8	942 ± 477
Medium-statured	T13	San Ignacio	Rhiz	19.6 ± 3.6	16.8 ± 9.0	769 ± 271
Medium-statured	T14	San Ignacio	Rhiz	16.1 ± 4.1	18.5 ± 9.8	693 ± 268
Medium-statured	T15	Chupadores Chico	Rhiz	8.4 ± 0.8	3.2 ± 1.7	487 ± 99
Medium-statured	T16	Chupadores Chico	Rhiz	13.0 ± 5.1	8.8 ± 5.7	379 ± 139
Medium-statured	T17	Chupadores Chico	Rhiz/Lag	21.1 ± 2.9	13.9 ± 4.1	531 ± 156
Medium-statured	T18	Chupadores	Rhiz	20.8 ± 3.6	14.0 ± 2.8	498 ± 140
Medium-statured	T19	San Ignacio	Rhiz	22.7 ± 1.7	27.7 ± 9.9	1007 ± 158
Medium-statured	T20	Canoa	Rhiz	23.0 ± 4.2	23.1 ± 13.0	736 ± 168
Medium-statured	T21	Bellavista	Rhiz	17.7 ± 1.7	20.2 ± 7.9	1321 ± 853
Medium-statured	T22	Chupadores Chico	Rhiz	12.9 ± 2.2	19.2 ± 11.2	1039 ± 344
Medium-statured	T4	Tortuga	Rhiz	22.9 ± 1.5	26.6 ± 8.7	1180 ± 255
Medium-statured	T5	Tortuga	Rhiz/Lag	19.8 ± 1.4	10.1 ± 3.4	693 ± 333
Medium-statured	T6	Tortuga	Rhiz	18.4 ± 1.6	10.0 ± 4.5	1061 ± 333
Medium-statured	T7	Bocana	Rhiz	14.4 ± 2.7	11.1 ± 4.2	888 ± 262
Medium-statured	T8	Bocana	Rhiz/Lag	16.7 ± 2.9	12.0 ± 2.3	1288 ± 238
Tall	TM1	Mondragón	Rhiz	22.4 ± 6.0	32.6 ± 17.9	585 ± 179
Tall	TM10	Mondragón	Rhiz/Lag	11.8 ± 2.8	18.7 ± 9.5	985 ± 186
Tall	TM11	Mondragón	Rhiz/Lag	14.5 ± 2.1	29.2 ± 11.5	1245 ± 289
Tall	TM12	Mondragón	Rhiz	17.8 ± 2.4	34.3 ± 16.8	1104 ± 448
Tall	TM3	Mondragón	Rhiz	17.3 ± 1.4	28.0 ± 14.4	660 ± 271
Tall	TM8	Mondragón	Rhiz	17.7 ± 3.1	31.9 ± 10.0	812 ± 365
Tall	TM9	Mondragón	Rhiz	23.5 ± 4.7	40.9 ± 20.0	401 ± 156

Note: T and TM = transect code, Rhiz (*Rhizophora mangle*), Lag (*Laguncularia racemosa*).

3.2. Aboveground Carbon

Aboveground carbon ranged from $73.6 \pm 8.3 \text{ Mg C ha}^{-1}$ in medium-statured mangroves to $192.2 \pm 29.2 \text{ Mg C ha}^{-1}$ in tall mangroves. We found statistical differences in aboveground C with respect to the marine ecotone; in medium-statured mangroves only, carbon decreased beyond 100 m inside the mangrove forest (Table 3).

Table 3. Carbon stocks of medium-statured mangroves varied according to distance from the estuary edge in the gulf of Guayaquil, Ecuador.

Seaward Edge (m)	Aboveground Carbon ($\text{Mg} \cdot \text{ha}^{-1}$)	
25	85.8	a
50	86.7	a
75	83.0	a
100	78.3	a
125	59.1	b
150	48.6	b

Different letters denote a significant difference ($p < 0.05$) in mangrove strata.

3.3. Soil Carbon

Soil C concentrations decreased with depth and are statistically different ($p < 0.05$) at 1 m depth, but at greater depths (Figure 5). This suggests that soil C in the surface layers is most affected by the conversion from mangroves to shrimp farms (Figure 5). Carbon stocks in roots and sediments at 1 m depth were 247.3 ± 21.8 in medium-statured mangroves and $227.2 \pm 26.7 \text{ Mg C ha}^{-1}$ in tall mangroves. In addition, at a depth of 2 m, we found 379.2 ± 30.3 and $345.4 \text{ Mg C ha}^{-1}$, respectively. In shrimp ponds, the average stocks were $81.9 \pm 13.6 \text{ Mg C ha}^{-1}$ at 1 m depth and $126.9 \pm 16.3 \text{ Mg C ha}^{-1}$ at 2 m depth, 50% less than the soil carbon stocks under mangrove forests (Figure 6).

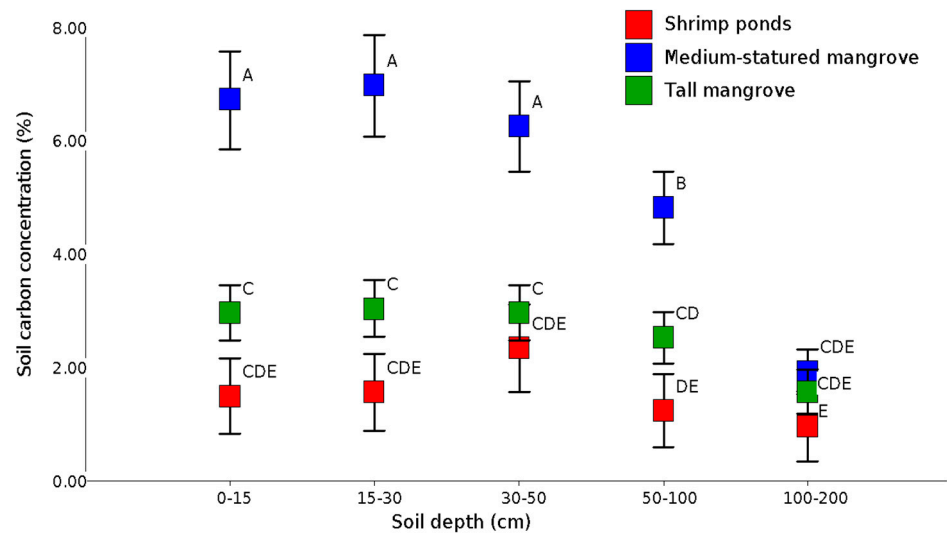


Figure 5. Soil carbon concentrations in mangrove stages and shrimp ponds (different letters represent statistically significant differences ($p < 0.05$) in soil pools between different mangrove strata).

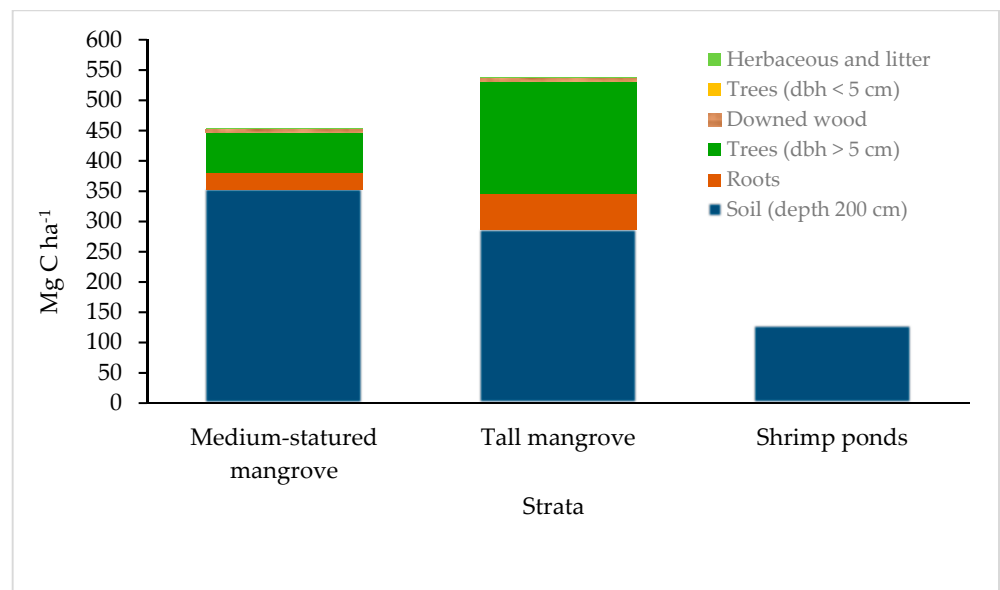


Figure 6. Total carbon stocks in compartments of the mangrove forest and shrimp ponds at 200 cm of depth.

3.4. Total Carbon Stocks

The total carbon stock of the gulf of Guayaquil was $320.9 \pm 20.8 \text{ Mg C ha}^{-1}$ to 1 m soil depth and $452.8 \pm 28.3 \text{ Mg C ha}^{-1}$ to 2 m soil depth for medium-statured mangroves. For tall mangroves, those stocks were 419.4 ± 55 and $537.6 \pm 72.3 \text{ Mg C ha}^{-1}$ for the same respective soil depths. In sharp contrast, shrimp farms had soil stocks of $81.9 \pm 13.69 \text{ Mg C ha}^{-1}$ and $126.9 \pm 16.3 \text{ Mg C ha}^{-1}$, also at 1 and 2 m depths, respectively. Thus, we can infer that land use change caused the loss of 70% of C stored in the ecosystem (Table 4).

Table 4. Carbon stocks (Mg ha^{-1}) in mangrove forests and shrimp ponds in the gulf of Guayaquil, Ecuador.

	Medium-Statured Mangroves	Tall Mangroves	Shrimp Ponds
Transect	17	7	5
Trees > 5 cm dbh	67.88 ± 8.39	186 ± 26.76	–
Trees < 5 cm dbh	0.38 ± 0.20	0.06 ± 0.03	–
Woody debris	5.36 ± 1.00	6.05 ± 3.61	–
Total aboveground carbon	73.62 ± 8.39 a	192.20 ± 29.90 b	–
Roots	26.76 ± 2.88	59.06 ± 6.16	–
Soil 1 m	220.57 ± 22.89	168.19 ± 21.30	81.91 ± 13.69
Soil 2 m	352.51 ± 31.49	286.39 ± 38.27	126.98 ± 16.33
Total soil and roots carbon (1 m)	247.33 ± 21.81 a	227.25 ± 26.57 a	81.91 ± 13.69 b
Total soil and roots carbon (2 m)	379.26 ± 30.35 a	345.46 ± 43.57 a	126.98 ± 16.33 b
Ecosystem carbon (1 m)	320.95 ± 20.88 a	419.45 ± 55.66 a	81.91 ± 13.69 b
Ecosystem carbon (2 m)	452.13 ± 28.32 a	537.65 ± 66.70 a	126.98 ± 16.33 b

Different letters denote a statistically significant difference ($p < 0.05$) in ecosystem pools between mangrove stands and shrimp ponds.

Carbon stocks at the landscape level add to 37,790,578.7 Mg C in medium-statured mangroves, 6,844,224.4 Mg C in tall mangroves, and only 12,610,084.0 Mg C in shrimp farms. The gulf ecosystem stores over 57 million Mg C stored, which is equivalent to more than 210 million Mg of CO_2e (Table 5). Since 80% of those stocks are stored in the mangroves, their large importance as C sinks at the ecosystem and landscape levels is emphasized.

Table 5. Ecosystem carbon pools (C Mg ha^{-1}) by land use.

Land Use	Area (ha)	C (Mg ha^{-1})	Total Carbon (Mg C)	Mg CO_2e
Medium-statured mangrove	117,746.0	320.9	37,790,578.7	138,691,423.8
Tall mangrove	16,317.1	419.4	6,844,224.3	25,118,303.4
Shrimp ponds	153,950.4	81.9	12,610,084.6	46,279,010.6
Total	288,013.6		57,244,887.7	210,088,737.8

4. Discussion

4.1. Mangrove Forest Strata

The mangrove forests in the gulf of Guayaquil are mainly dominated by three species: *Rhizophora mangle*, *Laguncularia racemosa*, and *Avicennia germinans*, with associations of *R. mangle* with *L. racemosa* in small areas [34,35]. The abundance and dominance of *R. mangle* reached 99%, with maximum heights of around 40 m and dbh measurements between 0.10 and 165, similar to previous reports [36]. *Rhizophora's* dominance could be attributed to its greater rates of establishment and development due to its propagule dispersal strategy [34]. The opposite happens with seeds of other mangrove species, which face difficulties in germinating and becoming established [2]. Additionally, physiological tolerance of some mangrove species to a variety of geophysical factors may also explain the higher dominance of this species [37].

4.2. Aboveground Carbon

We measured carbon stocks of 73.6 Mg C ha^{-1} for medium-statured mangroves, similar to estimates of 92.56 Mg C ha^{-1} in fringe mangroves in Brazil [38] (Table 4). Our estimate of aboveground carbon in tall mangroves was 192.2 Mg C ha^{-1} , 26% greater than in

the riparian mangrove forests of Cayapas Mataje reserve in northern Ecuador [39]. Overall, our aboveground carbon estimates match those from other Latin America mangrove forests (Table 6).

Table 6. Aboveground carbon stocks in Latin American mangrove forests.

Country	Height (m)	Species	Aboveground Carbon (Mg ha ⁻¹)	Author
Dominican Republic		<i>R. mangle</i>	133	
Honduras		<i>R. mangle</i> – <i>L. racemosa</i>	143.9	[40]
Costa Rica	>10	<i>R. mangle</i>	151	
Mexico		<i>R. mangle</i>	236	
Ecuador		<i>R. mangle</i> – <i>L. racemosa</i>	108.2	This study

Aboveground carbon differences in the two mangrove strata are closely related with overall forest structure (tree diameter and density, basal area, and height), with greater aboveground carbon increasing with diameter and height [41]. Additionally, these values might be attributed to various environmental factors, net primary productivity, and anthropogenic and natural disturbances, as well as the aggregation rates of organic allochthonous material [42].

Medium-statured forests receive scarce contribution of fresh water since the average precipitation is 400 mm, which allows a deep intrusion of saline water, it could increase stress and lower productivity of the aerial biomass [43]. Additionally, aboveground carbon could be limited by sediment inputs that limit the availability of soil nutrients [44]. In contrast, tall mangrove forests receive freshwater discharge from surrounding mountains, and precipitation exceeds 885 mm y⁻¹, causing salinity to be lower. The more favorable environment results in greater tree height and dbh [2,45]. This suggests that larger aboveground carbon stocks in the study area are related to quality of the upstream sediment and higher soil fertility [32].

The differences we found in aboveground carbon of medium-statured mangroves relative to the distance from the shore (Table 3) coincide with other studies, which also found lower aboveground C at 110 m from the canal in Caribbean mangroves [46]. These differences are attributed to physiographic heterogeneity, tidal amplitude, and salinity intrusion, which affect mangrove tree size and forest structure, as well as species composition [45].

4.3. Soil Carbon

The soil C concentration (%) for both strata indicates there is greater carbon accumulation in the first centimeters of the soil profile (Figure 5). Our results are similar to data from mangroves in Brazil and Mozambique, which showed the highest organic carbon content in the first 60–100 cm of the profile [47,48]. These results might be attributed to high biological activity and decomposition rates near the soil surface [49]. Additionally, processes such as carbon diagenesis results in the gradual degradation of labile carbon, resulting in a decrease of organic matter with increasing soil depth [50]. In addition, this pattern is attributed to the decline in biological processes and anoxic conditions [10,51].

We found higher soil C concentrations in medium-statured mangroves than in tall mangroves. This finding might be attributed to this stratum having saturated soil conditions that promote retention of organic matter and restrict soil respiration, resulting in reduced decomposition rates of organic matter and mineralization of C [1,47,49]. These differences might also be related to the inputs of organic matter such as litter, decaying roots, exudates from roots, microbial biomass, and the activity of micro- and mesofauna [8,52,53]. These factors are directly related to the availability of oxygen, nutrients, and temperature and low availability of cations that support the formation and stability of humic substances in the soil [52]. Finally, heterogeneous spatial characteristics present in intertidal environments and differences in soil texture could also be influencing soil carbon concentration [54,55].

Soil and roots carbon stocks at depths of 0–100 cm of medium-statured mangroves reached 247.3 Mg C ha⁻¹ and were not significantly different from that of tall mangroves (227.2 Mg C ha⁻¹). These results are 62%–68% lower than those reported in mangrove

forests in northern Ecuador [39]. However, data from our study are similar to those in Pacific mangroves of Costa Rica, with $297.7 \text{ Mg C ha}^{-1}$ [45], and values between 183 and 246 Mg C ha^{-1} in mangrove forests of coastal Australia [56]. Further, our results are close to C estimates in Caribbean and South African mangroves (266 Mg C ha^{-1} and 176.9 to 262 Mg C ha^{-1} , respectively) [40,57].

Carbon stocks for shrimp ponds were $81.9 \text{ Mg C ha}^{-1}$ (soil and roots), only 26% of those in mangrove forests. Similar to other studies [40], we found that land use change from mangrove to aquaculture use represented the decrease of more than 50% of soil carbon stocks. This confirms that anthropogenic activities contribute enormously to soil carbon losses from conversion [58]. The loss of soil C stocks occurs when mangrove trees are cut down and large quantities of soil is removed for construction of ponds. This promotes oxidation of carbon, which results in CO_2 emissions to the atmosphere [59,60]. The loss of carbon stocks in mangrove soils could account for 12% of total emissions from global tropical deforestation and 10% of worldwide deforestation [40,61].

4.4. Total Carbon Stocks

Our results are lower than those for Central and South America mangrove forests [40, 62], ranging from only 9%–17% of total stocks in those studies in shrimp ponds to 34–89% in medium-statured and tall mangroves (Table 5). However, our carbon stock estimates for tall mangroves are similar to those made for Colombian Pacific mangroves (400 Mg C ha^{-1}) [63]. These differences could be related to differences in tree species composition and forest structure, forest conservation status, soil depth, carbon concentration, and freshwater proximity [32,63,64].

Soil carbon stocks in both mangrove strata represented about 80% of the total ecosystem stocks in our study. These results agree with estimations by Donato [10] and Kauffman [40], who indicate that between 49 and 90% of total mangrove ecosystem carbon is stored in soil [56], and highlight the role of mangrove soil as an important carbon pool. Locally, land use change to shrimp ponds is causing the loss of more than 90% of carbon stored in undisturbed mangrove forests [65], while globally, the conversion of coastal ecosystems to other land uses contributes with 3%–19% of CO_2 emissions caused by deforestation [66].

Starting in 1960 and facilitated by the lack of legal protection and enforcement, mangrove forests in Ecuador were converted to shrimp aquaculture because this became one of the most important income streams for the country. Our study estimated carbon stocks in mangrove forests and shrimp ponds to show the future potential of mangrove forests in climate change mitigation, as the areas originally lost can be restored back into mangrove forests. The results underline the importance of conservation and management measures as well as the inclusion of these ecosystems in mechanisms such as REED + for protecting stored carbon. Additionally, this article contributes to a better understanding of impacts of land use change, and it provides information for decisionmakers to support and take action for the protection of mangrove forests.

5. Conclusions

Our study describes two strata of mangrove cover (medium-statured and tall) and one of aquaculture use (shrimp farms) in the Gulf of Guayaquil. The area of shrimp production currently exceeds the area of mangrove forests because of historical mangrove forest clearing. The mangrove areas show differences in aboveground carbon stocks, attributed to environmental factors such as saline water intrusion and variability of average annual precipitation, which controls freshwater inputs into the system. Belowground C stocks triple those found in shrimp farms, and our results show that the greatest impact of land conversion is seen in the first 100 cm of the soil profile.

Currently, carbon storage in mangrove forests attracts global attention because of the climate change mitigation potential, and thus it is necessary to continue improving our knowledge of aboveground and belowground C stocks, particularly focusing on the mechanisms behind the C accumulation, which we do not directly address in our study.

Determining carbon stocks at the landscape level is the first step to include these ecosystems in climate action mechanisms such as REED+, which would help ensure their conservation and enhancement of the stored carbon. This information can also be included in global C measurements or at country level and serve as an important resource for establishing mitigation and adaptation initiatives to climate change, such as that which Costa Rica and Colombia did recently by including blue carbon targets in their Nationally Determined Contributions (NDC) to the UNFCCC.

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