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First Assessment of Carbon Stock in the Belowground Biomass of Brazilian Mangroves

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ABSTRACT

Studies on belowground roots biomass have increasingly reported the importance of the contribution of this compartment in carbon stock maintenance in mangrove forests. To date, there are no estimates of this contribution in Brazilian mangrove forests, although the country has the second largest area of mangroves worldwide. For this study, trenches dug in fringing forests in Guaratiba State Biological Reserve (Rio de Janeiro, Brazil) were used to evaluate the contribution of the different classes of roots and the vertical stratification of carbon stock. The total carbon stock average in belowground roots biomass in these forests was 104.41 ± 20.73 tC.ha^{-1}. From that, an average of 84.13 ± 21.34 tC.ha^{-1} corresponded to the carbon stock only in fine roots, which have diameters smaller than 5 mm and are responsible for over 80% of the total belowground biomass. Most of the belowground carbon stock is concentrated in the first 40 cm below the surface (about 70%). The root:shoot ratio in this study is 1.14. These estimates demonstrate that the belowground roots biomass significantly contributes, more than 50%, to the carbon stock in mangrove forests. And the mangrove root biomass can be greater than that of other Brazilian ecosystems.

Key words: global climate change, Guaratiba State Biological Reserve, roots, Sepetiba bay, trench method.

INTRODUCTION

In recent decades, the scientific community has issued several advances and alerts with regard to global climate change, its implications, and its origins (IPCC 2014). These changes have their origin associated with the increasing emissions of greenhouse gases (GHG) such as carbon dioxide, sulfur, and nitrogen oxides (IPCC 2014). According to the monitoring carried out by the US Oceanic and Atmospheric Administration Agency, atmospheric carbon concentration reached the 400 ppm mark in 2013 (NOAA 2013).

Forests play an important role in the carbon cycle and its regulation and potentially play important parts in carbon sequestration and stock

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because of their large vegetal biomass as a major reason (Brown et al. 1992, Vieira et al. 2008, Guo et al. 2010, Donato et al. 2011). It is estimated that tropical forest ecosystems worldwide can store up to 193 PgC (Saatchi et al. 2011). Conversely, the loss of forest systems would imply the loss of the capacity to mitigate or reduce GHG concentration through organic carbon sequestration and stock (Harris et al. 2012, Zarin 2012), and it will contribute to additional emissions of carbon that is stored in these systems. Therefore, various forms of mitigation have been studied to reduce GHG concentration and/or emissions (IPCC 2014). Among them are those that use the conservation of vegetal biomass of forest ecosystems as carbon sinks and sequestrants (Cenamo et al. 2010, Soto-Pinto et al. 2010).

Mangrove forests have a tropical and subtropical distribution (Tomilson 1986, Schaeffer-Novelli et al. 2000) and great potential as atmospheric carbon sinks and sequestrants (Siikamaki et al. 2012). Even though they occupy less than 1% of the global tropical forest cover (Giri et al. 2011), these forests can globally store 4.03 PgC (Twilley et al. 1992), 13.1 PgC (Alongi 2014) to 20 PgC (Donato et al. 2011) of organic carbon. Both carbon stock and emission estimates based on the protection or loss of this system still have great uncertainty. This is because of the absence of information, both in relation to sequestration rates and carbon stocks in these forests on global and local scale (Donato et al. 2011). In addition, mangrove forests play an important role in the biogeochemical carbon cycle as presented by Alongi and Mukhopadhyay (2015), Bouillon et al. (2008, 2003) and Twilley et al. (1992), mainly due to its location in direct contact with the tides of the oceans, which provides an exchange of organic matter, with this adjacent environment, different from other forest systems.

According to Donato et al. (2011), carbon is mostly stored in the sediments, aerial vegetal biomass, and belowground biomass in the descending order. However recent studies suggest the importance of the carbon stock in the belowground biomass of mangrove forests (Abohassan et al. 2012), there are few estimates regarding this compartment (Komiyama et al. 2008). Among the estimates available in literature, a few are based on the use of trenches sampling, which despite being extremely labor intensive provide more accurate estimates for collecting larger volumes of roots than those provided by sampling based on core.

In Brazil, mangroves occur almost along the entire length of the Brazilian coast (Schaeffer-Novelli et al. 1990), stretching over 6,786 km (Schaeffer-Novelli et al. 2000). According to recent estimates, Brazil ranks second in the total area occupied by mangroves, with 1,071,083.74 ha (Magris and Barreto 2010), and has the largest contiguous mangrove area in the world, with 742,400 ha (Nascimento Jr et al. 2013). Therefore, the understanding of the contribution of Brazilian mangroves for carbon stock is fundamental to further understand the role of these forests on a global scale. Nevertheless, there is no estimate for the carbon stock in belowground biomass of these forests along the Brazilian coast.

Therefore, this study aims to present the first estimate of carbon stock in belowground biomass of Brazilian mangrove forests, using mangroves located in southeastern Brazil as a case study. In addition to the quantification of the total belowground biomass, this study was also based on the following question: what is the contribution of the belowground biomass to carbon stock in mangrove fringes in the Sepetiba bay?

MATERIALS AND METHODS

STUDY AREA

The study area is located in the Sepetiba Bay (Figure 1), approximately 70 km away from the center of Rio de Janeiro city, southeastern Brazil.

Guaratiba mangrove is protected under the Guaratiba State Biological Reserve. According to the Köppen classification, the climate can be divided into Aw, tropical hot and humid climate with a dry season in winter, typical of the lowland, and Af, tropical hot and humid climate without a dry season, characteristic of the adjacent slopes. The average annual temperature is 23.5°C, and the average annual rainfall is 1067 mm, with January and March being the months with the highest rainfalls and June and August the driest ones. The tidal regime is microtidal, with amplitude smaller than two meters. In the mangroves of Guaratiba, the innermost parts of the intertidal zones are only reached by spring tides, which create hypersaline plains. Therefore, there is a structural development gradient of the forest due to the reduction of tidal flood frequency and increased salinity toward the interior, characterizing three distinct physiographic types: fringe, basin, and transition with hypersaline plains. The sampling sites are located between coordinates 23º 00' 54"S; 43º 34' 44"W and 23º 00' 40"S; 43º 34' 14"W.

Three mangrove species described for this part of the Brazilian coast occur in the study area: *Avicennia schaueriana, Laguncularia racemosa,* and *Rhizophora mangle.* The fringe forests have a living basal area contribution of 65.2% of *A schaueriana,* 1.4% of *L. racemosa*, and 24% of *R. mangle* (Estrada et al. 2013). The basin forests have a living basal area contribution of 55% of *A. schaueriana,* 0.2% *L. racemosa*, and 31.4% of *R. mangle*. The transition forests to hypersaline plains have a living basal area contribution of 32.7% of *A. schaueriana* and 46.5% of *R. mangle*. The maximum diameter is 40 cm in fringe forest, where this study was developed. The forest structure parameters, as density, mean DBH, mean height and salinity are presented in table I.
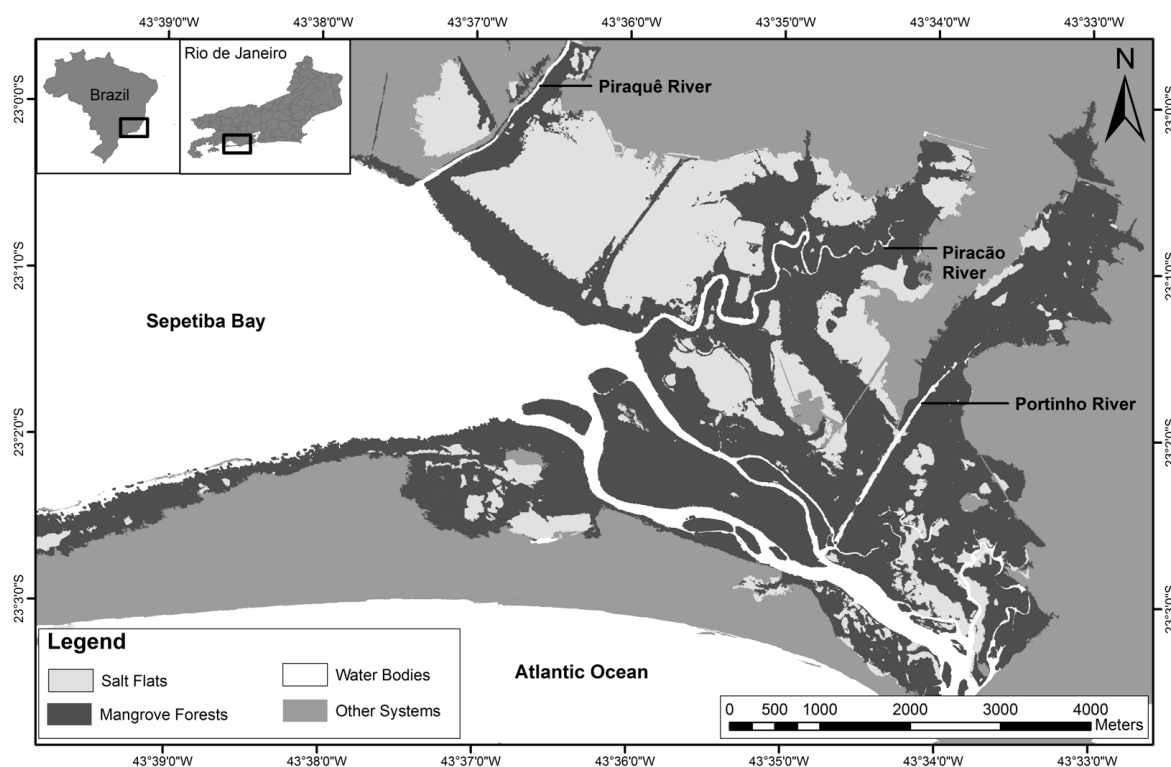

Figure 1 - Mangrove sampling sites on study area location, along the Piracão river in Guaratiba, Rio de Janeiro, RJ.

TABLE I
Structures parameters and intertiscial salinity from diferents physiographic type of Guaratiba mangrove. (mean ± standart deviation). Data from Estrada et al. (2013).

Physiographic type	Density (trunks. ha^{-1})	Mean DBH (cm)	Mean Height (m)	Salinity
Fringe	5895 ± 9399	10.1 ± 3.8	7.4 ± 2.3	35.3 ± 7.3
Basin	10260 ± 8554	5.8 ± 2.0	5.0 ± 1.8	40.9 ± 7.5
Transition	19001 ± 14426	3.0 ± 1.6	2.0 ± 1.2	42.2 ± 10.1

METHODS

The belowground root biomass was estimated using trenches digging. This sampling method was adopted because it allows more robust estimates as it evaluates a higher volume of sampled sediment in its entirety and reduces the loss of material (Komiyama et al. 1987). Five trenches with 1 m^3 volume (1 × 1 × 1 m) were excavated (Figure 2). The trenches were all positioned in the fringe forest on the margin of the Piracão river, located in the Guaratiba State Biological Reserve, and were placed approximately 150–200 m from each other, covering approximately 1 km of the forest. The excavation was stratified into 10 strata of 10 cm each. The substrate removed from each stratum was washed still in the study area, using a 1 mm mesh sieve. Roots were manually separated and cleaned from sediment excess and other organic debris. The material screened in the field was taken to the laboratory for a new wash in running water and full removal of the sediment using 0.25 mm mesh sieves. Roots were separated into the following diameter classes: less than 5 mm; between 5 and 10 mm; between 10 and 20 mm; between 20 and 50 mm and larger than 50 mm. This roots was not separated in live and dead roots. Apart from these, pneumatophores were also collected and stocks related to these structures were recorded in the first stratum. The screened roots were stored and oven dried at 70ºC to obtain the dry weight.

To transform biomass into carbon, the specific carbon contents found by Rodrigues et al. (2014) were applied: 42.6% for *L. racemosa* and *A. schaueriana* and 40% for *R. mangle*. Because the three species occur in Guaratiba's fringe forests, it was necessary to apply the weighting method of the carbon content, considering the relative dominance of each species in terms of basal area as described by Rodrigues et al. (2014). To compare the results of this study to the literature that present only belowground or aboveground biomass, biomass was converted into carbon stock. For aboveground biomass the carbon content of 45% provided by Twilley et al. (1992) was applied, and for belowground biomass the carbon content of 40.8% proposed by Khan et al. (2007) was used.

To improve reliability of these estimates, structural characterization was performed in the vicinity of each trench. For each sampling point, a 100 m² area plot was defined, with the trench at its center. All plants with more than 1 m tall were identified at the species level, tree heights were recorded with an optical rangefinder and the diameter measured at breast height (DBH; 1.30 m above ground level) of all trunks was measured. The trunks also had their status (dead or alive) verified. The average height, average DBH, and basal area were calculated for each plot. The relative contribution (%) in living and dead basal area of each species was also calculated.

Subsequently, the basal areas of all the trunks of the plot were added, considering the class (type and condition) and converted to m^2.ha^{-1}.

RESULTS

The structural parameters of the forest, where the trenches were excavated, are consistent with those presented by Estrada et al. (2013), with trunk density ranging from 1900 to 2500 live trunks.ha^{-1},

Figure 2 - Excavation of the five trench to remove the belowground root biomass. The excavation was conducted with scale support to measure the exact 1m³ volume of sediment. **a**) First trench; **b**) second trench; **c**) third trench; **d**) fourth trench; **e**) fifth trench.

the living basal area ranging from 25.96 to 36.84 m².ha^{-1}, the average DBH ranging from 11.00 to 12.66 cm, the average height ranging from 9.10 ± 2.58 to 10.33 ± 2.27 m, and the contribution in basal area indicating co-dominance of *A. schaueriana* and *R. mangle* (Table II).

The carbon stock estimates for Guaratiba mangrove belowground biomass ranged from 85.86 to 141.46 tC.ha^{-1}, with an average of 104.41 ± 20.73 tC.ha^{-1}. From this total, an average of 84.13 ± 21.34 tC.ha^{-1} corresponds to the carbon stock only in fine roots, with diameters smaller than 5 mm. The pneumatophores compartment presented a smaller carbon stock, averaging 0.13 ± 0.13 tC.ha^{-1}, which corresponds to less than 1% of all the carbon stock. Fine roots contribute up to 70% of the total belowground biomass; however, other authors have found smaller relationships of approximately 13% to 47% (Castañeda-Moya et al. 2011) and between 46 and 60% (Komiyama et al. 1987). In this study the contribution of fine roots was superior, with approximately 80.1 ± 6.4%. In all strata, fine roots with diameters smaller than 5 mm accounted for over 60% of the belowground biomass carbon stock, and in the lower strata (deeper than 50 cm) this contribution reached more than 90%.

TABLE II
Forest structure parameters of the plots measured around the trenches.

Trench	Density[1]	DBH[2]	Mean Height (±SD)[3]	BA[4]	Relative Dominance[5] (%)		
					Species	Live	Dead
T1	2,500	11.42	9.10 ± 2.58	29.91	A. schaueriana	48.5	14.3
					L. racemosa	0.0	0.0
					R. mangle	37.2	0.0
T2	2,200	12.66	9.70 ± 1.98	28.35	A. schaueriana	40.2	1.3
					L. racemosa	0.0	0.0
					R. mangle	57.5	1.1
T3	2,200	12.60	10.13 ± 2.20	29.38	A. schaueriana	47.0	1.1
					L. racemosa	4.5	5.5
					R. mangle	41.9	0.0
T4	1,900	14.66	10.33 ± 2.27	36.84	A. schaueriana	40.7	12.9
					L. racemosa	0.0	0.0
					R. mangle	46.4	0.0
T5	2,200	11.00	7.60 ± 2.32	25.96	A. schaueriana	30.4	19.5
					L. racemosa	0.0	0.0
					R. mangle	50.1	0.0

Footnote: [1](live trunks.ha^{-1}); [2]mean diameter at breast height (cm); [3]mean forest height (m); [4]basal area (m^2.ha^{-1}); [5]based on living basal area.

Most of the carbon stock is concentrated in the more superficial sediment layers, up to 0.4 m deep, and corresponds to more than 50% of the belowground biomass carbon stock. However, the highest average of all strata is observed between 0.3 and 0.4 m, with 16.23 ± 3.14 tC.ha^{-1}, which corresponds to 15.56% of the belowground biomass stock (Figure 3). The ratio between belowground root biomass stock and aboveground biomass stock (root:shoot) for the forests studied in Guaratiba is 1.14 based on estimates generated by Estrada et al. (2015) for the aboveground biomass carbon stock. This corresponds to a contribution of 53% of the carbon stock in plant biomass.

DISCUSSION

Belowground root biomass carbon stock in the world ranged from 0.5 tC.ha^{-1} to 263 tC.ha^{-1}. The average carbon stock in fringe forest of Guaratiba

mangroves was greater than about 80% of the values found in the literature.

Table SIII (Supplementary Material) depicts belowground biomass carbon stock values for different regions worldwide. For studies in which carbon stock values were not displayed, these were calculated using a more conservative approach, with a rate of 40.8% of carbon in the dry biomass. The stock estimated for Guaratiba was higher than that reported in most studies. However, other authors also found belowground biomass carbon stock values higher than those estimated for Guaratiba. There are several factors that can regulate the belowground biomass in mangrove forests, and consequently, the carbon stock associated with it. These factors include the position of the sampling area in relation to the water body, i.e., the flood tide frequency that the forest is subjected to, and the position in relation to the continent, i.e., if the forest is located in a more sheltered estuarine environment
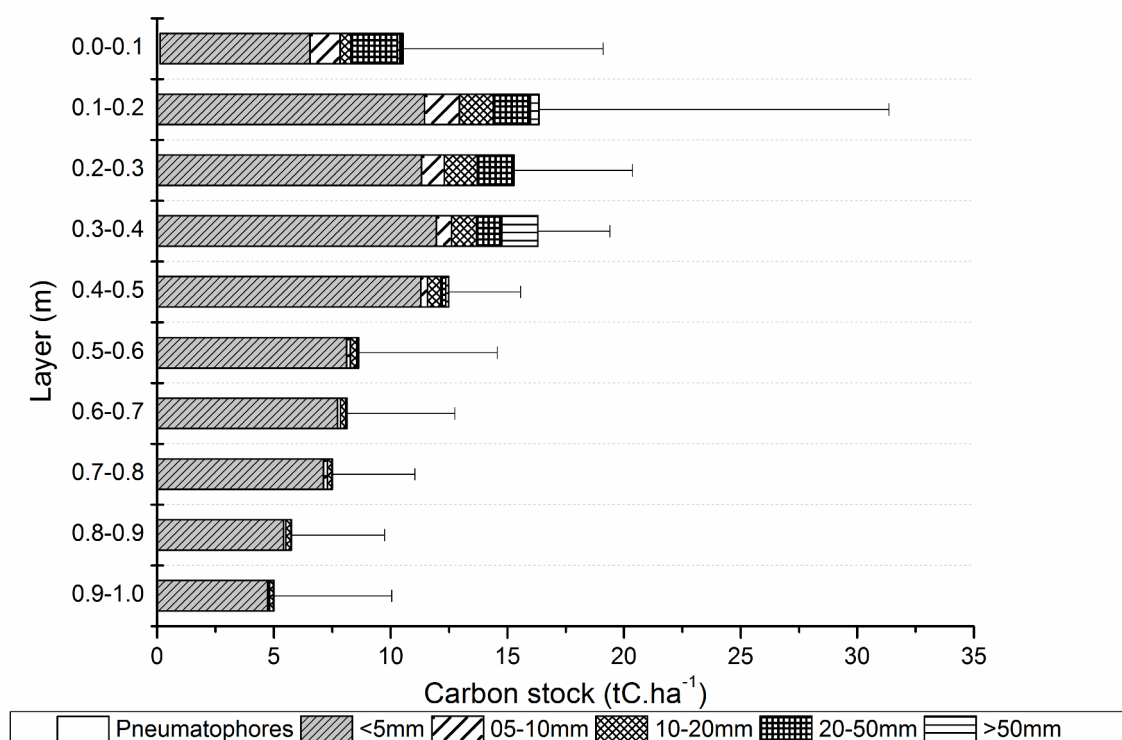
Figure 3 - Average carbon stock in root biomass by diameter classes in each deep.

or in an open area with a higher marine influence (Sherman et al. 2003, Donato et al 2011).

On the basis of the extensive review of belowground roots and aboveground biomass values of various forest land types in the world, Cairns et al. (1997) demonstrated that the root:shoot ratio ranges from 0.05 to 0.70, with an average of 0.26, with most studies reporting values between 0.20 and 0.30. The root:shoot ratio for mangrove forests, therefore, tends to be higher than that for terrestrial forests, which can be explained by the need for a greater support for aboveground biomass in unstable substrate (Komiyama et al. 2008) and by the possible increase in cambial activity induced by ethylene production in immersion conditions (Yamamoto et al. 1995). Further studies in other ecosystems in Brazil, show that BGB in mangrove systems may be higher than in other. For example, Ribeiro et al. (2011) shows much lower values for Brazilian Savanna (Cerrado) than this study,

even the mangroves occupying a much smaller area than Cerrado, wich occupies about 20% of Brazilian territory (MMA 2007). This distinctive feature of mangroves explains the importance of the belowground biomass as a carbon reservoir in that ecosystem, when compared with other forest systems. This shows that the carbon stock rates, in mangrove forest biomass, are considered high in relation to several others ecosystems (Cairns et al. 1997).

Thus the conservation of these forests allows the maintenance of carbon stock in the forest biomass. However, recent human activities have contributed to the degradation of these ecosystems (Ellison and Farnsworth 1996). In addition to these threats, mangroves are also threatened by possible climate changes (Soares et al. 2011). Processes of deforestation and degradation of these forests will allow the release of the carbon stock in the biomass as well as that stored in the sediment.

This means high amounts of carbon released into the atmosphere through decomposition and bioavailability processes. The conservation of forest ecosystems of mangroves, as well as other ecosystems, allows a consequent maintenance of the carbon stock in the plant biomass (Harris et al. 2012, Zarin 2012).

The root:shoot ratio in carbon stock ranges from 0.21 to 1.55 (Komiyama et al. 2008). The values found here are within this range, but the contribution of belowground biomass for carbon stock in Guaratiba is greater than 90% of the values found in literature. However, most recently Zhila et al. (2014) found a lower contribution of carbon stock of belowground biomass with 1.3% equivalent to 0.01 root:shoot ratio.

Salinity can reduce the root biomass of non halophytes plants (Bernstein and Kafkafi 2002). However this is inversely in halophytes, for these plants, increased salinity induces the growth of roots and the reduction of salinity inhibits roots´ growth (Bernstein and Kafkafi 2002). The root:shoot ratio can also be influenced by porewater salinity, where there may be a reduction of the aboveground biomass in relation to belowground biomass (Bernstein and Kafkafi 2002). This is to compensate for the soil conditions and reduce the need for nutrients and water by reducing the aerial part and increasing the biomass of roots to increasing the uptake of water and nutrients (Bernstein and Kafkafi 2002).

The highest concentration of carbon stock in the first layers of sediment was also found by Khan et al. (2007) other mangrove forests in the Indo-Pacific region. Donato et al. (2012) also reported a similar behavior for other mangroves where the stock tends to markedly decrease after the first 40 cm depth. The belowground biomass can be divided into compartments according to the diameter of the root (Komiyama et al. 1987), and consequently its carbon stock too. In a mangrove forests in southern Thailand over 50% of total root biomass was allocated in the fine roots (<2 mm diameter), the

ratio ranged from 46.4% to 66.4%, which shows a high root biomass of fine roots (Komiyama et al. 1987). Zhila et al. (2014) found a contribution of 27% and 37% of fine roots in carbon stock of the total forest biomass.

The fine roots in mangroves are concentrated in lateral branches that arise from perennial roots. The fine roots with diameters smaller than 2 mm are the primary source of water and nutrient uptake by plants and play an important role in the ecosystem, since without them the nutrients could not be absorbed and many inorganic and organic compounds have their cycles incomplete or damaged (Chalermchatwilai et al. 2011).

CONCLUSIONS

This study presented the first carbon stock estimates for the belowground biomass in southwestern Atlantic mangrove forests. The values found for Guaratiba, ranged from 85.86 to 141.46 tC.ha^{-1}, with an average of 104.41 ± 20.73 tC.ha^{-1} (southeastern Brazil) are within the range reported in the literature, being compatible with the highest estimates presented for other regions. The trench sampling method, although very laborious, is considered, in the literature (Komiyama et al. 1987), more reliable and efficient because with this method there is practically no loss of material due to limitations of sampling in addition to the more representative volume of sampled material.

Although the aboveground biomass presents relevant participation in the mangrove forest carbon stock, the belowground biomass contribution has proven to be increasingly important as new studies are conducted showing that the ratio of aboveground and belowground biomass can be less than 1:1. That is, the belowground biomass can contribute more than 50% of the total biomass of mangrove forests. For Guaratiba the root:shoot ratio is 1.14 in the forests studied.

This first carbon stock estimate of the belowground biomass of Brazilian mangrove forests begins to fill a huge gap of knowledge regarding this country›s contribution to the mitigation of global warming, particularly considering that Brazil has the second largest area coverage of mangroves in the world. More efforts should be made to ensure that new estimates arise and allow not only the reduction of the uncertainty of the national inventory of carbon emissions but also the understanding of the carbon stock variability in this compartment in local, regional, and latitudinal scales.

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SUPPLEMENTARY MATERIAL

TABLE SIII - World mangroves carbon stock on belowground biomass for mangroves. (*carbon stock values estimated by converting the original biomass data with 40.8% of carbon in biomass rate proposed by Khan et al. 2007).