Assessment of Mangrove Carbon Stocks in Cameroon, Gabon, the Republic of Congo (RoC) and the Democratic Republic of Congo (DRC) Including their Potential for Reducing Emissions from Deforestation and Forest Degradation (REDD+)

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Abstract

We present results of the field assessment using a total of fifteen 0.1 ha mangrove permanent sample plots (PSPs) in four selected countries in Central Africa, including: Cameroon, Gabon, Republic of Congo and Democratic of Republic, which together account for 90 % of mangroves in Central Africa. Above- and belowground carbon stocks were computed using data from the PSPs in all four countries. Long-term monitoring data in Cameroon were used to estimate carbon sequestration rates. Four major carbon pools were considered: aboveground carbon, belowground root carbon, deadwood and the soil organic carbon. All the eight mangrove species described in Central Africa were encountered in the study. The dominant species in Central Africa is *Rhizophora racemosa*, and it occupies more than 70 % of the forest formation. The average stand density ranged from a low of 450 tree/ha in degraded forest of RoC to a high of 3,256 tree/ha in undisturbed stands of Cameroon. Standing volume ranged from a low of 213 m^3/ha in RoC to a high of 428 m^3/ha in Cameroon; corresponding to aboveground biomass values of 251 and 505 Mg/ha, respectively. Together with the deadwoods, the total vegetation biomass in the study area ranged from a low of 394 Mg/ha in RoC to a high of 825 Mg/ha in Cameroon. Mean diameter increment for primary and secondary stems was 0.15 cm/year. This translates to above- and belowground annual biomass increments of 12.7 and 3.1 Mg/ha/year, respectively. Total ecosystem carbon in undisturbed system was estimated at 1520 ± 164 Mg/ha with 982 Mg/ha (or 65 %) in belowground component (soils and roots) and 538 Mg/ha (35 %) in the aboveground components. Carbon density differed significantly ($p < 0.05$) with forest

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conditions. The least total ecosystem carbon of 808 ± 236 Mg/ha was recorded in heavily exploited forests, translating to CO_2 equivalent of 2,962 Mg/ha. Undisturbed mangrove forests sequester annually 16.5 MgC/ha against 6.9 MgC/ha for degraded systems. Certain recommendations are made to improve and consolidate these estimates especially through validation of cover change, continuous monitoring PSP as well the development of site specific allometric equations for mangroves in Central Africa.

Keywords
Carbon accounting • Mangroves • REDD+ • Central Africa

Abbreviations

dbh	Diameter at breast height
DRC	Democratic Republic of Congo
FAO	Food and Agriculture Organization
PSP	Permanent sample plot
REDD	Reducing emissions from deforestation and forest degradation
RoC	Republic of Congo
UN-REDD	United Nations Reducing Emissions from Deforestation and Forest Degradation Programme
UNEP	United Nations Environment Programme
UNEP-WCMC	United Nations Environment Programme World Conservation Monitoring Centre

Introduction

Mangroves of West and Central Africa extend over 20,144 km^2, representing 59 % of the African mangroves or 11 % of the total mangroves area in the World (UNEP-WCMC 2007). These forests are particularly important for subsistence economies, providing harvestable wood and non-wood products, as well as ecosystem services such as shoreline protection, fish habitat and climate change mitigation through carbon sequestration. However, over-exploitation, conversion pressure and pollution effects have degraded or reduced mangroves in the region by about 20–30 % over the last 2 decades. Climate change effects now threaten the remaining mangroves in the region through increased precipitation and sedimentation. The consequences of current rates of mangrove deforestation and degradation in Central Africa are potentially enormous as these seriously threaten the livelihood security of coastal people and reduce the resiliency of mangroves to mitigate climate change effects.

'Reducing Emissions from Deforestation and forest Degradation' (REDD+) is an emerging international financial mechanism enabling tropical countries to get rewarded for their efforts in reducing CO_2 emissions from deforestation and forest degradation, and a number of Central African countries have embarked on ambitious national reforms and investments to improve forest landscapes management in order to benefit from REDD+. There are opportunities for mangroves to be included in national REDD+ strategies, especially in the light of recent findings that indicate that mangroves can store several times more carbon per unit area than productive terrestrial forests (Donato et al. 2011). Although mangroves cover only around 0.7 % (around 137,760 km^2) of global tropical forests (Giri et al. 2011), degradation of mangrove ecosystems potentially contributes 0.02–0.12 Pg carbon emissions per year, equivalent of up to 10 % of total emissions from deforestation globally (Donato et al. 2011). These make mangroves suitable candidate for REDD+ projects.

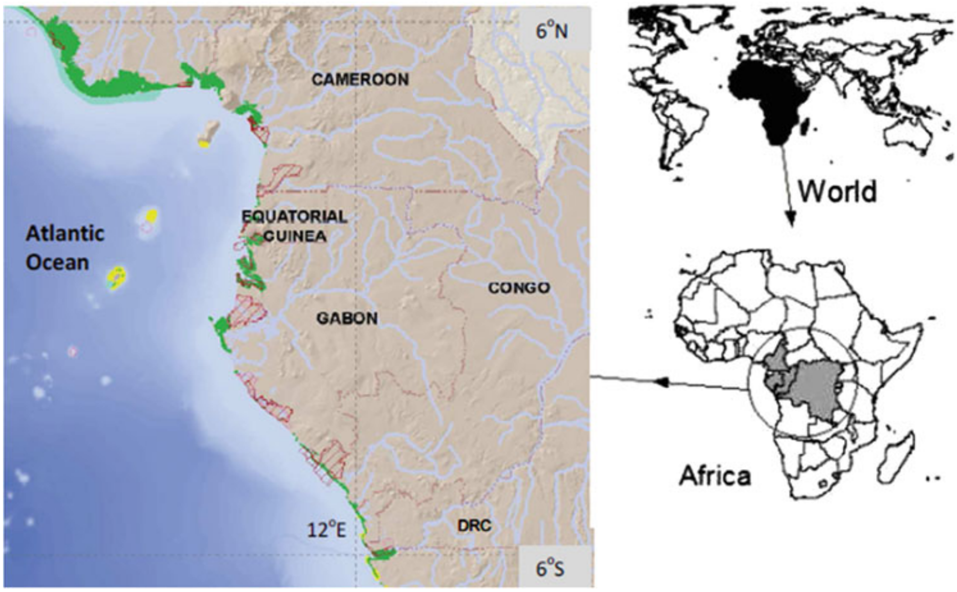

Fig. 1 Map showing the location of selected mangrove countries

Previously, no study existed in the Central Africa region quantifying mangrove carbon stocks, sequestration rates and possible emissions in response to their degradation. A key challenge for successfully implementing any REDD+ Project is the reliable estimation of biomass carbon stocks in forests. A reliable estimation of forest biomass has to take account of spatial variability, forest allometry, wood density and management regime. Many studies have been published on aboveground carbon stocks in tropical forests around the world (Komiyama et al. 2005), but limited studies exist on belowground root biomass and soil carbon. Knowledge is even more limited for mangroves, where localized allometric equations for different mangrove species are limited.

This chapter presents results of field assessment in the four selected countries in Central Africa, including: Cameroon, Gabon, RoC and DRC, which together account for 90 % of mangroves in Central Africa. The information can serve as a contribution to further improve our global understanding of the climate change mitigation potential of mangroves and a basis to establish initial baselines in future mangrove projects and REDD+ strategies in Central Africa.

Study Approach and Methodology

Descriptions of Project Area

Four pilot areas in Central Africa were selected for the study, including Cameroon, Gabon, DRC and RoC (Fig. 1; Table 1). Collectively, these pilot countries contain 90 % of mangroves in Central Africa. Further, DRC and the RoC are part of the UN-REDD programme countries; while Cameroon and Gabon take part in the World Bank Forest Carbon Partnership and have the highest mangrove covers in Central Africa. The following general criteria were used in selecting study sites:

- the forest structure and composition appear to be typical of other sites in the region,
- waterways and canals are reasonably navigable even during low tides to allow for access and transportation of equipment and materials,
- different forest conditions are represented,
- the area is not so readily accessible that sample plots may be illegally felled.

Biophysical Characteristics

A variety of habitat types (coastal lagoons, rocky shores, sandy beaches, mudflats, etc.) characterize the Central African coastline with a vast array of rivers flowing from the hinterlands into the Atlantic Ocean. The confluences of these rivers with marine waters form suitable conditions for the development of outstanding giant mangrove vegetation in the region that also harbours the world's second largest tropical rainforest. The climate in Central Africa is mainly equatorial characterized by abundant rains (3,000–4,000 mm in Cameroon, 2,500–3,000 mm in Gabon and RoC and 772 mm in DRC) and generally high temperatures with monthly average of 24–29 °C, with a dry season spanning November to March in Cameroon and June to October in DRC. A typical climate diagram in Central Africa (Cameroon) is given in Fig. 2. September is normally the month with the highest rainfall, while December has the least.

Table 1 Selected sites within the central African mangroves for ecosystem service assessment

Country	Number of mangrove sites	Study site	Forest conditions
Cameroon	5	South West region, Bamasso mangroves	Undisturbed transboundary mangroves near Nigeria border
		Littoral region, Moukouke	Undisturbed mangroves at the Cameroon estuary
		Littoral region, Yoyo mangroves	Heavily exploited mangroves of Cameroon estuary
		Littoral region, Youme mangroves	Moderately exploited mangroves of Cameroon estuary
		South region, Campo mangroves	Undisturbed mangroves transboundary mangroves at the Ntem estuary
Gabon	4	Province de l'Estuaire, Commune de Libreville	Undisturbed mangroves of Akanda National Park
		Province de l'Estuaire, Commune de Libreville	Heavily exploited peri-urban mangroves
		Province de l'Estuaire, Commune de Coco-Beach	Moderately exploited transboundary mangrove near Equatorial Guinea
		Province de l'Estuaire, Commune de Coco-Beach	Undisturbed mangrove Emone-Mekak estuarine
RoC	3	Département de Pointe Noire	Heavily exploited peri-urban of Louaya
		Département de Pointe Noire	Moderately disturbed mangroves located within the touristic centre of Songolo town
		Département du Kouilou	Undisturbed mangroves transboundary in Gabon–Angola border
DRC	3	Province du Bas-Congo, district de Boma the only mangrove zone in DRC entirely in Muanda Mangrove Park and	Heavily exploited mangrove within Marana Line
			Moderately exploited mangroves
			Undisturbed mangrove of Île Rosa Tompo

(continued)

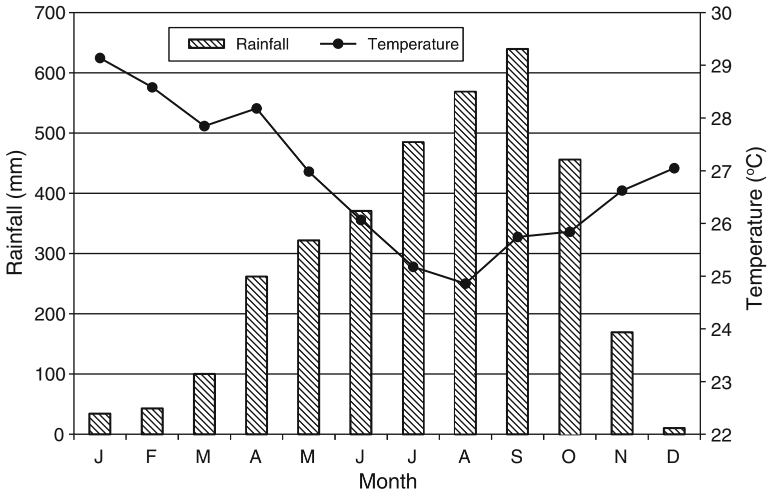

Fig. 2 Typical climate diagram in Central Africa. This particular diagram is for Doula-Edea Reserve, Cameroon

Table 2 Mangrove woody species found in the pilot areas

Mangrove species	Country			
	Cameroon	Gabon	RoC	DRC
Avicennia germinans	x	x	x	x
Conocarpus erectus	x	x		
Laguncularia racemosa	x	x		
Rhizophora harissonii		x		
Rhizophora mangle		x		
Rhizophora racemosa	x	x	x	x
Associated species				
Hibiscus sp	x	x		
Phoenix sp		x		
Total	5	8	2	2

Composition and Distribution of Mangroves in Central Africa

Mangrove formation in Western and Central Africa is characterized by low species composition common with new world mangroves (Tomlinson 1994). In Central Africa, there are 8 mangrove species of economic importance (UNEP-WCMC 2007). The largest blocks of mangroves in the region are found in deltas and large rivers estuaries in Cameroon and Gabon (UNEP-WCMC 2007). The dominant species is *Rhizophoraceae racemosa* which accounts for more than 70 % of the forest formation. The species fringes most shorelines and river banks, attaining up to 50 m in height with tree diameter of over 100 cm around the Sanaga and Wouri estuaries marking one of the tallest mangroves in the world (Blasco et al. 1996, p. 168). Other important mangrove species in the region are *Rhizophora mangle*, *Rhizophora harissonii*, *Avicennia germinans* (Avicenniaceae), *Laguncularia racemosa* and *Conocarpus erectus* (both Combretaceae) (Table 2). Undergrowth in upper zones can include the pantropical *Acrostichum aureum* (Pteridaceae) where the canopy is disturbed. *Nypa fruticans* (Arecaceae) is an invasive mangrove palm introduced in Nigeria from Asia in 1910 and has spread to Cameroon.

Common mangrove associates in Central Africa include Annonaceae, *Cocos nucufera* (Areaceae), *Guiboruti demensei* (Caesalpiniaceae), *Achornea cordifolia* (Euphorbiaceous), *Dalbergia ecastaphylum* and *Drepenocarpus lunatus* (both Fabaceae), *Pandanus candelabrum* (Pandanaceae), *Hibiscus tilaeceus* (Malvaceae), *Bambus avulgaus* (Poaceae) and *Paspalum vaginatum* (Poaceae), among others (Ajonina 2008).

Socioeconomic Importance

Fishing is a major economic activity along the West-Central African coastline especially in Central Africa with a population of about 4 million living in or around mangrove ecosystems (UNEP-WCMC 2007). About 60 % of fish harvested in these rural areas is of artisanal origin. Open drying, salting, icing, refrigerating and smoking are the common methods used to preserve fish in the region (Feka and Ajonina 2011 citing others). Mangrove wood is widely preferred for fish smoking within coastal areas of this region because of its availability, high calorific value, ability to burn under wet conditions and the quality it imparts to the smoked fish (Oladosu et al. 1996). Fish-smoking and fish-processing activities are largely responsible for more than 40 % degradation and loss of mangroves in the West-Central African coastal region (UNEP-WCMC 2007).

Quantification of Carbon Pools

Carbon density was estimated with data from existing and newly established rectangular 0.1 ha (100 m × 10 m) permanent sample plots (PSP). Existing PSPs in Cameroon provided an excellent opportunity to model stand dynamics and carbon sequestration potential of the mangroves in the region. Based on mangrove area coverage in each country 5 PSPs in Cameroon, 4 in Gabon, 3 in RoC and 3 in DRC were selected for the study (Table 1). Measurement protocol consisted of species identification, mapping, tagging and measurements of all trees inside the plot using modified forestry techniques for mangroves (Pool et al. 1977; Cintron and Novelli 1984; Kauffman and Donato 2012). Transect and plots boundaries were carefully marked and GPS points taken. Detailed procedures for establishment of PSP are given in Ajonina (2008). Four carbon pools were considered in the present study, including: vegetation carbon pools (both above and belowground), litter, coarse deadwood and soil.

Measurement of Vegetation Carbon

An important carbon stock in forestry is the aboveground component. Trees dominate the aboveground carbon pools and serves as indicator of ecological conditions of most forests. In each PSP, three plots of 20 m × 10 m were established along transect at 10-m intervals (Fig. 3a). Inside the plots, all trees with diameter of the stem at breast height (dbh_{130}) ≥ 1.0 cm were identified and marked. Data on species, dbh, live/dead and height were recorded for all individuals. In *Rhizophora*, dbh was taken 30 cm above highest stilt root. Aboveground roots and saplings (dbh $\leq$ 1 cm) were sampled inside five 1-m^2 plots placed systematically at 1 m intervals along the 10 m × 10 m plot (Fig. 3b). Newly recruited saplings were enumerated, while missing tags were replaced by reference to initial plot maps.

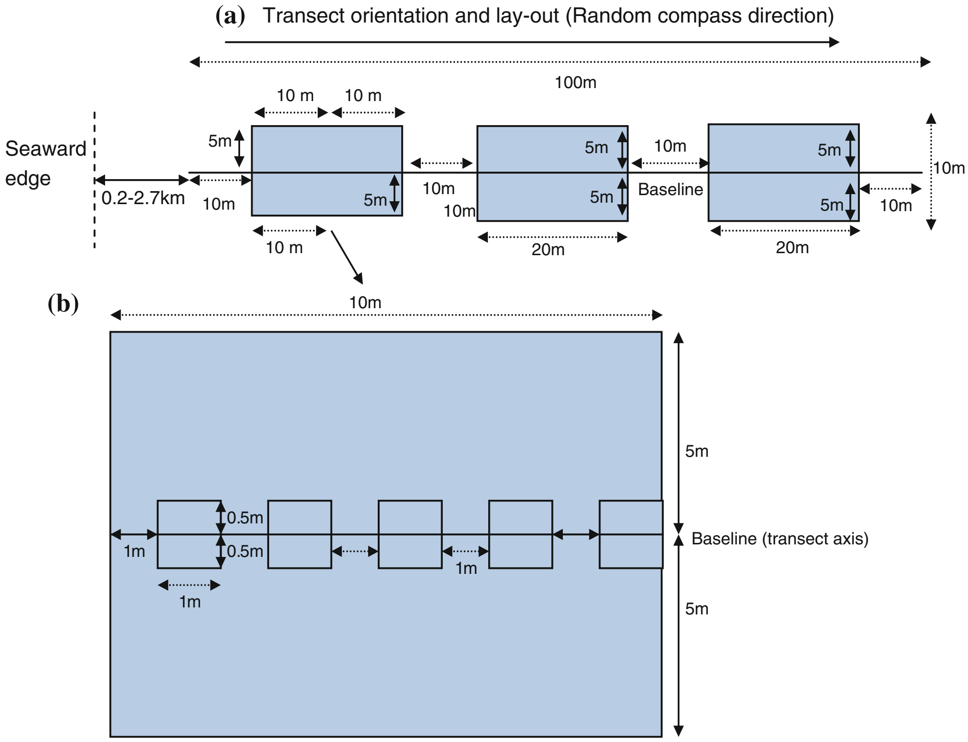

Fig. 3 **a** Schematic layouts of mangrove forest stands permanent sample plots. **b** Roots and sapling inventories (after Ajonina 2008)

Dead and Downed Wood

Dead wood was estimated using the transect method whose application is given in Kauffman and Donato (2012). The line intersect technique involves counting intersections of woody pieces along a vertical sampling transect. The diameter of deadwood (usually more than 0.5 cm in diameter) lying within 2 m of the ground surface were measured at their points of intersection with the main transect axis. Each deadwood measured was given a decomposition ranking: rotten, intermediate or sound.

Soil Samples

Mangrove soils have been found to be a major reservoir of organic carbon (Donato et al. 2011), and given the importance of this carbon pool, we describe the methodologies used to calculate soil carbon in detail. Soil carbon is mostly concentrated in the upper 1.0 m of the soil profile. This layer is also the most vulnerable to land-use change, thus contributing most to emissions when mangroves are degraded. Soil cores were extracted from each of the 20 m × 10 m plots using a corer of 5.0 cm diameter and systematically divided into different depth intervals (0–15, 15–30, 30–50, and 50–100 cm); following the protocol by Kauffman and Donato (2012). A sample of 5 cm length was extracted from the central portion of each depth interval to obtain a standard volume for all sub-samples. A total of 180 soil samples were collected and placed in pre-labelled plastic bags—Cameroon (60 soil samples), Gabon (48), RoC (36) and DRC (36). In the laboratory, samples were weighed and oven-dried to constant mass at 70 °C for 48 h to obtain wet:dry ratios (Kauffman and Donato 2012). Bulk density was calculated as follows:

$$\text{Soil bulk density}\ \left(\mathrm{g\,m^{-3}}\right) = \frac{\text{Oven} - \text{dry sample mass (g)}}{\text{Sample volume } (\mathrm{m^3})} \tag{1}$$

where, Volume = cross-sectional area of the corer × the height of the sample sub-section.

Of the dried soil samples, 5–10-g sub-samples were weighed out into crucibles and set in a muffle furnace for combustion at 550 °C for 8 h through the process of loss on ignition (LOI), and cooled in desiccators before reweighing. The weight of each ashed sample was recorded and used to calculate organic concentration (OC). Total soil carbon was calculated as:

$$\begin{aligned}\text{Soil C}\ (\mathrm{Mg/ha^1}) &= \text{bulk density}\ (\mathrm{g/cm^3}) \\ &\quad * \text{soil depth interval (cm)} * \%\,\mathrm{C}\end{aligned} \tag{2}$$

The total soil carbon pool was then determined by summing the carbon mass of each of the sampled soil depth.

Data Analysis and Allometric Computations

General field data were organized into various filing systems for ease of analysis and presentation. Both structural and biophysical data were entered into prepared data sheets.

Later, the data were transferred into separate Excel Work Sheets containing name of the country, zone and other details of the site. Sample data sheets for different data types are given in the Annex 1. Standing volume was determined using locally derived allometric relations from sample data with dbh as the independent variable:

$$v = 0.0000733 * D^{2.7921} (R^2 = 0.986, n = 677) \quad (3)$$

where

v volume

D diameter of the stem for the range: 1 cm $\leq D \geq$ 102.8 cm

Biomass conversion/expansion factor (BC/EF), which is the ratio of total aboveground biomass to stand volume, and shoot/root ratio (SRR) developed by Ajonina (2008), Ajonina, D. R. R. Pelz, and Chuyong (2012, Tree and stand volume equations for mangrove forests in the Atlantic coastal region of Cameroon, Central Africa, Unpublished manuscript), Ajonina, D. R. R. Pelz, and Chuyong (2012, Tree biomass expansion, partitioning and shoot-root ratio models for above- and below-ground carbon stock estimations for mangrove forests in the Atlantic coastal region of Cameroon, Central Africa, Unpublished manuscript) were used for the estimation of total tree biomass and carbon densities. The BC/EF used in the study was 1.18 (Ajonina 2008) which is comparable to that reported for humid tropical forests by Brown (1997).

Tree, Stand Dynamics and Carbon Sequestration Estimations

Using PSP in Cameroon, we estimated periodic annual increment (PAI) of the forest as a function of mortality and recruitment of seedlings at the beginning and end of each growing period. Development of detailed carbon sequestration estimates will, however, require long-term studies on regeneration, stand dynamics and also the distribution pattern of the seedlings under mother trees.

Deadwood

Deadwood volume was estimated using the protocol by Kauffman and Donato (2012):

$$\text{Volume} \quad (\text{m}^3/\text{ha}) = \Pi^2 * \frac{\sum_{i=1}^{n} d_i^2}{8L} \quad (4)$$

where $d_i = d_1, d_2 \ldots d_n$ are diameters of intersecting pieces of deadwood (cm) L = the length of the intersecting line (transect axis of the plot) generally $L = 20$ m being the length of each plot or 100 m being the length of transects. Deadwood volumes were converted to carbon density estimates using the different size-specific gravities provided by Kauffman and Donato (2012).

Results and Discussion

Floristic Composition and Distribution

Structural attributes (tree height, basal area, stand density, species composition, etc.) of the mangroves of Central Africa are provided in (Tables 2, 3). All the mangroves described in Central Africa were encountered during the present study (Table 2). The dominant and prominent species is *R. racemosa* that occur in expansive pure stands across the countries. There were only two species that were found in RoC and DRC. These results are in conformity with earlier surveys (e.g. UNEP-WCMC 2007; Ajonina 2008; Ajonina et al. 2009) and confirm Central African mangroves as being generally species poor as compared to the Indo-west pacific mangroves that may have up to 52 species (Tomlison 1986; Duke 1992; Spalding et al. 2010). Common mangrove associates that were encountered in the pilot areas include *Hibiscus* sp, *Phoenix* sp and *A. aureum*.

There is no obvious zonation that is displayed by the dominant mangrove species in Central Africa. The seaward side as well as creeks is mostly occupied by *R. racemosa*, whereas *R. mangle, A. germinams*, and *A. aureum* mosaic covers the middle and outer zones. In a few places in Cameroon, we found the invasive *Nypa* palms growing in association with *R. mangle* and *R. racemosa* on creek margins.

Stand Density, Volume and Biomass

Table 3 provides vegetation inventories for Central Africa mangroves. The average stand density ranged from a low of 450 tree/ha in heavily exploited forest of RoC, to a high of 3,256 tree/ha in undisturbed stands of Cameroon. In most undisturbed plots, the stem density decreased exponentially with increasing diameter. These are typical reversed ‘J’ curves for stands with a wide range of size classes and by inference also age classes (Fig. 4). This pattern was, however, distorted in heavily exploited mangroves stands in the region, where size classes above 30 cm were literally missing.

Standing volume ranged from a low of 213 m^3/ha in RoC to a high of 428 m^3/ha in Cameroon; corresponding to aboveground biomass values of 251 and 505 Mg/ha, respectively. Together with the deadwoods, the total vegetation biomass in the study area ranged from a low of 394 Mg/ha in RoC to a high of 825 Mg/ha in Cameroon to (Table 3).

Table 3 Structural characteristics of mangroves in Central African

Country	Tree density (Nr trees/ha)	Max height (m)	Mean diameter (cm)	Basal area (m^2/ha)	Stand volume (m^3/ha)	Aboveground biomass (Mg/ha)	Belowground biomass (Mg/ha)	Dead woods (Mg/ha)	Total biomass (Mg/ha)
Cameroon	3,256	52.1	4.6	25.1	427.5	505	306	15	825
Gabon	1,467	41	9.5	24.5	288.9	341	151	21	512
RoC	1,667	25.2	7.7	18.8	213	251	122	20	394
DRC	1,267	27	9.1	24.5	346.9	409	185	69	663

All stems with $DBH > 1.0$ cm inside PSPs plots were measured
Extract of calculation from Ajonina (2008) as follows
$AGB = BEF_{ABG} * \text{stand volume}$
$BEF = 1.18$, $BGB = BEF_{BGB}eqn * \text{trunk volume} = (1.385 * Diam^{-0.4331}) * \text{trunk volume}$
Where $BEF_{BGB}Equation = (1.385 * Diam^{-0.4331})$

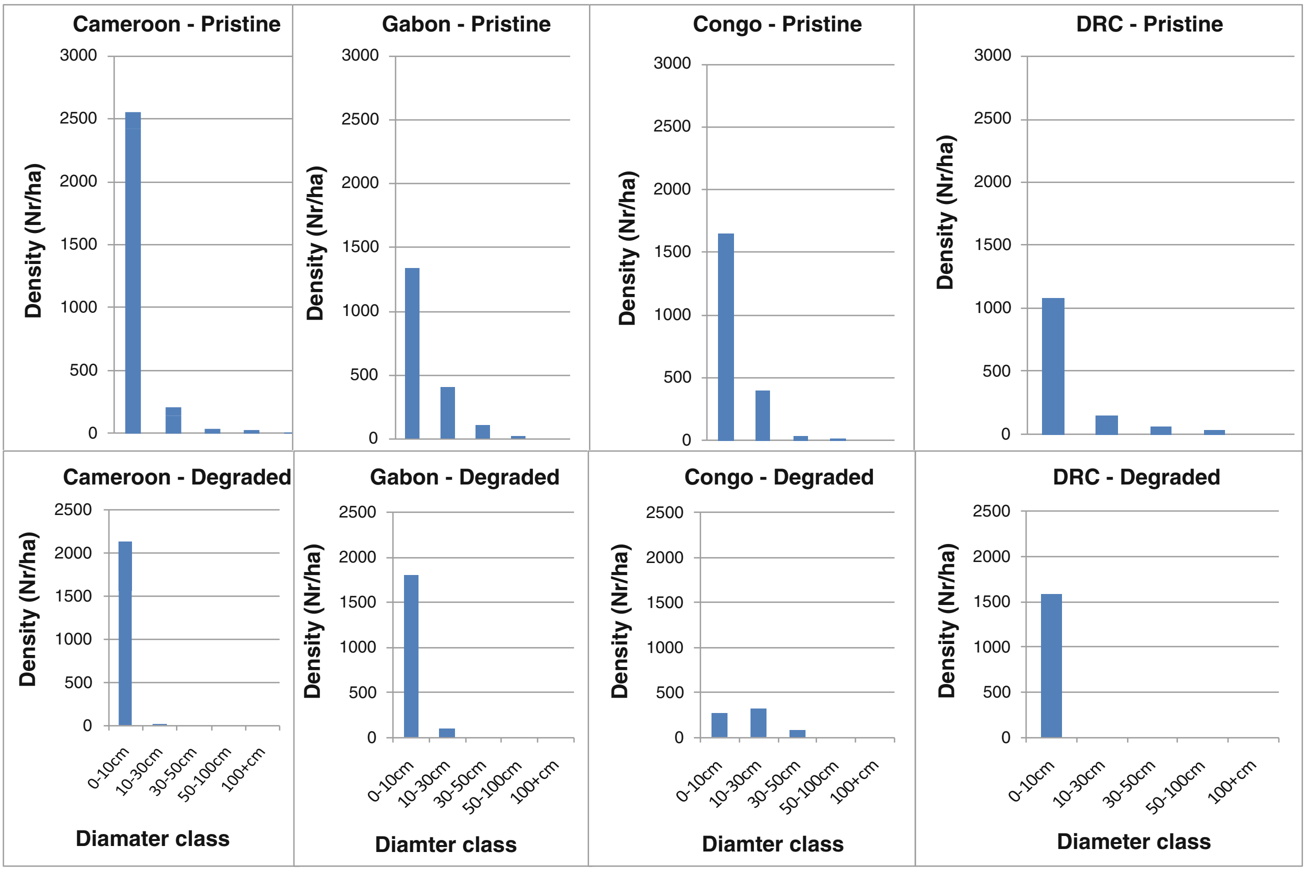

Fig. 4 Stem class distributions in Central mangrove forest

Carbon stocks

Soil Organic Carbon

There was high variability in the concentration of soil organic carbon ($p < 0.05$) with undisturbed sites showing higher carbon concentrations than exploited forests. Across the region, the average quantity of soil organic carbon amounted to 827 ± 170 Mg/ha. The undisturbed stands recorded the highest amount of mean soil organic carbon (967 ± 58 Mg/ha; Table 4). This was followed by heavily and moderately exploited sites that recorded an average SOC of 774 ± 163 and 741 ± 190 Mg/ha, respectively. The results are in conformity with high content of organic carbon that is associated with mangrove sediments (Donato et al. 2011, found an average of 864 Mg/ha in the Indo-Pacific; Adame et al. 2013, found up to 1,166 Mg/ha in the Mexican Caribbean). Alluvial deposition from multiple rivers flowing through the mangroves into the Atlantic

Table 4 Soil organic carbon (*SOC*) along the different forest conditions in Central Africa mangroves

Forest condition	Soil Depth (cm)				Total (Mg C/ha)
	0-15	15-30	30-50	50-100	
Undisturbed	157.8 ± 22.8	182.4 ± 70.7	230.5 ± 39.9	396.7 ± 108.6	967.4±57.6
Moderately exploited	169.1± 34.5	140.0± 45.6	167.2± 86.3	303.9± 198.0	780.2± 162.9
Heavily exploited	130.1 ± 18.1	147.0 ± 33.6	156.6 ± 58.4	306.8 ±195.5	740.6 ±189.6

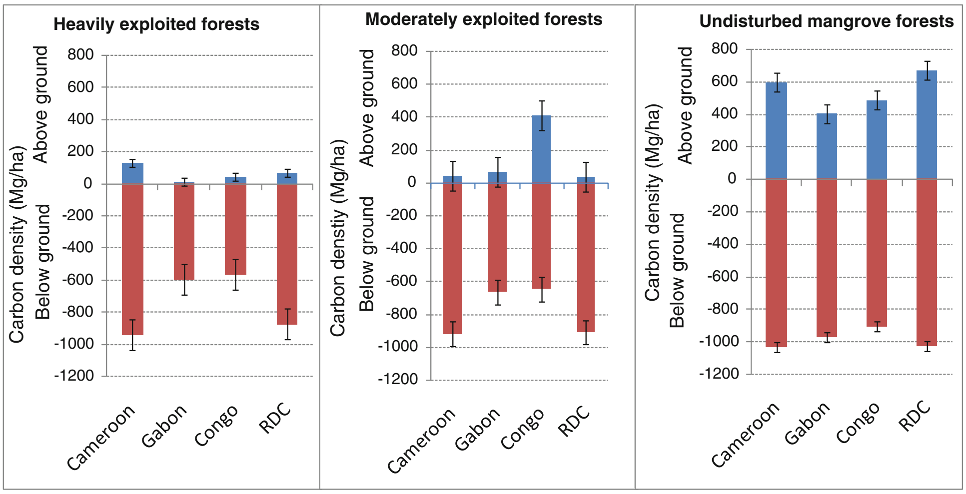

Fig. 5 Partitioning of carbon stocks in mangroves of Central Africa under different conditions

Table 5 Total ecosystem carbon stocks in mangroves of Central Africa under different perturbation regimes

Pools	Heavily Exploited		Moderately Exploited		Undisturbed	
	Trees Mg/ha	SE	Mg/ha	SE	Mg/ha	SE
Aboveground						
Live component	58.0	50.4	123.3	179.7	467.1	70.0
Dead component	6.1	3.7	16.4	18.1	70.6	85.2
Total Aboveground	64.1	49.9	139.6	181.4	537.7	116.5
As % total	7.2	4.0	14.1	16.6	35.1	4.2
Belowground						
Tree-roots	3.1	1.4	12.1	18.8	15.1	4.2
Total Soil	740.6	189.6	773.6	162.9	967.4	57.6
Total Belowground	743.6	190.9	785.7	149.8	982.5	60.8
As % total	92.8	4.0	85.9	16.6	64.9	4.2
Total ecosystem carbon stock (Mg/ha)	807.8	235.5	925.4	137.2	1520.2	163.9

Carbon pools of trees (aboveground) were calculated as the product of tree stand biomass multiplied 0.5
CO_2 value is derived by multiplying C stocks by 3.67, the molecular weight ratio of CO_2 to C

Ocean could explain high organic carbon content in the soils of even mangroves that are in degraded conditions. There was high variation in SOC in the 50–100-cm depth as compared to the rest of the zones (Table 4, Fig. 5).

Total Ecosystem Carbon

Based on the four major carbon pools accounted in this study, total ecosystem carbon in undisturbed mangrove of Central Africa was estimated at 1,520 ± 164 Mg/ha with 982 Mg/ha (or 65 %) in belowground component (soils and roots) and 538 Mg/ha (35.0 %) in the aboveground biomass (Fig. 5). Total ecosystem carbon stocks differed significantly ($p < 0.05$) with forest conditions. The lowest ecosystem carbon of 808 ± 236 Mg/ha was recorded in moderately degraded forests, translating to CO_2 equivalent of 2,962 Mg/ha (mean: 808 ± 236 Mg/ha) (Table 5). These figures are comparable to other studies around the world, which have shown average values of

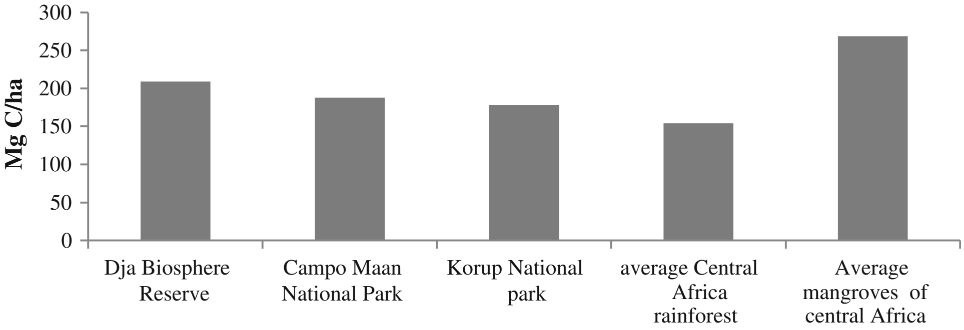

Fig. 6 Aboveground carbon stocks of selected terrestrial rainforest in Congo basin and the mangroves sampled in this study

1,023 ± 88 MgC/ha in the Indo-Pacific (Donato et al. 2012) and 987 ± 338 MgC/ha in Mexico (Adame et al. 2013).

Although it is clear that undisturbed forests contain the largest amounts of carbon, the difference between moderately exploited and highly exploited systems is less clear. The relatively high carbon contents in exploited systems could be explained by the fact that soils in exploited systems could be receiving carbon input from outside the system through flood water, alluvial deposits and tides. High soil carbon figures in highly exploited as well as moderately exploited forests in RoC and DRC were influenced by a peri-urban setting that suffers pollution effects. Furthermore, the relatively high carbon deposits in soils of exploited systems shows that not all soil carbon is oxidized and emitted to the atmosphere when the system becomes degraded; part of this remains captured in the soil column. The significant difference in carbon stocks between non-disturbed and moderately exploited systems points to the possibility that mangroves release carbon stocks relatively quickly after degradation, even if degraded moderately, and that it is important for mangroves to remain in completely undisturbed states if they are to maintain maximum carbon values.

Carbon Dioxide (Greenhouse Gas) Emission Potential

The most vulnerable carbon pools following mangrove deforestation and degradation are the aboveground carbon as well as soil carbon from the top 30 cm. Estimating emissions from land-use change was conducted using the uncertainty-propagation approach detailed in Donato et al. (2011). For the mangroves of Central Africa, a conservative low-end estimate of conversion impact was used, with 50 % aboveground biomass loss, 25 % loss of soil C from the top 30 cm, and no loss from deeper layers. Use of low-end conversion impact in the current study is justified by low-level reclamation of mangroves for aquaculture and agriculture in Central Africa. Using these conservative estimates, we estimate that 1,300 Mg of carbon dioxide would be released per ha of cleared pristine mangrove in Central Africa. A recent report estimates that 771 km^2 of mangrove were cleared in Central Africa between 2000 and 2010 (UNEP-WCMC 2012), equating to estimated emissions of 100,152,000 Mg of carbon dioxide. Of course, not all the carbon dioxide is released immediately, and these emissions occur over decades.

Comparison with Adjacent Central African Rainforests of the Congo Basin

Ecosystem carbon storage reported in the mangroves of Central Africa is among the largest for any tropical forest (IPCC 2007). We made comparisons of mangrove carbon stocks with some of the reported carbon stocks of the terrestrial Congo basin rainforest (Fig. 6). For consistency, we have only utilized aboveground biomass, as most of the studies in terrestrial forests lacked belowground carbon stocks. Aboveground carbon pools were 209 Mg/ha in Dja Biosphere Reserve (Djuikouo et al. 2010), 188 Mg/ha Campo Ma'an National Park (Kanmegne 2004) and 178.5 Mg/ha in Korup National Park (Chuyong, unpublished data), all in Cameroon. The average aboveground carbon pool for undisturbed rainforest in Central Africa was 154 Mg/ha. This is lower than the 538 MgC/ha found in the mangroves of this study, underscoring the value of mangroves as carbon stocks. When soil carbon is added to the equation, the difference between the carbon storage potential of mangroves and terrestrial rainforests could become even greater.

The extremely high carbon content of mangroves compared to terrestrial forests is often explained by the high levels of organic carbon in the soil, which is typical of many coastal ecosystems including seagrasses and salt marsh. The reason for the high organic carbon content in the soil is the accretion rates of these ecosystems as they keep up with sea-level rise, sometimes over thousands of years, and trap detritus and sediments from tidal movement and alluvial deposits. Most terrestrial ecosystems reach maximum carbon content in their soils over decades or even centuries, but coastal ecosystems can keep on accreting over millennia

Table 6 Biomass accumulation in the Central African mangrove forests

Disturbance regimes	Mean periodic annual increment				
	Diam (cm/year)	Basal area (m^2/year)	Volume (m^3/year)	AGB (tonnes/ha/year)	BGB (tonnes/ha/year)
Heavily exploited	0.34	0.05	0.35	0.38	0.40
Moderately exploited	0.42	1.67	9.66	10.43	3.35
Undisturbed	0.06	0.02	25.34	27.36	5.67
All regimes	0.15	0.56	11.78	12.72	3.14

Figures are annual size-specific growths under different exploitation regimes

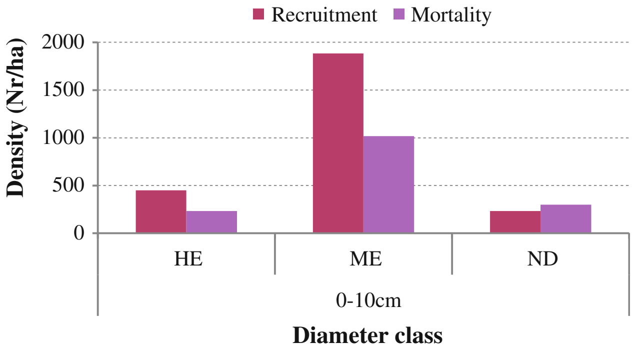

Fig. 7 Recruitment and mortality in mangrove forests

Table 7 Carbon sequestration in mangrove forests under different exploitation regimes

Exploitation regime	Biomass (MgC/ha/year)		
	AGC	BGC	Total
Heavily exploited	0.2	0.2	0.4
Moderately exploited	5.2	1.7	6.9
Undisturbed	13.7	2.8	16.5
Average	6.4	1.6	7.9

and create sediment deposits several metres deep. Emissions of this stored carbon can be avoided by maintaining mangroves in an intact state through REDD + activities, policies and projects.

Carbon Sequestration in Central African Mangrove Forests

Forest Dynamics: Growth and Biomass Accumulation

Net growth was higher in moderately exploited forests (ME) than in heavily exploited (HE) and undisturbed (UND) (Fig. 7, Table 6). This implies that there is a threshold level for exploitation to guarantee stand development. FAO (1994) recommends a minimum of 12 trees/ha parental mangrove trees (standards) be retained during harvesting operations to act as seed bearers for the next generation. Although it is still early to foretell the nature of future forest in Central Africa mangroves, mortality rate observed in the present study is in conformity with the FAO (1994) values of 50 % loss observed during the 1–10 years growing period.

Apart from Cameroon, growth data were not available for other mangrove areas in the region. Mean annual diameter increment (MAI) for primary and secondary stems under different management regime was 0.15 cm/year. This translates to above- and belowground annual biomass increment of 12.7 and 3.1 Mg/ha/year, respectively. The values are consistence with published productivity data in Malaysia (Ong et al. 1993) and Kenya (Kairo et al. 2008). As expected, heavily degraded forests had the lowest biomass increment, whereas the moderately exploited and undisturbed forests had higher biomass increment (Table 6).

Carbon Sequestration

Carbon sequestration rates were found to vary with forest conditions (Table 7). Aboveground components had higher sequestration rates (6.4 MgC/ha/year) compared to belowground carbon pools (1.6 MgC/ha/year). Undisturbed forests sequestered on average 16.5 MgC/ha/year against 0.4 and 6.0 MgC/ha/year by heavily and moderately degraded systems, respectively. Mean sequestration rate for all forest conditions was 7.9 MgC/ha/year.

Conclusion

Mangrove forests in Central Africa are very carbon rich with carbon stocks in natural undisturbed forests in trees more than 2–3 times that of adjacent tropical rainforest. About 65 % of carbon stocks in natural undisturbed mangroves are stored in the soil layers with higher proportions in some disturbed forests. The large reservoirs of carbon stored by the exceptional and gigantic mangrove systems of Central Africa are thus important for climate change mitigation. We estimate that undisturbed mangroves contain

1,520 ± 164 Mg/ha with 982 Mg/ha (or 65 %) in the belowground component (soils and roots) and 538 Mg/ha (35.0 %) in the aboveground biomass. In moderately exploited mangrove ecosystems, 91.7 % of total ecosystem carbon was found in the soil component. These figures are higher than other studies around the world (Indo-Pacific and Mexico), but given the gigantic nature of these trees (up to 50 m high and 1 m diameter), and the large alluvial deposits in the soils from the River Congo, this is certainly possible. Using conservative estimates, we estimate that 1,300 Mg of carbon dioxide would be released per ha of cleared pristine mangrove in Central Africa. These estimates were made using the carbon values collected in the field in Central Africa. A recent report estimates that 771 km^2 of mangrove were cleared in Central Africa between 2000 and 2010 (UNEP-WCMC 2012), equating to estimated emissions of 100,152,000 Mg of carbon dioxide, although of course this carbon dioxide would be emitted over a time span of decades. Therefore, the mangroves of Central Africa could be among the most carbon-rich ecosystems in the world, and of value for climate change mitigation internationally.

Continuous monitoring through mangrove permanent plot systems would improve the quality of the data. Regular re-measurement of permanent mangrove forest plots would allow the gauging of not only dynamics of carbon but also general mangrove ecosystem dynamics (growth, mortality, recruitment) for carbon and other Payment for Ecosystem Services initiatives, as well as for providing baselines for REDD+ strategies in the region. More allometric studies for African mangroves would further improve the quality of the data and would allow the development of location and species-specific equations. Data collection can also be improved by the strengthening of existing networks and partnerships such as the African Mangrove Network.

REDD+ strategies can incentivize and support conservation, sustainable management of forests and enhancement of forest carbon stocks. Strengthening the existing networks (African Mangrove Network, the East African Mangrove Network, etc.) can generate a large-scale impact of mangrove forest protection and restoration initiatives through reforestation and sustainable management techniques as well as building capacities in various domains of mangrove conservation and sustainable management. Sustainable forest management practices to reduce mangrove deforestation can address some of the main causes of deforestation in the region, notably wood for fish smoking and also growing urbanization. To reduce use of wood for fish smoking, improved technology for fish-smoking stoves could be introduced that would generate more heat and energy from less wood, thus decreasing consumption. Deforestation from urbanization could be reduced by ensuring that mangrove protection is integrated into coastal and marine protected area networks that are properly enforced and policed. The network of mangrove and marine protected areas could include seaward extensions of existing coastal parks in order to conserve biodiversity and in order for mangroves to fully provide their role as hatcheries and nursery grounds for aquatic fauna, as well as shoreline protection against erosion and storms. The results showing the high value of mangroves in this chapter are not only relevant to planning of networks of marine protected areas, but also to all integrated coastal and marine spatial planning. Information of the high value of ecosystem services provided by mangroves can be integrated into spatial planning exercises; for example so that conservation targets for ecosystem services for local communities can be determined and planned for. This could improve the well-being of communities in the area that benefit from the ecosystem services provided by mangroves.

Overall, this chapter provides a case for the inclusion of mangroves in national REDD+ strategies given their high carbon value, and also the levels of threat to the ecosystem and the associated rates of loss in the region. We hope that it can serve as a baseline study for future carbon market or climate change mitigation strategies, as well as providing evidence for the high value of mangrove ecosystems. Furthermore, it points to the mangroves of Central Africa being an exceptional ecosystem on a global scale, with higher carbon stocks measured here than in other mangroves or even adjacent rainforests.

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