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Carbon emissions from degraded mangroves of Tudor and Mwache creeks, Mombasa, Kenya

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ABSTRACT

Climate change is associated with changes in the concentration of greenhouse gases (GHGs) in the atmosphere. This is accelerated by the degradation and loss of forests through anthropogenic activities, leading to carbon (C) emissions thus raising atmospheric C levels and temperature. Mangroves sequester 14% of C in the oceans despite occupying less than 0.5% of the coastal ocean.With global deforestation contributing more than 20% of all carbon dioxide (CO_2) emissions, continued mangrove degradation is likely to significantly elevate the concentration of GHG in the atmosphere and aggravate global warming with its attendant consequences. In the present study, we report the storage of C and emissions from degraded mangroves in two heavily impacted peri–urban creeks namely Tudor creek and Mwache creek of Kenya. In Tudor creek the mangroves neighbors an ever–increasing informal settlement, subjecting mangroves to anthropogenic pressure mainly overexploitation for fuel–wood, building materials and as a waste disposal site. Mwache creek mangroves experienced a massive dieback following flooding and vast sedimentation from the Indian Ocean Dipole in 1997/98 and 2006. In the Island, species, which could not withstand long periods of submergence, were also greatly affected with some dying during the flooding period. Transects perpendicular to the shore, were identified prior to field work using Google earth images based on vegetation density and stand structure laid in preselected highly degraded and less degraded sections of the mangroves. Stratified random sampling based on vegetation density for three C pools (above ground, below ground and soils) was used to collect data. The total ecosystem carbon stock was estimated at 101.64±57.3C $t.ha^{-1}$ and 246.14±47.2 $t.ha^{-1}$ in Tudor and Mwache creeks respectively. There were significant differences in ecosystem C ($p=0.0013$) between highly degraded and less degraded sites within the creeks. There was 71.38 $t.ha^{-1}yr^{-1}$ and 91.32 $t.ha^{-1}yr^{-1}$ of carbon lost translating to 261.96 $t.ha^{-1}yr^{-1}$ and 335.13 $t.ha^{-1}yr^{-1}$ CO_2 equivalents emissions for Mwache and Tudor respectively. The rate of C loss calls for pertinent management strategies like formulating a management plan, awareness creation, energizing community efforts in reforestation among others to curb degradation hence reduced emissions.

KEYWORDS: Carbon sequestration, CO_2 emission, Mangrove degradation, Anthropogenic pressure, Mangrove creeks in Kenya

1. INTRODUCTION

Mangrove ecosystems occur at the sea–land interface because of complex interactions of various climatic and edaphic factors. Although covering only 0.7% of the total tropical forests of the world [1] mangroves forests are keystone coastal ecosystems providing numerous services and ecological functions, which will be lost if degradation continues. Ecologically mangroves provide nursery grounds for numerous fisheries, birds, vertebrates, and invertebrates [2]. Mangroves are actors in oxygen production, C sequestration, water quality regulation, biodiversity supporters and maintaining the rearing and breeding grounds thus playing an important role for healthy coastal ecosystems [2].

Despite the importance, mangroves are threatened by overexploitation, conversion to other land uses – aquaculture, saltpans, agriculture and human settlement, diversion of freshwater flow and mining, pollution and damming of rivers. Currently the annual global decline rate of mangroves stands at 1–2 % reducing mangroves to less than 50% of the original cover [3].

Mangroves sequester 14% of C in the oceans despite occupying less than 0.5% of the coastal ocean [4]. This is mainly captured in the above ground, below ground vegetation components and the biggest part (up to 90%) in the sediments with mangroves leading (950 MgC ha^{-1}), Boreal (200 MgC ha^{-1}), temperate (160 MgC ha^{-1}) and Tropical upland (150 MgC ha^{-1}) [5]. Mangroves have a far greater capacity than terrestrial habitats to achieve long–term C sequestration in sediments, arising in part from the extensive below ground biomass burying approximately 18.4 Tg C yr^{-1} [6]. Mangroves degradation leads to pronounced high emissions. As land use affects soils to deeper layers, the large C–stores generate large GHGs emissions when disturbed.

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Improved estimates of mangrove C storage have recently been obtained at global scales [7], but to date estimates of C emissions are less studied. Since reducing C emissions will be a global concern for centuries, long–term C sequestration capacity must be accounted for in the benefits associated with mangrove restoration and protection. The large C–stores of mangroves end up generating large amount of GHGs [3].

As forests are removed, the organic C built up over decades to millennia is re–mineralized and eroded, and release CO_2 [8]. Naturally, CO_2 in the atmosphere is re–absorbed by plants and trees, but degradation reduces natural C sinks, which maintain a balance in the Earth's atmosphere. About 20% of global C emission is directly contributed by deforestation and since mangroves store about 3–5 times more C, than terrestrial ecosystem, their continued degradation contributes to elevated C emissions [5]. The effect of this extra CO_2 is that the overall temperature is increasing (global warming) on a day–to–day basis but the climate is changing in unpredictable ways (from floods and hurricanes to heat waves and droughts). The 35% loss of mangroves over the past two decades resulted in release of large quantities of C aggravating global warming phenomenon. Carbon emissions rates following mangrove degradation will elucidate the impact of the mangroves loss in aggravating global warming and associated climate change effects.

In Kenya, mangroves cover only 3% of the forest area or 1% of the total area of the country [9]. The major threats to mangroves are overexploitation, land conversion to –aquaculture, saltpans, agriculture, and settlement, diversion of freshwater flow and mining, pollution and damming of rivers [3]. The subjection of the mangroves to the increasing human population, economic pressure, and degradation, has been reflected directly in increased coastal erosion, shortage of building material and firewood and reduction in fisheries [10]. The strength, attractiveness, and durability of some species like *Rhizophora, Heritiera, Bruguiera* and *Ceriops*, for poles, boats, housing, charcoal and non–wood products like tannins, have led to their massive extraction. This leads to the loss of goods and services and accelerated effects and impacts of climate change due to C emissions. The situation is worse in peri–urban mangroves (Tudor and Mwache creeks) which are under pressure due to over–harvesting [2].

Recent detailed studies in Kenya have indicated that some mangrove forests have suffered the highest ever–recorded losses of mangroves globally [11]. Mombasa mangroves have suffered between 46 and 87% (2.7 – 5.1% loss annually) cover loss between 1992 and 2009 [9, 11]. The amount of C stored in different ecosystems is well–studied [12]. Information on deforestation, land-use change, and their contribution to global anthropogenic CO_2 emissions is available. Past studies [12, 13] quantified total ecosystem C stocks but without specifically assessing the impact of deforestation on carbon emissions. Studies monitoring C losses over longer periods, or the emission of other GHGs, are lacking [8]. Little has been done to quantify C emissions due to mangrove degradation. Carbon emissions from these ecosystems are uncertain due to lack of broad–scale data on C emissions.

Carbon emissions occur through many pathways (respiratory processes by aerobic organisms, tidal exchange, fermentation etc.), but they are less significant and controlled by natural sinks. Emissions due to loss in vegetation cover are the most significant. This study assessed C dynamics between highly degraded and relatively less degraded sites. Assessment provided information on C emissions due to degradation, which is paramount in the analysis of the link between mangroves degradation, C emissions, and climate change. It gives a detailed analysis of C emissions and shows a linkage between anthropogenic activities, C emissions, and climate change.

2. MATERIALS AND METHODS

Study area: The study was carried out in the mangroves of Tudor and Mwache creeks due to the presence of widespread mangroves and high anthropogenic and natural drivers (Fig. 1). These are peri–urban creeks where mangroves have faced threats due to high population pressures, poor upstream land use practices and indirect impacts of climate change like massive flooding and sedimentation. The mangroves have recorded annual declining rates of between 2.7 – 5.1% [14]. Tudor creek (4°2' S, 39°40' E) is located Northwest of Mombasa and extends 10 – 15 km in land. It has a surface of approximately 20 km^2 at mean sea level and comprises of shallow channels, mud banks and mangrove forests. It has two main seasonal rivers, Kombeni and Tsalu draining over 45,000 and 10,000 ha respectively [14]. Mangroves extend over an area of 1,641 ha, mainly composed of *Rhizophora mucronata Lamk, Avicenia marina* (Forssk.) Vierh., and *Sonneratia alba* J. Smith., with no distinct zonation along the tidal gradient [15]. The Tudor Creek Island is mainly composed of *S. alba* and some *R.mucronata* species. There are pronounced human activities as evidenced with continued deforestation and presence of new cut stumps. The Island is easily accessible from Mikindani especially during high tides for transportation of wood products. Influences from land–based activities are minimal. Sediments (mud and sand) in some parts cover the mangroves.

Mwache Creek (4°3.01'S, 39.06°38.06'E), is located 20 km

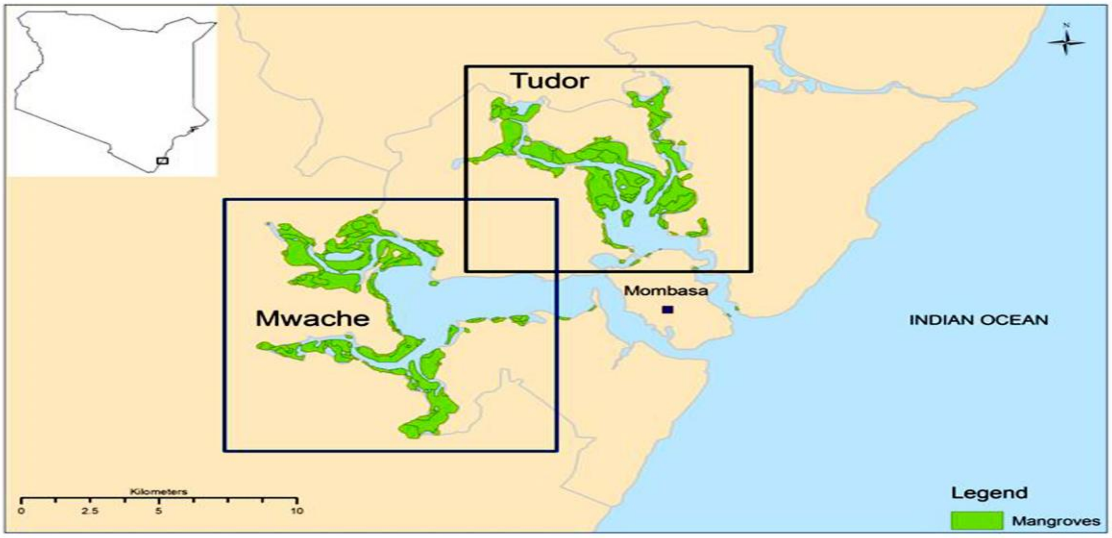


Figure 1: Mangroves areas of Tudor and Mwache creeks [Source 13]

Northwest of Mombasa. The total wetland area is approximately 1,500 ha whereby about 70% is covered with basin and riverine mangroves with a distinct mangrove–fringed channel in the lower sections [16]. The dominant species are *A. marina*, *R. mucronata*, *Ceriops tagal* (Perr.) C. B. Rob., and *S. alba* [17]. The creek receives freshwater from seasonal Mwache River. The rate of sediment production within Mwache River basin reaches a high of 3,000 $t.yr^{-1}$ due to poor upstream land–use activities, high rainfall intensity during the rainy season and steep land gradient [17]. The Mwache Creek Island is mainly composed of *S. alba* and some *R.mucronata* species. There are reduced human activities and influences from land based activities due to inaccessibility and continued wave action. The creeks support many bird and fish species.

The climate in the creeks and Mombasa in general is under the influence of monsoon winds creating two rainy seasons. Heavy rains occur during the Southeast monsoon (March – May) and short rains during the Northeast monsoon (October – November). Mean annual rainfall is 900 mm with a great inter annual variability. Dry spell occur between January – February and August – September. The Ocean waters are characterized with semi–diurnal tides having a tidal variation of about 4.0 m and 1.8 m within spring and neap respectively [14]. Temperatures ranges from 24 – 33^{o}C with an annual evaporation being around 1900 mm. Relative humidity is high all year round with its peak during the wet period.

Social economic activities of the inhabitants along the creeks include; subsistence farming, fishing, wood harvesting, charcoal burning which supports a population of about 50,000 persons [18]. There is poor infrastructural development, with low class housing and less social amenities. Mangroves in these creeks are overstressed due to overexploitation as substantiated by poor stand structures [13]. The swelling population along the creeks poses and amplifies the pressure on the mangroves due to the demand for economic well being and a site for waste disposal. An assessment of carbon stocks and emissions estimations due to these losses was necessary.

Sampling Procedure: In both creeks, transects were laid in preselected sites based on vegetation density and stand structures on highly degraded and relatively less degraded sections of the forest. These transects, which were perpendicular to the shore were identified prior to field work using Google earth images (Fig. 2) based on the density of the vegetation and stand structure. Data was collected using stratified random sampling based on stand density for three C pools (above ground, below ground and soils). In the mangroves, from the shoreline towards the mainland, 10 x 10 m plots, approximately 100 m apart were laid along intertidal transects. Within the plot, trees with diameter ≥ 2.5 cm were identified; their heights (m) measured using *suunto* Hypsometer, diameter at breast height (cm) measured using forest calipers and recorded. Stumps were counted in each plot. Soil samples were obtained from the centre of the plot at low tide using an open–faced soil corer, sample sub–divided along the profile into 0 –15, 15 –30, 30 –50 and 50 –100cm. Sampling was done up to 1 m as carbon content below one meter is negligible [19]. Sub–samples of 5 cm were taken from the mid–section of each sub–sample. To avoid sample contamination, the sampling tools were cleaned after each sample collection. The samples were sealed,

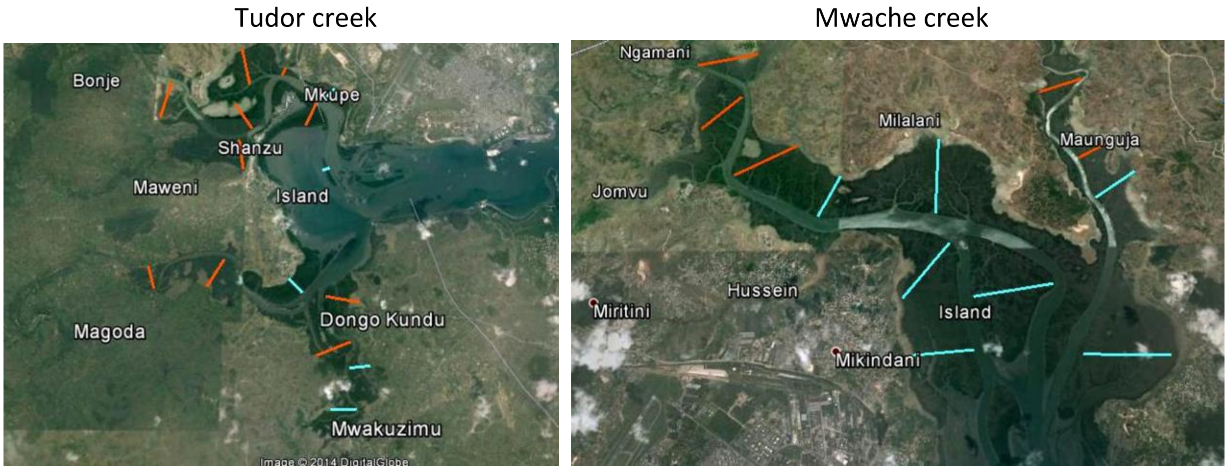


Figure 2: Google earth showing Tudor and Mwache creek sampling sites

labeled and stored in a cool box at approximately 4°C and taken to the soil biological laboratory for analysis. The GPS coordinates of the plots were recorded. Organic carbon concentration was analyzed in the biological laboratory (section 2.4) to quantify soil C stock.

Biomass and carbon estimation: The diameter from all the trees was used in the estimation of biomass and C by the application of species specific and general allometric equations for mangroves. The above ground biomass (AGB) and below ground biomass (BGB) were estimated from data collected on the vegetation structure and the specific wood densities (ρ), using the allometric equations. The specific tree densities for the various mangrove species generated from allometric work in Zambezi and Mozambique mangrove forest which are within the Western Indian Ocean (WIO) region [20] were borrowed. Total ecosystem biomass was obtained by summing up the biomass values per plot and averaging the values in all plots to get the average biomass in a site for both AGB and BGB (Table 1). Using the biomass and general allometric equations the ecosystem carbon was estimated as illustrated in table 1.

Table 1: Equations for the estimation of biomass and carbon

Parameter	quation	Reference
AGB	.251* ρ*DBH$^{2.46}$	Komiyama et al., 2005; 2008
BGB	.199*ρ$^{0.899}$ *DBH$^{2.22}$	Komiyama et al., 2005; 2008
AGC	GB*0.464	Kauffman et al., 2011
BGC	GB* 0.39	Kauffman et al., 2011
Total Biomass	GB +BGB	Kirui, 2006
Total Carbon	GC +BGC	Kirui, 2006

ρ – Specific wood density

Soil organic carbon analysis: The semi–quantitative method of loss–on–ignition (LOI) was used to determine soil organic matter (SOM). The oven–dried samples used in the determination of bulk density were homogenized by grinding and sieved using a 2mm sieve to remove debris. From each sample a pair of 5–gram sub–samples, were taken and put into pre–weighed crucibles and then set into a muffle furnace for combustion at 450°C for 8 hours and then cooled before their weight was recorded again. Loss of soil organic matter (SOM) was noted as the difference in the mass of the soil before and after heating.

$$\text{SOM} = [\{\text{initial weight (g)} - \text{final weight (g)}\} / \text{initial weight (g)}] * 100 \text{ .... Eq. i}$$

Total organic carbon (TOC) was estimated and scaled up to obtain the carbon pools for the entire study site from a regression equation developed and used in previous study in the same sites [12].

$$\text{TOC (MgC ha}^{-1}) = \text{BD (g cm}^{-3}) * \text{Soil Depth Interval (cm)} * \%\,\text{C .... Eq. ii}$$

Carbon emissions: Due to degradation, an assessment was done to estimate C emissions. In both creeks the ecological parameters and geomorphic situation was considered uniform but stand structure differed due to degradation. The selected sites were adjacent to each other for uniformity and comparisons. After estimating individual pools for each specific area, the C stock decreases in the three pools were calculated. Carbon emissions were worked using the carbon Gain–Loss and tier 2 method [5]. The estimates were worked out by getting the difference in C stocks between the highly degraded and the relatively less degraded at two different times. To estimate the rate of C stocks changes using the Gain–Loss and tier 2 method, equation 2.5 was used [5].

$$\Delta C = (C_{t2} - C_{t1}) / (t_2 - t_1) \text{ ....Eq. iii}$$

Where:

ΔC = Annual C stock change in the pool, tonnes C.yr^{-1}

C_{t1}= Carbon stock in the pool at time t_1, tonnes C

C_{t2}= Carbon stock in the pool at time t_2, tonnes C

Any net decrease in C stock was converted to equivalent CO_2 emissions by multiplying the net C stock change by 3.67 (stochiometric ratio of CO_2 and C) [5].

$$CO_2 \text{ Emissions } (t.ha^{-1}yr^{-1}) = 3.67 * \text{Carbon stocks change} \ldots\ldots \text{Eq. iv}$$

Data was analyzed using EXCEL and STATISTICA Version 8.0, significant differences by Tukey's test and means compulsion using Duncan's Multiple Range Test (DMRT) to determine the relationship between mangroves degradation and C emissions. The difference in C stocks between the study sites (highly degraded and relatively less degraded) was used to determine carbon emissions.

3. RESULTS

3.1 Biomass distribution

The mean live biomass in Tudor creek mangroves was estimated at 111.88±85 $t.ha^{-1}$, from 80.91±63 $t.ha^{-1}$ AGB and 30.97±22 $t.ha^{-1}$ BGB. The largest overall contributor was South Mikindani with 276.08±257 $t.ha^{-1}$ while the least was Maunguja with 12.15±7.22 $t.ha^{-1}$ (Table 2). The highly degraded sites recorded the least mean biomass (26.6±6.1 $t.ha^{-1}$) while the less degraded sites recorded the highest mean biomass (197.2±41 $t.ha^{-1}$). Tudor creek biomass showed a significant difference (Tukey test) in AGB amongst the sites (p=0.0048), and a significant difference (p=0.0040) between the highly degraded and the relatively less degraded sites. There was a significant difference (p=0.0030) in total biomass amongst the sites, and a significant difference in total biomass (p=0.0012) between the highly degraded and less degraded sites. Mwache creek mangroves recorded a mean biomass of 148.71±117.21 $t.ha^{-1}$ from 104.94±83.32 $t.ha^{-1}$ AGB and 43.77±33.89 $t.ha^{-1}$ BGB. The Island contributed the largest overall biomass (307.99±64.44 $t.ha^{-1}$) comprising 214.16±44.75 $t.ha^{-1}$ AGB while Dongokundu contributed the least overall biomass (12.94±2.00 $t.ha^{-1}$) comprising 8.19±1.30 $t.ha^{-1}$ AGB. The biomass contribution from the Island was the highest in both creeks. This was 16% higher than the overall mean for Mwache creek. The highly degraded sites recorded the least mean biomass (31.50±15.75 $t.ha^{-1}$) while the less degraded sites recorded the highest mean biomass (265.92±31.26 $t.ha^{-1}$) (Table 2). Mwache creek also showed a variation in AGB between the highly degraded and less degraded sites with a significant difference (p=0.001). There was a significant difference (p=0.0049) between the highly degraded and the relatively less degraded sites for AGB, BGB and total biomass as well. Across the various sites, there was a decline in biomass distribution from the shoreline through the mid section and lastly towards the main land.

3.2. Carbon pools

Vegetation pools: Tudor creek mangroves had a mean C of 49.29±37.7 $t.ha^{-1}$ from AGC of 37.2±29.1 $t.ha^{-1}$ and BGC of 12.1±8.61 $t.ha^{-1}$. The largest contributor (South Mikindani) had a mean of 122±114C $t.ha^{-1}$ while the least contributor was Maunguja with 5.29±3.23C $t.ha^{-1}$. The highly degraded sites recorded the least mean C (11.62±2.65 $t.ha^{-1}$) while the less degraded sites recorded the highest (86.98±18.34 $t.ha^{-1}$) (Table 3). Variations were recorded in both AGC and BGC with a small significant difference (p=0.0047) between the highly degraded and the relatively less degraded sites. There was a slight significant difference (p=0.048) in the AGC between the highly degraded and the relatively less degraded sites. There was a significant difference in total C (p=0.045) between the highly degraded and the relatively less degraded sites. The mean C in the mangroves of Mwache creek was estimated at 65.76±51.9 $t.ha^{-1}$ from AGC of 48.69±38.6 $t.ha^{-1}$ and BGC of 17.07±13.2 $t.ha^{-1}$. The contribution was largest from Island (135.97±28.44C $t.ha^{-1}$) and least from Dongokundu (5.65±0.88C $t.ha^{-1}$). Carbon contribution from the Island was the highest when compared with the rest of the sites in both creeks. The Island contributed more than two fold the overall mean C for all the sites.

Table 2: Biomass distribution in Tudor and Mwache creek mangroves

	Highly Degraded sites				**Relatively Less Degraded sites**			
Tudor creek								
Sites / C	Ngamani	Jomvu	Maunguja	**Mean**	Husein	S.Mikindani	Mikindani	**Mean**
AGB (t/ha)	10.7±5.3	18.8±11	23.7±4.3	**17.7±3.8**	129.8±99	204.7±99	97.8±74	**144.1±31**
BGB (t/ha)	4.96±2.1	8.65±4.5	13.1±2.3	**8.89±2.3**	49.2±33	71.4±64	38.5±26	**53.0±9.7**
T. B (t/ha)	15.6±7.4	27.5±16	36.7±6.6	**26.6±6.1**	179±99	276±99	136.4±99	**197.2±41**
Mwache creek								
Sites /C	Bonje	Dongokundu	Magoda	**Mean**	Maweni	Mkupe	Island	**Mean**
AGB (t/ha)	12.3±0.28	8.19±0.07	44.3±1.07	**21.6±0.83**	147±1.35	203.6±3.8	214±0.75	**188.3±20**
BGB (t/ha)	6.41±0.15	4.75±0.03	18.5±0.39	**9.88±0.32**	57.8±0.47	81.4±1.35	93.8±0.29	**77.7±10**
T. B (t/ha)	18.7±11.9	12.9±2.00	62.8±22.9	**31.5±15.8**	204.8±36	285±102	307.9±64	**265.9±31**

Table 3: Carbon (Mean SE) distribution in the creeks

	Highly Degraded sites				**Relatively Less Degraded sites**			
Tudor creek								
Sites/C	Ngamani	Jomvu	Maunguja	**Mean**	Husein	S.Mikindani	Mikindani	**Mean**
AGC (t/ha)	4.91±2.45	8.66±5.44	10.9±1.99	**8.15±1.74**	59.7±47.1	94.2±88.7	44.9±34.2	**66.3±14.6**
BGC (t/ha)	1.94±0.82	3.37±1.76	5.09±0.89	**3.47±0.91**	19.2±13.2	27.8±25.2	15.1±10.2	**20.7±3.77**
T. C (t/ha)	6.84±3.27	12.03±1.2	15.9±4.82	**11.6±2.65**	78.9±3.33	122±114	60.0±44.4	**87.0±18.3**
Mwache creek								
Sites /C	Bonje	Dongokundu	Magoda	**Mean**	Maweni	Mkupe	Island	**Mean**
AGC (t/ha)	5.72±3.66	3.80±0.60	20.6±7.72	**10.0±5.30**	68.2±12.6	94.5±35.4	99.4±20.8	**87.4±9.67**
BGC (t/ha)	2.49±1.57	1.85±0.28	7.21±2.45	**3.85±1.68**	22.5±3.73	31.7±10.3	36.6±7.69	**30.3±4.12**
T. C (t/ha)	8.22±5.23	5.65±0.88	27.8±10.2	**13.9±6.99**	90.8±16.3	126.2±45	135.9±28	**117.6±14**

There was a great significant difference (p=0.001) between the Island and the overall mean. The highly degraded sites recorded the least mean C (13.89±6.99C t.ha^{-1}) while the relatively less degraded sites recorded the highest mean C (117.64±13.7C t.ha^{-1}) (Table 3). In Mwache creek, there was a slight significant difference in AGC amongst the sites (p=0.0049), and a significant difference (p=0.0047) between the highly degraded and the relatively less degraded sites. There was a significant difference (p=0.042) in the BGC between the highly degraded and the relatively less degraded sites and the same was witnessed in total C (p=0.043) between the highly degraded and the relatively less degraded sites. From the shoreline to the main land, there was a decline in carbon.

Soil organic carbon: The soil organic carbon (SOC) in the mangroves of Tudor creek was estimated at 52.34±2.05 t.ha^{-1}. The least was from Ngamani (27.39±0.9C t.ha^{-1}) while the highest was from Jomvu (67.87±1.6C t.ha^{-1}). There was a significant difference (p=0.048) in the mean SOC amongst the sites. There was no significant difference in SOC (p=0.052) between the highly degraded and the relatively less degraded sites. There was a steady increase in SOC along the depth profile in both the highly degraded and the relatively less degraded sites whereby 0 –15cm depth interval had an average of 21.64±4.1C t.ha^{-1}, whereas the 50 –100cm depth interval had an average of 102.05±2.4C t.ha^{-1} and they displayed a significant difference (p=0.046). There was a steady increase in SOC from the shoreline to the main land.

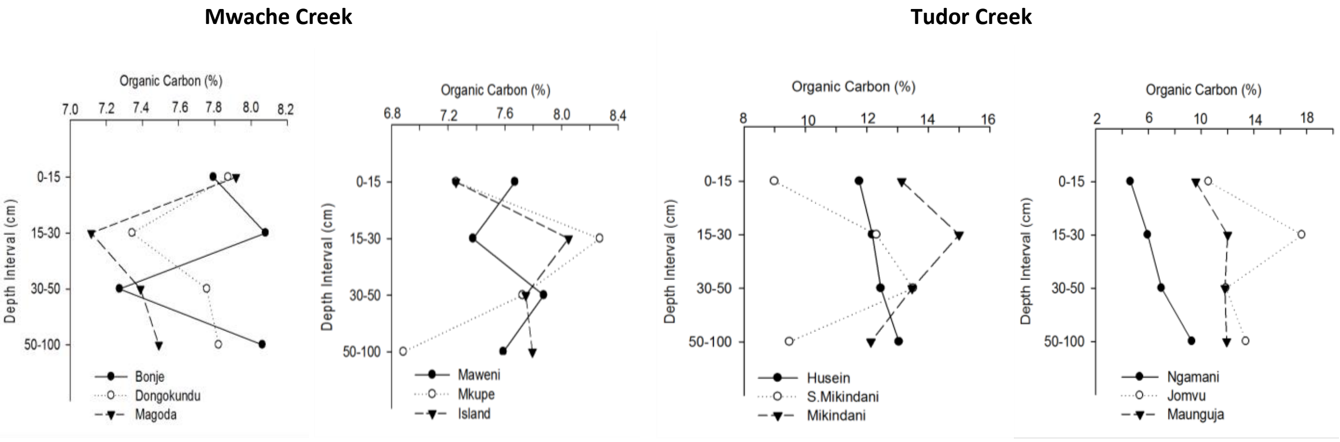
The SOC in the mangroves of Mwache was estimated at 180.38±4.67 t.ha^{-1}. The least was from Maweni (135.02±3.88C t.ha^{-1}) while the highest was from Bonje (242.59±87.03C t.ha^{-1}). The SOC from the Island (209.56±41.7C t.ha^{-1}) was relatively higher but less than Bonje. The highly degraded sites had higher SOC (185.04±28.8 t.ha^{-1}) while the less degraded site the least organic C (175.72±15.6 t.ha^{-1}). There was no significant difference (p=0.051) in the mean SOC amongst the sites. There was a steady increase in SOC along the depth profile in both the highly degraded and the relatively less degraded sites with a significant difference (p=0.042).

3.3. Organic carbon concentration

Soil organic C concentration showed a wide variation in both Tudor and Mwache creeks. In Tudor the C concentration ranged from 6.73±0.45% (Ngamani) to 16.28±1.2% (Maunguja), while that of Mwache was between 7.12±0.46% (Mkupe) and 8.02±0.32% (Maweni). Tudor creek had a mean of 11.39±0.9% C, while Mwache had 7.64±0.02% C (Fig. 3). In both creeks, there was no distinct pattern in C concentration along depth profile. Tukey's test showed no significant difference in the concentration of SOC amongst the sites in both creeks (p=0.052). Tudor creek mangroves showed a significant difference (p=0.046) in C concentration between highly degraded and less degraded sites. Contrastingly, there was no significant difference (p=0.050) in C concentration between highly degraded and relatively less degraded sites in Mwache creek mangroves. In both creeks, along intertidal transects there was variations in the SOC concentration with a slight increase in the middle section and a decrease towards the mainland, but there was no significant difference (p=0.055) in SOC concentration.

3.4. Total organic carbon

Ecosystem C stock was estimated from the summation of the C storage in the three main pools that is, AGC, BGC, and sedimentary C. The total ecosystem carbon stock in Tudor creek was estimated at 101.64±57.3C t.ha^{-1}.



Highly Degraded Sites Relatively Less Degraded Sites Highly Degraded Sites Relatively Less Degraded Sites

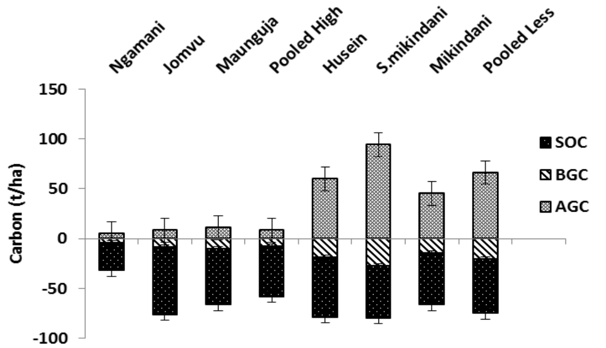
Figure 3: Organic carbon concentration distribution in Mwache and Tudor creeks

This comprised of 37.22±6.3 t.ha^{-1} AGC, 12.08±0.2 t.ha^{-1} BGC and 52.34±2.05C t.ha^{-1} SOC (Fig.4a). The values show that the soil C contributed about 51% of the entire ecosystem C stock while AGC and BGC accounted for 37% and 12% respectively. The highest ecosystem C stock (173.96±7.5C t.ha^{-1}) was estimated at South Mikindani and the least (34.24±4.1C t.ha^{-1}) was estimated at Ngamani. The total ecosystem carbon stock in Mwache creek was estimated at 246.14±47.2 t.ha^{-1}, comprising of 48.69±38.66 t.ha^{-1} AGC; 17.07±13.22 t.ha^{-1} BGC and 180.38±46.72C t.ha^{-1} from the sediments (Fig.4b). These values shows that the soil carbon contributed about 73% of the entire ecosystem C stocks while the AGC and BGC accounted for 20% and 7% respectively. The highest ecosystem C stock (342.59±21.9C t.ha^{-1}) was estimated at Island and the least (159.78±12.5C t.ha^{-1}) was at Dongokundu. The ecosystem carbon stock in the Island was more than two fold the least contributor.

3.5. Carbon emissions

There were variations in different parameters between the highly degraded and the relatively less degraded sites in both creeks. Taking differences in carbon stocks between the highly degraded and the relatively less degraded sites then, 7.67 t.ha^{-1} AGC, 0.53 t.ha^{-1} BGC, 99.52 t.ha^{-1} sediments C and total of 91.32C t.ha^{-1} (Table 5) were lost. This translates to a percentage loss in C of 35% AGC, 4.8%, BGC, 40% sediments and a total C loss of 32%. In Mwache creek, taking differences in C stocks in Mwache between the highly degraded and the relatively less degraded sites, 29.41 t.ha^{-1} AGC, 9.06 t.ha^{-1} BGC, 32.86 t.ha^{-1} sediment C and a total of 71.38C t.ha^{-1} (Table 5) are lost. There was a great percentage loss in C with the AGC losing up to 27%, BGC losing 26% and a total C loss of 18% annually. Carbon stocks for Tudor and Mwache creeks were estimated at 284.27±16.85 t.ha^{-1} and 388.9±63.2 t.ha^{-1} as at 2012[12, 13].

Tudor creeks



Mwache creeks

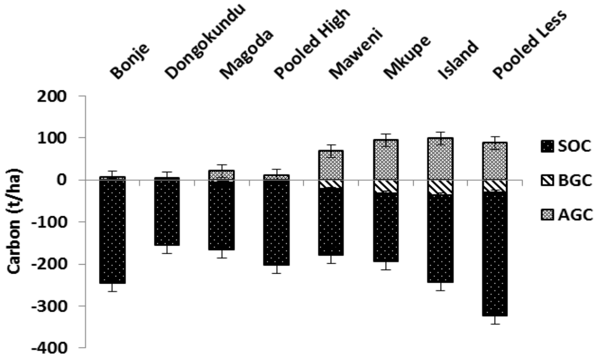


Figure 4: Ecosystem carbon pools in different sites in Tudor and Mwache creeks

This study estimated C stocks in Tudor at 101.64±57.3 t. ha^{-1} and 246.14±47.2 t.ha^{-1} for Mwache. The C stock change within the two years period in Tudor creek was 183.63 t.ha^{-1} leading to a C emission rate of 91.32 t.ha^{-1}yr^{-1}, translating to 335.13 t.ha^{-1}yr^{-1} CO_2 equivalents for Tudor (Table 4).

Table 4: Carbon stock change and emissions

Carbon Pools	Carbon Stock 2012	Carbon Stock 2014	C. Stock Change	Emission t/ha/yr	% Annual C. Loss	**CO_2 Equivalents**
Tudor creek						
AGC	21.88±3.38	37.22±6.3	15.34	7.67	35.05	**28.15**
BGC	11.02±4.04	12.08±0.2	1.06	0.53	4.81	**1.95**
SOC	251.37±9.07	52.34±2.05	199.03	99.52	39.59	**365.22**
TOC	284.27±27	101.64±57.3	182.63	91.32	36.78	**335.13**
Mwache creek						
AGC	107.5±14.8	48.69±38.66	58.81	29.41	27.36	**107.92**
BGC	35.2±4.3	17.07±13.22	18.13	9.06	25.74	**33.27**
SOC	246.1±71.5	180.38±4.67	65.72	32.86	13.35	**120.59**
TOC	388.9±63.2	246.14±47.2	142.76	71.38	18.35	**261.96**

Table 5: Carbon emissions between degraded and less degraded

Carbon Pools	Relatively Less Degraded	Highly Degraded	Carbon Stock Change	**CO_2 Equivalents**
Mwache creek				
AGC	87.35±9.66	10.03±5.30	77.32	**283.76**
BGC	30.29±4.12	3.85±1.68	26.44	**97.02**
SOC	185.04±5.15	175.71±9.54	9.33	**34.25**
TOC	293.35±18.93	198.93±16.53	94.42	**346.53**
Tudor creek				
AGC	66.87±7.65	8.22±1.30	58.65	**215.25**
BGC	20.69±2.11	3.47±1.42	17.22	**63.20**
SOC	54.39±2.63	50.29±11.9	4.10	**15.047**
TOC	121.26±13.23	61.98±16.51	59.28	**217.56**

The C stock change within that period of two years in Mwache creek mangroves was 142.76 $t.ha^{-1}$ leading to C emission rate of 71.38 $t.ha^{-1}yr^{-1}$, translating to 261.96 $t.ha^{-1}yr^{-1}$ CO_2 equivalents (Table 4). The values and results above show that Tudor had a poor stand structure within the study sites. The two peri–urban creeks are facing both natural and anthropogenic disturbances but with some variations depending on the severity of the disturbance. Differences in C stock between the highly degraded and relatively less degraded sites, shows that Tudor creek emits less C from the soils than Mwache (Table 5).

4. DISCUSSION

4.1. Biomass distribution

Stand structure is a reliable indicator of forest development and mangrove structure has a direct bearing on carbon stocks. The pronounced human activities in the nearby farming areas have lead to increased high silt deposition evidenced by shallow sandy soils and large mudflats. Highly degraded sites had a higher stump density (Fig. 5) due to over harvesting (Fig. 6), but were not a general case. Sites, which experienced the massive die back due to the Indian Ocean Dipole (phenomena where the Indian Ocean floods and causes sedimentation of the mangrove forest an aftermath of climate change related phenomena which occurred in 1997/98 and 2006), were degraded but had less stump density. Anthropogenic influences (indiscriminate and unregulated harvesting, raw domestic sewage and enhanced siltation) have had cumulative effects on the structure and regeneration of forest. This has lead to low nutrients availability and life supporting factors, which has caused massive stunted growth. Total available biomass depends on the species, height, diameter, and prevailing environmental conditions. The live biomass in the mangroves of Mwache and Tudor varied significantly. The many small trees in Mwache contributed less overall biomass than Tudor. Young tree stand has less accumulated biomass compared to older stands. In both creeks, the highly degraded sites had the least biomass due to overexploitation. Differences in pressure intensity explain the higher biomass in Mwache compared to Tudor. Due to its close proximity to informal settlement, Tudor creek experiences overexploitation. Again, the differences in biomass can be attributed to the differences in environmental conditions as they control variation in forest structure. Species that grow in frequently inundated sites had a higher biomass than those that thrive in landward edges. This explains why the Island had a higher biomass as compared with other sites. At the Island, there is less pressure due to poor accessibility and no influence from land based processes.

Figure 5: Highly degraded site of Mwache creek mangroves (Nyamao, 2014)

Figure 6: Stacks of young Rhizophora ready for collection by boats (Nyamao, 2014)

The reduced biomass towards the landward is because of increasing salinity with distance upslope from the seaward edge of the intertidal flats and poor nutrients, dry ground accompanied with sedimentation. Previous study at Mwache [10] estimated AGB at 229.38±53.28 t.ha^{-1}, which is much higher than the findings of this study (Table 2). This could be attributed to continue harvesting and poor regeneration, but falls within the ranges of 6.8 to 460 t.ha^{-1} which was reported in a review of tropical mangroves.

4.2. Organic carbon concentration

Along intertidal transect there were variations in the SOC concentration with a slight increase in the middle section and a decrease towards the mainland, analogous to previous results in Tudor and Mwache [12, 13]. The high SOC concentration in the central section may be due to good stand structure, reduced wave action, more deposition, reduced wash and salinity. This also explains why the SOC concentration is higher at the Island as compared with other sites. There was no significant difference in SOC concentrations between highly degraded and relatively less degraded sites in Mwache creek may be due to limited differences in stand structure. The current structural state and the relatively low values of SOC in the forest are an indication of loss of previously buried C from the area [12]. Mwache lost less cover than Tudor which lost 87% of its mangrove cover [13].The significant difference in SOC concentrations between the highly and relatively less degraded sites in Tudor creek is due to intense pressure thus greater mangrove loss. It has widespread illegal distilleries, which have decimated the mangroves.

4.3. Carbon pools

On both creeks, the relatively less degraded sites had a higher C than the highly degraded sites (Fig.4). The high C in the less degraded site is attributed to the good stand structures and the variations amongst the sites. On both creeks there was a steady increase in organic carbon along depth profile and may be attributed to compaction with time. The carbon variations experienced with distance from the shores to the mainland may be due to reduced activities towards the mainland and massive sedimentation. The AGC was more than two fold the BGC, may be due to poor roots development. This shows that degradation reduces biomass and subsequently C. The high C stocks are consistent to analogous studies in the same sites [12, 13]. The results of this study show marked differences in C distribution in various sites within the mangroves, with higher values at the Island and less values at the highly degraded sites. The variations are due to different climatic conditions, management conditions, salinity levels, age, forest type and above all intensity of pressure. At the Island, there are reduced activities and less pressure due to limited accessibility hence high carbon stocks. This shows that Islands are good sites for carbon sequestration. In both creeks, a relatively higher proportion of the ecosystem C pool was deposited in the mangrove sediments. This is in agreement with past studies that mangrove sediments are viable site for organic C storage [21].

Total C was higher in Mwache than Tudor creek may be due to intense pressure experienced by Tudor due to its proximity to the village whereby up to 87% of mangroves were lost [13]. Although highly degraded, Bonje in Mwache creek had the largest overall carbon (242.59±87.03C t.ha^{-1}) a factor attributed to the high C in the sediments due to natural die back. AGC and BGC amongst the sites in Mwache creek was probably because of the poor distribution of vegetation. There is reduced carbon deposits at the Island as compared to Bonje may be due to over wash. The global climate change working synergistically with increased anthropogenic factors threatens the resilience of the mangroves [17] as they are the most prominent ecosystems in the low–lying coastal areas of the tropics.

This leads to more loss of carbon resulting to increased temperatures, changing hydrologic regimes, rising sea level, increased coastal erosion, sedimentation and increasing frequency and intensity of storms and above all increased CO_2 levels [22]. Given the global mangrove cover of 170,000 Km^2 the total amount of C sequestered by mangroves is approximately 25.5 x 10^6 t C yr^{-1} [11]. This suggests that the persistent anthropogenic and natural disturbance reduces significantly the sequestration potential of the mangroves as exemplified by reduced C stocks estimates.

4.4. Carbon emissions

Estimating degradation and land use emissions in mangroves is a useful exercise, but is made difficult by a paucity of data on BGC storage in most regions, which includes combined data on C concentrations, bulk density and depth as well as land use change effects on C pools 19]. The informal settlement in Tudor draws energy in form of fuel wood from the mangroves apart from widespread distilleries. The difference in C between the highly degraded and the relatively less degraded sites shows hastened carbon emissions. Much more will be released if conservation measures are not adopted and implemented effectively. From the shores towards the mainland there was an increase in C up to the central section but declined towards the mainland. This could be because of well–built mangroves along the shoreline, good stand structure at the central section due to poor accessibility and poor mangroves towards the mainland due to poor environmental and edaphic conditions accelerated by overexploitation due to easy accessibility. The total amount of C sequestered by mangroves is approximately 25.5 x 10^6 t C yr^{-1} [11]. A loss of 1% of mangrove C stocks from land use change could approximately double the GHGs emissions from these ecosystems [19], thus the ever–increasing populations adjacent to these creeks means increased pressures translating to increased emissions and consequently accelerated effects of climate change. When mangroves and other tropical wetlands are cleared, a significant portion of soil organic is oxidized, likely affecting even deep layers and leading to relatively large C emissions [19]. A small disturbance releases a lot of C and for instance initial published estimates for C released from Indo–pacific mangroves with land use change ranged from approximately 400 – 1400 Mg CO_2 equivalents per hectare cleared, depending on severity of disturbance. Worldwide, forests are estimated to release 80 Pg (petagrams) of CO_2 into the atmosphere annually [11] part of this (363.67 $t.ha^{-1}$) is from mangroves, thus it is clear that estimating C emissions from their degradation is necessary. Deforestation generates approximately 8 – 20% of the anthropogenic C emissions globally [19], hence need for practical tool for supporting sustainable forest management in order to reduce his impact.

5. CONCLUSION

There is need to estimate C emissions in coastal areas to accorded significant importance in mitigating climate change. This study revealed high and continued degradation as shown in the reduced biomass and accelerated C emissions. This is also hastened by reduced C sinks. The less C concentration in sediments shows less organisms' activities and increased compaction with time due to lack of decomposing materials. All these are accelerated by the ever–increasing population in the adjacent informal settlement accompanied with the effects of the Indian Ocean Dipole. To counter this, timely action to maximise C sequestration potential of mangroves to supplement to their conservation and sustainable utilization for continued supply of ecosystem goods and services together with economic growth and development is of quintessence.

To safeguard the ecology of these creeks, there is necessity to sustainably manage mangroves in a manner that improves their pliability to pressures. Their protection through economic incentives could lead to reduction in degradation but with sound and enough education on their values and creation of awareness to change the mind set. This study provides baseline information on C emissions to solicit support from all the stakeholders. Providing mangrove dependants with alternative and cheap sources of energy will discourage exploitation for fuel wood. Strict penalties for wood extractors will deter mangrove cutting. Restoration projects should be initiated and energized at the community level for creation of a sense of ownership and improve mangroves coverage. Encourage conservation and compensation through carbon credits.

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AUTHOR'S CONTRIBUTION

Wycliff Nyamao formulated field methodology, collected the data, carried out laboratory work, and wrote the text and general editorial work. John Kiplangat assisted in data collection, and data analysis. Lilian Mwihaki assisted in fieldwork data collection, laboratory work. Dr. Jared Bosire and Dr. George Ogendi did supervision.