Global Ecology and Conservation 35 (2022) e02100

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Impact of mangrove planting on forest biomass carbon and other structural attributes in the Rufiji Delta, Tanzania

Elinasi Monga[a,*,1], Mwita M. Mangora[b,2], Carl C. Trettin[c,3]

[a] International Union for Conservation of Nature, Tanzania Country Office, Tanzania
[b] University of Dar es Salaam, Institute of Marine Sciences, Zanzibar, Tanzania
[c] Center for Forested Wetlands Research, Southern Research Station, USDA Forest Service, Cordesville, SC, USA

A R T I C L E I N F O

Keywords:
Mangrove degradation
Carbon stock
Restoration
Climate change mitigation
Rufiji Delta

A B S T R A C T

Mangrove forests provide important ecosystem services to the human society and nature including mitigation of climate change. The quality and quantity of ecosystem services offered by mangrove forests are however at risk when mangroves are degraded. The restoration of mangrove areas is considered as a natural solution to recover lost ecosystem services such as securing of carbon stocks. This study was set to assess the extent to which mangrove planting activities compensate for the loss of biomass carbon stocks and other structural attributes in Rufiji Delta-Tanzania through analysis of biomass carbon loss and gain as a result of conversion of mangroves forest into rice farms and planting of mangroves respectively. Circular sampling plots were established in good, degraded and restored mangrove areas where total tree heights and Diameter at Breast Height (DBH) of all standing trees were measured and recorded by species and used to compute biomass carbon stock. The mangrove species composition changed from 7 in 1989 to 2 species in degraded plots in 2016. The species dominance changed from *Avicennia marina* in 1989 to *Rhizophora mucronata* in 2016 in good mangrove plots and from *A. marina* and *Sonneratia alba* to an invasive *Baringtonia racemosa* in degraded plots. *Bruguiera gymnorrhiza* was the only mangrove species used for restoration through planting in the delta and the overall survival rate was 37%. The above-ground carbon (AGC) and below-ground carbon (BGC) for the good natural mangrove plots ranged from 28.18 to 299.43 and 16.00–164.51 Mg C ha^{-1} respectively compared to 0–150.88 and 0–967.01 Mg C ha^{-1} in the degraded plots. The total biomass carbon stock in the good natural mangrove plots ranged from 44.14 to 463.94 Mg C ha^{-1} while for the degraded plots the range was 0–247.89 Mg C ha^{-1}. The carbon stocks in 5, 10 and 15 year old planted mangroves were 13.65, 20.13 and 57.53 Mg C ha^{-1} respectively. The biomass loss of 172.91 Mg C ha^{-1} was estimated in a period of 25 years (1989–2016), equivalent to an annual loss rate of 6.9 Mg C ha^{-1}year^{-1}, demonstrating that degradation has a significant contribution to loss of carbon stocks. Nevertheless, an average of 3.8 Mg C ha^{-1}year^{-1} was stocked by 15 years old planted mangroves, demonstrating that there is potential for the planted mangroves to compensate for the lost carbon if the anthropogenic drivers such as rice farming is controlled. These findings call for urgent collective actions among stakeholders to consider and improve the integrated management of the delta.

* Corresponding author.
E-mail address: e.monga@yahoo.com (E. Monga).
[1] orcid number 0000-0003-2655-2260.
[2] orcid number 0000-0002-9504-2718.
[3] orcid number 0000-0003-0279-7191.

https://doi.org/10.1016/j.gecco.2022.e02100
Received 26 July 2021; Received in revised form 21 March 2022; Accepted 21 March 2022
Available online 24 March 2022

1. Introduction

Mangrove ecosystems provide a range of goods, services and support high levels of biodiversity (Duarte et al., 2005). A growing body of literature suggests that mangroves are highly potential in sequestering significant amounts of CO_2 (Donato et al., 2011; Ajonina et al., 2014; Jones et al., 2015; Stringer et al., 2015; Trettin et al., 2016, 2021). Despite their small cover of about 0.81% of the global tropical forests (Bunting et al., 2018; FAO and UNEP, 2020; Spalding and Leal, 2021), mangroves represent a globally important carbon sink (Donato et al., 2011; Sanderman et al., 2018). They were reported to store 4.19 billion tons of carbon in 2012, with Indonesia, Brazil, Malaysia and Papua New Guinea accounting for more than 50% of the global stock (Hamilton and Friess, 2018). Regardless of this critical role, continued degradation of mangroves world-wide has been highlighted in the recent years (Thomas et al., 2017; Hamilton and Friess, 2018; FAO and UNEP, 2020; Goldberg et al., 2020; Spalding and Leal, 2021). Thirty five percent of the global mangrove cover has been lost since early 1990s (Thomas et al., 2017). About 60% of the loss recorded between 2000 and 2016 occurred due to human pressures especially through conversion to aquaculture and agriculture (Goldberg et al., 2020; Spalding and Leal, 2021). Global-scale remote sensing data shows that annual rates of mangrove deforestation averaged 0.13% between 2000 and 2016 (Goldberg et al., 2020; Spalding and Leal, 2021). Continued degradation and loss contribute to the emission of carbon and this has large economic impact. Two percent of global mangrove carbon was lost between 2000 and 2012, equivalent to a maximum potential of 317 million tons of CO_2 emissions (Hamilton and Friess, 2018), resulting in estimated economic loss of US $ 9.86–42 billion (Pendleton et al., 2012). This justifies the potential of mangroves to the global greenhouse gas budgets and the importance and urgency for their conservation.

As a measure to safeguard mangrove resources, Tanzania took several initiatives intended to strengthen mangrove management in the country. Between 1989 and 1991, the country developed the Management Plan for the Mangrove Ecosystem of mainland Tanzania (Semesi, 1992). The management plan produced mangrove cover maps covering the whole mainland coastline divided in ten blocks with clusters showing trees species, stand height and stand density. As for state forest reserves, the management plan divided the mangroves into four management areas; the areas restricted for conservation, degraded and deforested areas for restoration, areas for sustainable utilization and areas set aside for other sustainable investments (Semesi, 1992). Despite these management arrangements, there is growing rate of mangrove degradation and deforestation in various mangrove forest reserves in the country, which is largely associated to inadequate enforcement of the laws and policies responsible for mangrove management (Semesi, 1992; Wang et al., 2003; Mangora, 2011; Mayunga and Uhinga, 2018; Monga et al., 2018). While several definitions exist for forest degradation and deforestation (Lund, 2009, 2014, 2015), the ones used by IPCC (2000) are adopted here that deforestation is the conversion of forest land to non-forest land whilst forest degradation is loss of forest quality, such as a reduction of aboveground biomass, in areas that remain as forests. The main drivers of mangrove degradation and deforestation are over-exploitation and conversion to other land uses such as agriculture, aquaculture and salt making (Semesi, 1992; Wang et al., 2003; Mangora, 2011; Mangora et al., 2016; Mayunga and Uhinga, 2018; Monga et al., 2018). The annual loss rate of 0.52% of mangrove cover has recently been estimated in the Rufiji Delta, the largest mangrove forest reserve in the country (Monga et al., 2018). Whilst it is well known that conversion to rice farming contributes most to mangrove degradation in the delta, less is known on the impact of such losses on the mangrove ecosystem function and service of carbon storage.

Like in other parts of the world, restoration of mangroves has received a lot of attention in Tanzania in the recent past, in response to the growing negative impacts of the losses of mangroves. According to accredited definition, forest restoration is intentional activities to re-establish the presumed structure, productivity, function and species diversity of the forest originally present at a site (Gilmour et al., 2000). However, this is not always the case in Tanzania as mangrove restoration activities often focuses on recovery of forest structure of deforested areas. Some commonly reported negative impacts of mangrove losses in Tanzania include coastal erosion and decline of fishery resource (Monga et al., 2018; Lagomasino et al., 2019). In Rufiji Delta for instance, river banks erosion is observed in the deforested areas due to factors highly associated with cutting for rice farming activities (Monga et al., 2018). As an attempt to support regrowth of mangroves in deforested areas, several restoration programs have been implemented in many parts of Tanzania including in Rufiji Delta (UNEP, 2020). The restoration programmes in Rufiji Delta started in 1990 s with financial support from development partners such as Norwegian Agency for Development Cooperation (NORAD), United Nation Development Programme (UNDP), Global Environment Facility (GEF) and United Nation Environment Programme (UNEP). Between 1994 and 2005, NORAD supported planting of 840 ha of mangroves in the Delta through Mangrove Management Project (Peter, 2013). Since then, there have been growing restoration interest from different stakeholders. Following NORAD's support, another project called Marine and Coastal Environment Management Project (MACEMP) (funded by GEF) was initiated which planted 112 ha of mangroves by 2011 (Tanzania Forest Service (TFS) Agency office records at Rufiji Delta). Between 2015 and 2019 the Division of Environment under the Vice President's Office through Kibiti District Council implemented a mangrove planting project that planted 792 ha (Mangora, pers comm). While mangrove restoration efforts have increased in terms of number of hectares planted every year, lack of monitoring and evaluation plans for the restoration programmes has limited knowledge on the extent that planting compensate for the lost carbon stock in the delta due to degradation. This study was designed to assess the impact of mangrove degradation and deforestation to the biomass carbon stock and the extent to which restoration activities through planting compensate for the lost carbon stock and structural attributes by analysis of biomass carbon loss and gain due to degradation and planting activities respectively, with reference to the adjacent good natural stand.

2. Materials and methods

2.1. Study area

The Rufiji Delta is located about 200 km south of Tanzania's largest city of Dar es Salaam. The delta experiences long rain season between February and May and short rain season between October and December (Japhet et al., 2019). The average precipitation during long rain seasons is 100–280 mm month^{-1} and 10–120 mm month^{-1} during short rain seasons (Nicholson, 2001; Doody and Hamerlynck, 2003). The mean annual rainfall is around 1200 mm year^{-1} (Semesi, 1992) and the temperature range is 24–31 °C throughout the year (Richmond et al., 2002). The delta is part of the largest river basin that drains about 20% of the country, with a mean annual flow of 800 m^3 s^{-1} (Duvail and Hamerlynck, 2007). Rufiji river has strong flow period during long rain seasons.

The delta contains the largest continuous mangrove forest in East Africa and rich in biological diversity (Semesi, 1992). Eight mangrove species have been reported to occur and well represented in the delta, namely *Avicennia marina*, *Sonneratia alba*, *Ceriops tagal*, *Lumnitzera racemosa*, *Bruguiera gymnorrhiza*, *Rhizophora mucronata*, *Xylocarpus granatum* and *Heritiera littoralis* (Wagner and Sallema-Mtui, 2016). One of the distinctive characteristics of the delta is the existence of permanent settlements within the forest reserve, where about 49,000 people live in the villages in and around the delta (Mwansasu, 2016), dependent on mangroves and associated resources exploitation such as fisheries and agriculture for livelihoods (Semesi, 1992). Main mangrove ecosystem services of

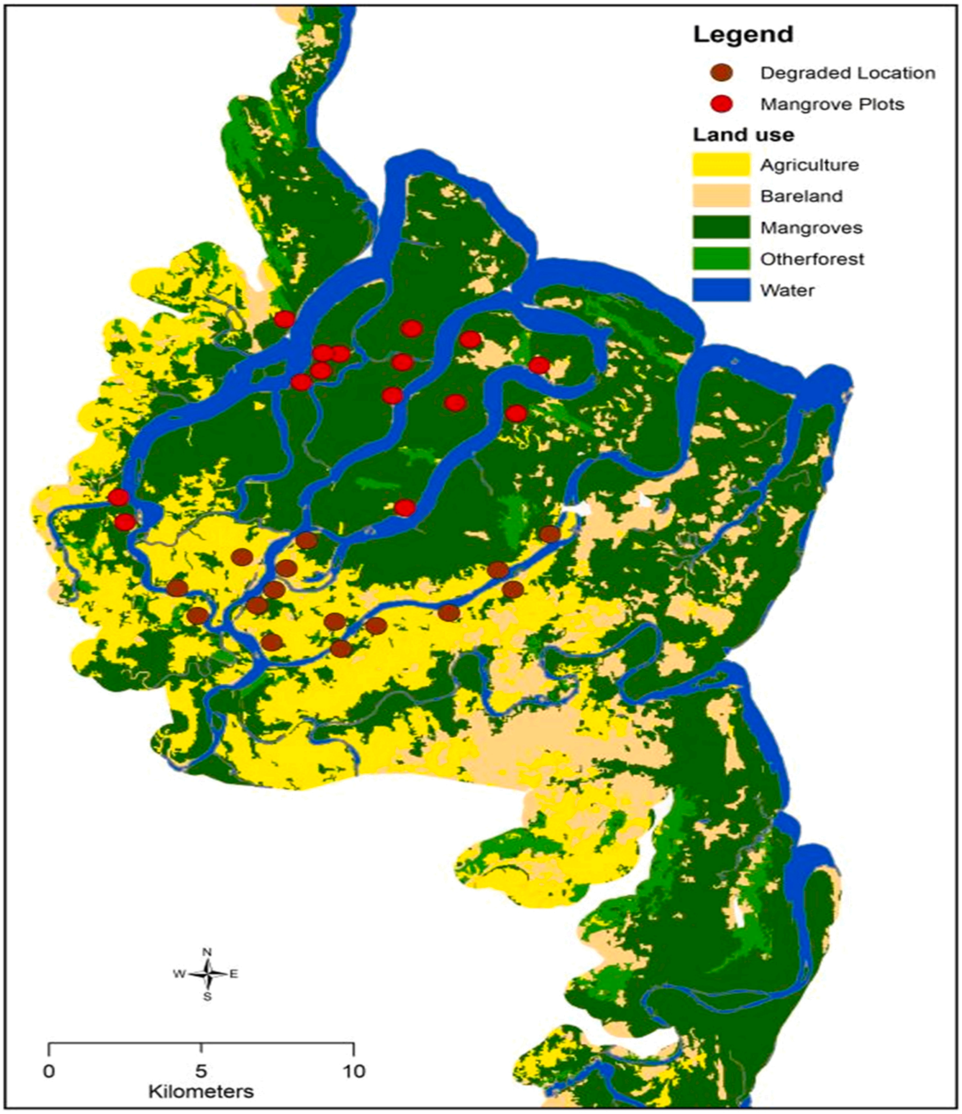

Fig. 1. Location of sampling plots in the study site, dark red points are the degraded mangrove plots and light red are the good natural mangrove plots overlaid on the land cover change map adopted from Monga et al. (2018). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

socio-economic importance to people in the delta include rice farming, mangrove cutting for poles and timber and fishing for both food and income security (Nyangoko et al., 2021). Rice farming activities in the delta involves clearing of mangroves to allow space for farming (Semesi, 1992; Nindi et al., 2014; Monga et al., 2018). Mangrove poles and timber from Rufiji Delta feed local markets in major coastal cities and towns especially Dar es Salaam, Tanga and the islands of Zanzibar. For local area management purposes, the delta has been categorized into three major blocks: northern, central and southern blocks (Semesi, 1989). The northern block has about half of the total mangrove cover in the delta. The block receives more freshwater, is relatively more accessible and therefore more frequently utilized for local and commercial interests than the other blocks (Brown et al., 2016). This study was conducted in the northern delta block, where clearance of mangroves for rice farming activities is concentrated and therefore vastly targeted for restoration programmes.

2.2. Data collection

2.2.1. Sampling procedure

2.2.1.1. Good and degraded mangrove stands. The 1989 mangrove cover maps used to develop the mangrove management plan for mainland Tanzania, (Semesi and Howell, 1992) was used to guide the purposive designation of two contrasting mangrove areas - a good natural mangrove that had fairly remained intact by 2016 and a degraded area as a result of clearance for rice farming. The 1989 map was used because it was developed with clusters showing trees species, stand height and stand density of the entire delta. In each area, purposive allocation of 15 sampling circular plots of 0.04 ha (11.3 m radius) as per Trettin et al. (2016) was done (Fig. 1). The plots were overlaid on the land cover change map adopted from Monga et al. (2018). The plots were located at least 1 km apart (where close related pair was found). All field data collection was conducted during February 2017, shortly before the start of the long rains.

2.2.1.2. Planted mangrove stand. Two officers from TFS field station at Nyamisati and 2 community members who had adequate experience and knowledge of the delta and engaged in the previous restoration activities were consulted to support the selection of the planted mangrove fields based on age. Twelve planted fields were identified, three each with 2, 5, 10 and 15 year old planted mangroves. These years were proposed because the consulted community members and TFS field officers could recall the years when planting was done and distinguish planted mangroves with such age classes. The identified planted fields had different areal sizes, with the smallest around 3 ha. Three circular sampling plots each with an area of 0.04 ha (11.3 m radius) were established on each of the selected mangrove planted fields. One plot was established at the center of the planted fields and each of the other two plots at 10 m on the opposite side of the center plot.

All established plots for the planted site were located on the landward side of the delta, close to where the main Rufiji River separates into distributaries that feed the delta. This is the area of the delta which has been largely affected by rice farming and therefore open for restoration activities (Monga et al., 2018). All 12 mangroves planted plots were active with rice cultivation, but at different stages, some with grown rice and others at preparatory stages. In all planted plots, *B. gymnorrhiza* was the only species used for restoration. According to the narratives by the TFS field officers and members of the community, *B. gymnorrhiza* is preferred for planting due to its better performance in terms of fast growth and high survival, availability of abundant propagules and their easy of handling.

2.2.2. Measurements

2.2.2.1. Good natural and degraded mangrove stands. Tree biomass in good natural and degraded mangrove areas

In all plots in both good natural and degraded mangrove areas, all trees (mangroves and non-mangroves) were identified and diameter at breast height (DBH = 1.3 m above ground) and height was recorded for both the saplings and overstory trees by species. All trees with DBH less than 10 cm were considered as saplings. DBH was measured using a diameter tape. Height was measured using Haglof Vertex III hypsometer. Above ground biomass (AGB) and below ground biomass (BGB) pools for mangroves were determined for each live tree. Species-specific equations (Eqs. 1–6) and the general equations (Eqs. 7–8) for mangroves of Tanzania by Njana et al. (2016b) were used to calculate AGB and BGB.

Species specific equations:

A. marina

$$\text{AGB: } 0.25128 \times \text{dbh}^{2.24351} \tag{1}$$

$$\text{BGB: } 1.42040 \times \text{dbh}^{1.44260} \tag{2}$$

R. mucronata

$$\text{AGB: } 0.25128 \times \text{dbh}^{2.26026} \tag{3}$$

$$\text{BGB: } 1.42040 \times \text{dbh}^{1.68979} \tag{4}$$

S. alba

$$\text{AGB: } 0.25128 \times \text{dbh}^{2.21727} \tag{5}$$

$$\text{BGB: } 1{\cdot}42040 \times \text{dbh}^{1\cdot65760} \tag{6}$$

General equations:

$$\text{AGB} = 0.25128 \times \text{dbh}^{2\cdot24034} \tag{7}$$

$$\text{BGB} = 1{\cdot}42040 \times \text{dbh}^{1\cdot59666} \tag{8}$$

Loss of carbon

Biomass estimates were converted to carbon equivalent by using carbon concentration factors of 0.39 and 0.50 for below ground and above ground biomass respectively as suggested by Kauffman and Donato (2012). Amount of carbon loss was estimated as the result of conversion of mangrove forest into rice fields between 1989 and 2016 (sampled year). Carbon losses were estimated by using carbon gain-loss and tier 2 methods by IPCC (2006). The carbon stocks differences between natural mangrove stands and planted mangrove areas (rice farming) were calculated to get the amount of carbon loss.

2.2.2.2. Performance of planted mangrove stand. Determination of survival rate

Mangrove planting space used in Rufiji Delta is 1 m (rows and columns), although not necessarily in strict straight rows. This planting space is locally suggested by TFS field officers based on experience from natural regeneration. The number of mangrove plants available in the plots were counted and recorded by species. The total number of mangrove trees planted in a plot was calculated based on the mangrove planting density in Rufiji Delta (1 m rows and columns, 400 trees/≈400 m^2). Survival rate of the planted mangroves in plots was then estimated through Eq. 9. The results of the plots were extrapolated to trees per hectare. All other growing mangroves out of planted rows and columns but within the plots were considered as natural regeneration and were counted, recorded by species and their densities (seedlings/ha) computed accordingly. Mangroves that survived but intentionally removed through cutting were considered by their stumps as survived trees.

$$\%\text{SR} = \text{n/N x } 100 \tag{9}$$

Where: %SR = Survival rate, n = mangroves present in the plot, N = total mangroves initially planted (400 trees/≈ 400 m^2).

The plot condition such as level and type of disturbances was assessed and recorded. Cutting and farming were considered as disturbances in the planted areas. Flowering and propagule production of the planted mangroves were also assessed and recorded in all plots.

Measurement of tree diameter and height

For the planted plots, measuring tape and diameter tape were used to measure height and diameter respectively of the planted mangrove seedlings, saplings and older trees. Height was measured from the end of the propagule to the highest plant tip where the stem shoots grow. The root collar diameter (RCD) was measured by a diameter tape at 1 cm above the soil. The DBH of 5, 10 and 15 year old trees were measured and recorded. DBH of 2 year old plants were not measured because of their small sizes. The annual mean growth rates of RCD, DBH and height of the mangrove age classes were calculated by simple division of the mean RCD, DBH and height by the age of planted mangroves. As reported by Basyuni et al. (2012), the stem heights, diameters and basal area of planted mangroves are the indices of plant growth, development and biomass accumulation. Measured height and DBH was then used to estimate above and below ground biomass using specific Eqs. 10 and 11 developed by Perera et al. (2012) for *B. gymnorrhiza*.

$$\text{AGB} = 0.289 \text{ x } \text{D}^{2\cdot327} \tag{10}$$

$$\text{BGB} = 0.1 \text{ x } \text{D}^{2\cdot364} \tag{11}$$

Where AGB is above-ground biomass in kg per tree, D is DBH in cm and BGB is below ground biomass in kg per tree.

The biomass densities were respectively multiplied by concentration factors of 0.39 and 0.50 for below ground and above ground estimates in order to obtain carbon mass (Kauffman and Donato, 2012).

2.3. Statistical analysis

Statistical tests were performed using SPSS version 16 to compare means. Mean values were subjected to paired samples T-test at significance level of 0.05 to find the variation of mean carbon stocks in different carbon pools between for the good natural mangrove and degraded mangrove sites. For the planted mangrove data, one-way analysis of variance (ANOVA) was used to test the variation of means of survival rate, RCD, DBH, BA and height for 2, 5, 10 and 15 year old planted mangroves. The analysis was carried out using Least Significant Differences ($P < 0.05$).

3. Results

3.1. Species composition

In 1989, the good natural mangrove plots were dominated by *A. marina* (7 plots) while degraded plots were dominated by *H. littoralis* (7 plots). The dominance of other species in the good natural mangrove site were *R. mucronata* dominant in 6 plots and *S. alba* in 2 plots. The dominance in the other pair (degraded site) were *A. marina* in 3 plots, *S. alba* in 3 plots, *R. mucronata* in 1 plot and a mixture of *A. marina* and *C. tagal* in 1 plot. In 1989, the pairs of the plots had mangroves of the same height and stand density. The average height was approximately 10 m for trees in both sites.

In 2016, the plots in the good natural mangrove site were dominated by *R. mucronata* (6 plots) while the degraded site was dominated by *B. racemosa* (4 plots). The dominance of other species in the natural mangrove site was *A. marina* in 4 plots, *C. tagal* in 3 plots and *X. granatum* and *S. alba* in 1 plot each. The dominance of other species in the degraded site includes *A. marina* and *B. gymnorrhiza* in 1 plot each. Nine (9) plots had no trees in degraded area. Eight mangrove species were recorded in the mangrove plots in 2016 compared to only 2 mangrove species recorded in the degraded plots. The stand density of mangroves was between 175 and 2925 trees/ha in mangrove site and 300–550 trees/ha in degraded site.

In planted plots, *B. gymnorrhiza* was the only mangrove species planted. An average of 10,000 seedlings is planted in 1 ha at a spacing of 1 m. The survival of planted mangroves decreased with age. The highest and lowest survival rates of the planted mangroves were 45% (4533 trees/ha) and 28% (2766 trees/ha) respectively, recorded at the 2 and 15 year old mangroves plots. The overall average survival rate was 37% (3691 trees/ha).

3.2. Growth patterns

The average height was greater than 10.6 m for trees in good natural mangrove site and 3.5 m in the degraded site. In planted plots, height, root collar diameter (RCD) and basal area (BA) increased with age (Table 1). Only two *R. mucronata* trees were recorded naturally regenerating within one of the 15 year old planted plots and had height and DBH of 7 m, 8.5 cm and 9.8 m and 10.4 cm respectively.

The annual mean growth rates of RCD, DBH and height range between 1.45 ± 0.41 cm to 1.94 ± 0.53 cm, 0.38 ± 0.15 cm to 0.73 ± 0.44 cm and 0.42 ± 0.11 m to 0.57 ± 0.16 m respectively for 2, 5, 10 and 15 year old planted mangroves (Table 2). The annual mean height growth rate decreased with age of planted mangroves. RCD had highest annual growth rates at all mangrove ages (2, 5, 10 and 15) than the rest of other growth parameters (height and DBH). The overall annual mean growth rates of RCD, DBH and height were 1.67 ± 0.43 m, 0.51 ± 0.20 m and 0.47 ± 0.13 m respectively.

3.3. Disturbance and reproduction of planted mangroves

The stump density ranged between 133 stumps ha^{-1} in 2-year-old planted plots to 1733 stumps h^{-1} in 5 year old planted plots (Table 3). All stumps recorded in 2 year old planted mangroves were *H. littoralis* and were from natural stock. Stumps in the rest of other age classes (5, 10 and 15-year-old planted mangroves) were *B. gymnorrhiza* and were from planted stock. The calculation of survival rate above considered 83 stumps as survived trees as they grew but were cut by farmers. A total of 4, 52, 5 and 26 stumps were recorded in 2, 5, 10 and 15 year old planted plots respectively. All 4 stumps recorded in 2 year old planted plots were *H. littoralis* and the remaining 83 stumps in 5, 10 and 15 year old planted plots were *B. gymnorrhiza*. Flowering and seedlings production were observed on trees 5 year old and above which is an indication that flowering and propagule production of *B. gymnorrhiza* planted in Rufiji Delta starts at the age of 5.

3.4. Biomass carbon stocks

Above ground C in the good natural mangrove site was largely contributed by *A. marina* and *B. gymnorhiza*, where each contributed by 36.8% and 22.5% respectively compared to 56.64% and 42.61% contributed by *B. racemosa* and ground vegetation respectively in the degraded (rice farming) site. Plot 13 in degraded site had 30 large *B. racemosa* due to high regeneration of tree species in the area (Table 4).

Above ground biomass and BGB carbon stock for the degraded site ranged between 0 and 150.88 and 0–97.01 Mg C ha^{-1} and between 28.18 and 299.43 and 16.00 – 164.51 Mg C ha^{-1} for mangrove site respectively. Total biomass C stock ranged between 0 and 247.89 Mg C ha^{-1} in the degraded site and 44.14–463.94 Mg C ha^{-1} for the mangrove site (Table 4). Tree biomass contributed 63% and 43% while ground vegetation contributed 0.9% and 31% of the total biomass C of mangrove and degraded plots respectively. Except for farm field plot 13, all means between two sites were significantly different at $p = 0.05$, based on individual two-sample t-tests.

In planted mangrove plots, the lowest biomass C was estimated in the plots of 5 year old mangroves regardless of high tree density in the area. The highest biomass C was estimated in plots with 15 year old mangroves contrary to low tree density in the plots (Table 5).

Table 1
RCD, DBH, BA and height (mean±SD) of planted mangroves in Rufiji Delta.

Parameters	Age (years)				Test of variation	
	2	5	10	15	F	P
Survival	4533 ± 873	3933 ± 1155	3533 ± 2517	2766 ± 551	24.42	0.001
RCD	2.9 ± 0.82	8.95 ± 2.49	14.76 ± 2.56	29.15 ± 7.94	12.6	0.001
DBH	–	3.65 ± 2.19	3.78 ± 1.47	6.55 ± 3.34	2.8	0.001
BA (m^2ha^{-1})	–	8.0 ± 11.4	13.0 ± 12.1	43.0 ± 40.2	4.7	0.001
Height (m)	1.14 ± 0.31	2.25 ± 0.5	4.24 ± 1.08	6.45 ± 2.01	2.5	0.001

Table 2
Annual growth pattern of planted mangroves at different growth ages (mean±SD).

Year	RCD (cm)	DBH (cm)	Height (m)
2	1.45 ± 0.41	–	0.57 ± 0.16
5	1.79 ± 0.50	0.73 ± 0.44	0.45 ± 0.10
10	1.46 ± 0.26	0.38 ± 0.15	0.42 ± 0.11
15	1.94 ± 0.53	0.44 ± 0.02	0.43 ± 0.13

Table 3
Plots conditions, disturbances and planted mangroves growth development (arf = active rice field, Hd = High density).

Plot	Plot condition	Stumps/ha	Stump species	Flowering
2	Arf	133	*H. littoralis* (old)	No
5	Arf	1733	*B. gymnorrhiza*	Yes
10	Arf	167	*B. gymnorrhiza*	Yes
15	Arf	867	*B. gymnorrhiza*	Yes

Table 4
Carbon density (Mg C ha^{-1}) from biomass within good natural mangrove site and degraded site (rice farms).

Degraded mangrove site				Good natural mangrove site			
Plots	AGC	BGC	Total Biomass C	Plots	AGC	BGC	Total Biomass C
1a	–	–	–	1b	73.40	41.82	115.22
2a	–	–	–	2b	299.43	164.51	463.94
3a	–	–	–	3b	53.41	32.75	86.16
4a	–	–	–	4b	264.41	148.94	413.35
5a	–	–	–	5b	105.01	59.77	164.78
6a	0.12	0.07	0.19	6b	28.18	16.00	44.18
7a	–	–	–	7b	72.97	42.15	115.12
8a	3.43	2.25	5.68	8b	92.92	50.27	143.19
9a	–	–	–	9b	236.59	143.69	380.28
10a	5.17	3.38	8.55	10b	53.17	31.98	85.15
11a	–	–	–	11b	109.60	62.45	172.05
12a	–	–	–	12b	264.41	148.94	413.35
13a	150.88	97.01	247.89	13b	60.69	34.47	95.16
14a	–	–	–	14b	53.84	33.46	87.30
15a	3.87	2.30	6.17	15b	110.78	70.35	181.13

The total biomass for the mangroves with 5, 10 and 15 years of the age was 13.65, 20.13 and 57.53 Mg C ha^{-1} respectively. Above ground C and BGB C contributed to the total biomass by 77.5% and 22.5% respectively for all age classes of the planted mangroves. The annual biomass C accumulation rate for the 5, 10 and 15 year old *B. gymnorrhiza* was estimated at 2.7, 2.0 and 3.8 Mg C $ha^{-1}year^{-1}$ respectively.

3.5. Carbon loss and gain

Biomass C stock equivalent to 179.46 Mg C ha^{-1} was lost from mangrove ecosystem in the Rufiji Delta between 1989 and 2016 (25 years) due to degradation caused especially by rice farming. This is equivalent to emission rate of 7.18 Mg C $ha^{-1}year^{-1}$. In the same delta, mangrove restoration activities support estimated biomass C accumulation of 57.53 Mg C ha^{-1} in a period of 15 years, equivalent to 3.8 Mg C $ha^{-1}year^{-1}$.

Table 5
Tree density and biomass of the planted mangroves in the Delta.

Age of mangroves (Years)	Tree density (Trees ha^{-1})	AGC (Mg C ha^{-1})	BGC (Mg C ha^{-1})	Total biomass C (Mg C ha^{-1})
5	3933	10.63	3.02	13.65
10	3533	15.65	4.48	20.13
15	2766	44.49	13.04	57.53

4. Discussion

4.1. Species composition, height and stand density

There have been changes in species composition in both, mangrove and degraded sites. In 1989, the degraded and mangrove study sites in the Rufiji Delta had 8 mangrove species with the same height and density. In 2016, 6 species were not found in the degraded site. The change of the dominance of *A. marina* to *R. mucronata* in the mangrove site could be due to legal and illegal cutting for poles in the delta. Trettin et al. (2016) recorded up to 8550 stumps ha^{-1} in inventory plots in Rufiji Delta, suggesting the removal of mangroves by cutting in the area. However, Trettin et al. (2016) did not specifically report which species the stumps represented, which could indicate species preference for cutting. The disturbances of mangroves including uncontrolled cutting has been reported to contribute to the changes of mangrove species composition (Dahdouh-Guebas et al., 2005). The dominance of *R. mucronata* is not only in the delta but has recently been reported in other mangrove stands in Tanzania (Alavaisha and Mangora, 2016; Njana et al., 2017).

In the degraded site the species dominance changed from *H. littoralis to B. racemosa*, a mangrove associate due to rice farming activities. Monga et al. (2018) reported rice farming activities in the delta was of shifting nature, where the abandoned and fallow fields were highly colonized by *B. racemosa.* Japhet et al. (2019) reported two factors might have contributed to rapid colonization of *B. racemosa* in the degraded site. Firstly, is the nature of the seed of *B. racemosa,* which is coated with buoyant fibrous tissue allowing them to be carried great distances by water currents. Secondly, *B. racemosa* can sprout from stumps. Sprouting is important in forest regeneration, as many species can produce either sprouts originating from boles or branches (above ground sprouts) or subterranean tissues (root sprouts) (Guariguata and Ostertag, 2001). This second factor is however only possible in the agriculture fields where farmers do not apply fire in the clearance of the farm fields. In the process of farm preparation some farmers in the delta cut trees and set fire to clear the area ready for rice planting. *B. racemosa* has pioneering characteristic and is also a freshwater bound species and therefore an ecological indicator for availability of freshwater and land suitable for agriculture in the delta.

The mangrove planted plots were part of degraded plots and originally had diverse mangrove species. Most of mangrove planted areas in the delta were initially covered by *H. littoralis* before they were cleared by small scale traditional rice farmers (Brown et al., 2016; Monga et al., 2018). The plots have been planted by only one species of mangrove, *B. gymnorrhiza*. Based on local experience, *B. gymnorrhiza* perform better than other species. The better performance of *B. gymnorrhiza* for restoration activities in the delta compared to other species can be associated with high tolerance of wide range of ecological and environmental parameters which influence early growth of mangroves. Mangora et al. (2016) found that *B. gymnorrhiza* seedlings perform better in a broad range of light, salinity and waterlogging compared to *H. littoralis* seedlings which are limited to a small range and concluded that *B. gymnorrhiza* is a potential candidate species for restoring vulnerable mangrove forests.

There has been little increase of the average height of trees from approximately 10 m to greater than 15 m in a period of 30 years in the mangrove site. This could be due to change in species composition because of human disturbances including cutting for poles and logging for timber. The average trees height of 5 m estimated from some plots with trees in the degraded site recorded in 2016 may be explained by shifting nature of rice farming activities in the delta. Farms in the delta are cultivated in a rotation of 3–5 years before farmers move on to open new farm plots by clearing mangrove forests (Monga et al., 2018). This rotational farming seems to allow regeneration and growth of trees to approximately 5 m. Hastuti and Hastuti (2018) reported the growth height of up to 5.2 m and 7.8 m for *A. marina* and *R. mucronata* respectively in a period of 5 years. The ongoing planting activities in the delta could also explain for the availability of mangroves in some degraded plots. The lowest mangrove stand density recorded in the mangrove site in plot 6 in 2016 could be due to cutting pressure. The species composition in plot 6 changed from *R. mucronata* dominant in 1989 to *A. marina* dominant in 2016 suggesting the removal of *R. mucronata* in the area. *Rhizophora mucronata* is among most mangrove preferred species for poles in Rufiji Delta (Semesi, 1998; Monga et al., 2018).

The survival rate of the planted mangroves in Rufiji Delta has been estimated at 37% for the *B. gymnorrhiza*. This can be considered as moderate rate when compared to survival rates reported in other countries. The survival rate of 28% of planted *B. gymnorrhiza* was reported at Gazi Bay in Kenya just after two years (Kirui et al., 2008). In the same Bay, high survival rates of 86.2% and 87.3% of *A. marina* and *C. tagal* were respectively recorded, albeit on experimental plots (Kirui et al., 2008). Lower survival rate of *B. gymnorrhiza* in Gazi Bay was attributed by high salinity level in the area beyond 8–26 PSU which result into high mortality rate for both samplings and trees (Kirui et al., 2008), unlike Rufiji Delta that receive regular freshwater inflow. Ha et al. (2003) reported 30% survival rate of *Kandelia candel* in North Vietnam after one year, this low survival rate was due to what was thought to be strong waves in the planted area. The survival rate of the planted mangroves in the delta might improve if some measures would be taken to control farming activities in the area. Currently, most of planted areas are still active rice farms with evidence of removal of planted mangroves. Fresh stumps recorded in the restored areas indicate that farmers are cutting down restored mangroves as a strategy to enhance light and space for rice to grow well. The ongoing farming activities in the restored areas are due to land tenure issues between TFS Agency and community members in the delta (Mshale et al., 2017). Community members believe that they deserve to continue living and farming in the delta because they have been living in the delta before the area was gazetted as forest reserve in early 1900 s. However, TFS understand that all human activities in the delta are illegal because the area was gazette as a forest reserve.

4.2. Biomass carbon stocks

Higher total biomass carbon stock recorded in the mangrove plots (44.14–463.94 Mg C ha^{-1}) than in the degraded (0–247.89 Mg C ha^{-1}) and restored plots (13.65–57.53 Mg C ha^{-1}) is due to the nature of rice farming activities in the Delta where large areas are totally cleared to pave way for farm fields. The restored plots are also active farms. Depending on the nature, the land use change can remove nearly all biomass carbon (Sasmito et al., 2016). Sasmito et al. (2016) estimated total remove of biomass carbon due to forest cutting and removal of up to 85% of biomass carbon due to aquaculture activities. The average total biomass carbon stocked in 15 year old restored mangroves (57.53 Mg C ha^{-1}) is about 30% of the average carbon stocked by mangrove plots (natural stand) (197.36 Mg C ha^{-1}) and three times more than the carbon stocked in degraded plots (17.9 Mg C ha^{-1}). Cameron et al. (2018) reported similar observation in restored mangroves of Sulawesi, India which accumulated one-third of the total carbon stocked by natural mangrove stand after 10 years. Mangroves reach their growth maturity at the age between 10–15 years and literatures suggest mature mangrove systems are carbon neutral (Alongi, 2014). Estrada and Soares (2017) also reported that the carbon stock in the above ground biomass tends to increase and sequestration tends to decrease linearly with age. The time period for the restored mangroves to restock the same quantity of carbon stored by undisturbed mangroves depend on annual accumulation rate. Sasmito et al. (2020) reported an average of 25 years for the restored mangrove to stock carbon equivalent to that stocked by the natural stands at biomass accumulation rates of 3.6 ± 1.1 Mg C ha^{-1} $year^{-1}$ if disturbances are controlled. Similar annual accumulation rate of 3.8 Mg C ha^{-1} $year^{-1}$ has been reported by this study in Rufiji Delta. However, the time period to accumulate the same quantity of carbon as natural stand in the delta may be longer because rice farming activities are not controlled in restored plots in Rufiji Delta.

The AGC recorded by this study in the mangrove plots (28.18–299.43 Mg C ha^{-1}) is within range of C biomass reported by several other recent studies. Stringer et al. (2015) reported AGB C ranged from 75.4 to 268.5 Mg C ha^{-1} depending on mangrove height classes in Zambezi river delta; Kirui (2006) reported 226 Mg C ha^{-1} for mangroves in Gazi Bay and Abino et al. (2014) reported 263.8 Mg C ha^{-1} in mangrove forest of Bahile in Philippines. Other studies reported values different from values obtained by this study. Alemayehu et al. (2014) reported the ABG C was 148.07 Mg C ha^{-1} for mangroves in Mida Creek and Ajonina et al. (2014) reported 537.7 Mg C ha^{-1} in undisturbed mangroves of central African countries. Above ground biomass carbon reported by this study in the degraded plots (0–150.73 Mg C ha^{-1}) differs from values reported by other studies in disturbed mangroves. For instance, Ajonina et al. (2014) reported 64.1 Mg C ha^{-1}in heavily exploited mangroves in central African countries. The highest AGC stock was recorded in plot 13 which had larger trees of *B. racemosa*. The plot appeared to have been completely abandoned from rice farming activities. The quantity of carbon stocked by restored mangroves in Rufiji Delta at the age of 5 (13.65 Mg C ha^{-1}), 10 (20.13 Mg C ha^{-1}) and 15 (57.53 Mg C ha^{-1}) varies with the value reported elsewhere. For instance, Matsui et al. (2012) reported *R. mucronata* and *B. cylindrica* stocked 98.7 Mg C $ha^{-1}$and 28.8 Mg C ha^{-1}respectively 10 years after they were planted in excavated area. Contrary, low rates of biomass accumulation, 1.04 Mg C $ha^{-1}$for *R. mucronata* and 0.53 Mg C ha^{-1} for BC was reported in the unexcavated area in the same period. This suggest that the quantity of carbon stocked and the rate of stocking is influenced by number of factors including the age of the restored forest, management approach and planted species.

4.3. Growth pattern, disturbance and reproduction of planted mangroves

The basal area reported in restored areas in the delta increased with the age of planted mangroves. This is the normal growth pattern as the larger the trees the larger the basal area (Japhet et al., 2019). Japhet et al. (2019) estimated basal areas of 0.12 m^2 ha^{-1} (98 trees/ha) and 0.98 m^2 ha^{-1} (334 trees/ha) of mangroves regenerated naturally in rice abandoned fields about 5 years ago (early succession) and 10–15 years ago (intermediate succession) respectively. This implies that restoration activities support fast regeneration of degraded mangrove areas in the delta than natural regeneration. This study reported larger basal area (43.0 m^2 $ha^{-1} \pm 40$) in 15 year old planted mangroves than in undisturbed 20 year old mangroves (17.6 m^2 $ha^{-1)}$ reported by Japhet et al. (2019). This variation could be due to high steam density (2766 trees/ha) in 15 year old planted plots compared to 417 trees/ha reported in 20 year old undisturbed mangroves in Rufiji Delta (Japhet et al., 2019). The lower mean annual growth of height and DBH compared to RCD at the first 2 years of the planted mangroves in the delta could be explained that this is the stage when the seedlings are in stressful condition trying to acclimatize harsh conditions. These harsh conditions include salinity and water waves and therefore mangroves below 2 years old invest more on the primary growth including development of strong root system (Fromard et al., 1998). Planted mangroves in abandoned paddy farms in Myanmar showed similar growth patterns for *B. sexangula* at 4, 8 and 10 year old plants planted at an interval of 1.5 × 1.5 m (Aye and Takeda, 2020). The fastest mean annual growth of the RCD and DBH were recorded at the age between 10 and 15 years. This is can be related as the period when mangroves grow to its maturity and therefore plants invest more energy to increase its biomass.

Although planting activities in the delta have been conducted for over 3 decades, it has been done without specific guideline. The recently produced Guidelines on Mangrove Ecosystem Restoration for the Western Indian Ocean Region (UNEP-Nairobi Convention/USAID/WIOMSA, 2020) will assist future projects. The manual is critical for provision of important guidelines to be observed to improve restoration outcomes. Currently, important criteria for successful restoration such as site and seedlings selections are not well analyzed before planting activities. Open and easily accessible areas are mostly selected for restoration activities without any further assessment of soil and hydrological characteristics of the selected sites. Similar to site selection, there are also no seedlings quality control measures. Villagers are commissioned by restoration programmes to collect seedlings from nearby forest and sold to the restoration progamme ready for planting (UNEP, 2020). Consideration and control of the quality of seedlings is important as among other factors determines the survival rate and the quality of the forest stands (Srivastava and Bal, 1984; Krauss et al., 2008). Whilst the analysis indicated that the planted mangroves were performing better in the delta in terms of survival of seedlings and growth of trees, human pressure, which threatens planted mangroves still existed. High number of stumps was recorded in 5 and 15 year old planted plots. Planted mangroves in the delta were recorded to start flowering at the age of 5, therefore farmers are cutting more trees at this age to discourage future seedlings production. Another reason could be cutting for building poles. Mainoya et al. (1986) reported *B. gymnorrhiza* with the size of 8–16 cm basal diameter were highly preferred by coastal communities in Tanzania as construction poles because they are tough and termite-resistant.

5. Conclusion

Mangroves in Rufiji Delta store significant amount of biomass carbon and therefore critical for climate change mitigation programmes such as REDD+. However, rice farming activities in the area substantially increases carbon loss through degradation and reduce sequestration capacity of mangroves. The restoration activities in the delta have indicated some potential to compensate for the lost biomass carbon stocks. The amount of carbon loss due to rice farming activities in the Rufiji Delta established and presented by this work is a wakeup call to all actors to commit investment in mangrove conservation and management in the delta. To reduce pressure to mangroves, community members in the delta must be empowered to engage in ecosystem friendly off-farm livelihoods such as fishing and beekeeping. For restoration of ecological functionality of the degraded mangrove areas, planting of multiple species commonly found in the delta such as *R. mucronata*, *A. marina, C. tagal* and *B. gymnorhiza* should be piloted and promoted contrary to the current promotion of single species of *B. gymnorhiza*. Further, the government (TFS) should devise practical mechanisms to collaborate with other stakeholders in developing and implementing an integrated delta management plan.

5.1. Limitations and assumptions

Mangrove restoration may compensate for the loss of both biomass and soil carbon stocks (Sasmito et al., 2019). However this study report only on how planted mangroves compensate for the loss of biomass carbon stocks. Soil component was excluded from this study because baseline soil carbon data for deforested areas could not be obtained. In addition, in this study we assumed that change in mangrove species composition in deforested areas in Rufiji Delta is mainly attributed to degradation. Other factors such as change in salinity and hydrological systems might have also influenced such changes, which warrants further studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was funded by the United States Agency for International Development (USAID) through the Sustainable Wetlands Adaptation and Mitigation Program (SWAMP) implemented by the US Forest Service. Tanzania Forest Services (TFS) Agency provided the field coordination support through its Field Station at Nyamisati in the Rufiji-Delta. Constructive comments from the anonymous reviewers are highly appreciated.

References

Abino, A.C., Castillo, J.A.A., Lee, Y.J., 2014. Species diversity, biomass, and carbon stock assessments of a natural mangrove forest in Palawan, Philippines. Pak. J. Bot. 6, 1955–1962.
Ajonina, G.N., Kairo, J., Grimsditch, G., Sembres, T., Chuyon, G., Diyouke, E., 2014. 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+). Estuaries World 177–189.
Alavaisha, E., Mangora, M.M., 2016. Carbon stocks in the small estuarine mangroves of Geza and Mtimbwani, Tanga, Tanzania. Int. J. For. Res. 2016, 11. Article ID 2068283.
Alemayehu, F., Onwonga, R., Kinyanjui, M.J., Oliverv, W., 2014. Assessment of mangrove covers change and biomass in Mida Creek, Kenya. Open J. For. 4, 398–413.
Alongi, D.M., 2014. Carbon cycling and storage in mangrove forests. Annu. Rev. Mar. Sci. 6, 195–219.
Aye, W.M., Takeda, S., 2020. Conversion of abandoned paddy fields to productive land through mangrove restoration in Myanmar's Ayeyarwady Delta. Water Environ. 18, 417–429 https://doi.org/10.1007/s10333-020-00791-x.
Basyuni, M., Baba, S., Kinjo, Y., Putri, L.A.P., Hakim, L., Oku, H., 2012. Salt-dependent increase intriterpenoids is reversible upon transfer to fresh water in mangrove plants *Kandelia candel* and *Bruguiera gymnorrhiza*. J. Plant Physiol. 169, 1903–1908.
Brown, I., Mwansasu, S., OveWesterberg, L., 2016. L-band polarimetric target decomposition of mangroves of the Rufiji Delta, Tanzania. Remote Sens. 8, 140–154.
Bunting, P., Rosenqvist, A., Lucas, R., Rebelo, L.M., Hilarides, L., Thomas, N., Hardy, A., Itoh, T., Shimada, M., Finlayson, M., 2018. The global mangrove watch—a new 2010 global baseline of mangrove extent. Remote Sens. 10 (10), 1669, 10.3390/rs10101669.
Cameron, C., Hutley, L.B., Friess, D.A., Brown, B., 2018. Community structure dynamics and carbon stock change of rehabilitated mangrove forests in Sulawesi, Indonesia. Ecol. Soc. Am. https://doi.org/10.1002/eap.1810.
Dahdouh-Guebas, F., Jayatissa, L.P., Di Nitto, D., Bosire, J.O., Lo Seen, D., Koedam, N., 2005. How effective were mangroves as a defence against the recent tsunami? Current Biol. 15, R443–R447.
Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves amongst the most carbon-rich forests in the tropics. Natl. Geosci. 4, 293–297.
Doody, K., Hamerlynck, O., 2003. Biodiversity of Rufiji District—a Summary. (Technical report no. 44, Rufiji Environment Management Project). IUCN,, Gland, Cambridge.
Duarte, C.M., Middelburg, J.J., Caraco, N., 2005. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 2, 1–8.
Duvail, S., Hamerlynck, O., 2007. The Rufiji River flood: plague or blessing? Int. J. Biometeorol. 52, 33–42.
Estrada, G.C.D., Soares, M.L.G., 2017. Global patterns of above ground carbon stock and sequestration in mangroves. Biol. Sci. https://doi.org/10.1590/0001-3765201720160357.
FAO, UNEP., 2020. The state of the world's forests 2020. Forests, Biodiversity and People, Rome. ⟨https://doi.org/10.4060/ca8642en⟩.
Fromard, F., Puig, H., Mougin, E., Marty, G., Betoulle, J., Cadamuro, L., 1998. Structure, above-ground biomass and dynamics of mangrove ecosystems: new data from French Guiana. Oecologia 115, 39–53.
Goldberg, L., Lagomasino, D., Thomas, N., Fatoyinbo, T., 2020. Global declines in human-driven mangrove loss. Glob. Change Biol. DOI: 10.1111/gcb.15275.
Gilmour, D.A., San, N.V., Tsechalicha, X., 2000. Rehabilitation of Degraded Forest Ecosystems in Cambodia, Lao PDR, Thailand and Vietnam: an Overview. IUCN-Asia, Cambridge.

Guariguata, M.R., Ostertag, R., 2001. Neotropical secondary forest succession: changes in structural and functional characteristics. For. Ecol. Manag. 148, 185–206.
Ha, H.T., Duarte, C.M., Tri, H.N., Terrados, J., Borum, J., 2003. Growth and population dynamics during early stages of the mangrove *Kandelia candel* in Halong Bay, North Viet Nam. Estuar. Coast. Shelf Sci. 58, 435–444.
Hamilton, S.E., Friess, D.A., 2018. Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012. Nat. Clim. Change 8, 240–244 https://doi.org/10.1038/s41558–018-0090–4.
Hastuti, E.D., Hastuti, R.B., 2018. Growth characteristics of mangrove seedling in silvofishery pond – the allometric relationship of height, diameter and leaf abundance. IOP Conf. Ser. Earth Environ. Sci. 130, 012015.
IPCC., 2000. In: Watson R.T. et al., (Ed.), Land Use, Land-Use Change and Forestry: a Special Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland, IPCC, 375.
IPCC., 2006. Inter-governmental Panel on Climate Change. Good practice for Land Use,Land-Use Change and Forestry.
Japhet, E., Mangora, M.M., Trettin, C., Okello, J.A., 2019. Natural recovery of mangroves in abandoned rice farming areas of the Rufiji Delta, Tanzania. WIO J. Mar. Sci. 18 (2), 25–36.
Jones, T.G., Ratsimba, H.R., Ravaoarinorotsihoarana, L., Glass, L., Benson, L., Teoh, M., Carro, A., Cripps, G., Giri, C., Gandhi, S., Andriamahenina, Z., Rakotomanana, R., Roy, P.F., 2015. The dynamics, ecological variability and estimated carbon stocks of mangroves in Mahajamba Bay, Madagascar. J. Mar. Sci. Eng. 3, 793–820.
Kauffman, J.B, Donato, D.C., 2012. Protocols for the measurement, monitoring and reporting ofstructure, biomass and carbon stocks in mangrove forests. Working Paper 86, CIFOR, Bogor, Indonesia, 50.
Kirui, B.K., 2006. Allometric Relations for Estimating Aboveground Biomass of Naturally Growing Mangroves *Avicennia marina* Forsk (Vierh) and *Rhizophora mucronate* Lam along the Kenya Coast (MSc thesis). Egerton University.
Kirui, B.Y.K., Huxham, M., Kairo, J., Skov, M., 2008. Influence of species richness and environmental context on early survival of replanted mangroves at Gazibay, Kenya. Hydrobiologia 603, 171–181.
Krauss, K.W., Lovelock, C.E., McKee, K.L., Lo ́pez-Hoffman, L., Ewe, S.M.L., Sousa, W.P., 2008. Environmental drivers in mangrove establishment and early development: a review. Aquat. Bot. 89, 105–127.
Lagomasino, D., Fatoyinbo, T., Lee, S., Feliciano, E., Trettin, C., Shapiro, A., Mangora, M.M., 2019. Measuring mangrove carbon loss and gain in deltas. Environ. Res. Lett. 14 (2019), 025002.
Lund, H.G., 2009. What is a degraded forest? White Paper on Forest Degradation Definitions. Prepared for FAO, 39.
Lund, H.G., 2014. Revised. Definitions of Old Growth, Pristine, Climax, Ancient Forests, Degradation, Desertification, Forest Fragmentation, and Similar Terms (Online publication), Forest Information Services, Gainesville, VA.
Lund, H.G., 2015. Rev* Definitions of Forest, Deforestation, Afforestation, and Reforestation, Forest Information Services, Gainesville, VA (Note, this paper has been continuously updated since 1998.).
Mainoya, J.R., Mesaki, S., Banyikwa, F.F., 1986. The distribution and socio-economic aspects of mangrove forests in Tanzania. In: Kunstadter, P., Bird, E.C.F., Sabhasri, S. (Eds.), Man in the Mangroves, 87–. United Nations University, Tokyo, p. 95.
Mangora, M.M., 2011. Poverty and institutional management stand-off: a restoration and conservation dilemma for mangrove forests of Tanzania. Wetl. Ecol. Manag. 19, 533–543.
Mangora, M.M., Lugendo, B.R., Shalli, M.S., Semesi, S., 2016. Mangroves of Tanzania. In: Bosire, J.O., Mangora, M.M., Bandeira, S., Rajkaran, A., Ratsimbazafy, R., Appadoo, C., Kairo, J.G. (Eds.), Mangroves of the Western Indian Ocean: status and management. WIOMSA, Zanzibar, pp. 33–49.
Matsui, N., Keiyo, Morimune, Wijarn, M., Jirasak, C., 2012. Ten year evaluation of carbon stock in mangrove plantation reforested from an abandoned shrimp pond. Forests 3 (2), 431–444. https://doi.org/10.3390/f3020431.
Mayunga, J., Uhinga, G.A., 2018. Mapping spatio-temporal distributionof mangroves in Mafia Island in Tanzania using landsat imagery. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-4/W8.
Monga, E., Mangora, M.M., Mayunga, J.S., 2018. Mangrove cover change detection in the Rufiji Delta in Tanzania. WIO J. Mar. Sci. 17, 1–10.
Mshale, B., Senga, M., Mwangi, E., 2017. Governing mangroves: unique challenges for managingTanzania's coastal forests. USAID Tenure and Global Climate Change Program, Bogor, Indonesia, CIFOR; Washington, DC.
Mwansasu, S., 2016. Causes and Perceptions of Enviromental Change in the Mangroves of Rufiji Delta, Tanzania. Implications for Sustainable Livelihood and Conservation (Doctoral thesis in physical geography), Stockholm, Sweden, 2016.
Nicholson, S., 2001. Climatic and environmental change in africa during the last two centuries. Clim. Res. 17 (2), 123–144.
Nindi, S. J., Machano, H., Rubens, J., 2014. Remote Sensing Study of Rufiji Mangrove, Tanzania from1990 to 2010. WWF Tanzania Country Office, Dar es Salaam, 49.
Njana, M.A., Bollandsås, M.O., Eid, T., Zahabu, E., Malimbwi, R.E., 2016b. Above- and Belowground tree biomass models for three mangrove species in Tanzania: a nonlinear mixed effects modelling approach. Ann. For. Sci. 73, 353–369.
Njana, M.A., Zahabu, E., Malimbwi, R.E., 2017. Carbon stocks and productivity of mangrove forests in Tanzania. South. For. 1–16.
Nyangoko, B.P., Berg, H., Mangora, M.M., Gullström, M., Shalli, M.S., 2021. Community perceptions of mangrove ecosystem services and their determinants in the Rufiji Delta, Tanzania. Sustainability 13, 63. https://doi.org/10.3390/su13010063.
Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S., Craf, T.C., Fourqurean, J.W., Kauffman, J.B., Marba, N., Megonigal, P., Pidgeon, E., Herr, D., Gordon, D., Baldera, A., 2012. Estimating global "Blue Carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLoS One 7, e43542.
Perera, K.A.R.S., Sumanadasa, W.A., Amarasinghe, M.D., 2012. Carbon retention capacity of two mangrove species, *Bruguiera gymnorriza* (L.) Lamk and *Lumnitzera racemose* Willd. in Negombo estuary, Sri Lanka. J. Fac. Grad. Stud. Univ. Kelaniya 1, 56–70.
Peter, L., 2013. Assessment of the Status of Mangrove Vegetation and Their Degradation in Rufiji Delta in Tanzania (MSc thesis report), University of Ghana, 161.
Sanderman, J., Hengl, T., Fiske, G., Solvik, K., Adame, M., Benson, L., Bukoski, J., Carnell, P., Cifuentes-Jara, M., Donato, D., Duncan, C., Eid, E., Ermgassen, P., Ewers Lewis, C., Macreadie, P., Glass, L., Gress, S., Jardine, S., Jones, T., Nsombo, E., Rahman, M., Sanders, C., M, Spalding, E., 2018. A global map of mangrove forest soil carbon at 30 m spatial resolution. Environ. Res. Lett. 13 (5), 12, 10.1088/1748-9326/aabe1c art. no. 055002.
Sasmito, S.D., Taillardat, P., Clendenning, J., Friess, D.A., Murdiyarso, D., Hutley, L.B., 2016. Carbon stocks and fluxes associated with land-use and land-cover change in mangrove ecosystems: a systematic review protocol. Working Paper 211. CIFOR, Bogor, Indonesia.
Sasmito, S.D., Taillardat, P., Clendenning, J.N., Cameron, C., Friess, D.A., Murdiyarso, D., Hutley, L.B., 2019. Effect of land-use and land-cover change on mangrove blue carbon: a systematic review. Glob. Change Biol. 2019 (25), 4291–4302.
Semesi, A.K., 1989. The mangrove resources of the Rufiji delta, Tanzania. Paper In: Proceedings of the Presented at a Workshop on Marine Sciences in East Africa on 4–16 November, 1989. Institute of Marine Sciences, University of Dar es Salaam.
Semesi, A.K., 1992. Developing management plans for the mangrove forest reserves of mainland Tanzania. Hydrobiologia 247, 1–10.
Semesi, A.K., Howell, K., 1992. The mangroves of the Eastern African region. UNEP. Nairobi 45.
Semesi, A.K., 1998. Mangrove management and utilization in Eastern Africa. Ambio 2 (8).
Spalding, M.D., Leal, M. (Eds.), 2021. The State of the World's Mangroves 2021. Global Mangrove Alliance.
Srivastava, P.B. L. ,Bal, H.S., 1984. Composition and distribution pattern of natural regeneration after second thinning in Matang mangrove reserve, Perak Malaysia. In: Soepadimo, E., Rao, A.N., Macintosh, D.J. (Eds.), Proceedings of the Asian Symposium on Mangrove Environment: Research Managements, Kuala Lumpar, Malaysia, 761–784.
Stringer, C.E., Carl, C.T., Stanley, J.Z., Tang, W., 2015. Carbon stocks of mangroves within the Zambezi River Delta, Mozambique. For. Ecol. Manag. 354, 139–148.
Thomas, N., Lucas, R., Bunting, P., Hardy, A., Rosenqvist, A., Simard, M., 2017. Distribution and drivers of global mangrove forest change, 1996–2010. PLoS One 12 (6), e0179302 https://doi.org/10.1371/journal.pone.0179302.
Trettin, C.C., Dai, Z., Zarnoch, S.J., Mangora, M., Njana, M., Otieno, J., Tang, W., Fang, W., Fatoyinbo, T., Lee, S.K., Lagomasino, D., Simard, M., 2016. Assessment of Carbon stocks in the Rufiji River Delta. Tanzan. East Afr. Mangrove Carbon Proj. Rep. 66.

Trettin, C.C., Zhaohua, D., Tang, W., Lagomasino, D., Thomas, N., Kuk Lee, S., Simard, M., Ebanega, M.O., Stoval, A., Fatoyinbo, T.E., 2021. Mangrove carbon stocks in Pongara National Park, Gabon. Estuar. Coast. Shelf Sci. https://doi.org/10.1016/j.ecss.2021.107432.
UNEP-Nairobi Convention/USAID/WIOMSA, 2020. Guidelines on Mangrove Ecosystem Restoration for the Western Indian Ocean Region. UNEP, Nairobi, p. 71.
Wagner, G.M., Sallema-Mtui, R., 2016. The Rufiji estuary: climate change, anthropogenic pressures, vulnerability assessment and adaptive management strategies. West. Indian Ocean Estuar. World [DOI 10.1007/978-3-319-25370-1-12].
Wang, Y., Bonynge, G., Nugranad, J., Traber, M., Ngusaru, A., Tobey, J., Hale, L., Bowen, R., Makota, V., 2003. Remote sensing of mangrove change along the Tanzania Coast. Mar. Geod. 26, 35–48.