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Carbon dynamics and sequestration by the urban mangrove forests of Dar es Salaam, Tanzania

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Abstract

This study intended to 1) determine spatial and temporal changes of mangrove forests, 2) identify drivers of mangrove deforestation and forest degradation, 3) determine historical carbon storage, sequestration and deforestation emissions by mangrove forests, and 4) determine whether mangrove forests are a source or sink of CO_2 in Dar es Salaam, Tanzania. Mangrove forests have decreased from 4,813 hectares in 1986 to 1961 hectares in 2016. The following were prominent drivers of deforestation in descending order: clearing mangrove forests for salt pans; hotel construction; settlement; and charcoal making. Tree removals for firewood and building poles were also prominent drivers of mangrove forest degradation. Similarly, carbon stored in mangrove forests has decreased from 1,131,055 tonnes CO_2e in 1986 to 460,835 tonnes CO_2e in 2016. Sequestration of CO_2 by mangrove forests is estimated at 133,516 (1986-1995); 106,110 (1995-2006) and 69,616 (2006-2016) tonnes CO_2e year^{-1}. Conversely, mangrove deforestation has resulted in emissions of about 27,400, 16,500 and 24,000 tonnes CO_2e year^{-1} in 1986-1995, 1995-2006 and 2006-2016, respectively. Urban mangrove forests play an important environmental role in mitigating climate change and amelioration of local weather through the large carbon stocks they store and sequester. Mangrove forests in the study area remain a net carbon sink, however, the sink role played by mangrove forests in the study area is decreasing rapidly. The declining spatial and temporal trends of urban mangrove forest cover has resulted in a systematic decrease in the total carbon stored and sequestered by mangrove forests. In the absence of timely measures of preserving and rehabilitating degraded mangrove areas, the mangrove forests of Dar es Salaam may become the source of CO_2. The study recommends effective urban land use planning and effective law enforcement to ensure a win-win situation through sustained ecosystem services offered by urban mangrove forests to support economic growth.

Keywords: carbon storage, carbon emission, carbon sink, drivers of carbon stock change, mangrove forest

Introduction

Global carbon emissions are increasing rapidly. Recently, IPCC (2014) reported that CO_2 emissions have increased by about 90 % since 1970. Emissions from fossil fuel combustion and industrial processes contribute about 78 % to the increase of the total greenhouse gas emissions from 1970 to 2011 (IPCC, 2014; Boden *et al.*, 2017). Urban areas and their development are characterised by high concentrations of transport and industries which yield high emissions of CO_2 and other greenhouse gases (Parrish and Zhu, 2009; Bettencourt and West, 2010; Hillman and Ramaswami, 2010; Seto and Satterthwaite, 2010; URT, 2014). Consequently, emissions cause climate change, air pollution and affect human health (Epstein, 2001; Hunter, 2003; Svirejeva-Hopkins *et al.*, 2004; Parrish and Zhu, 2009; IPCC, 2014; URT, 2014).

There is a strong interest in stabilizing the atmospheric abundance of CO_2 and other greenhouse gases to mitigate the risks of global warming (Kerr, 2007; IPCC, 2014). In order to mitigate climate change, UN member parties have set a target, in the Paris Agreement, of limiting average warming to 2 °C above pre-industrial

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temperatures. Three strategies aimed at lowering CO_2 emissions for mitigating climate change have been proposed (IPCC, 2014); these include (i) reduction of global energy use, (ii) development of low or no-carbon fuel, and (iii) sequestration of CO_2 from point sources or the atmosphere.

Urban areas are characterised by high concentrations of transport and industries and are thus a source of high emissions. Despite being sources of high emissions, mangrove forests, other forest types and trees outside forests exist in many urban areas. The forests and trees serve as carbon sinks. A carbon sink is any process, activity or mechanism that removes a greenhouse gas from the atmosphere.

Destroying forests and trees release CO_2 into the atmosphere. For this reason, forests and trees such as mangroves are vital in fighting global warming because they counteract carbon emissions from such sources as industries and transportation (Saenger, 2002; Donato *et al.*, 2011; Njana *et al.*, 2018; Mauya *et al.*, 2019).

Apart from carbon storage and sequestration, mangrove forests attenuate storm surges (Zhang *et al.*, 2012) and offer other environmental and livelihood benefits (Saenger, 2002; FAO, 2007). Therefore, when mangrove forests are disturbed (e.g., land use/land cover conversion) they release large amounts of CO_2 and result in loss of many other environmental and livelihood benefits. Effective management of urban mangrove forests is thus important.

Mangroves are known for the immeasurable ecological and economic ecosystem services they provide. However, the literature shows that mangroves are among the most vulnerable ecosystems worldwide and are declining rapidly (Kuenzer *et al.*, 2011). According to FAO (2007) approximately 3.6 million ha of global mangroves have been lost between 1980 and 2005 due to conversion of mangrove forests to other land uses. Both natural and anthropogenic factors are responsible for the loss of mangroves (Ilman *et al.*, 2016; Gevaña *et al.*, 2018).

The impact of different factors causing losses of mangroves and the response of the mangroves varies between developed and developing countries and may also vary between urban and rural settings. For example, industrial pollution could be one of the most important factors in urban settings (Tam and Wong, 2000) while conversion of mangrove areas to agriculture could be a factor in rural settings (Mwansasu, 2016).

In Mainland Tanzania, mangroves are distributed along the coastline from the north (Tanga) to the south (Mtwara) with Dar es Salaam (which is the former capital of Tanzania) having about 2,500 hectares (Semesi, 1992; Wang *et al.*, 2003) of mangrove forest. Various studies have been conducted in an attempt to generate information to support effective management of mangroves in the country. A study by Semesi (1992) provided countrywide baseline information on the distribution, status, coverage and uses of mangroves in the country. Other studies (Alavaisha and Mangora, 2016; Njana *et al.*, 2018) have reported on biomass or carbon densities. These studies are either generic in nature or provide information at national scale and are not entirely focused on urban mangroves.

A few site-specific studies, for example Mwansasu (2016), have looked at causes and perception of environmental changes in mangroves of the Rufiji delta in rural areas of south-eastern Tanzania, while Katundu (2006) carried out a similar study in urban areas of Kunduchi and Mbweni in Dar es Salaam. The former study focused on mangroves in rural areas while the later study addressed social and ecological resilience of mangrove ecosystems in urban areas.

The current study 1) determined spatial and temporal changes of mangrove forests, 2) identified drivers of mangrove deforestation and forest degradation, 3) determined historical carbon storage, sequestration and deforestation emissions by mangrove forests, and 4) determined whether the mangrove forests of Dar es Salaam were sources or sinks of CO_2.

Methods

Study area

This study was conducted in the Dar es Salaam Region of Tanzania. Dar es Salaam is the former capital and remains the main commercial centre and most industrialized and urbanized city in Tanzania, with a population of more than 5 million people. Dar es Salaam Region is located along the Indian Ocean on the east coast, situated between latitudes 6° 36’ and 7° 0’ S and longitudes 39° 0’ and 33° 33’ E. The region is estimated to cover 1 800 km^2 and comprises five Districts (Ilala, Kigamboni, Kinondoni, Temeke, and Ubungo). Only Ubungo District is not located on the coast and has no mangrove forests.

Dar es Salaam is divided into three ecological zones; lowlands, middle plateau and the hilly areas in northern and western parts of the region. Dar es Salaam is characterized by a modified equatorial climate with a mean temperature of 29°C. The average rainfall is 1000 mm ranging from 800 to 1300 mm. Humidity is around 67 % and 96 % in the morning and afternoon, respectively. Prevailing winds are south-westerly from April to October and north-westerly monsoon winds from November and March (URT, 2004). Mangrove forests in Mainland Tanzania cover about 110,000 hectares, 2,500 hectares of which are found is Dar es Salaam. Mangrove forests were declared as forest reserves in 1947 (MNRT, 1991).

Research methods

Both quantitative and qualitative research methods were used in this study. Spatial and temporal changes of mangrove forests, carbon storage and sequestration, and carbon emissions due to mangrove deforestation were determined using quantitative research methods. Quantitative methods were also used to determine whether the urban mangrove forests of Dar es Salaam are net carbon sinks or otherwise. Conversely, qualitative methods were applied to assess the drivers of mangrove deforestation and forest degradation. In this study, deforestation refers to the conversion of mangrove forest cover to non-mangrove forest cover while mangrove forest degradation refers to selective tree removal resulting into a decrease of forest quality and productivity.

Quantitative research methods

Spatial and temporal changes of mangrove forests were determined through mapping and change detection of mangrove forest cover and productivity (or forest condition) in the study area. Temporal change of mangrove forest cover was carried out for 20 years, from 1986 to 2016, divided into four data points of 1986, 1995, 2006 and 2016. The study period of 20 years was considered suitable for determining historical carbon storage, sequestration and emissions in the study area and is in line with the time series studies in the literature (Wang *et al.*, 2003; Long *et al.*, 2013; Njana *et al.*, 2021). Accordingly, the study utilised Landsat images, which were previously successfully used in spatial and temporal analysis of mangrove cover (e.g. Wang *et al.*, 2003; Hong *et al.*, 2020). Landsat images provided time series data at a resolution of 30 m since 1980s.

Freely available Landsat images were downloaded from the US Geological Survey National Centre for Earth Resources Observations and stacked using ERDAS Imagine software to obtain colour composite images. Dry season images which ensure relatively higher classification accuracy (e.g., Liu *et al.*, 2015; Kenduiywo *et al.*, 2020) were selected where possible from Landsat archives. Although coastal areas in the study area are often cloudy, only images with less than 10 % cloud were selected. Image enhancement was employed to improve the interpretability, while the histogram equalization method was used for contrast enhancement of the image so that all the information from the input image was represented. After the enhancement of colour composites, supervised classification was used for image classification. The Spatial Analyst Tool in ArcGIS 10.3 was used for image classification. Sample points collected in the field were used for validation of the results. The interpretation was validated with information collected from local and especially older people who had good knowledge of changes in the mangrove cover over time, including the areas covered by forest, buildings, and water.

The classified images for different years were then vectorised and clipped to obtain the area in hectares (ha) of mangroves forest at each location. Productivity or condition of mangrove forests was assessed using the Normalised Difference Vegetation Index (NDVI). NDVI values were derived using Eq. (1).

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad \text{............................ Eq. 1}$$

Where NIR = Near infra-red band and RED = Red band.

NDVI for each location was calculated for each year using ERDAS Imagine software. The maximum, mean and minimum NDVI values were recorded for each study site. NDVI has been applied successfully in many studies on mangrove forests (e.g. Zhu *et al.*, 2015; Gupta *et al.*, 2018; Hong *et al.*, 2020).

Total carbon stored and sequestered by mangrove forests may be estimated using two datasets: (i) mangrove forest cover/change (ha); and (ii) CO_2 equivalent density (tonnes CO_2e ha^{-1})/CO_2 equivalent sequestration density (tonnes CO_2e ha^{-1} $year^{-1}$). The later dataset is commonly derived using forest inventory data. However, forest inventory was beyond the scope of the current study, and secondary information was applied for this purpose. Recently, Njana *et al.* (2018) reported aboveground and belowground CO_2 equivalent densities for mangrove forests using national forest inventory data. Similarly, the study reported aboveground CO_2 equivalent and belowground CO_2 equivalent sequestration densities for mangrove forests using national level permanent sample plot data.

This study considered both above- and belowground carbon pools. Therefore, the total CO_2 equivalent density (TCD, tonnes CO_2e ha^{-1}; i.e. sum of aboveground CO_2 equivalent and belowground CO_2 equivalent densities) and the total CO_2 equivalent sequestration density (TCSD, tonnes CO_2e ha^{-1} $year^{-1}$; i.e. sum of aboveground CO_2 equivalent and belowground CO_2 equivalent sequestration densities) from Njana *et al.* (2018) were applied in the estimation of total carbon stored and sequestered by the mangrove forests of Dar es Salaam. TCD was also applied in the estimation of carbon emissions due to mangrove deforestation. The total annual carbon stored (TC), sequestered (TACS, tonnes CO_2e $year^{-1}$) and emitted (TACE, tonnes CO_2e $year^{-1}$) due to deforestation of mangrove forests in Dar es Salaam were derived using Eq. 2, Eq. 3 and Eq. 4 respectively. Similar procedures were applied by Njana *et al.* (2021) in the estimation of carbon storage, sequestration and emissions from forests in relation to land use and land cover change.

$$TC = A * TCD \quad \text{.........................} \text{ Eq. 2}$$

$$TACS = A_{FF} * TCSD. \quad \text{........................} \text{ Eq. 3}$$

$$TACE = A_{FN} * TCD.. \quad \text{........................} \text{ Eq. 2}$$

Where A = Area of mangrove forest cover (ha), A_{FF} = Area of mangrove forest cover remaining (ha), A_{FN} = Area of mangrove forest cover converted to non-mangrove forest cover divided by time; i.e. annual mangrove deforestation (ha $year^{-1}$).

Net carbon sink/net carbon source was determined by subtracting TACE from TACS. A positive resultant value implied a net carbon sink and a negative resultant value implied a net carbon source.

Qualitative research methods

Qualitative data for identifying drivers of mangrove deforestation and forest degradation was derived from Participatory Rural Appraisal (PRA) methods (Sandham *et al.*, 2019), and field observations. PRA methods employed in this study included focus group discussion (FGD) and indepth interviews with key informants. Four Districts with patches of mangrove forests were purposively selected for FGD. These include Kinondoni, Temeke, Ilala, and Kigamboni. The results from the analysis of mangrove forest cover and change were the basis for defining the mangrove forest patches (i.e. 11 patches) in the study area, and FGDs were conducted at each of these sites. FGD involved people living adjacent to mangrove forests and who were asked to identify driving factors of mangrove forest cover change in the study sites.

A neighbourhood Chairperson or the Neighbourhood Executive Officer (NEO) or their representative assisted in mobilizing participants for FGD and prepared the venue for the exercise. FGD comprised of 5 to 8 people including both males and females living closest to the individual patches of mangrove forests. The discussion was guided by open-ended questions such as *why, how, what, when*, and by the extent of change and productivity (quality) of mangrove forest cover in the study area from 1986 to 2016. The historical timeline was also conducted with at least two people in every site in order to 1) understand the history of the neighborhood/street and the people who are living in the study site, and 2) identify key events and how they related to the trends in the mangrove forests. The results from FGD were triangulated during in-depth interviews with key informants, who included District Forest Managers from Tanzania Forest Service (TFS) and ward and sub ward leaders in all the four districts endowed with mangrove forest patches.

Results from both FGD and in-depth interviews were subjected to content analysis according to Cavanagh (1997). Detailed analysis of research and other official reports such as the Mangrove Forest Management Plan for Dar es Salaam was also carried out to obtain further historic information. Finally, the results on drivers of mangrove deforestation and forest degradation were summarised in tabular form.

Results

Spatial and temporal changes of mangrove forests in Dar es Salaam

Land cover (LC) analysis revealed that there are 11 patches of mangrove forests in Dar es Salaam (Fig. 1). The patches were of variable size. The largest and smallest patches of mangroves were at Mtandika (1986-2006) and Ras Kilomoni (1986-2016). From 2016 the largest patch of mangrove forest changed to Mbezi river. Overall, Dar es Salaam had 4,813 ha of mangrove forests in 1986 which declined to 1,961 ha in 2016 (a decrease of 59 %). All sites exception Kunduchi creek (1995-2006) experienced a decline in mangrove forest cover (Fig. 2). Sites with larger patches recorded relatively higher loss of cover than did the smaller patches.

salt pans, hotel construction, settlements, and charcoal making were prominent drivers of mangrove deforestation across sites. Similarly, tree removal for firewood and building poles were prominent drivers of mangrove forest degradation across sites.

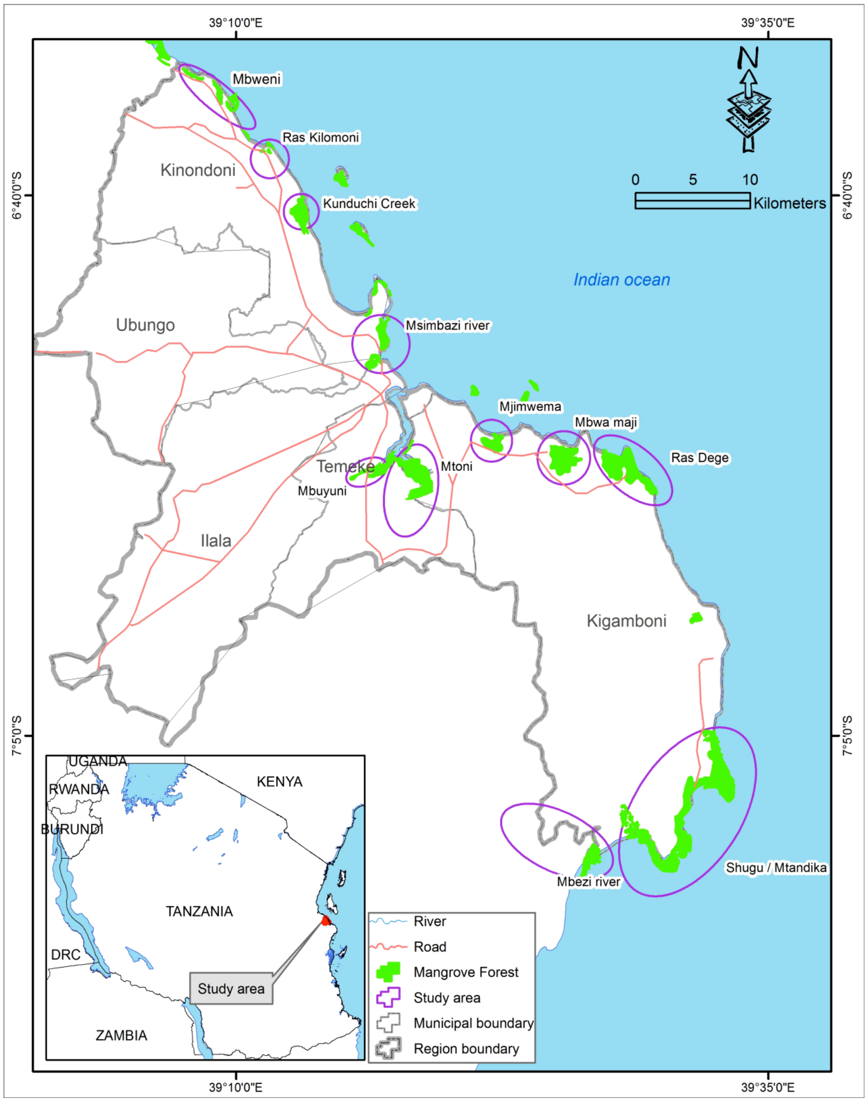

Figure 1. Patches of mangrove forests in Dar es Salaam.

Generally, the trend of NDVI values shows a decreasing trend from 1986 to 2006, yet for the period of 2006 to 2016 there was a significant increase in NDVI values for all sites (Fig. 3).

Drivers of deforestation and degradation of mangrove forests

Drivers of deforestation and degradation of mangrove forests in the study area are presented in Table 1. In descending order, clearing mangrove forests for

Trends of carbon stored in the mangrove forests of Dar es Salaam

The total carbon stored in mangrove forests of Dar es Salaam has been declining over time from 1,131,055 tonnes CO_2e in 1986, 883,835 tonnes CO_2e in 1995, 702,415 tonnes CO_2e in 2006, and 460,835 tonnes CO_2e in 2016. Site-specific statistics also show a similar declining trend over time. However, between 1995 and 2006 there was an increase of CO_2e of about 1,200 tonnes CO_2e (Fig. 4).

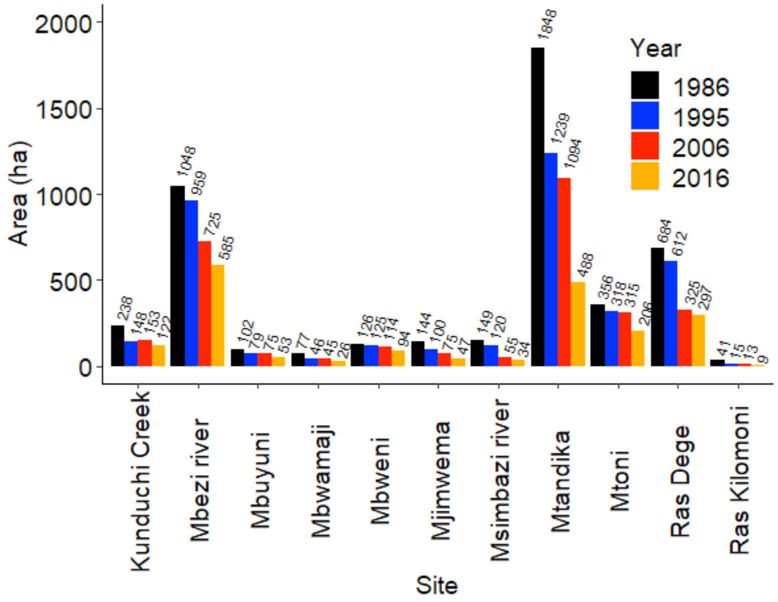

Figure 2. Mangrove forest cover in Dar es Salaam over time.

Trends of total annual carbon sequestration by mangrove forests of Dar es Salaam

Sequestration of CO_2 by mangrove forests of Dar es Salaam is estimated at 133,516 (1986-1995), 106,110 (1995-2006), and 69,616 (2006-2016) tonnes CO_2e year^{-1}. Overall statistics showed a decreasing trend of CO_2 sequestration with a decrease of more than 50 % between 2006 and 2016, relative to CO_2 sequestration observed between 1995 and 2006. Although, the site-specific distribution of CO_2 sequestration showed mixed results, the proportions are in general the same across time (Fig. 5).

Trends of total annual carbon emissions due to mangrove deforestation in Dar es Salaam

Mangrove deforestation resulted in emissions of about 27,400, 16,500 and 24,000 tonnes CO_2e year^{-1} in 1986-1995, 1995-2006 and 2006-2016, respectively. Site-specific results in Fig. 6 further show that loss of mangrove forest cover in Mtandika between 1986 and

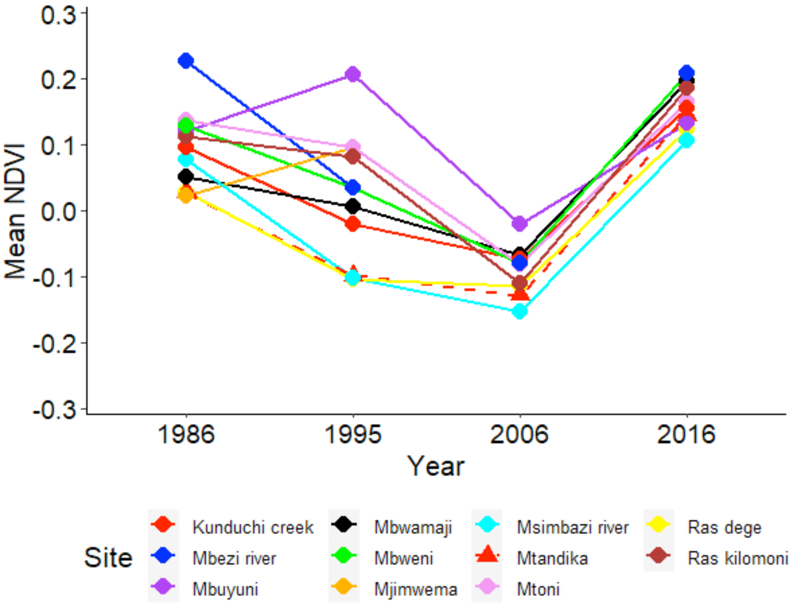

Figure 3. Trends of NDVI at the study sites.

Table 1. Drivers of deforestation and forest degradation.

SN	**Drivers**	**Study sites**											
		Kunduchi	**Mbezi river**	**Mbuyuni**	**Mtoni**	**Mbwa maji**	**Mbweni**	**Mjimwema**	**Msimbazi river**	**Ras Dege**	**Ras Kilomoni**	**Mtandika**	**%**
Drivers of deforestation													
1.	Charcoal making		√					√		√		√	40
2.	Hotel construction	√				√		√		√	√		50
3.	Industrial waste			√	√				√				20
4.	Infrastructure construction								√	√	√		30
5.	Rice farming			√	√	√				√			30
6.	Salt pans	√		√	√		√	√		√	√		60
7.	Settlement	√				√		√	√				40
Total cases		3	1	3	3	3	1	4	3	5	3	1	
Drivers of mangrove forest degradation													
1.	Boat making										√		10
2.	Firewood	√		√	√	√	√	√		√			60
3.	Medicines	√											10
4.	Building Poles	√				√		√			√	√	50
Total cases		3	0	1	1	2	1	2		1	2	1	

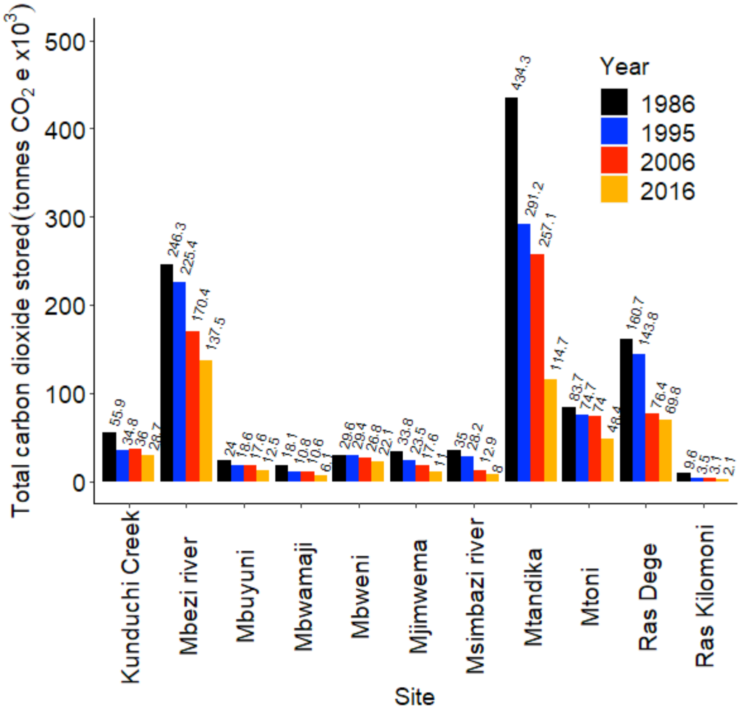

Figure 4. Carbon stored in the mangrove forests of Dar es Salaam over time.

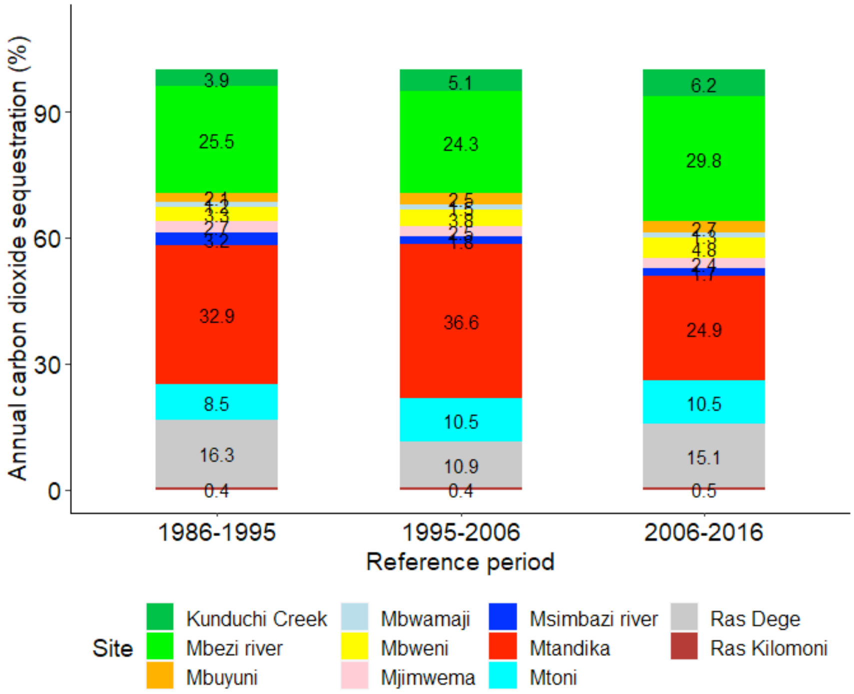

Figure 5. Total annual carbon sequestration by mangrove forests across sites.

1995 as well as from 2006 to 2016 contributed more than 50 % of total emissions in the study area. Similarly, loss of mangrove forest cover between 1995 and 2006 in Ras Dege and Mbezi river was responsible for more than 30 % of the total emissions from Dar es Salaam mangroves.

Mangrove forests of Dar es Salaam: Are they a net carbon sink or a net carbon source?

Whether mangrove forests of Dar es Salaam are a net sink or a net source of CO_2 was determined by comparing TACS and TACE for different periods under consideration. The results in Fig. 7 show that TACS was

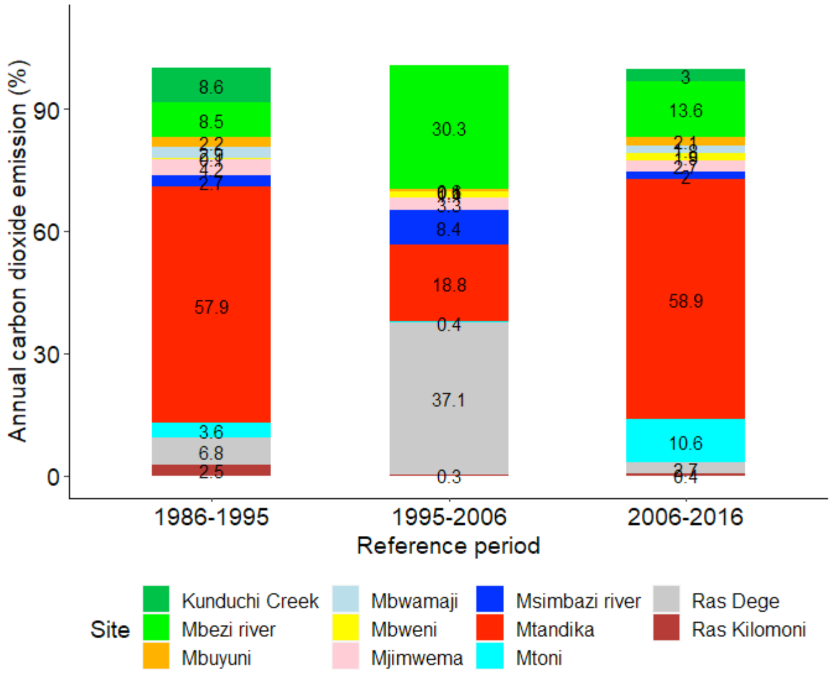

Figure 6. Total annual carbon emission from mangrove forests across sites.

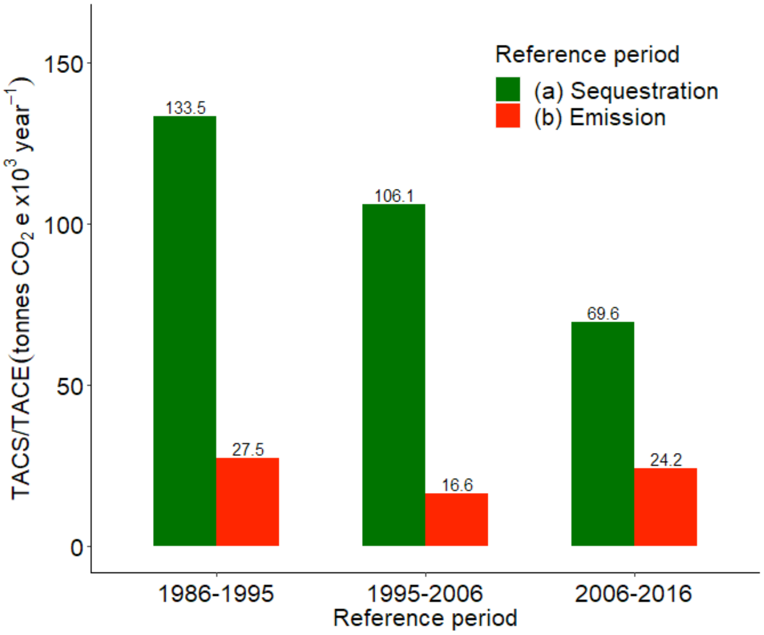

Figure 7. Annual carbon sequestration and emissions over time.

systematically higher than TACE from 1986 to 2016 implying that the mangrove forests of Dar es Salaam are a net sink of CO_2. The net carbon sink was 106, 89.5 and 45.4 tonnes CO_2e year^{-1} in 1986-1995, 1995-2006 and 2006-2016, respectively.

Discussion

Urban ecosystems such as the mangrove forests of Dar es Salaam regulate climate and local weather by removing greenhouse gases (GHG) such as CO_2 from the atmosphere, reducing heat strains and filtering air pollutants (Njana *et al.*, 2018). Such ecosystems may on the other hand propagate climate change when they are destroyed through their conversion into other land uses/land covers or through unsustainable exploitation. Given that mangroves store large quantities of carbon per unit area (Njana *et al.*, 2018; Mauya *et al.*, 2019), their conversion to other land uses/covers or unsustainable use may cause large emissions per unit area. Emissions cause climate change and resultant extreme weather conditions, air pollution affecting human health, and impair sustainable development in general (Epstein, 2001; Hunter, 2003; Svirejeva-Hopkins *et al.*, 2004; Parrish and Zhu, 2009; IPCC, 2014; URT, 2014). Therefore, global efforts aim at, among other things, stabilizing the atmospheric abundance of CO_2 and other greenhouse gases through sequestering CO_2 from point sources or from the atmosphere.

The analysis of land use and land cover changes are central in supporting global efforts of stabilizing the atmospheric abundance of CO_2 and other greenhouse gases. More importantly, the results from land use and land cover and their changes are pre-requisites for effective urban land use planning. The findings from this study show a decreasing trend of mangrove forests from 1986 to 2016 in Dar es Salaam. Such results are consistent with the national, regional and global trends of mangrove forests both in urban and rural areas (Wang *et al.*, 2003; FAO, 2007; Hong *et al.*, 2020). However, there is a discrepancy in the estimated acreage of mangrove forests lost in Dar es Salaam compared to the findings by Wang *et al.*, (2003). Such discrepancy is attributable to differences in methodological approaches, analysis techniques, cloud cover in the images used, the data used and the reference period. For example, differences in the estimates of mangrove cover between the Wang *et al.* (2003) study and the present study could be due to misclassification of mangrove forests (e.g. Long *et al.*, 2013).

The quality of mangrove forests was estimated using NDVI which declined from 1986 to 2006. The trend of mangrove NDVI during this period was similar to the trend of mangrove forest cover for the same period. However, contrary to the further declining trends of mangrove forest cover between 2006 and 2016, NDVI results showed that the quality of mangrove forests improved from 2006 to 2016. In the early 1990s, the Forest and Beekeeping Division developed mangrove management plans for all mangroves in mainland

Tanzania including Dar es Salaam (MNRT, 1991). The management plans proposed a number of activities such as replanting in degraded mangrove stands, environmental conservation education to the local communities and enhancement of law enforcement. Effective implementation of such activities in Dar es Salaam started around 2000s through the Mangrove Management Project funded by NORAD under the Forest and Beekeeping Division. Replanting of mangroves in degraded mangrove stands and natural regeneration of mangroves as a result of effective law enforcement and compliance resulted into improved productivity of mangroves in Dar es Salaam; hence the observed rise of NDVI values from 2006 to 2016. This finding is consistent with the findings of Feller *et al.* (2017) who revealed that conservation and rehabilitation efforts coupled with natural regeneration may promote gains in specific mangrove areas.

The study also identified anthropogenic drivers of mangrove deforestation and degradation. Similar drivers are reported in the existing literature (e.g. Wang *et al.*, 2003; Mohamed *et al.*, 2009; Kithiia and Lyth, 2011; Troung and Do, 2018; Hong *et al.*, 2020). Drivers of deforestation and degradation of urban mangrove forests identified in the present and many other studies are very much associated with population growth. High population in urban areas such as Dar es Salaam is characterised by high demands for natural resources (e.g. charcoal for energy) and land uses other than forestry. Studies show that growth of cities affects the environment directly and indirectly and has been a source of much pollution due to large consumption of fuel for transportation, for example (Bettencourt and West, 2010; Hillman and Ramaswami, 2010). The literature indicates that, since 1950, the proportion of the world's population living in urban areas has increased from 13 % to more than 50 % (UNPD, 2011) suggesting that urbanization is the main obstacle to sustainable development (McDonald, 2008). Although the total urban area worldwide remains a relatively small fraction of the earth's terrestrial surface, urbanized areas account for roughly 75 % of the global consumption of resources (Angel *et al.*, 2005; Pacione, 2009). The drivers of mangrove deforestation and degradation identified in this study are useful in designing and developing strategies for REDD+. Direct drivers and underlying causes of deforestation and forest degradation such as those reported in this study are the basis for development and designing of REDD+ strategies that are aimed at the reduction of emissions from deforestation and forest degradation, improvement of management of forests, as well as conservation and enhancement of forest carbon stocks.

The findings of this study demonstrate that the urban mangrove forests of Dar es Salaam store and sequester large quantities of atmospheric CO_2 and thereby contribute to climate regulation. In addition, studies show that urban mangroves ameliorate local weather and filter air pollutants due to economic development activities in the cities (Alavipanah *et al.*, 2015; Fan *et al.*, 2015; Rotem-Mindali *et al.*, 2015; Kayet *et al.*, 2016; Rousta *et al.*, 2018). Both total stored and sequestered carbon by the urban mangrove forests of Dar es Salaam had been declining from 1986 to 2016. A decreasing trend of forest cover due to urbanization was also previously reported by Delphin *et al.* (2015). The current study shows that trends of carbon stocks, sequestration and emissions are linked to spatial and temporal dynamics of mangrove forest cover in the city. Accordingly, emissions due to mangrove deforestation are high. Although it was revealed that mangrove forests in the study area are a net carbon sink, the sink role played by mangrove forests is decreasing rapidly. It is expected that these findings will stimulate dialogues and pave the way for making appropriate decisions on the management of urban mangrove forests.

The loss of urban mangrove forests does not only threaten regulatory ecosystem services of storing and sequestering greenhouse gases, which poses environmental challenges to the present and future generations, but also has other severe negative impacts. Such impacts include loss of other ecosystem services including coastal protection against storm surge and loss of breeding sites for fish and habitat for several marine species. Therefore, management of urban mangrove forests needs to be enhanced.

Success of conservation efforts of urban mangrove forests relies on strategies and interventions aimed at addressing drivers of mangrove deforestation and degradation. Priorities should be focused on that include addressing the drivers causing substantial impacts on carbon storage and sequestration (e.g. charcoal making, salt pans etc.) since such ecosystem services are fundamental for the mitigation of climate change that affects many sectors of the economy. Therefore, effective urban land use planning, law enforcement, as well as awareness creation and education are recommended.

Conclusion

Urban mangrove forests play an important environmental role in mitigating climate change and ameliorating the severity of local weather conditions through the large carbon stocks they store and sequester. However, the declining spatial and temporal trends of urban mangrove forest cover have resulted in a systematic decrease of the total carbon stored and sequestered by mangrove forests in Dar es Salaam. Such a trend is largely and indirectly caused by high urbanization. Consequently, emissions due to mangrove deforestation are high. In addition, mangrove forests in the study area are still a net carbon sink. However, the sink role played by mangrove forests in the study area is decreasing rapidly. In the absence of timely measures for preserving and rehabilitating degraded mangrove areas, mangrove forests of Dar Salaam may be transformed into a source of CO_2. The findings from this study are expected to stimulate dialogues and pave the way for making appropriate decisions and taking appropriate measures on the conservation of urban mangrove forests. This study therefore recommends effective urban land use planning and law enforcement, awareness raising and education aimed at achieving both sustained ecosystem services offered by urban mangrove forests and economic growth.

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