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Land Use Land/Cover Change Reduces Woody Plant Diversity and Carbon Stocks in a Lowland Coastal Forest Ecosystem, Tanzania

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Abstract: The East-African lowland coastal forest (LCF) is one of Africa's centres of species endemism, representing an important biodiversity hotspot. However, deforestation and forest degradation due to the high demand for fuelwood has reduced forest cover and diversity, with unknown consequences for associated terrestrial carbon stocks in this LCF system. Our study assessed spatio-temporal land use and land cover changes (LULC) in 1998, 2008, 2018 in the LCF ecosystem, Tanzania. In addition, we conducted a forest inventory survey and calculated associated carbon storage for this LCF ecosystem. Using methods of land use change evaluation plug-in in QGIS based on historical land use data, we modelled carbon stock trends post-2018 in associated LULC for the future 30 years. We found that agriculture and grassland combined increased substantially by 21.5% between the year 1998 and 2018 while forest cover declined by 29%. Furthermore, forest above-ground live biomass carbon (AGC) was 2.4 times higher in forest than in the bushland, 5.8 times in the agriculture with scattered settlement and 14.8 times higher than in the grassland. The estimated average soil organic carbon (SOC) was 76.03 ± 6.26 t/ha across the entire study area. Our study helps to identify land use impacts on ecosystem services, supporting decision-makers in future land-use planning.

Keywords: remote sensing and GIS; IVI; soil organic carbon; Wami Mbiki-Saadani ecosystem



Citation: Ntukey, L.T.; Munishi, L.K.; Treydte, A.C. Land Use Land/Cover Change Reduces Woody Plant Diversity and Carbon Stocks in a Lowland Coastal Forest Ecosystem, Tanzania. *Sustainability* **2022**, *14*, 8551. <https://doi.org/10.3390/su14148551>

Academic Editor: Zbigniew Zwolinski

Received: 5 June 2022

Accepted: 30 June 2022

Published: 13 July 2022

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1. Introduction

Tropical forests play an essential role in the global carbon cycle. They store approximately 40–50% of the total carbon stocks in terrestrial ecosystems of the world, account for around 30–40% of global net primary production [1–3], are currently under threat due to deforestation [4]. Tropical montane forest's (TMFs) above-ground live biomass carbon (AGC) varies along the elevation gradient and with soil physico-chemical properties [1] but is not tested in lowland coastal forests (LCF). Land-use changes are associated with ecosystem carbon stock changes and are the second largest cause of carbon emission after fossil fuel combustion [5]. Intensification of human pressure associated with resource extraction is widespread, but AGC losses and localized extinction of many important tree species for carbon storage and climate regulation are uncertain [6,7].

Recently, human economic development and population increase have enhanced deforestation and forest degradation in East Africa [8–10], often related to fuelwood, selected logging, which strongly changes the woody carbon balance [11]. It is clear that trees play significant roles in carbon storage and forest ecosystem functioning; thus, any alteration in their distribution in a forest ecosystem will likely exacerbate ecosystem degradation [12]. Forest plant species diversity can modify the rate of carbon fluxes and mitigate the effects of climate change [13]. However, current forest degradation rates, including deforestation and a general decline in plant species diversity and composition, have influenced forest

ecosystem processes, such as carbon cycling [14]. Little is known about how tree biodiversity influences carbon storage in LCFs ecosystem [15,16]. Following forest loss, plant species richness generally decreases while the plant species assemblage becomes less even and more structurally homogeneous [17]. The loss of biodiversity substantially affects AGC storage in lowland systems and diverse and complex tropical forests [18,19]. However, the association of soil carbon stocks and functional diversity remains a knowledge gap in LCFs [20]. It is still unknown if these patterns are reliable in the LCF ecosystem [10].

The eastern African LCF ecoregion is one of Africa's centers of species endemism. It is distributed over six countries (Somalia, Kenya, Tanzania, Mozambique, Zimbabwe, and Malawi) [21], with Tanzania comprising large parts of it [21,22]. These coastal forests are fragmented, small and surrounded by resource-poor communities with a high demand for land and forest resources [23,24], and the LCF ecosystem in Tanzania faces high anthropogenic pressure, including deforestation and forest degradation [22,25,26]. It is not well known how plant diversity and associated carbon stocks are affected in this LCF system [27].

We assessed how ecosystem structure (above-ground biomass of live trees and associated carbon stocks (AGC), below-ground carbon stocks (BGC), herbaceous plant carbon, soil organic carbon, plant species composition and diversity) has changed over two decades following land use/land cover (LULC) class changes in the LCF ecosystem of Tanzania. We aimed to estimate the forest cover change and quantify associated AGC and BGC using Remote Sensing and a forest inventory data set between the years 1998 and 2018. We assessed woody and herbaceous plant species diversity and important value index (IVI) population structure of woody plants across 80 sample plots of 15-m radius in different LULC classes in the LCFs ecosystem, Tanzania, from 1998 to 2018. We investigated whether species with high IVI, an index that quantifies the ecological significance of a species in a specific community [28], will be negatively affected by land use land cover change.

We hypothesized that a forest cover decline will negatively affect woody plant species' diversity, IVI, and carbon stocks. We also hypothesized that land-use changes will result in lower soil organic carbon across all LULC categories. We further expected that a higher woody vegetation species richness and evenness would result in higher above-ground carbon values. We projected future land use land cover change up to 2048 using module for land use change evaluation (MOLUSCE) model in QGIS.

Our findings help to inform decision-makers on the urgent need to strengthen the conservation of the highly fragile LCFs ecosystem to save its numerous endemic tree and animal species. We further contribute to the understanding of how deforestation can hamper climate change mitigation effects by reducing the terrestrial carbon sink.

2. Materials and Methods

2.1. Study Area Description

We studied the lowland tropical coastal forest (LCF) ecosystem in Tanzania, located in 5°0'40" and 6°0'40" S, 37°50'0" and 38°50'0" E in the wildlife-rich north-eastern tourist circuit ([29]; Figure 1). The area occupies approximately 5397 km² and spans an altitudinal gradient of approximately 875 m above sea level (masl) [26,30] around the Wami River sub-basin, which links terrestrial and marine ecosystems [30–32] (Figure 1). This LCF lies in one of the world's known hotspots of biological diversity, including both the Eastern Arc Mountains and coastal forest [26]. The mean daily temperature is 25 °C and means annual rainfall of over 1000 mm [30,33], with dry periods from July to October and wet periods from November to December and March to June. The area is comprised of a complex mosaic land cover interspersed with human settlements and pastoralists, shifting cultivation agriculturalists, and large-scale agriculture, mainly sugar plantations in the eastern part of the ecosystem. There is a high demand for fuelwood, primarily charcoal, which poses significant challenges for plant species diversity and carbon emissions due to these anthropogenic activities [26].

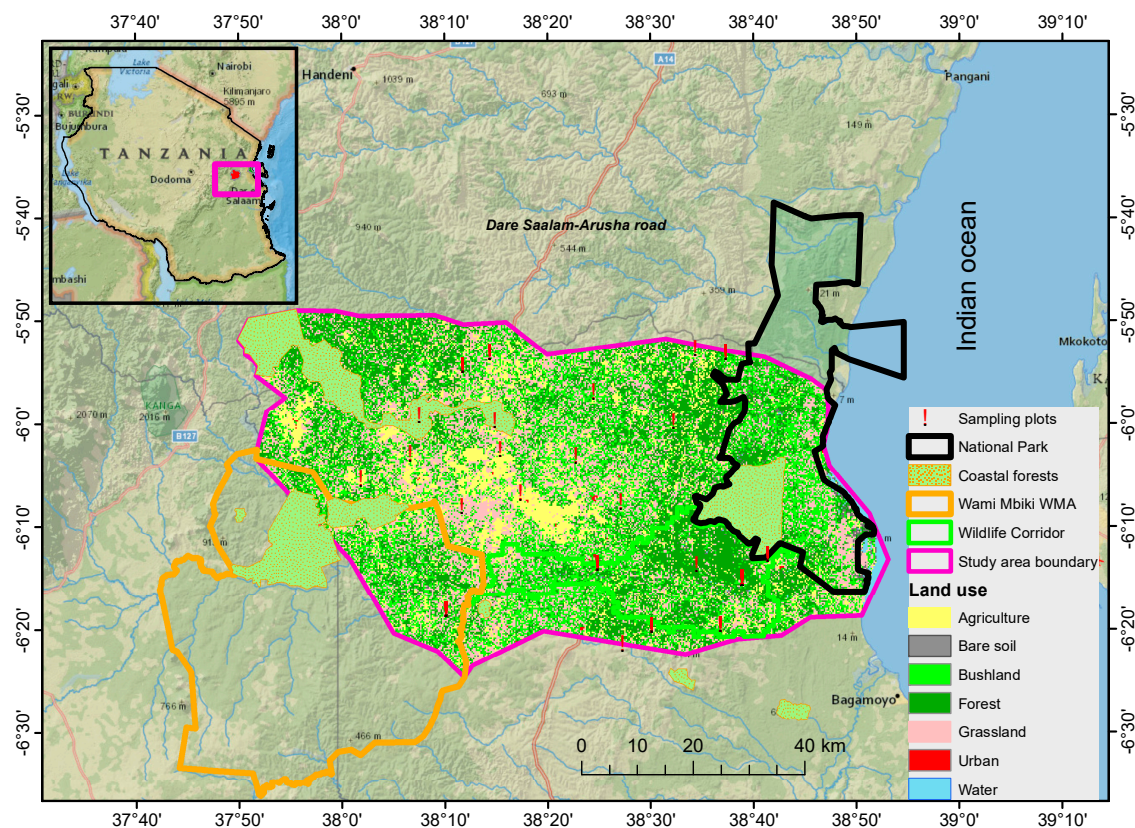


Figure 1. Map of the study area within the lowland coastal forest ecosystem, Tanzania, and location of sampling plots for woody, herbaceous vegetation and soil assessment (red circles). WMA, wildlife management area, National Park, Saadani National Park. Land use cover was based on the year 2018 land use classification.

2.2. Remote Sensing Image Classification and Predictive Model

In consideration of seasonality, cloud cover and phenological effects, we selected dry season remote sensing images (Landsat TM & Landsat 8) with a minimum cloud cover of <10% from Earth Explorer (<https://earthexplorer.usgs.gov> (accessed on 25 January 2022)) from 1998, 2008, and 2018 for land use/cover (LULC) change classifications, downloaded via Google Earth Code Editor [34,35]; see also [26]. The land use prediction was carried out using open-source software QGIS version 2.18 using modules for land use change evaluation (MOLUSCE) plug-in. MOLUSCE uses the Artificial Neural Network (ANN), Multi-Criteria Evaluation (MCE), Weights of Evidence (WOE) and Logistic Regression (LR) methods to model land use/cover transition potential and simulate future land use change [36–41]. In this study, we used artificial neural network (multi-layer perceptron) and cellular automata (CA) to map future land use for the years 2028, 2038 and 2048 [36].

2.3. Vegetation Assessment

Using stratified random sampling procedures, we assessed woody and herbaceous vegetation in 80 sample plots (according to) [10]; i.e., Forest: N = 25, Bushland: N = 24, Agriculture with scattered settlements: N = 11, and Grassland: N = 20 plots) based on the proportional area cover of each LULC class according to the 2018 land use map. Within these LULC classes [26], we assessed woody and herbaceous plant biomass, plant species diversity, and plant and soil carbon stocks. The overall cover of these LULC classes summed up to a total area of 526,285 ha (98.4% of the total area) in 2018.

We employed a concentric plot design within a radius of 15 m for woody vegetation [42] and used 1 m × 1 m plots for herbaceous vegetation, based on the most recent land use map of the year 2018. We located inter-plot distances systematically 900 m apart

in North-South directions. Our sampling strategy followed the National Forestry Resource Monitoring and Assessment (NAFORMA) procedures [42]. For each woody species individual within the plot, we measured diameter at breast height (DBH), defined as 1.3 m above ground level, with adjustments for swollen tree bases, injuries, fluting and other deformities [43–45]. We used allometric models for species-specific carbon stock estimation across the different carbon pools of vegetation and soils according to the literature (Table 1). We identified each woody plant species according [46–48] and each grass species according to [49,50]. Plant species diversity was expressed as Shannon diversity index, and we assessed evenness and richness [51]. We measured woody plant species composition and population structure by counting and recording all plants with diameter less than five centimetres as regenerating seedlings.

Within each woody vegetation plot, we established one (1 m × 1 m) quadrat at the centre of the 15 m radius circle, whereby all grasses within this plot were identified, cut at the stem base, collected, and fresh weight of vegetative samples was determined using a weighing balance in the field. A portion of 50% of fresh grass from each quadrant was taken for lab analysis [44]. In our analyses, we did not consider forbs as their cover was <5% across all plots. The loss on ignition (LOI) method was used to determine the percentage of carbon in herbaceous (grassy) materials [52,53] on 50% of fresh material collected in the field, oven-dried and burnt in the furnace for organic carbon estimation [54]. We calculated the herbaceous (grass) carbon percentage according to [52,53,55]. To estimate the BGC components (e.g., for roots of grassy samples) in herbaceous sampling plots we used 0.24 as a default root to shoot ratio for below-ground woody biomass [56]; (see also Table 1). The herb assessment just focused on biomass and associated carbon stocks.

2.4. Soil Sampling and Physico-Chemical Analyses

Soil samples were collected in four compass directions at the rim of each woody vegetation sample plot (15 m from the centre of the sample plot) in the east, south, west and north directions [42]. We excavated 500 g of soil up to 30 cm deep using a standard soil auger of 76 mm diameter and divided the sample into three composite samples at three depths (0–10 cm, 10–20 cm, and 20–30 cm per plot [57]. In total, we collected 189 soil samples from the four different LULC classes for laboratory soil analysis.

Soil bulk density was taken at a cross-section in each plot using a sampling cylinder (10 cm height and 6.35 cm diameter) [58]. The wet weight of soils was measured using a field-scale weigh balance, then samples were labelled and oven-dried for lab carbon estimation. Samples were sieved through a 2 mm mesh and subsequently analyzed for soil organic carbon via wet oxidation using the Walkley–Black method [59].

The following equation provided the respective organic carbon estimate:

$$\text{Organic C\%} = \frac{(\text{meq of K}_2\text{Cr}_2\text{O}_7 - \text{meq of FeSO}_4) \times 0.336}{\text{Oven} - \text{dry soil (g)}} \quad (1)$$

The Walkley–Black method for the determination of organic carbon in soils has been found to give approximately 89% recovery of carbon as compared to the dry combustion method [60]. For our analyses, we considered the fine earth fraction of soil samples less than 2 mm while fine roots, rocks and stone materials were left out as these fine particles comprise the majority of the reactive soil surface [60–62]. Rocks and bigger soil aggregates may physically trap elements/nutrients that cannot be extracted, hence, making carbon quantification difficult [62]. We calculated soil organic carbon stocks for each sampling soil depth separately [63].

The total nitrogen (N) in soils was estimated following the Kjeldahl method [64].

We estimated soil pH (at 1:2.5 soil/H₂O) using a pH meter, whereby 10 g of soil sample was placed into a 50 mL beaker and mixed with 20 mL of CaCl₂ solution [65]. The pH meter was calibrated using two buffer solutions, i.e., one with neutral pH (7.0), and the other based on the range of pH in the soil.

We used the common hydrometer method [60,61] on 50 g of oven-dried soil in a baffled stirring cup containing distilled water and 10 mL of sodium hexametaphosphate solution [60]. We took hydrometer readings precisely 2 h after the suspension had been mixed [60]. From the percentage of sand, silt and clay calculated on the datasheet, the textural triangle diagram was used to determine the texture class of the studied soil samples [60,61].

2.5. Woody Plant Species Diversity

We used the Shannon diversity index [66] and the important value index (IVI) [66] to understand plant species composition. The importance value index is the index used to determine the overall significance of each species in the community structure, which affects the survival and dominance of many other species in the community [67]. The removal or addition of species with a high importance value index (IVI) results in significant shifts in the plant community's composition and structure, which may affect carbon storage and species diversity [68,69]. According to [69], we determined the IVI as the average of the sum of the relative density (RD), relative frequency (RF), and relative dominance (Rdo), each expressed as a percentage [70], of each tree species across all LULC classes. The higher the IVI, the more influential the plant is for the community, and its loss would present more significant damage [66]. We also estimated stem basal area based on diameter at breast height (DBH) as a measure of tree density [71].

2.6. Carbon Estimation

The woody vegetation's above and below-ground carbon stocks (AGC and BGC, respectively) were estimated based on allometric equations for different lowland tree species [72,73] in Tanzania (Table 1). Data on wood gravitation density (wood mass) of species identified within the sampling plots during vegetation assessment were obtained from a global database of wood specific gravity [74]. Grass carbon was estimated according to [56]. Soil carbon was assessed according to [63,75], (Table 1).

Table 1. Summary of carbon pools estimated for different plant and soil components including above-ground and below-ground woody, grassy and soil organic mean carbon stocks across different land use land cover change classes [26] and according to the reference literature for methods used in lowland coastal forests. AGC, above-ground live biomass carbon; BGC, below-ground carbon; SOC, soil organic carbon; C Pool, carbon pools; SE, standard error of the mean. Ctotal refers to the carbon pool across the entire system.

| C Pool | Allometric Equations | Mean C Density (t/ha) | ±SE | Reference |
|----------------------|---------------------------------------------------|-----------------------|------|------------|
| AGC _{woody} | $0.9569 \times dbh^{2.0085} \times \rho^{0.4908}$ | 61.2 | 17.8 | [72,73] |
| BGC _{woody} | $5.3854 \times dbh^{1.30709} \times \rho^{1.047}$ | 34.9 | 7.3 | [42,73] |
| C _{grass} | CH = B × C (%) | 2.5 | 0.1 | [56] |
| SOC | SCO = C% × BD × Depth | 76.0 | 6.3 | [57,59,63] |
| C _{total} | | 172.1 | 31.4 | |

2.7. Statistical Analysis

We correlated AGC against tree species Shannon diversity index, richness and evenness, based on the biodiversity-ecosystem function hypothesis that species diversity drives biomass production [76–79]. The analyses were carried out using R-Software 3.0.1, Vienna, Austria [80] and the vegan biodiversity library.

The woody carbon stocks within the LCF for the years 1998 and 2008 was estimated using average carbon stocks across forest, bushland, and agriculture with scattered settlement, based on our field survey and LULC classes of the year 2018. Next, the woody biomass value quantified using the LULC classes of the year 2018 was used to estimate carbon

densities for the years between 1998 and 2008 [10,81–83]. Finally, we estimated the total carbon stocks for the entire study area by multiplying the average carbon stocks per ha by the total LULC class area (ha) for each of the time steps (1998, 2008) [81,83]. We conducted a non-parametric analysis using Kruskal-Wallis's test followed by the Games-Howell post-hoc test to determine variations in woody and grassy above and below-ground carbon, and plant diversity index variations across different LULC classes.

3. Results

3.1. Land Cover Change in the LCF Ecosystem over the Last 20 Years

The LULC class maps for 1998, 2008, and 2018 showed significant variations in the patterns of LULC classes (Figure 2). Forest cover dropped in the year 2018 to 31.4% of its original value in the year 1998. On the other hand, grassland cover substantially increased from 8.6% in the year 2008 to 27.6% in year 2018, suggesting high forest conversion to grassland and other land cover classes. Over the past two decades, the LCF ecosystem has witnessed a forest loss of almost 50% (Table A1). In contrast, agriculture with scattered settlement and grassland increased threefold, while bushland remained relatively constant between the years 1998 and 2018, as did bare soil and water resources (Table A1, Figure 2). Urban settlement area only slightly and not significantly increased by less than 1%.

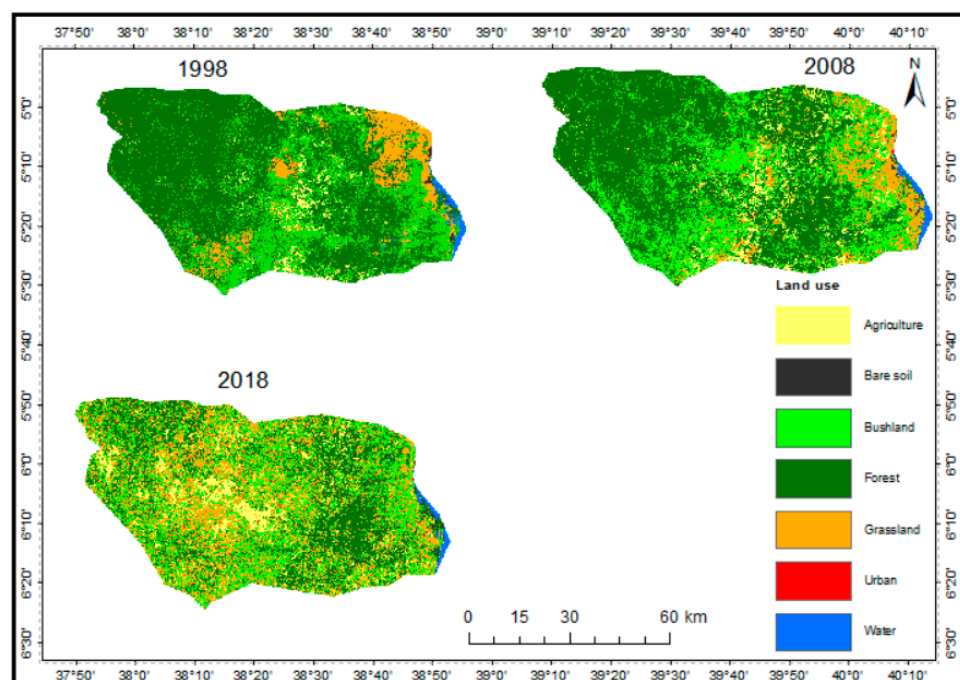


Figure 2. Land use/land cover maps for the lowland coastal forest ecosystem, Tanzania, for the years 1998, 2008, and 2018. Categories are based on Landsat image classification for 1998, 2008 and 2018 (see also [26]). Agriculture, agriculture and scattered settlement.

We created two transition matrices on LULC classes for the 1998–2008 and 2008–2018 periods by analyzing change detection using cross-tabulation (see Appendix A: Tables A2 and A3). The transition matrices clearly showed the large-scale conversion of forest land and bushland into agriculture with scattered settlement and grassland over two decades (Table A3). However, forest cover was gained from other cover classes in a few instances (see Tables A2 and A3). Our LULC class change scenarios using open source QGIS and the Module of Land Use Change Evaluation (MOLUSCE) plug in (Figure 3) showed that the forest area is expected to decrease by 46.2 km² from 2018 to 2048 while agriculture with scattered settlements is likely to increase by 20.4 km². Bushland is expected to decrease by 13.9 km² over three decades (2018–2048). The solid lines (grey = forest, yellow = bushland and blue = agriculture with scattered settlement) indicate the measured land use/cover classes for 1998, 2008, and 2018, and the predicted linear

trends of the land use/cover classes for 2028, 2038, and 2048 based on our model (dotted lines). The total estimated carbon stocks were based on three land use/cover classes only (i.e., agriculture with scattered settlement, forest, and bushland between 1998 and 2018). In regression equations, x represents time, y represents area change of respective land use/cover class (Figure 3).

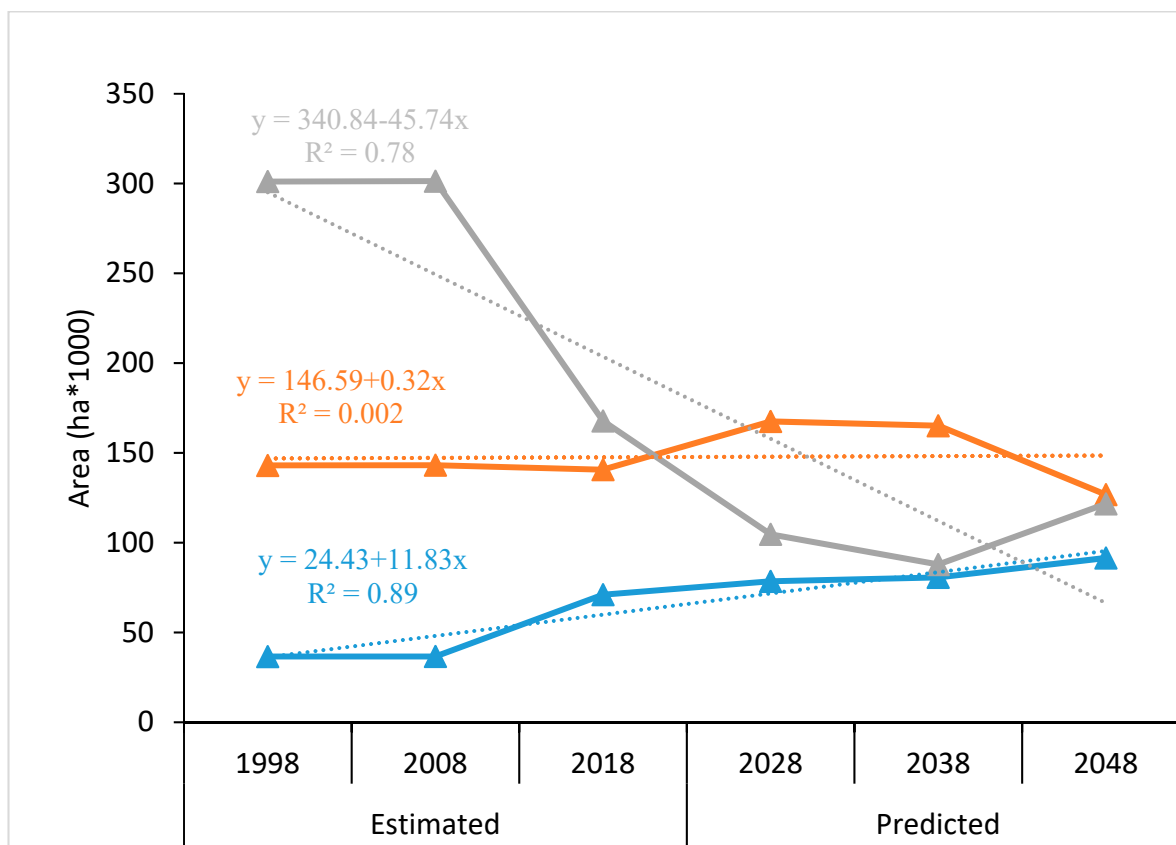


Figure 3. Land use/land cover class trends as assessed from 1998 to 2018 and further predicted over the next 30 years (2028–2048) using QGIS and Module of Land Use Evaluation (MOLUSCE) plugin [38–40] in the lowland coastal forest ecosystem, Tanzania.

3.2. Plant Species Diversity and Composition

We identified 87 different tree species from 25 families and 59 genera across all LULC classes (Supplementary Material Table S1). The dominant families were Fabaceae (21 species), Combretaceae (9 species), Euphorbiaceae (7 species) and Rutaceae and Sapotaceae (6 species each). The tree species richness significantly differed among LULC classes ($\chi^2 = 6.39$, $p = 0.041$), with forest having slightly higher species richness than bushland while agriculture with scattered settlements had the lowest species richness. However, species evenness was not significantly different between LULC classes ($\chi^2 = 0.12$, $p = 0.939$), nor was the Shannon diversity index ($\chi^2 = 0.12$, $p = 0.147$), indicating few dominant species. (Table 2). We identified 13 different grass species belonging to 10 families (Supplementary Materials Table S2).

Table 2. Mean (\pm SE) values for Shannon diversity index (Diversity), evenness, and richness for woody and herbaceous plant species across different land use/cover classes in the lowland coastal forest of the Wami Mbiki-Saadani ecosystem, Tanzania, in the year 2018. Mean values in the columns followed by lower case letters are statistically significant at $p < 0.05$ based on a Games–Howell post hoc test.

| LULC Classes | Diversity | Evenness | Richness |
|--------------|-------------------|-------------------|-------------------|
| Bushland | 1.27 \pm 0.16 a | 0.29 \pm 0.04 a | 4.16 \pm 0.63 a |
| Agriculture | 0.38 \pm 0.38 a | 0.28 \pm 0.14 a | 1.00 \pm 0.00 b |
| Forest | 0.92 \pm 0.18 a | 0.28 \pm 0.04 a | 5.70 \pm 0.79 c |
| Grassland | 0.16 \pm 0.03 a | 0.25 \pm 0.21 a | 2.54 \pm 0.69 a |

The important value index (IVI) results revealed that only two tree species (*Ehretia amoena* and *Sterculia appendiculata*) were found to occupy all three LULC classes (Supplementary Material Table S3) while most species dominated in one or two land-use types. *Combretum molle* and *Diospyros squarrosa* were dominant in both forest and bushland. Agriculture with scattered settlements was dominated by *Deinbollia borbonica*, and *Flugea virrosa*, whereas the dominant woody species in bushland were *Steganotaenia araliacea*, *Combretum collinum*, *Senegalia goetzei*, *Terminalia mollis* and *Senegalia nigrescens*. For the forest land use, dominant tree species were *Spirostachys africana*, and *Tamarindus indica* (Table S3). In grassland, the most dominant species were *Cyperus kyilingia*, and *Cymbopogon plurrinotus* (Table S2).

3.3. Carbon Stocks in Vegetation

The above-ground carbon stocks (AGC) of woody and grassy vegetation differed significantly across LULC classes ($\chi^2 = 9.71$, $df = 2$, $p = 0.008$), with forest AGC being more than twice as high as bushland and more than ten times as high as agriculture with scattered settlement and grassland (Table 3). The below-ground carbon was significantly different across LULC classes ($\chi^2 = 11.37$, $df = 2$, $p = 0.003$) with forest having more than two times higher BGC than bushland, ten times higher than agriculture with scattered settlement and more than thirty-eight times higher than grass land (Table 3). There was a strong positive correlation between above-ground woody carbon and above-ground grassy carbon ($r = 0.79$, $p < 0.001$) as well as a positive correlation between below-ground woody and grassy carbon ($r = 0.62$, $p = 0.003$). Species richness and Shannon diversity index (H') explained 26.9% and 8.2% of the variations in the AGC stocks in bushland, 15.6%, 6.0% in agriculture with scattered settlements and 11.8%, and 1.9% in the forest, respectively, the contribution to carbon storage differed among the land cover types. The relationship between AGC stock and species richness showed a significant positive correlation ($r = 0.616$, $p < 0.001$). The relationship between species diversity (Shannon diversity) and AGC were not significant different nor was species evenness among different LULC classes. The most dominant plant species contributed to about 46% of total AGC. *Tamarandus indica* contributed the most on AGC (10.8%) with mean DBH 38.0 ± 9.8 cm, followed by *Diospyros squarrosa* (8.6%), mean DBH 12.5 ± 0.6 cm, followed by *Manilkara mochisia* (19.5%), mean DBH 15.5 ± 1.1 cm and *Spirostachys africana* (4.6%) with a mean DBH of 16.0 ± 1.3 cm and other plant species individually contributed less than 4.0% of the AGC. The dominant plant species in the forest LULC class contributed most to the AGC (63.7%), and those for bushland contributed to 10.2%.

There was a significant relationship between AGC and DBH class of trees ($\chi^2 = 8.56$, $df = 3$, $p = 0.036$), whereby highest mean carbon storage was found in 10–15 cm DBH and the lowest in the 3–5 cm dbh class (Table 4). Further, the highest mean BGC was also found for the tree DBH class of 10–15 cm ($\chi^2 = 8.39$, $df = 3$, $p = 0.039$; Table 4).

Table 3. Mean (\pm SE) values for woody and grassy above-ground live biomass carbon (tC/ha) and below-ground carbon (tC/ha) combined across different land use/cover classes in the lowland coastal forest ecosystem, Tanzania, in the year 2018. Mean values in the columns followed by lower case letters are statistically significant based on a Games–Howell post hoc test.

| Land Use | AGC (tC/ha) | BGC (tC/ha) |
|-------------|------------------|------------------|
| Grassland | 2.51 \pm 0.1 a | 0.6 \pm 0.0 a |
| Bushland | 15.4 \pm 5.6 a | 8.9 \pm 2.0 a |
| Agriculture | 6.4 \pm 5.8 a | 2.3 \pm 1.7 b |
| Forest | 36.9 \pm 6.3 b | 23.0 \pm 3.6 c |

Table 4. Mean (\pm SE) values for woody above-ground live biomass carbon (AGC in tC/ha) and below-ground carbon (BGC) across different diameter at breast height (DBH) classes in the lowland coastal forest of Wami Mbiki-Saadani ecosystem, Tanzania, in the year 2018. Mean values in the columns followed by lower case letter “a” are not statistically significant based on a Games–Howell post hoc test.

| DBH Class (cm) | AGC (t/ha) | BGC (t/ha) |
|----------------|-------------------|------------------|
| 10–15 | 46.0 \pm 15.2 a | 26.3 \pm 6.3 a |
| >15 | 41.4 \pm 11.3 a | 23.2 \pm 5.1 a |
| 3–5 | 15.2 \pm 2.6 a | 11.2 \pm 1.9 a |
| 5–10 | 18.5 \pm 4.6 a | 11.9 \pm 2.8 a |

3.4. Soil Carbon (SOC) and Nitrogen (TN)

Soil Organic Carbon was not significantly different across LULC classes but slightly higher in the agriculture with scattered settlement compared to forest and bushland ($\chi^2 = 3.53$, $df = 3$, $p = 0.317$). The SOC concentration decreased significantly with soil depth, being highest in upper soil depths, particularly in the forest ($\chi^2 = 39.75$, $df = 2$, $p < 0.001$) (Figure 4a). Total nitrogen (TN) varied significantly among soil depths ($\chi^2 = 51.0$, $df = 2$, $p < 0.001$) but not across different LULC classes ($\chi^2 = 1.76$, $df = 3$, $p = 0.624$) (Figure 4b). The mean SOC at 0–10 cm depth was significantly higher in forest LULC class than other LULC classes, and grassland showed the lowest SOC (Figure 4a). TN stocks significantly decreased with increasing soil depths (Figure 4b) in all LULC classes. TN concentration was higher in the upper 20 cm (0–20 cm) layer than in the lower soil layer.

3.5. Overall Carbon Stocks

We calculated total carbon stocks for the entire LCF ecosystem in WMS by summing up mean carbon stocks for all carbon pools (vegetation = woody and herbaceous above and below-ground carbon stocks) and SOC per area of different LULC classes. Based on our allometric models and predicted values using the MOLUSCE model until 2048 for forest, agriculture with scattered settlement and bushland [37,38,84], we found that overall carbon stocks decreased from 8.8 million tons in 2018 to 7.0 million tons in 2048, assuming that the rate of forest conversion remains the same.

3.6. Relationship between Soil Organic Carbon and Soil Physico-Chemical Properties

Mean soil pH ranged from 6.4 ± 0.1 to 7.4 ± 0.2 across all LULC classes, indicating that the CLF ecosystem had soils that were moderately to slightly acidic [85].

There was a significant difference in soil pH ($F = 5.75$, $p < 0.05$) among LULC classes, while % silt, % clay and % sand showed no significant differences among LULC classes (Table 5). SOC showed a strong positive correlation with % clay and % silt in soils while it was negatively correlated with % sand (Figure 5). Total SOC in the lowland coastal forest ecosystem showed a significant positive correlation with TN stocks ($r = 0.22$, $p < 0.05$).

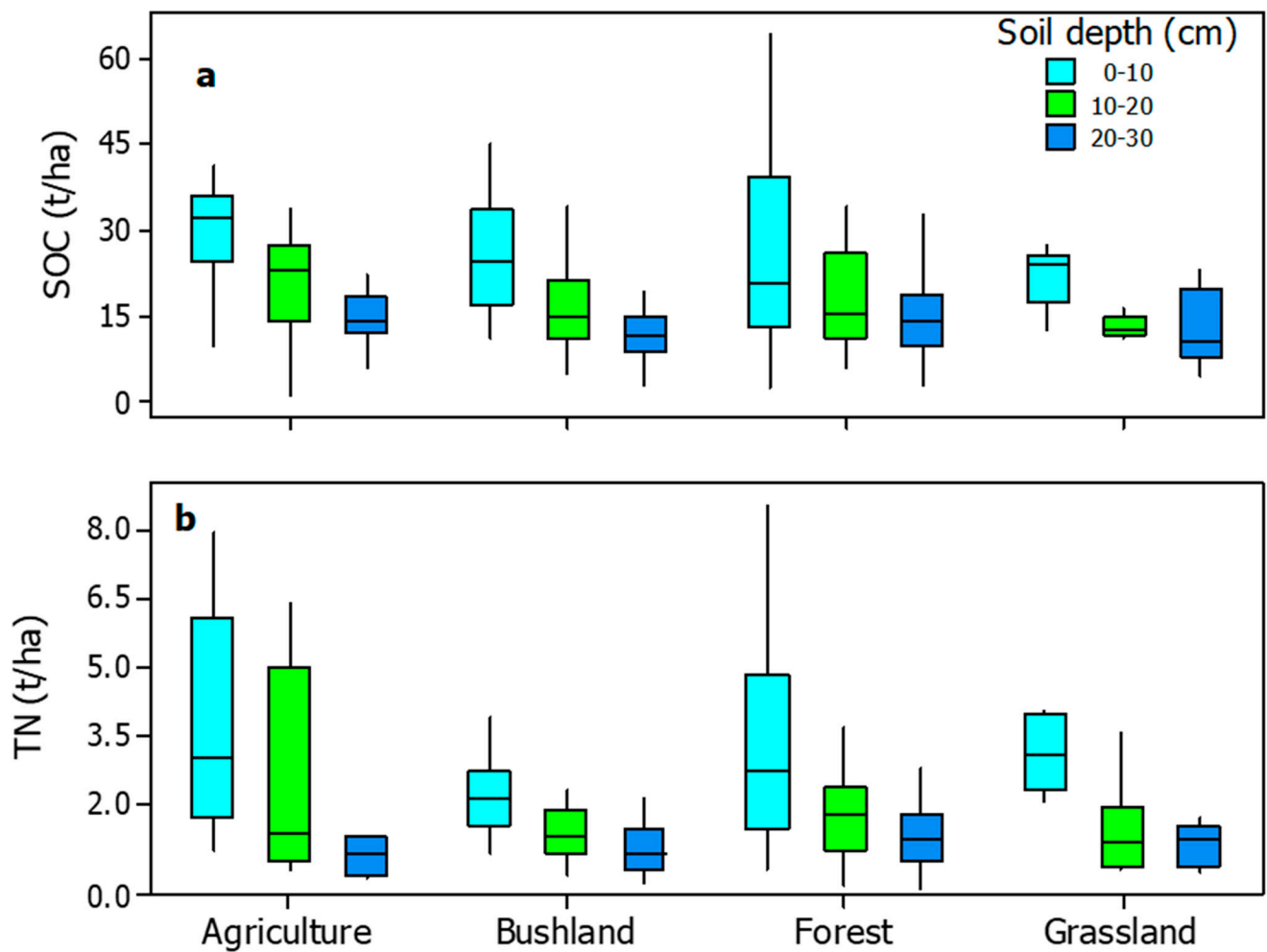


Figure 4. Soil organic carbon (SOC, (a)), Total nitrogen (TN, (b)) at three soil depths (0 to 10 cm, 10 to 20 cm, 20 to 30 cm) in a lowland coastal forest ecosystem, Tanzania. Box plots show ranges of 25% and 75% quartiles. The tips of the whiskers indicate the 5th and 95th percentiles. The middle line in the box indicates the median.

Table 5. Mean (\pm SE) values of soil physical properties and soil pH of the lowland coastal forest ecosystem, Tanzania. Mean values in the columns followed by lower case letters are statistically significant at $p < 0.05$ based on a Games–Howell post hoc test.

| Land Use | pH | % Clay | % Silt | % Sand |
|-------------|-----------------|------------------|-----------------|------------------|
| Bushland | 6.5 \pm 0.1 a | 36.8 \pm 2.3 a | 6.4 \pm 0.6 a | 56.8 \pm 2.5 a |
| Agriculture | 6.4 \pm 0.1 b | 50.3 \pm 5.8 a | 6.0 \pm 1.0 a | 43.7 \pm 6.1 a |
| Forest | 6.5 \pm 0.2 c | 46.0 \pm 2.9 a | 5.6 \pm 0.6 a | 48.4 \pm 3.3 a |
| Grassland | 7.4 \pm 0.2 d | 36.2 \pm 3.2 a | 5.4 \pm 0.6 a | 58.3 \pm 3.6 a |

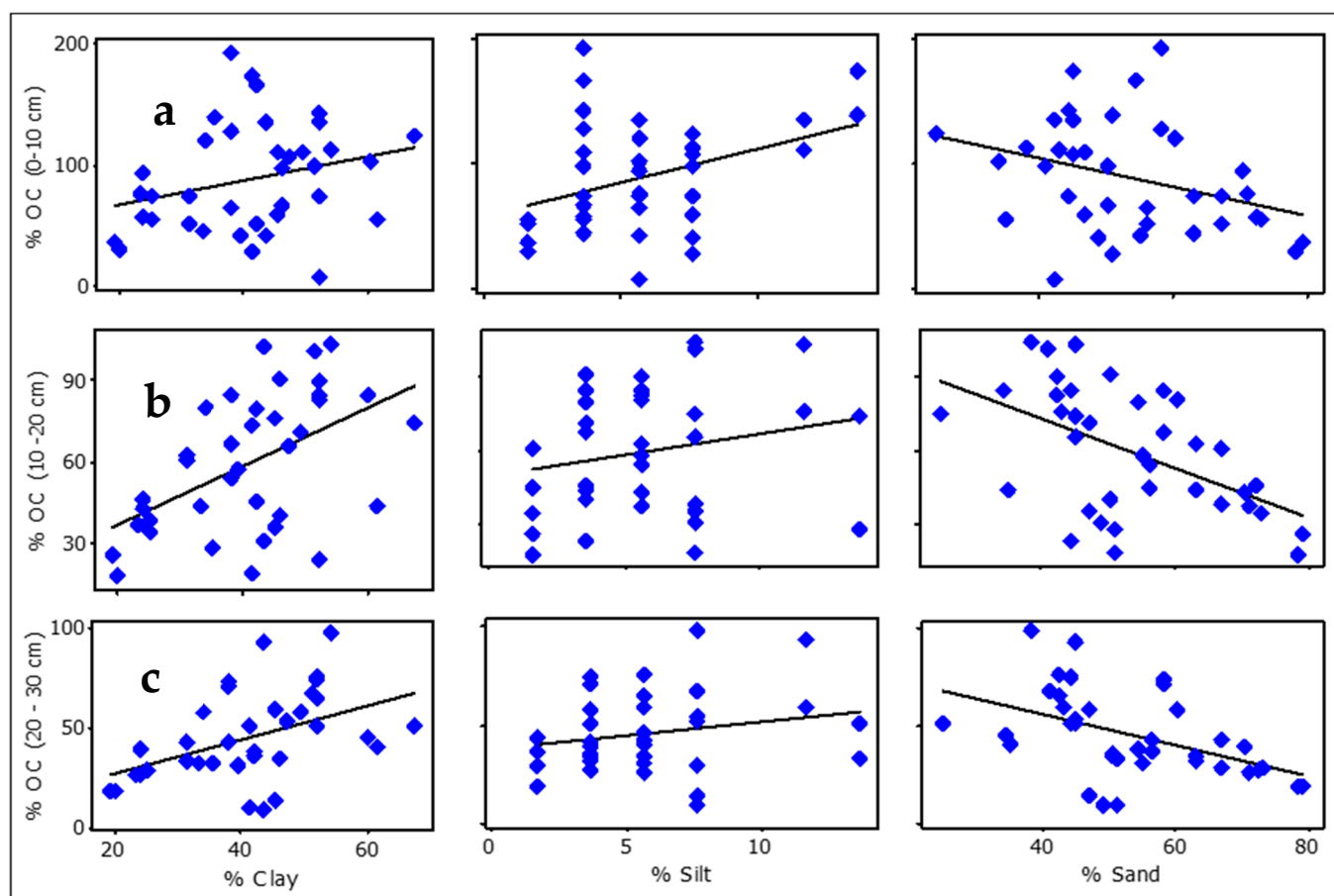


Figure 5. Influence of soil particle distributions (i.e., % clay, % silt, and % sand) on soil organic carbon across soil depths (a) 0–10 cm, (b) 10–20 cm, (c) 20–30 cm in lowland coastal forest ecosystem, Tanzania.

4. Discussion

4.1. Forest Loss and Agricultural Expansion in the LCF-Ecosystem

We found that agriculture with scattered settlement have expanded in the LCF ecosystem over the last 20 years while forest has declined. Likely, these changes have been caused by rapid human population growth, agricultural expansion, infrastructure development, and forest clearance for timber and charcoal production [86,87]. Globally, a decline in forest cover has been associated with increased human population and decreased biodiversity [88–90], as was seen in our study. Furthermore, the intensification of agriculture is generally associated with human population growth in many African countries [91], which has led to an increase in food and higher income demands in rural areas of the LCF ecosystem [92]. These anthropogenic activities have caused vulnerability of land, degradation, and loss of carbon and negatively affected biodiversity conservation [93]. We observed that large areas had been cleared for large-scale agricultural expansion during the ground-truthing, especially for pineapple and sugar cane plantations. Some of the factors which might have caused changes in LULC classes, particularly during the second decade (years 2008–2018), was an increase in socio-economic activities, population increase, agriculture expansion and high demand for fuel wood, especially for mega cities such as Dar-Es-Salaam and Tanga [25,26]. Other factors can be attributed to infrastructure projects such as the construction of Msata-Bagamoyo tarmac road and the establishment of Saadani national park during the year 2004, which promoted an increase in population due to tourism activities. We, thus, highlight that the LCF ecosystem needs particular attention for protection as infrastructure development and agriculture rises, since the LCF comprises a fragile ecosystem of high biodiversity

4.2. Woody Plant Species and Composition across LULC Classes

Our study showed that tree species diversity was high in forest LULC class compared to other LULC classes, and can be compared with other studies [94] who reported high species diversity and richness in closed forest, respectively, than in open woodland in coastal forest, Kenya. Judged by the important value index (IVI), we found six dominant tree species within the forest LULC class, while bushland was dominated by nine plant species and agriculture with scattered settlement by three. These dominant plant species are endemic and near endemic to lowland coastal forests, they are known for their economic potential as they are being used for timber, charcoal production, medicinal plants and for other non-timber forest products, which makes them more prone for over exploitation [23,95]. Globally, most of the LCF are located ≤ 600 masl and within 50 km of the coastal area, with high levels of endemism [95]. As we found fewer dominant species across all LULC classes compared to other LCF systems [96], we presume that the LCF will soon encounter reduced ecological functioning [96]. With expanding agriculture, more diversity will be lost as forests are being converted into agriculture or settlements, similar to studies in Ethiopia [97]. Our results also agree with other studies in LCFs [6,98] who found the decline of plant species diversity as a result of forest degradation for charcoal making, and forest conversion to farm land [99].

4.3. Relationship between Plant AGC, Diversity and Composition

This study found significant positive effects of species richness on AGC stocks. A positive correlation between AGC and tree species richness in the LCF ecosystem is similar to other studies [44,98,100] who reported a positive association between species richness and woody dry biomass in temperate and tropical forests at small plot size (<1 ha). While this finding accords with some recent studies that controlled environmental variables [101,102], it also supports the commonly described pattern in the highly diverse natural forest: biomass and carbon stocks increases with an increase in diversity. Several local and global studies on forest ecosystems have shown a positive association between species richness and forest biomass or carbon [96,103–106]. We found some highly abundant and naturally favoured dominant species such as, *Tamarandus indica* and *Sterculia appendiculata* in the forest LULC class. However, mean tree species evenness and Shannon diversity were not significantly different between the LULC classes, probably due to the generally high land-use conversion in the LCF ecosystem over the last decades. A low plant diversity may result in less effective resource utilization [44] and a decrease in forest biomass [107,108]. Our results also showed a unimodal pattern between species evenness and AGC, mainly at smaller DBH classes, suggesting that tree size is an essential determinant of the diversity-AGC relationship.

4.4. Tree Species Population Structure and AGC

We estimated woody vegetation carbon stocks based on well-established allometric model for lowland coastal forest ecosystem [42,109], there was no individual species specific allometric model for the studied species thus we relied on these allometric models for lowland coastal forest. The results showed that many trees (5–15 cm) contributed substantially to AGC storage at the lowland coastal forest ecosystem. Wood density of dominant tree species and basal area are the critical parameters for accurately estimating biomass and associated carbon content [74]. Our results on total carbon estimation of the LCF system, summing up to about 172.1 ± 31.4 MgC/ha, are within the range of estimates reported by other studies in LCF [10,110–112]. For example, Erica 2019 reported that the average AGC was 99.8 MgC/ha in South Africa while [99] reported AGC in LCF ranging between 311.7 ± 23.7 MgC/ha in intact forest versus 73.5 ± 12.3 Mg C/ha in degraded forest. Our carbon stock estimates can also be compared with those of other tropical montane forests (TMFs) ranging between 16.8 MgC/ha and 222.1 MgC/ha [113,114]. We found a significant correlation between woody plant species biodiversity and carbon storage, consistent with several other studies' findings [98,104,115,116].

4.5. Impacts of Land Use Land Cover Change on Soil Organic Carbon Stocks

High SOC in the upper layer (0–10 cm) of the soil, in concordance with other studies [117–119], indicates that much carbon may be lost if the soil's upper layer is disturbed. The high SOC we found in the natural forest class, which was also found by [9,56,120], might be attributed to the frequent addition of litter [121], the presence of root networks and the modified microclimates, which retard the decomposition role of organic matter [9]. In the LCF system, the conversion of natural forests into agriculture with scattered settlement has likely induced a substantial reduction of organic carbon in the soils. In our study, the contribution of SOC to the total carbon stocks of the LCF ecosystem was 44.2%, while contributions of AGC and BGC were lower, highlighting the importance of keeping soils undisturbed in this system.

We estimated that the total carbon stock of the LCF ecosystem had declined by almost half over the last two decades by the year 2018, likely due to the extensive conversion of forest cover into other LULC classes. Compared to other studies in the African continent [122], our estimates of annual forest conversion rates were high in the LCF ecosystem. However, our results agree with [110], who reported that forest loss in protected areas in LCF ecosystems is about nine times slower than in unprotected areas. Nevertheless, the LCF still suffers from high forest loss, probably from the increased demand for fuelwood and construction materials from nearby megacities of Dar-es-Salaam, Tanga, Kibaha, and Morogoro [110,123].

5. Conclusions

Our study on impacts of LULC on tree species diversity and carbon storage has shown variations in species diversity with LULC classes and carbon stocks. Generally, the results showed significant variations in LULC between periods under investigation in LCF ecosystem. Collectively these LCFs support many rare and poorly known plants and animal species which believed to be endemic species and subspecies of global conservation significance, several rare mammals, reptiles and amphibians and an invertebrate fauna with many rare and undescribed species. Our results suggest that the intensity of land-use conversion lowered the stored carbon, which is a consequence of biomass loss. This, in turn, is associated with decreasing species composition across different LULC classes which are very important for storing carbon. The most dominant plant species contributed to about 46% of total AGC. *Tamarandus indica* contributed the most on AGC, followed by *Diospyros squarrosa*, *Manilkara mocharia*, and *Spirostachys africana*. Our finding highlights an urgent need to strengthen the conservation of LCF of the WMS ecosystem to save the numerous trees and animal species endemic to these remaining coastal forests and the centre of biological hotspots and mitigate climate change effects by reducing carbon dioxide emissions. We highlight that the LCF ecosystem needs particular attention for protection as infrastructure development and agriculture intensification, since the LCF comprises a fragile ecosystem of high biodiversity. We also highlight that our LCF study site harboring a large number of endemic species and being located within a biodiversity hotspot of eastern Africa, must be protected to conserve biodiversity and carbon stocks for long run. We recommend the joint effort for communities living within or adjacent to these lowland coastal forests and government and other conservation agents to conserve these vital ecosystems for current and future generations.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su14148551/s1>, Table S1: List of tree species identified in the study area at lowland coastal forest ecosystem, Tanzania. Table S2: Herbaceous species composition and dominance based on Important Value Index (IVI) of the grassland land-use types in lowland coastal forest of Wami mbiki –Saadani (WMS) ecosystem, Tanzania (RF, relative frequency; RD, relative density; Rdo, relative dominance; IVI, importance value index, N, number of species in a sampling plot). Table S3: Plant species composition and dominance based on the importance value index (IVI) of the three different land-use types in lowland coastal forest of Wami mbiki–Saadani (WMS)

ecosystem, Tanzania (RF, relative frequency; RD, relative density; Rdo, relative dominance; IVI, importance value index, BAN, basal area; N, number of species in a sampling plot).

Author Contributions: L.T.N.: conceptualization, methodology, software, formal data analysis, data curation, writing initial draft preparation, project administration; L.K.M. and A.C.T.: methodology, validation, interpretation of results; A.C.T. and L.K.M.: reviewing and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Information consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful to S.W. Smith for comments by on an earlier version of this manuscript. Special thanks to Y.J. Magangali, who helped during data collection, and S. Shomari for tree species identification in the field; J. Herbert for soil sample collection and analysis, O. Simon from the Institute of Resource Assessment (IRA), University of Dar Es Salaam, and S. Kitereja from Forest Training Institute (FTI) for technical support during land use/land cover classifications. Thanks to Kisampa conservancy for accommodation and transport during data collection and to the District governments of Bagamoyo, Chalinze and Handeni for granting a permit to do research in their area. Thanks to all game scouts who helped me during data collection. We thank the IDEA WILD FUND for field equipment support. This research has clearance permit No: 2020-209-NA-2020-082 from Tanzania Commission for Science and Technology (COSTECH).

Conflicts of Interest: The authors declare no potential conflict of interest.

Appendix A

Table A1. Land use/land cover (LULC) class area (in ha and%) over 1998, 2008, and 2018 in Tanzania's Wami Mbiki-Saadani (WMS) ecosystem. LULC classes are based on Landsat image classification.

| Year | 1998 | | 2008 | | 2018 | | 1998–2008 | | 2008–2018 | | 1998–2008 | | 2008–2018 | | 1998–2008 | | 2008–2018 | |
|-------------|-----------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|-----------------------|-----------|----------|-----------|-----------------------|-----------|----------|-----------|-----------------------|
| Land Cover | Area (ha) | Area (%) | Area (ha) | Area (%) | Area (ha) | Area (%) | Area (%) | Area (%) | ha/year | km ² /year | (%/year) | (%/year) | ha/year | km ² /year | (%/year) | (%/year) | ha/year | km ² /year |
| Agriculture | 18,818 | 3.5 | 36,580 | 6.8 | 70,797 | 13.2 | 3.3 | 6.4 | −2 | −3422 | −9.4 | −9.4 | −2 | −3422 | −9.4 | −9.4 | −2 | −3422 |
| Bare soil | 776 | 0.2 | 2760 | 0.5 | 4364 | 0.8 | 0.4 | 0.3 | −198 | −160 | −25.6 | −5.8 | −198 | −160 | −25.6 | −5.8 | −198 | −160 |
| Bushland | 135,757 | 25.3 | 143,725 | 26.9 | 140,137 | 26.2 | 1.5 | −0.7 | −797 | 359 | −0.6 | 0.2 | −797 | 359 | −0.6 | 0.2 | −797 | 359 |
| Forest | 323,250 | 60.4 | 301,197 | 56.3 | 167,958 | 31.4 | −4.1 | −24.9 | 2205 | 13,324 | 0.7 | 4.4 | 2205 | 13,324 | 0.7 | 4.4 | 2205 | 13,324 |
| Grassland | 50,146 | 9.4 | 45,720 | 8.6 | 147,393 | 27.6 | −0.8 | 19 | 443 | −10,167 | 0.9 | −22.2 | 443 | −10,167 | 0.9 | −22.2 | 443 | −10,167 |
| Urban area | 66 | 0 | 213 | 0 | 336 | 0.1 | 0 | 0 | −15 | −12 | −22.3 | −5.8 | −15 | −12 | −22.3 | −5.8 | −15 | −12 |
| Water | 6235 | 1.2 | 4843 | 0.9 | 4046 | 0.8 | −0.3 | −0.2 | 139 | 80 | 2.2 | 1.6 | 139 | 80 | 2.2 | 1.6 | 139 | 80 |
| Total | 535,048 | 100 | 532,278 | 100 | 526,621 | 100.1 | | | | | | | | | | | | |

Table A2. Land use/land cover (LULC) matrix by cross-tabulation of 1998 to 2008 (in ha) for the low land coastal forest of WMS ecosystem. The land use classes for the years 1998, 2008, and 2018 are defined in Table 1.

| Year: 1998 | | | | | | | | | |
|-------------|-------------|-----------|----------|---------|-----------|-------|-------|------------|------------|
| Year: 2008 | Agriculture | Bare Soil | Bushland | Forest | Grassland | Urban | Water | Total 2008 | Gross Gain |
| Agriculture | 18,555 | 1 | 9047 | 5788 | 3130 | 0 | 60 | 36,580 | 18,025 |
| Bare Soil | 75 | 218 | 717 | 619 | 989 | 0 | 142 | 2760 | 2541 |
| Bushland | 0 | 21 | 53,016 | 68,350 | 22,065 | 1 | 269 | 143,723 | 90,707 |
| Forest | 0 | 57 | 54,735 | 239,048 | 6885 | 2 | 472 | 301,199 | 62,151 |
| Grassland | 175 | 466 | 17,976 | 8978 | 16,860 | 0 | 1266 | 45,721 | 28,861 |
| Urban Area | 11 | 0 | 80 | 28 | 42 | 52 | 0 | 213 | 161 |
| Water | 2 | 12 | 205 | 422 | 175 | 0 | 4024 | 4841 | 817 |
| Total 1998 | 18,819 | 776 | 135,776 | 323,232 | 50,145 | 55 | 6234 | 535,036 | |
| Gross loss | 264 | 557 | 82,760 | 84,185 | 33,285 | 3 | 2209 | | 203,263 |

Table A3. Land use/land cover (LULC) matrix by cross-tabulation between 2008 and 2018 low land coastal forest of WMS ecosystem. The land use classes for 1998, 2008, and 2018 are defined in Table 1 (ha).

| Year 2018 | Year 2008 | | | | | | | Total 2018 | Gross Gain |
|-------------|-------------|-----------|----------|---------|-----------|-------|-------|------------|------------|
| | Agriculture | Bare Soil | Bushland | Forest | Grassland | Urban | Water | | |
| Agriculture | 6561 | 807 | 18,746 | 40,563 | 4052 | 0 | 63 | 70,793 | 64,232 |
| Bare Soil | 171 | 126 | 774 | 1132 | 1702 | 0 | 458 | 4362 | 4236 |
| Bushland | 11,567 | 657 | 44,284 | 66,010 | 17,448 | 14 | 155 | 140,135 | 95,851 |
| Forest | 7495 | 291 | 35,839 | 116,704 | 7260 | 3 | 361 | 167,952 | 51,249 |
| Grassland | 10,718 | 793 | 44,025 | 76,670 | 15,068 | 0 | 132 | 147,407 | 132,339 |
| Urban Area | 56 | 16 | 19 | 18 | 30 | 196 | 1 | 336 | 140 |
| Water | 12 | 71 | 34 | 99 | 159 | 0 | 3672 | 4046 | 374 |
| Total 2008 | 36,580 | 2760 | 143,721 | 301,196 | 45,721 | 213 | 4842 | 535,032 | |
| Gross loss | 30,018 | 2634 | 99,438 | 184,492 | 30,652 | 17 | 1170 | | 348,422 |

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