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Evaluating Soil Carbon as a Proxy for Erosion Risk in the Spatio-Temporal Complex Hydropower Catchment in Upper Pangani, Northern Tanzania

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Abstract: Land use conversion is generally accompanied by large changes in soil organic carbon (SOC). SOC influences soil erodibility through its broad control on aggregate stability, soil structure and infiltration capacity. However, soil erodibility is also influenced by soil properties, clay mineralogy and other human activities. This study aimed to evaluate soil organic carbon as proxy of soil erosion risk in the Nyumba ya Mungu (NYM) catchment in Northern Tanzania. Soil organic carbon (SOC) was measured by an AgroCares scanner from which the soil organic matter (SOM) was derived using the conversional van Bemmelen factor of 1.72. A regression analysis performed between the measured loss on ignition (LOI) values and SOM from the AgroScanner showed a strong positive correlation in all land use classes (LOI_{FL} R^2 = 0.85, r = 0.93, $p < 0.0001$; LOI_{CL} R^2 = 0.86, r = 0.93, $p = 0.0001$; LOI_{GL} R^2 = 0.68, r = 0.83, $p = 0.003$; LOI_{BS} R^2 = 0.88, r = 0.94, $p = 0.0001$; LOI_{BL} R^2 = 0.83, r = 0.91, $p = 0.0002$). This indicates that SOC from the soil scanner provided a good representation of the actual SOM present in soils. The study also revealed significant differences in the soil aggregate stability (WSA) and SOM stock between the different land use types in the Upper Pangani Basin. The WSA decreases approximately in the following order: grassland > forest land > bare land > cultivated > bush land. Land use change can thus potentially increase the susceptibility of soil to erosion risk when SOC is reduced. Since WSA was directly related to SOM, the study indicates that, where formal measurements are limited, this simple and inexpensive aggregate stability test can be used by farmers to monitor changes in their soils after management changes and to tentatively assess SOC and soil health.

Keywords: aggregate stability; soil organic matter; AgroScanner; loss on ignition; soil slake test

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1. Introduction

The changing demographics in Tanzania have created an increasing demand for land, food and water, leading to changes in land and water use. While the land remains constant, the demand for food and water is expanding linearly while the population increase in Tanzania is growing exponentially, with an average growth rate of 3% annually [1]. For instance, in 1950, Tanzania's population was 7.6 million people, growing to 61.5 million people in 2021 [1]. Deforestation and the loss of permanent vegetation through the fast expansion of agricultural land and growing urbanization with respect to population increase has accelerated soil loss rates and downstream siltation [2–5]. The mean rate of soil loss by water in Tanzania is 4.1 and 10.1 $tha^{-1}yr^{-1}$ for all land cover classes and per cropland, respectively [6]. The sedimentation rate in the catchment's (the Nyumba ya Mungu) hydropower reservoir is averagely 1.5 $g\,cm^{-2}yr^{-1}$ [7]. Studies by Vanmaercke, Poesen, Broeck, and Nyssen [8] revealed that the sediment yield in East Africa typically range between 100 to 1000 t/km^2/year. The global watch forest also showed the deforestation rate in Tanzania whereby, from 2001 to 2020, Tanzania lost 2.7 Mha of tree cover, equivalent to a 10% decrease in tree cover since 2000, and 910 Mt of CO_2 emissions (www.globalforestwatch.org accessed on 7 September 2021). Unsustainable land use practices are the major cause of the degradation of Tanzania's agricultural soils. Soil degradation is activated by many physical, chemical, biological and ecological processes that lower the quality and potential productivity of the soil [9,10]. Increased rates of soil erosion remove both soil particles and associated nutrients from the land [11]. Unsustainable soil management is therefore a primary cause of the reduced agronomic productivity in Tanzania [12].

The stability of the soil aggregates is vital for a healthy soil structure and protection against erosion. Soil organic matter (SOC) plays a crucial role in the formation of stable aggregates. It stabilizes soil structure, improves the soil's physical properties and enhance nutrient recycling [13,14]. Soil aggregates are the building blocks of soil structure, and soil aggregate stability is therefore commonly used as an indicator of soil physical quality [13,15–17]. Aggregate stability is defined as the resistance of the aggregate soil breakdown against the external destructive effects of rainfall, runoff and wind. Generally, soils with a higher aggregate stability have higher resistance to erosion and a better water infiltration. Soil aggregate stability is dependent on multiple soil properties such as soil organic matter content and soil texture [18,19]. SOM supports aggregate stability through increasing the mechanical strength, increasing the cohesion within the aggregates and lowering the wettability [20,21]. SOM is influenced by natural factors, such as the changing of rainfall frequency and the input of plant residuals to the soil [22,23]. However, humans also influence SOM across a range of timeframes through the harvesting of the live and dead vegetation, cropping, applying manure or compost, plowing [24], deforestation [25] and afforestation [26]. Changes in SOM subsequently have substantial impacts on soil aggregate stability [24,26,27]. Different size fractions in soil aggregates also have different percentages of carbon present, which influences their stability and erodibility. Macro-aggregates have less organic matter by mass, leading to a lower aggregate stability and a high erodibility factor thus becoming prone to erosion while the micro-aggregate is less susceptible to erosion [28]. The amount of carbon present in the size fractions of aggregates enables the determination of the amount of organic matter that can potentially be lost due to the erosion process, which adversely affects the structural condition of the soil [29].

There is currently still a lack of understanding on the dynamics and role of soil organic matter on soil erodibility in Tanzania's complex soil systems. Although erosion risk is controlled by many factors, there is a need for an evaluation of the erosion risk linked to soil quality, an approach that has widespread applicability in the resource-poor agropastoral communities of Tanzania. In this context, SOM seems promising due to its all-embracing influence on the physical, chemical and biological properties of soils [30], which makes it very sensitive to management, among other attributes. The aim of this study was to evaluate the soil carbon as a proxy for soil erosion risk in the Nyumba ya Mungu catchment. Moreover, the impacts of land use change on SOM and aggregate stability were assessed based on the influence on soil erodibility.

2. Materials and Methods

2.1. Study Site

The Upper Pangani Basin (UPB) in northern Tanzania includes the highlands of the Africa's highest peak, Mt. Kilimanjaro (5985 m), and fifth highest peak, Mt. Meru (4566 m). The catchment has a total land and water area of about 13,000 km^2 [31], extending between the Latitudes 3°00′00″ and 4°3′50″ South, and the Longitudes 36°20′00″ and 38°00′00″ East. The area experiences a tropical climate with altitude effects on temperature and rainfall, with a long wet/rain season from March to May and a short rainy season from October to December [32,33]. In addition to seasonality, the climate is affected spatially through altitude effects on temperature and rainfall. The average rainfall in the lowlands (800 m.a.s.l) is 900 mm/year, and in the highlands (2200 m.a.s.l), it is >2200 mm/year [34–37]. Catchment's geology is volcanic, comprising olivine and alkaline basalts, phonolites, trachytes, nephelinites and pyroclastics [37–39]. The major soil types in the watershed comprise Nitisols, Luvisols, Solonchaks, Chernozems, Leptosols and Histosols [40] (Figure 1). The Nitisols cover the highlands to the lowlands and are predominantly developed on volcanic material. They are usually deeply and well-drained and have a stable structure and a high clay and nutrient content. With proper management, they have medium to high potential for rain-fed agriculture. The Luvisols are mostly constrained to the lowlands of the catchment. They are highly weathered with a subsurface accumulation of clay and are characterized by low nutrient retention and a high susceptibility to surface crusting and erosion. However, with proper management, they have a medium agricultural potential. The Solonchaks are located in lowland depressions or salt pans and are characterized by high rates of evaporation of runoff water, leaving a high concentration of soluble salts. They have a limited potential for cultivation, only with salt tolerant crops. Most Solonchaks are therefore used for extensive grazing or as natural reserves. Histosols are acidic, organic soils that form when fallen plant material decomposes more slowly than it accumulates [41]. They are constrained to wetlands on the upper parts of Mount Kilimanjaro and Mount Meru, where they have formed under almost permanently saturated conditions. Chernozems are the dominant soil type in the Kikuletwa sub-catchment. They are fertile soils that are currently mostly used for agricultural production. These soils are characterized by a high degree of biological soil mixing and soil organic carbon, leading to the formation of biologically stabilized soil aggregates on the soil surface [42]. Leptosols are generally weak aggregated coarse or medium-textured soils with limited profile development, mostly located in the highlands and in the Kikuletwa sub-catchment. The soil erodibility factor of the dominant soil types in the catchment ranges from 0.012 to 0.026 t ha h $ha^{-1}MJ^{-1}$ mm^{-1}, according to Fenta et al. [6], which suggests that the catchment has significant soil aggregate stability. The land cover in the catchment is mostly driven by the rainfall-elevation gradient ranging from permanently wet montane forests on the higher altitudes to savannah grassland on the lowlands [43]. The agricultural activities are mostly concentrated on the lower slopes between 900 and 1800 m.a.s.l, where the majority of the population established.

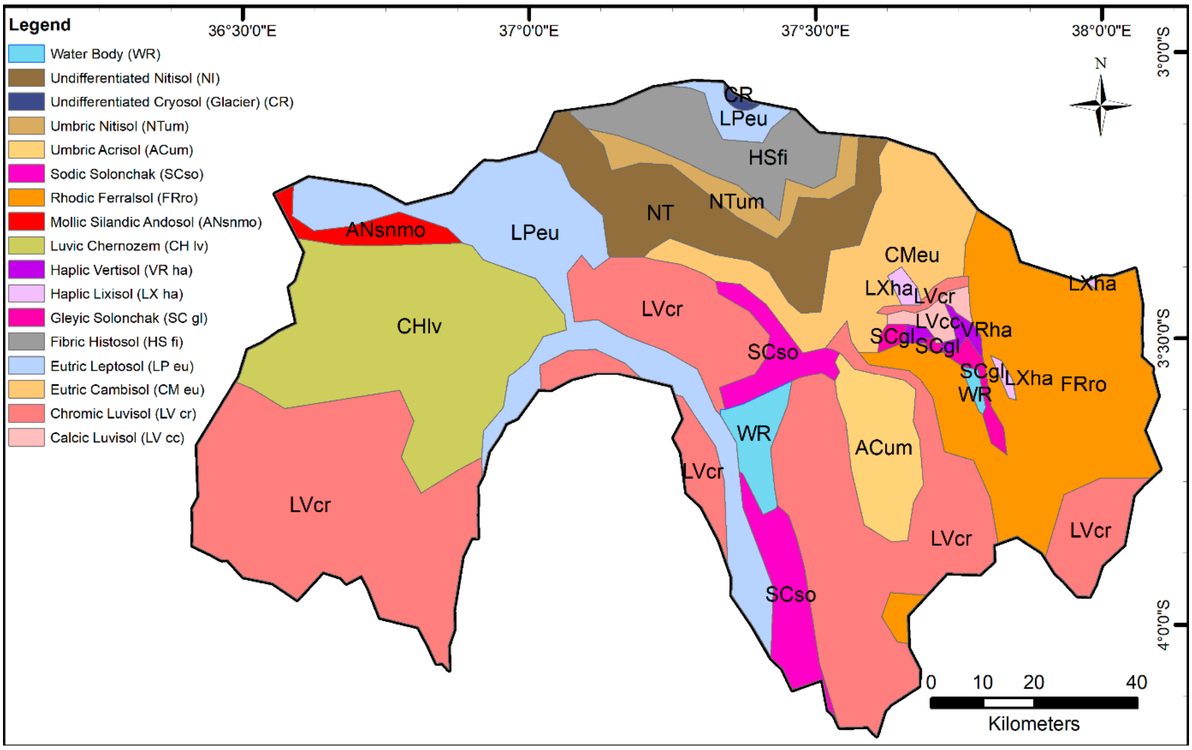


Figure 1. The map of the Upper Pangani Basin details the major soil types in the catchment [40].

2.2. Data Acquisition for Land Use Classification

Ortho-rectified and geometrically corrected Landsat images (Landsat 4–5 and Landsat 8) with a resolution of 30m were obtained from the USGS Earth Explorer website (https:glovis.usgs.gov/ accessed on 7 September 2021). For this specific study, Landsat images captured in February 1987 for Landsat 4–5 and 2017/18 for Landsat 8 were selected based on the lack of interfering cloud cover and ability to reconstruct land cover change over time. Before the analysis, the images were projected to UTM zone 37S allowing spatial assessment in combination with other spatial data of the study area [44].

2.3. Image Classification of Different Land Use Classes

Geo-tagged photos and field notes were gathered during multiple ground-truthing campaigns to offer a comprehensive documentation of the land cover spectrum. By using these ground observations, complemented with Google Earth images, the major land cover types in the area were delineated into spectral signature files. The supervised classification by maximum likelihood algorithm method in ArchMap uses these signature files to extrapolate across the full Landsat image database into the pre-defined land cover classes. A visual examination and comparison with high resolution aerial imagery from Google Earth was used to remove potential incorrectly classified features. A raster calculator function was used to direct the correct elevation of a particular land use class based on the expert knowledge of the study area as explained by Taweesuk et al. [45]. The Expert classification is aimed at improving classification accuracy thus used to integrate remote-sensed data with other sources of georeferenced information such as digital elevation model (DEM), land use data and spatial texture. A total of 9 major classes of land cover were classified, representing both changes due to natural drivers and human influence (Table 1).

Table 1. Land use/cover classes and their description.

S/N	Land Use/Cover Class	Description
1	Agricultural land (CL)	All cultivated land with crops and harvested crops
2	Water (WT)	Including water in wetlands, rivers, irrigated areas and fish ponds
3	Grassland (GL)	Areas dominated by short and tall grasses and bare soils in the dry season.
4	Bush land (BS)	Areas dominated with shrubs and less closed canopy
5	Bare land (BL)	Areas includes gullies, bare soils, rocky, sand and quarry
6	Built-up area (BLA)	Man-made infrastructure (urban and rural settlements) and roads (tarmac or paved)
7	Forest (FL)	Includes natural and planted forests with closed trees and closed canopy
8	Wetland (WTL)	Areas moderately saturated with water seasonally or permanently
9	Glacier ice (GLA)	Includes areas enclosed with glacier and ice

2.4. Soil Scanning to Estimate Soil Organic Matter

An AgroCares scanner, a portable handheld Near Infrared (NIR) sensor for soil scanning [46], was used to scan the soil samples to evaluate SOC content. The scanner is connected to an app (“soil cares app” downloaded from Google Play/Apple store) using a smartphone via Bluetooth. A spectral analysis of the scanned soil is sent to the application on the smartphone via Bluetooth. Subsequently, the smartphone application connects to AgroCares’s global calibration database to convert the spectral image into the required soil data.

A hand trowel and scoop were used to collect a soil sample between 0–5 cm depth, which was put in a bucket and well mixed. The samples were clearly labelled, and the coordinates of the sampling location were recorded using an Infinix Hot 9 Android 10 XOS 6.0. The scanner was calibrated in situ following manufacturer instructions. The scanner was placed on the sub-samples (drawn from the bucket) on the sample tray, and per soil sample, the scanner performed 5 scans. Using the reflectance signature and global calibrated database, the application estimated the following soil parameters: soil organic carbon (g/kg), pH, soil texture class, total Phosphorus (g/kg), Potassium (mmol+/kg), soil temperature (○C) and Cation exchange capacity (mmol+/kg). The SOM was derived from the estimated SOC using the conversional van Bemmelen factor of 1.72 [47,48]. The conversion factor is based on the assumption that the organic matter is 58% carbon [49].

2.5. Loss on Ignition to Estimate Soil Organic Matter

Loss-on-ignition was determined on the oven-dried subsamples of soil fractions. Approximately 20 g of air-dry soil was added to previously ignited and weighed porcelain crucibles, dried at 105 °C for 12 h in a ventilated oven, cooled in a desiccator and weighed again. Finally, the crucibles were ignited at 550 °C for 4 h in a muffle furnace (Cole-Parmer® StableTemp). After ignition, the crucibles were cooled in a desiccator and weighed. The LOI was calculated as the difference between the oven-dry weight (DW) before and after ignition and related to oven-dry soil, as shown in Equation (1):

$$LOI_{550} = \frac{DW_{105} - DW_{550}}{DW_{105}} \times 100 \quad (1)$$

The values of the SOM obtained in percentages were compared with the SOM derived from the loss on ignition.

2.6. Soil Aggregate Stability (Slake Test)

Soil aggregate stability in water was assessed using a semi-quantitative method adapted from the USDA-ARS Soil Slake test method [50], wherein a value was assigned to the assessed soil samples based on the stability of soil aggregates in water (WSA). Soil sample aggregates with a diameter of approximately 10mm were collected using a trowel from different land use types and subsequently air-dried at room temperature. The air-dried aggregates were placed on a 6-mm mesh that was fixed on a basket cup. The basket cup with soil aggregates was subsequently immersed with water on top of the mesh. Following the behavioral criteria of the aggregates in water, (Table 2), the slaking away of the soil fragments was recorded for five minutes. For each soil sample, a soil stability score was rated according to the time required for 50% of the soil aggregates and the proportion of the soil fragments remaining on the mesh after the five minutes of immersion.

Table 2. Criteria for scoring soil stability in water adapted from Herrick et al. [50].

Stability Class	Criteria for Assignment to Stability Class (for "Standard Characterization")
0	Soil too unstable to sample (falls through sieve).
1	50% of structural integrity lost within 5 s of insertion AND or <10% remains after agitation
2	50% of structural integrity lost 5–30 s after insertion AND or <10% remains after agitation
3	50% of structural integrity lost 30–300 s after insertion AND or <10% remains after agitation
4	10–25% of soil remains after 5 min agitation
5	25–50% of soil remains after 5 min agitation
6	50–75% of soil remains after 5 min agitation
7	75–90% of soil remains after 5 min agitation
8	>90% of soil remains after 5 min agitation

2.7. Statistical Analysis

Initially, a regression analysis was conducted to determine the correlation between SOM content % derived from the scanner and SOM content % derived from the LOI experiments. Data were subsequently tested for normality, where, for the WSA, only values for forest land and cultivated land were normally distributed ($p < 0.0005$ and $p < 0.018$, respectively). For LOI, only forestland and bush land were also normally distributed ($p < 0.036$ and $p < 0.008$, respectively) and normally undistributed to the rest of land uses, while for SOM, only bush land data were normally distributed. Following these results, the non-parametric Kruskal–Wallis test was carried out in SPSS (Statistical Package for Social Science) to test if there were significant differences in the measured LOI, scanned SOM and estimated WSA between the different land use types. The differences were subsequently visualized using boxplots allowing a comparison of the mean values and variability of LOI, SOM and WSA within and between land use sites.

3. Results and Discussion

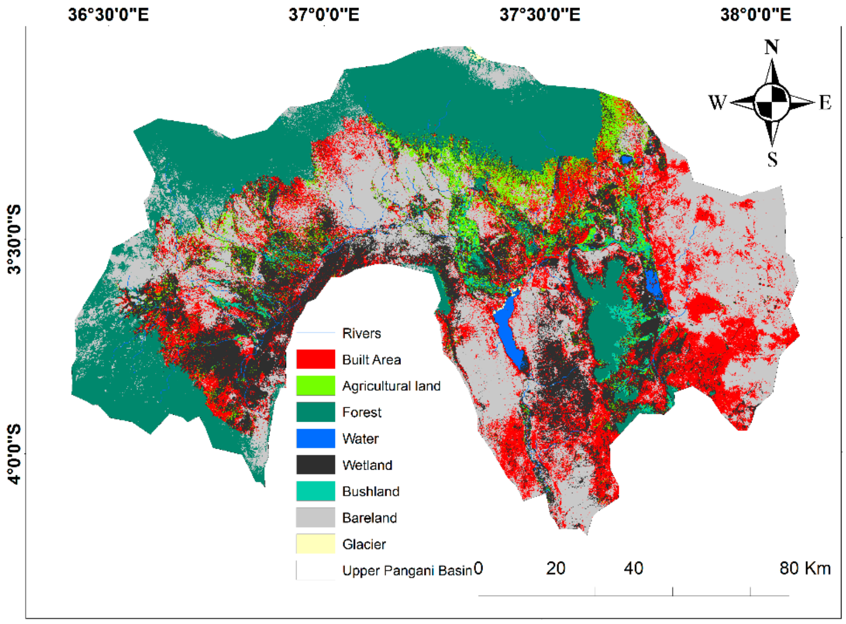
3.1. Land Use/Cover Changes

A visual and numerical representation of the land cover changes are summarized in (Figure 2) and in (Table 3), respectively. The summary provides the information on the specific land cover types that has been converted to others and those that have been resistant to change. The net decrease in forest, bare land, grassland and bush land are clear distinguishing trends that evidence their conversion to mostly agriculture land by 34.6% (4542 km^2). Built-up areas were observed to have significantly increased by 6.17% (809.9 km^2). This corresponds to previous studies that observed high levels of deforestation and the loss of permanent vegetation through the fast expansion of agricultural land and growing urbanization [2–5,51]. The local manifestation of urbanization includes the establishment of the Siha district and the emergence of many villages and urban suburbs along roads across the catchment [52,53]. The expansion of agricultural land and settlements has also led to the disappearance of riparian forests and the degradation of riverbanks in the lowlands [2]. Another pronounced change is the considerable net decrease in wetlands by −3.96% (519.8 km^2) that would have been caused by drainage and potentially climatic change and variability. The conversion of the catchment land cover types, for instance, the montane forests on mountain slopes, grassland and bush land to small- and large-scale plantations in the lowlands, is evidence of increased land use pressures [54,55] and response to climate change impacts [56]. Another notable change evidenced by the literature is the decrease in the glaciers in the volcanic peaks of Mt. Kilimanjaro, which is an important indicator of environmental changes in the region [57,58]. Although the decrease in glaciers corresponds with the previous studies, the cloud cover in the top of the mountain may have influenced the classified image interpretation from which the spectral signatures from the Landsat images obscure the parts of the glacier, thus affecting the training samples as a result and impacting the absolute classification accuracy [59].

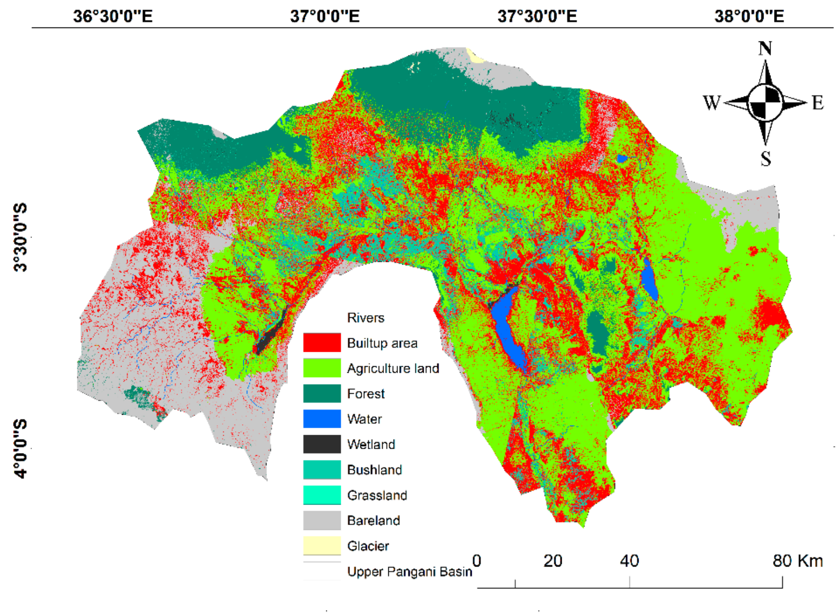
Table 3. Losses/gains in land use/cover areas.

LU Classes	1987		2018		1987–2018
	Area (km^2)	% of Total	Area (km^2)	% of Total	% Change
Built up	2203.35	16.8	3015.1413	22.9	6.17
Agricultural land	644.587	4.9	5191.2486	39.5	34.6
Forest	3302.27	25.16	1576.431	12.01	−13.15
Water	79.7715	0.61	106.7616	0.81	0.2
Wetland	562.757	4.29	42.7257	0.33	−3.96
Bush land	2147.58	16.36	1009.1025	7.69	−8.36
Grassland	224.251	1.71	9.4374	0.07	−1.64
Bare land	3950.95	30.1	2167.5091	15.66	−29.94
Glacier	10.5264	0.08	9.6413	0.92	−0.012

The historical land use land cover change in the catchment is confirmed by other previous studies, which include the conversion of shrub and grassland and light vegetation to cultivated land from 1987 to 2005 in the Kahe plains [60], increased forest degradation in the lowlands from 1606 ha to 5170 ha between 1973 and 2000 [61], the conversion of about 39.5% of bush land to agricultural land between 1973 and 2000 [34], the degradation of more than 41 km^2 of the forest between 1952 and 1982 [62], the conversion of about 49.97 km^2 of shrubs and bush land to agriculture and other uses from 1961 to 2000 in the Kirua Vunjo division [59] and increased cultivated land from 54% (in 1973) to 63% in 2000 on the southern and eastern slopes [63].



(**a**)



(**b**)

Figure 2. Land cover maps derived from Landsat imagery of (**a**) 1987 and (**b**) 2018, respectively detailing the changes in land use land cover from 1987 to 2018.

3.2. Comparison of Scanner and Laboratory Estimates of SOM

While SOM derived from the AgroCares scanner and converted using the van Bemmelen factor of 1.72 had higher values in all land types than those derived from LOI, a simple regression analysis between LOI and the estimated % SOM from the AgroScanner showed a strong positive correlation ((a) LOI_{CU} R^2 = 0.86, r = 0.93, p = 0.0001; (b) LOI_{GL} R^2 = 0.68, r = 0.83, p = 0.003; (c) LOI_{FL} R^2 = 0.85, r = 0.93, p = 0.0001; (d) LOI_{BS} R^2 = 0.88, r = 0.94, p = 0.0001; (e) LOI_{BL} R^2 = 0.83, r = 0.91, p = 0.0002), Figure 3). From an environmental perspective, the LOI and SOM were significantly different between land uses, decreasing in the following order: bare land > forest land > bush land > cultivated land > grassland and bare land > forest land > grassland > bush land > cultivated land (Appendix A). However, the SOM for forest land and bare land were close at approximately 5% each, while the LOI for cultivated land and grassland were also similar at 2%. Most soils in the catchment are characterized by a high clay content [64] that has the ability to contain more carbon [65,66]. Although the SOM stocks were significantly different among the land use systems, a similar pattern was observed between the forest land and bare land (Appendix A). This similar pattern might be explained by their dominating soil textures that were primarily loam to clay loam because these textures support the function of the soil biological community by providing a large and moist surface area in water films around loam and clay loam particles that are often protected within aggregates [67,68]. The strong relationship between the laboratory measured SOM (LOI) and SOM from the AgroCares scanner showed that LOI is a good method for the determinations of SOM where formal measurements are limited.

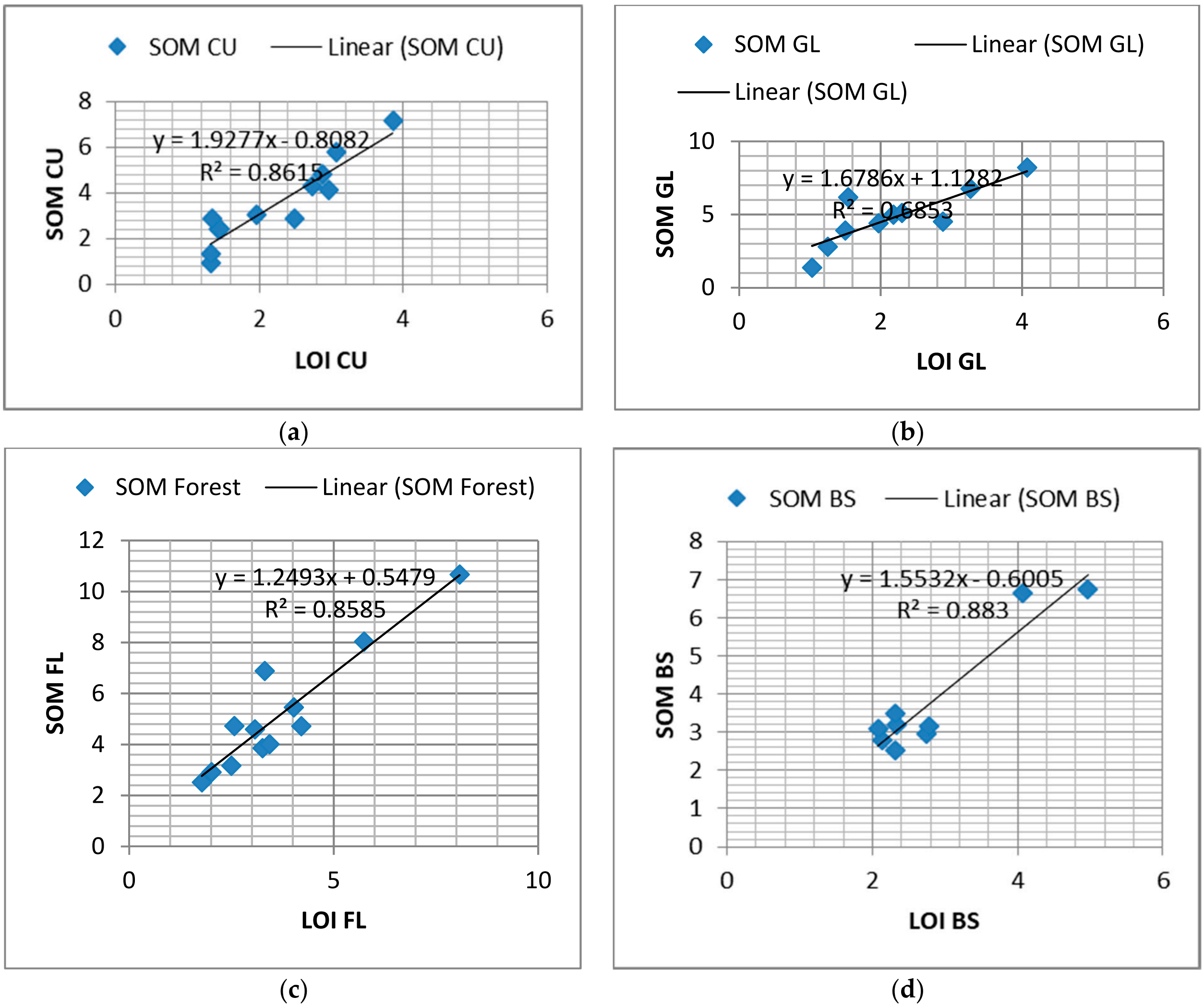
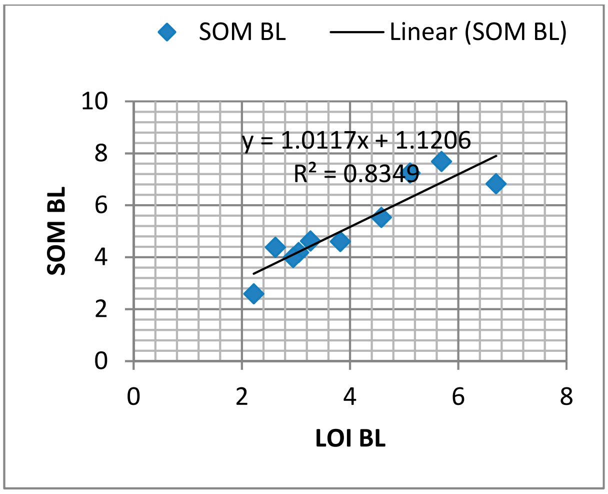


Figure 3. *Cont.*



(**e**)

Figure 3. Relationship between loss on ignition (LOI) and soil organic matter (SOM) in different land use types (**a**) cultivated land (**b**) grassland (**c**) forest land (**d**) bush land and (**e**) bare land.

3.3. Soil Organic Matter on Soil Aggregate Stability in Different Land Uses

This study showed that there are significant differences in the soil aggregate stability and SOM stock between the different land use types in the Upper Pangani Basin. The soil aggregate stability decreases approximately in the following order: grassland > forest land > bare land > cultivated land > bush land (Appendix A). The results indicated that SOM and WSA were influenced by land management type (Figure 4). Similar to SOM stocks, the WSA in arable soils was typically less than in grassland, forestland and bare land. However, the significant difference between WSA in cultivated land in comparison to other land use types was observed with a wide range in WSA here indicating high variability in soil behavior under low SOM conditions. While the means of SOM in forest land and bare land were almost similar, there was a substantial difference in the median values of WSA, which might be attributed by difference in soil texture. Soil textures support the function of the soil biological community by providing a large and moist surface area in water films around loam and clay loam particles that are often protected within aggregates [67,68]. This similar pattern observed within and between land use types imply that the SOM and WSA were not only related to land management type (Figure 4 and Appendix A) but were also influenced by other factors such as soil textural properties, geology, clay content, exchangeable cations and other human activities. A multiple linear regression was run to evaluate the influence of SOM and LOI in aggregate stability (WSA) where all variables were statistically insignificantly to the prediction $p < 0.05$ as follows: forestland (WSA, $R^2 = 0.235$, $p > 0.05$ (0.299)), cultivated land (WSA, $R^2 = 0.425$, $p > 0.05$ (0.083)), grassland (WSA, $R^2 = 0.119$, $p > 0.05$ (0.642)), bare land (WSA, $R^2 = 0.161$, $p > 0.05$ (0.540)), bush land (WSA, $R^2 = 0.072$, $p > 0.05$ (0.769)). The results suggest that the SOM has influence on aggregate stability. The Kruskal–Wallis test also showed that the difference between the medians of LOI and SOM were not significantly different in all land uses across categories of WSA, $p > 0.05$ (0.164 and 0.195), respectively, for bare land; $p > 0.05$ (0.277 and 0.267), respectively, for bush land; $p > 0.05$ (0.692 and 0.441), respectively, for grassland; $p > 0.05$ (0.386 and 0.262), respectively, for cultivated land; and $p > 0.05$ (0.127 and 0.197), respectively, for forestland (Figure 5), which implies that the aggregate stability is influenced by the SOM. The strong relationship between the LOI, SOM and WSA indicated that LOI approximation for WSA and the augmentation of organic matter in soil is a good strategy for farmers to reduce the risk of erosion.

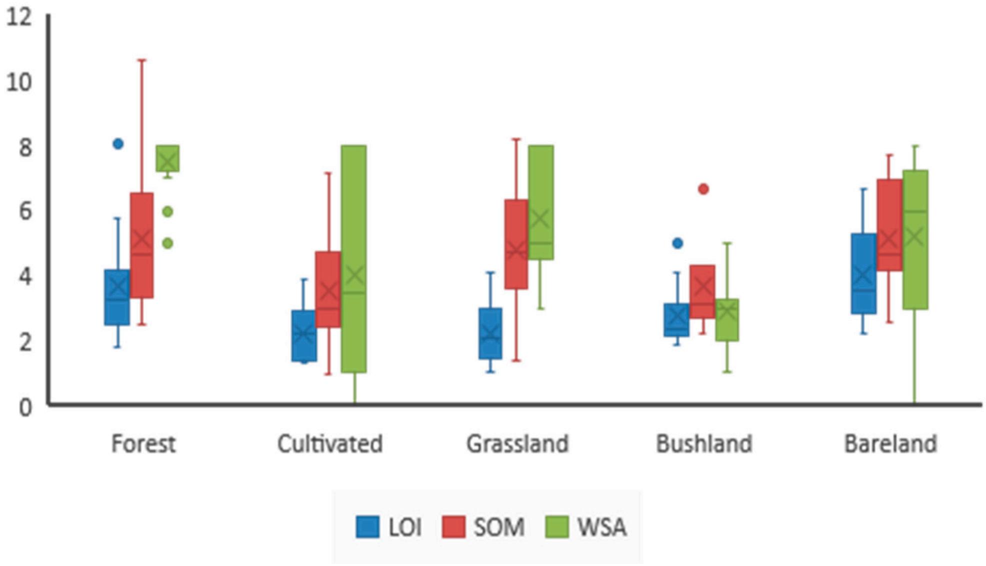


Figure 4. Boxplot comparing the ranges of LOI, SOM and WSA in each land use classification.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of LOI is the same across categories of WSA.	Independent-Samples Kruskal-Wallis Test	0.163	Retain the null hypothesis.
2	The distribution of SOM is the same across categories of WSA.	Independent-Samples Kruskal-Wallis Test	0.067	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is 0.05.

Figure 5. Kruskal–Wallis test results from SPSS.

The higher values of WSA in forest land and grassland indicate the stability of their soil structures in relation to longer-term vegetation cover. The forest soil exhibited the highest degree of the aggregate stability, which may be due to the higher SOM content input to soil vegetation cover, higher biological activity, and the protection of soils against degradative processes. The WSA was also high in the grasslands, which might be due to higher root biomass and the return of residuals to the soil. High root biomass and residues increase the organic matter content as the carbon source that support the water holding capacity in soil in turn becomes a conducive environment for the decomposition of organic matter [69]. The high WSA and SOM in bare land was unexpected and might be an influence on the high clay content, i.e., independent of land cover. Soil aggregate stability is affected by various parameters that act as binding agents, includes organic matter, soil texture, iron and aluminum oxides, carbonates and metal cations [70]. Increasing organic matter content enhances the stability of soil aggregates, and this is more distinct in soils with higher clay-fraction contents. The soil texture in the bare land was mostly clay loam and sandy clay loam, which have characteristics to immobilize different macro- and micronutrients and accelerate changes in the microbiological activity of the soil [17] (Appendix A). The low WSA and SOM content in cropland is typically an indication of tillage practices that reduce the soil aggregation process and aggravate soil loss through erosion. The weakening in the structural stability of cultivated soils may apparently be attributed to aggregate disruption and SOC distribution in various physical fractions, including tillage operations and other erosion-facilitating practices that lead to rapid breakdown [13,71]. The results of this study indicated that the cultivated lands have a lower SOM content compared to the natural land cover types. These results are in line with other studies elsewhere, indicating that cultivation usually markedly decreases soil carbon [67–69,72–74]. The forest conversion to cultivation land and settlement (Table 3) likely influences the level of organic carbon due to soil loss, and the more rapid oxidation process of SOC leads to rapid reductions in the SOM values of surface soils [75]. During cultivation, SOM can be lost through multiple processes such as tillage, increased erosion, reduction of vegetative input and biological activity. Therefore, the lower SOM in the catchment is evidence of the increasing conversion of land cover types to large scale plantations in the lowlands that may have influenced the hillslope erosion. In particular, the removal of plant residue from the soil surface layer through different land management practices, including cultivation, destroys soil macro-aggregate formation, which significantly alters soil texture and SOM and eventually increase soil erodibility. However, some crop land soils in the Msitu wa Tembo and Soko scheme had higher SOM and aggregate stability (Appendix A). This might be due to higher fertilizer input in cropland, which was revealed during the sampling campaign. The application of NPK fertilizer in the fields could have increased biological activity that promotes the formation of water-stable aggregates, which in turn improved the mechanical stability of soil aggregates by binding soil mineral particles [76]. The labile organic carbon (LOC) of SOM is responsible for organic amendments that enhance the water-stable aggregation process. In turn, the water-stable aggregation increases the availability of organic compounds that promote soil microorganism growth, which produces more extracellular polysaccharides and promotes aggregate formation [77]. The low WSA and SOM in bush land might be due to low root biomass production influenced by regular animal grazing that led to soil degradation. The present study and other studies by Nath and Lal. [78], Delelegn et al. [79] and Tang et al. [80] show that land use change has a major and important effect on soil aggregate stability, structure and, consequently, on water erosion.

The development of strategic land management plans based on the observed relationship between the slake test/aggregate stability and SOM is highly appropriate in soils with high clay contents because the distribution of clays in soil is associated with reduced infiltration and run-off, sediment load and crust formation [81]. Although the catchment soil sample were composed of large clay contents, substantial differences between the stability of aggregates in water was observed. From a sustainable land management perspective, soil organic carbon increases soil porosity and improves the mechanical flexibility to compression stress [82]. The cohesive effect of organic matter and its behavior to sustain soil microbial activities makes soil organic carbon content a good proxy for soil degradation [65]. The relationship between SOC content and the improved physical quality of soil, as well as the subsequent benefits for the quality of farmed soils, are widely acknowledged [83,84].

4. Conclusions

The soil slake test method adapted from the USDA protocol was appropriately used to separate aggregates from different land use management types. The WSA scores were directly related to SOM and land use management types, signifying that the stability of aggregates in water could be used as a simple method by agronomists to assess soil erosion risk and to monitor soil health following land use management changes. The results presented in this paper revealed that land use/cover changes through anthropogenic activities have direct impact on the SOM and on the WSA. Unsustainable land use change exposes the land to water erosion and subsequently influences the soil organic carbon pool and significantly affects the quality and composition of soil organic matter and its migration. Following land use change, the quality and quantity of the SOC pools are affected and, consequently, the particles of the soil aggregate distribution and stability of the aggregates are influenced. This study recommends the sustainable land use management practices including afforestation, revegetation, sustainable grazing management programs and agricultural practices that emphasize soil conservation tillage systems and crop management to conserve the soil organic carbon that will eventually support the aggregate stability and decrease the risk of erosion. The potential to use the slake test is due to its wide applicability for many years to specific conditions of the soils that were tested and adapted. The slake test scoring protocols seemed to reasonably increase the sensitivity of the test without compromising the feasibility of its application by land managers than the existing USDA version. The robust associations between the WSA, SOM and land management practices in this study suggest that, where soil and climate conditions are similar within a defined region, the rapid assessment of the WSA using this approach offers an inexpensive means of assessing and providing a numerical score of 'soil health' and is a potential proxy for the direct measurement of SOC, which in turn is used to detect changes imposed by management. The prospect of using WSA as a rapid proxy for SOC change by agronomists where advanced measurements are limited would offer agronomists with a new tool for monitoring soil health. More research is essential to initiate its potential in different soil types in a range of management scenarios.

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Appendix A

Table A1. LOI: SOM and WSA from different LU classes.

Forest Land							
S/N	Place	Coordinates (Latitude, Longitude)		Soil Texture	LOI	SOM	WSA
1	Msitu wa Mbogo	−3.52608	36.87787	Clay loam	2.01	2.9	5
2	Mbuguni B/Kubwa	−3.56427	36.9433	Loam	3.073	4.59	8
3	Mawalla TPC	−3.50929	37.43439	Clay loam	1.77	2.5	7
4	Kifaru H School	−3.52821	37.55433	Clay loam	8.077	10.66	8
5	Kochakindo Kahe M	−3.50574	37.52873	Clay loam	5.74	8.03	8
6	Kikuletwa Bridge	−3.54595	37.31344	Silty loam	3.26	3.85	8
7	Sakilla Meru 1	−3.33825	36.96451	Loam	4.2	4.7	8
8	Sakilla Meru 2	−3.33333	36.96379	Clay loam	3.43	4.01	8
9	TPC Msarakia	−3.50892	37.34286	Clay loam	3.31	6.88	8
10	Sakilla Meru 3	−3.33056	36.95861	Loam	4.02	5.45	8
11	Sakilla Meru 4	−3.33958	36.96833	Clay loam	2.57	4.72	6
12	Bwawani	−3.54067	36.85773	Clay loam	2.496	3.16	8
		Average			3.66	5.12	5.5

Table A1. *Cont.*

			Forest Land				
S/N	**Place**	**Coordinates (Latitude, Longitude)**		**Soil Texture**	**LOI**	**SOM**	**WSA**
			Cultivated				
1	Soko Scheme	−3.47948	37.50149	Clay loam	1.44	2.39	8
2	Kikuletwa bridge	−3.55414	37.30683	Silty loam	1.46	2.43	7
3	Kituri Mwanga	−3.50029	37.55564	Sandy Clay loam	1.97	3.04	4
4	Longoi kwa sadala	−3.40601	37.26669	Clay	1.35	2.89	8
5	Machame Gabriella	−3.33576	37.23301	Clay	2.73	4.32	5
6	Kochakindo Kahe/Msh	−3.4979	37.53082	Loam	3.86	7.14	3
7	Mnadani Machame	−3.32695	37. 23079	Clay	2.49	2.86	1
8	Msitu wa Tembo	−3.57212	37.30344	Clay loam	2.88	4.82	8
9	Kituri Proper	−3.53708	37.53488	Sandy Clay loam	3.07	5.78	0
10	Hai Town	−3.3258	37.16489	Clay	2.96	4.15	1
11	Chekereni	−3.458273	37.541108	Silty loam	1.32	0.93	1
12	Kiomo Kahe/Msh	−3.48152	37.52188	Loam	1.33	1.32	1
		Average			2.24	3.51	3.92
			Grassland				
1	Kochakindo Kahe M	−3.50184	37.53162	Clay	2.88	4.51	8
2	Kituri Proper	−3.53377	37.53155	Loam	3.27	6.76	3
3	Tindigani Masaini	−3.43491	37.12334	Clay loam	4.07	8.20	5
4	Kiomu Majengo	−3.49196	37.53977	Loam	1.03	1.36	5
5	Chemchem	−3.58688	37.33495	Loam	1.25	2.79	8
6	Arusha Airport	−3.36487	36.61352	Loam	2.18	4.98	8
7	USA Leganga	−3.37275	36.84336	Clay loam	1.5	3.90	8
8	Mikocheni Kirungu	−3.59006	37.40077	Silty loam	1.54	6.17	5
9	Kahe Mashariki	−3.51569	37.51675	Loam	1.97	4.40	3
10	Ngaramtoni juu	−3.33712	36.62212	Loam	2.3	5.11	5
		Average			2.19	4.82	5.8
			Bushland				
1	Maweni Kikwe	−3.45577	36.83135	Clay	2.74	2.98	3
2	Kituri Proper	−3.5346	37.53488	Loamy Sand	2.13	2.79	3
3	Karangai USA	−3.4814	36.86903	Loam	2.32	2.51	5
4	Bwawani	−3.5486	36.85565	Clay loam	2.34	3.18	2
5	Soko village	−3.49737	37.48351	Loam	4.97	6.76	3
6	Mikocheni B	−3.59063	37.42077	Sandy Loam	2.32	3.49	3
7	Masama Rundugai	−3.42217	37.23557	Clay loam	2.79	3.15	3
8	Mawalla	−3.55303	37.42863	Clay loam	4.07	6.66	2
9	Msitu wa Tembo	−3.57212	37.30344	Clay loam	2.08	3.09	4
10	Chekereni Majengo	−3.47629	37.53977	Silty loam	1.89	2.22	1
		Average			2.86	3.7	2.9

Table A1. *Cont.*

Forest Land							
S/N	**Place**	**Coordinates (Latitude, Longitude)**		**Soil Texture**	**LOI**	**SOM**	**WSA**
Bareland							
1	Kia Kaloleni 1	−3.4401	37.04131	Clay loam	3.27	4.63	3
2	Lengijave	−3.20137	36.62547	Loam	3.05	4.18	8
3	Kia njiapanda	−3.37544	37.0482	Clay loam	2.62	4.39	0
4	Leisinyai	−3.46666	37.05372	Loam	2.95	3.99	8
5	Mikocheni A	−3.59006	37.40077	Silty loam	2.22	2.59	3
6	Mererani	−3.45943	37.03773	Clay loam	3.82	4.61	5
7	Sanya Palestina	−3.339693	37.08968	Clay loam	5.11	7.24	6
8	Sanya roadtall	−3.35777	37.09375	Sandy Clay loam	6.7	6.83	6
9	Sanya Power st	−3.37396	37.06587	Sandy Clay loam	5.69	7.69	6
10	Kia kaloleni 2	−3.43999	37.04177	Clay loam	4.58	5.54	7
		Average			4.00	5.2	5.2

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