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Assessment on the Soil Retention Service of Water Erosion in the Nile River Basin Considering Vegetation Factor Variance from 1982 to 2013

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Abstract: Water erosion has negative effects on agricultural productivity in Africa. The cover management factor (C factor) related to vegetation is the most influential parameter in the estimation of water erosion and reflects key interrelated cover and management information on the soil retention service of water erosion. However, the estimations of C factor on a large-scale display large differences. The Nile River Basin has suffered severe water erosion for several decades, while the soil retention service of water erosion from vegetation is still unclear. This study assesses the spatiotemporal change in soil retention service in the Nile River Basin from 1982 to 2013, based on the Revised Universal Soil Loss Equation (RUSLE) model. The comparison of six kinds of estimation methods showed that four methods could be used, whereas the other two were inappropriate. The average annual soil retention service based on the C factor variance ranged from 934.08–1240.56 (t ha⁻¹ y⁻¹), and spatially increased from south to north. The area of significant increasing and decreasing tendencies were 1.31×10^4 – 1.94×10^5 km² and 5.68×10^3 – 3.81×10^4 km², respectively. These results provide a reference for the selection of C factor methods and spatiotemporal evidence of the soil retention service of water erosion in the Nile River Basin.

Keywords: water erosion; C factor; soil retention service; mapping; tendency; Nile River Basin

1. Introduction

The acceleration of water erosion has plagued human beings since the dawn of settled agriculture [1]. Approximately 50% of the population heavily relies on local agriculture for food in Africa, which has led to extreme water erosion with poor management [2]. With limited resources to invest in soil retention service of water erosion management, the continued pressure on resources further aggravates land degradation due to water erosion, soil nutrient mining, deforestation and loss of biodiversity [3]. It is estimated that the range of agricultural yield reductions varied from 2% to 40% from 1970 to 1990, and the reductions in Africa by the year 2020 could reach 16.5% [4]. Because water erosion is a growing threat that affects the livelihoods of humans in Africa and is a threat to any future agriculture, the spatiotemporal change in the soil retention service of water erosion requires detailed tracking [5,6]. Accordingly, providing scientific guidance for the maintenance and management of the soil retention services of water erosion and, subsequently, enhancing this ecosystem service require a credible spatiotemporal assessment [7,8], which can help locate areas where water erosion is drastic and where the soil retention services need to be enhanced [9].

Revised Universal Soil Loss Equation (RUSLE) models are effective methods for evaluating the soil retention service of water erosion on a large scale [10,11]. A RUSLE model requires data on climate,

topography, soil and vegetation [12]. Among these parameters, vegetation affects nutrient removal and, in turn, plant productivity, which is closely related to the soil retention service intensity [13]. Thus, the vegetation growth plays a positive role in providing the soil retention service and preventing water erosion [14,15], and it refers to the cover management (C) factor in the RUSLE model [16,17]. Estimating the cover management factor (C factor) by specific local selection criteria parameters is therefore crucial for the credible assessment of water erosion and soil retention service [18].

The traditional method used to estimate the C factor value is the soil loss ratio, which is an estimate of the ratio of water erosion under actual conditions to losses occurring under a reference condition. The soil loss ratio calculation contains five subfactors (prior land use, canopy cover, surface cover, surface roughness and soil moisture) [19]. Each soil loss ratio value is weighted by the fraction of rainfall and runoff erosivity associated with the corresponding time period, and these weighted values are combined into an overall C factor value [20]. However, both methods are based on field experiments in which acquiring relative data for estimating the C factor is difficult to obtain in areas where little recorded data are available, such as Africa. Therefore, the detection of changes in the C factor based on remote sensing imagery is necessary in the analyses of the spatiotemporal changes of water erosion [21,22].

In the cover classification methods, C factor values can be assigned to cover types that were originally categorized as land cover maps [23]. For example, a spatial distribution map of C factor values in the Yanhe watershed on the Loess Plateau of China has been drawn in combination with C factors for other land use types [24]. This type of method can provide rapid C factor values but cannot take the detailed temporal variance in vegetation into account. The Normalized Difference Vegetation Index (NDVI) is one of the primary indices used for spatiotemporal vegetation monitoring and assessment [25], and forms different algorithms in C Factor calculations. Because various C factor evaluation methods are available, the C factor should be estimated with different methods at the same scale to improve the credibility of the assessment.

The Nile River Basin is a prominent farming community in Africa in which people rely on agricultural production for a living, and also has historically suffered from land degradation [26]. The main objective of this study is to estimate the spatiotemporal change in the soil retention service of water erosion based on the C factor variance in the Nile River Basin from 1982 to 2013. The objectives of this study are as follows: (a) to select effective C factor methods based on the land cover and NDVI data; (b) to assess the spatiotemporal characteristics of soil retention service of water erosion based on the RUSLE model; and (c) to quantify the tendency for changes in the soil retention service of water erosion with nonparametric linear regression analysis.

2. Materials and Methods

2.1. Study Area

The study area is a river catchment that flows through eastern and northern Africa and is located in the northeastern part of Africa (Figure 1). The total area of the Nile River Basin is 3.25 million km², accounting for 10% of the total area of Africa, and contains parts of Uganda, Egypt, Sudan and Ethiopia. The Nile River Basin is located from 5° N 33' E to 15° N 39' E, and the highest altitude is 5000 m. The Nile River, with a total length of 6670 km, is the world's longest river and contains the Blue Nile, with a length of 1450 km, and the White Nile. The Blue Nile and the White Nile join in Khartoum to form the Nile River. The river flows northeast and continues its course up to Egypt, where it enters Lake Nasser; then, the river flows further downstream to enter the Nile Delta before reaching the Mediterranean Sea [3]. The Blue Nile River flows south from Lake Tana and then west across Ethiopia and northwest into Sudan [27]. The climate of the Nile River Basin is obviously different from north to south and belongs to the savanna and tropical desert climates; for example, the Ethiopian highlands in the southern part of the basin are located in an important rainfall center. The climate is wet, with

the average annual rainfall ranging from 1000 to 2000 mm, whereas that of the Sudan border is dry, with the average annual rainfall ranging only from 25 to 200 mm.

Figure 1. Location and land use map of the study area.

2.2. Data Sources

The datasets in the soil retention service of water erosion assessment included the NDVI, land use and cover types, soil properties, slope and precipitation. The NDVI is used in the Global Inventory Modeling and Mapping Studies (GIMMS) (<https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v0/>), and the time series was from 1982 to 2013, with a time resolution of 15 days and a spatial resolution of 8 km. The GIMMS NDVI3g eliminates the effects of volcanic eruptions, solar elevation angles and sensor sensitivity over time. In this study, considering the advantage of the half-month resolution, both the yearly NDVI and the monthly NDVI were calculated. The yearly NDVI was set as the average of the monthly NDVI values when NDVI > 0.1. Then, we estimated the C factor based on the yearly NDVI. The land use and cover types are derived from the European Space Agency (ESA) Climate Change Initiative (CCI) (<http://maps.elie.ucl.ac.be/CCI/viewer/index.php>) version 2.0 with a resolution of 300 m from 1992 to 2013, and are grouped into eight land categories according to the United Nations Food and Agriculture Organization (FAO) land classification, including agriculture area, forest/shrub, grassland, wetland, built-up area, water/drainage area, barren area and mixture (shrub land/sparse vegetation).

The soil properties were derived from the Harmonized World Soil Database v1.2, which has a 30'' resolution production (<http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/en/>). The slopes were derived from the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), which has a resolution of 90 m (<http://www.gscloud.cn>). The precipitation was derived from the National Oceanic and Atmospheric Administration (NOAA) (<https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily>), and the time series was from 1982 to 2013 at daily level. Similarly, all datasets were resampled to an 8-km resolution using the average value after the factor calculation in the RUSLE (Table 1).

Table 1. Quantitative numbers on all Revised Universal Soil Loss Equation (RUSLE) factors.

RUSLE Factors	Data Resolution	Resolution	Quantitative Methods
C factor	NDVI (8 km), land use and cover	8 km 300 m	Table 2 for details.
R factor	Precipitation	Daily	Richardson model [28]
L factor	Slope	90 m	Grading method based on slope [29–31]
S factor			
K factor	Soil properties	30"	EPIC model [32]

2.3. Estimation of Water Erosion and Soil Retention Service

The RUSLE was designed to predict the long-term average water erosion due to runoff from specific field areas in specified cropping and management systems. The soil retention service is equal to the potential water erosion minus the actual water erosion. The RUSLE estimates the annual water erosion and soil retention service as follows:

$$A_r = R \times K \times L \times S \times C \times P \quad (1)$$

$$A_p = R \times K \times L \times S \quad (2)$$

$$A_c = A_p - A_r = R \times K \times L \times S \times (1 - C \times P) \quad (3)$$

where A_r is the estimated actual water erosion per year ($\text{t ha}^{-1} \text{y}^{-1}$), A_p is the estimated potential water erosion per year ($\text{t ha}^{-1} \text{y}^{-1}$), A_c is the estimated reduced water erosion per year (evaluated soil retention service amount) ($\text{t ha}^{-1} \text{y}^{-1}$), R is the runoff factor ($\text{MJ mm ha}^{-1} \text{h}^{-1} \text{y}^{-1}$), which expresses the erosivity occurring from rainfall and runoff at a particular location, K is the soil erodibility factor ($\text{t ha h ha}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$), L is the slope length and steepness factor, C is the cover management factor and P is the support practice factor. Deriving appropriate P factor values by remote sensing is difficult; thus, this study used a P factor value of 1. Since there are no specific methods for estimating these factors in this study, we selected the algorithms that were applied in global or African studies to estimate them [33,34].

According to soil retention service research in Africa and in the sub basin of the Nile River Basin, we divided the soil retention service of the Nile River Basin into five grades. The soil retention service (A_c) is divided into five levels: very low (<500), low (500–1500), moderate (1500–3000), high (3000–5000), and very high (>5000) (unit: $\text{t ha}^{-1} \text{y}^{-1}$).

2.3.1. Crop and Management Factor (C)

The C factor has a high sensitivity to natural and human activities and plays a significant role in estimating water erosion [35,36]. In this study, we adopted six methods to estimate the C factor and then selected four kinds of C methods to assess soil retention service. In the C1 method, the land use and cover types originally categorized by the USGS global ecosystems legend are reclassified into 8 types based on their similarities, and then the average value of the C factor is given to each land cover type in Table 2. Additionally, when select the better C factor methods for this area, this study selected four land cover types (agricultural, forest/shrub, grassland and mixture-shrub land/sparse vegetation) from which to extract the C factors, since their C factor values were clearly different in the different land cover types according to the rules. In the C2 method, the NDVI is based on the NOAA Advanced Very High-Resolution Radiometer (AVHRR); thus, $\alpha = 2$, and $\beta = 1$. In the C3–C5 methods, only the C factor must be estimated according to the formulas. In the C6 method, fc represents the vegetation coverage (%), which is obtained based on the NDVI. When the fc is greater than 78.3%, $C = 1$; when the fc is less than 0.1, $C = 0$; and when the fc is between 0 and 78.3%, C is calculated by the C6 formula. The six methods are shown as follows in Table 2.

Table 2. Cover management factor (C factor) estimation methods.

Method	Region	Source
C1: Agriculture area (0.65), forest/shrub (0.01), grassland (0.15), wetland (0.56), built-up area (1), water/drainage (0.01), barren area (0.28), mixture (0.40)	Global	[34]
$C2 = e^{[(1-\alpha) \times NDVI / (\beta - NDVI)]}$	Europe	[37,38]
$C3 = [(1 - NDVI) / 2]^{(1+NDVI)}$	Taiwan's Small Watershed	[39,40]
$C4 = 0.431 - 0.805 \times NDVI$	Southern France	[41]
$C5 = 1.02 - 1.21 \times NDVI$	Istanbul, Turkey	[42]
$C6 = 0.6508 - 0.3436 \lg fc$	Three Gorges Basin	[43]

Notes: fc represents vegetation coverage (%); $fc = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$; $\alpha = 2$; $\beta = 1$.

2.3.2. Erosivity Factor (R)

The R factor was originally computed for the total storm energy (E) times the maximum 30 min intensity (I30), or EI30, and was expressed as the rainfall erosion index, which can reflect the impact of potential of rainstorms on water erosion [19,44]. We obtained the average annual rainfall erosivity at 86 weather stations nationwide from 1982 to 2010 to obtain a raster layer of the rainfall that was interpolated with the inverse distance to a power method. Then, the annual rainfall erosivity was calculated using the Richardson model based on the average annual rainfall, which is expressed in Equation (4) [28].

$$R = 0.335P^{1.18} \quad (4)$$

In Equation (4), R represents the yearly rainfall erosivity, and P represents the average annual precipitation (mm).

2.3.3. Topographic Factor (LS)

The topographic factor reflects the impact of the water erosion slope length (L) and steepness (S) on water erosion. The LS factors are calculated by the slope, and the slopes are extracted from the DEM. The slope length factor is the water erosion normalized to the 22.13 m long slope in the RUSLE/USLE and is expressed as Equation (5), in which the slope exponent, m, is 0.2, 0.3, 0.4, and 0.5 for different increasing slope gradients [29]. The steepness is the water erosion normalized to the slope value of 5.12, and this study applied different formulas to calculate the steepness according to the different slope ranges; the steepness was calculated according to Liu (1994) [30] when the slope was more than 10° and otherwise was calculated according to McCool (1987) [31]. The LS equations are as follows:

$$L = \left(\frac{\varphi}{22.1} \right)^m \quad (5)$$

$$m = \begin{cases} 0.2, & \theta \leq 1^\circ \\ 0.3, & 1^\circ < \theta \leq 3^\circ \\ 0.4, & 3^\circ < \theta \leq 5^\circ \\ 0.5, & \theta > 5^\circ \end{cases} \quad (6)$$

$$S = \begin{cases} 10.8 \sin \theta + 0.036, & \theta < 5^\circ \\ 16.8 \sin \theta - 0.5, & 5^\circ \leq \theta < 10^\circ \\ 21.9 \sin \theta - 0.96, & \theta \geq 10^\circ \end{cases} \quad (7)$$

In Equations (5)–(7), φ is the noncumulative slope length (m), m is the slope length exponent, and θ is the slope angle.

2.3.4. Erodibility Factor (K)

The soil erodibility factor is the rate of erosion per unit erosion index from a standard plot, which is a quantitative description of the inherent erodibility of a particular soil [45]. This study area uses the EPIC [32] model to estimate the soil erodibility factor based on the soil properties, and the equation is as follows:

$$K = \frac{1}{7.6} \left\{ 0.2 + 0.3 \exp \left[0.0256 \text{SAN} \left(1 - \frac{\text{SIL}}{100} \right) \right] \right\} \left(\frac{\text{SIL}}{\text{CLA} + \text{SIL}} \right)^{0.3} \times \left(1.0 - \frac{0.25}{C + \exp(3.72 - 2.95C)} \right) \left(1.0 - \frac{0.7\text{SN}}{\text{SN} + \exp(22.9\text{SN} - 5.51)} \right) \quad (8)$$

In Equation (8), SN = 1–SAN/100, and SAN, SIL, CLA and C are the contents of sand, silt, clay and organic matter, respectively, in percentages.

2.4. Linear Regression

The Theil–Sen (TS) estimator uses a linear model to estimate the slope of the trend, and the Mann–Kendall (MK) statistical test is used to quantify the significance of the trends in a time series [46,47]; this latter test has been widely performed as the nonparametric trend analysis method to determine significant differences in remote sensing vegetation monitoring. The TS–MK only requires that the data are independent and that outlier effects can be eliminated regardless of the distribution sequence. Therefore, this study estimates the trend of soil retention service with the TS–MK method as follows [48,49]:

$$\text{slope} = \text{Median} \left(\frac{A_{c_j} - A_{c_i}}{t_j - t_i} \right) \quad S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(A_{c_i} - A_{c_j}) \quad \text{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

$$\text{sign}(A_{c_i} - A_{c_j}) = \begin{cases} 1 & \text{if } A_{c_i} - A_{c_j} < 0 \\ 0 & \text{if } A_{c_i} - A_{c_j} = 0 \\ -1 & \text{if } A_{c_i} - A_{c_j} > 0 \end{cases}$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{for } S < 0 \end{cases} \quad (9)$$

In Equation (9), A_{c_i} and A_{c_j} are the soil retention service values of the area in years i and j , respectively, and n represents the length of time based on S . A slope > 0 represents water erosion restoration, and a slope < 0 represents water erosion degradation. Additionally, t_i and t_j are the year numbers. If $|Z| > 1.64$, then the trend is significant.

3. Results

3.1. Selection of C Factor

A comparison of methods C1–C6 is shown in Figures 2 and 3, which contain the soil retention service, water erosion and C factor values. The calculation results for soil retention service and water erosion using the 2013 data are shown in Figure 4. The water erosion and soil retention service values for the Nile River Basin in 2013 based on the six methods were shown in Table 3. The C factor value differences for the four land cover types are shown in Figure 3. In the C1–C4 methods, the values of soil retention service are all approximately $1000 \text{ (t ha}^{-1} \text{ y}^{-1}\text{)}$, and the values of water erosion are less than $250 \text{ (t ha}^{-1} \text{ y}^{-1}\text{)}$, between the maximum $515.56 \text{ (t ha}^{-1} \text{ y}^{-1}\text{)}$ and the minimum $224.42 \text{ (t ha}^{-1} \text{ y}^{-1}\text{)}$ values. In addition, the value of the C factor is obviously different for the four land cover types in the C1–C4 methods. The C5 method has C factor values of 0.72, 0.66, 0.86, and 0.77 for the agricultural, forest/shrub, grassland and mixture types of land cover, respectively, which are difficult to distinguish;

the C6 method has water erosion and soil retention service values of 1161.96 and 285.21 ($\text{t ha}^{-1} \text{y}^{-1}$), respectively, where the value of the water erosion is too small and the value of soil retention service is too large and are thus not in accordance with the rules. Thus, the C5–C6 methods are difficult to use to estimate soil retention service in the Nile River Basin. Therefore, the combination of the results presented in Figures 3 and 4 shows that methods C1–C4 used in this study are reasonable, whereas methods C5–C6 are not appropriate for this study. Therefore, this study selected methods C1–C4 to estimate the soil retention services in the Nile River Basin.

Figure 2. Water erosion and soil retention service values based on methods C1–C6 (13 years). C1–C6 represent the six C factor estimation methods shown in Table 2.

Figure 3. Comparison of the C factors (C1–C6) obtained for the different land cover types. C1–C6 represent the six C factor estimation methods shown in Table 2.

Figure 4. Spatiotemporal characteristic map of the average annual C factor (C1–C4) from 1982 to 2013. C1–C4 represent the four C factor estimation methods shown in Table 2.

Table 3. Water erosion and soil retention service based on six C factor methods in 2013 ($\text{t ha}^{-1} \text{y}^{-1}$).

Six C Factor Methods	C1	C2	C3	C4	C5	C6
Water erosion	442.86	515.56	317.53	224.42	795.03	1161.96
Soil retention service	1000.53	916.7	1122.91	1219.40	631.57	285.21

3.2. Change Tendency of the C Factor

After mapping the average annual values of the C factor based on the C1–C4 methods, both spatial and temporal differences appeared (Figure 4). The C1 method shows spatial differences according to the land cover types and the C2–C4 methods, according to the extent of greenness. C1 shows a clear spatial difference according to the different land cover types, and C2–C4 show increasing values from south to north. Specifically, in the C1 method, the C1 distribution shows high values in the agriculture, wetland and built-up areas and low values in forest/shrub, water/drainage and grassland areas, which have high values in the center and south of the study area and low values in the southwest area. Compared to C1, C2–C4 show no significant differences in the land cover types; we can only see a rough spatial distribution from the direction. Combining the C1 method and C2–C4, C1 has a low value in Egypt, the southwest of Sudan and the center of Uganda, whereas C2–C4 has a low value in Sudan and around Uganda and Ethiopia. C1 shows a high value in northeast Ethiopia, the north of Sudan and around Uganda, whereas a higher value is evident in Egypt and the center of Uganda. In conclusion, the spatial distribution difference in the average annual C factor is mainly in Egypt and Uganda. From a temporal perspective, the tendency of the average annual C factor was similar in C1–C4, although some fluctuations around the mean were noted; however, the average annual C factor values obtained with C1–C4 were different (0.34, 0.37, 0.23, and 0.17, respectively).

3.3. Change Tendency of the Soil Retention Service

The average annual soil retention service calculated by the RUSLE model and based on the C1–C4 methods showed obvious spatiotemporal differences (Figure 5). On the whole, A1–A4 showed higher values in the southwest and east and lower values in the central and northern parts of this study area. The soil retention service in A1 yielded a higher soil retention service in the forest/shrub areas and a lower soil retention service in other land cover types. The spatial distributions of moderate and high soil retention service are consistent in A2–A4; however, A2 is different from A3–A4 in the distribution of low soil retention service. The average annual actual water erosion based on the same potential water erosion was 445.74, 524.12, 322.50, and 227.21 $\text{t ha}^{-1} \text{y}^{-1}$, and the potential water erosion was 1441.78 $\text{t ha}^{-1} \text{y}^{-1}$. There was an area of approximately 2.12×10^6 – $2.45 \times 10^6 \text{ km}^2$ with a very low and low soil retention service, which accounts for 70.12–80.86% of this area. An area of approximately 2.67×10^5 – $3.79 \times 10^5 \text{ km}^2$ had a high and very high soil retention service, which accounts for 8.80–12.51% of this area. From a regional perspective, the southwest of Sudan and the Ethiopia area have a higher soil retention service, and central Sudan and northern Egypt show a lower soil retention service. In view of the temporal tendency, the tendencies of the average annual soil retention service were similar in A1–A4, although some fluctuations around the mean were noted; however, the average annual soil retention service values shown in A1–A4 were different (1020.22, 934.08, 1139.76, 1240.56 ($\text{t ha}^{-1} \text{y}^{-1}$), respectively). In conclusion, the A2 soil retention service was less than the A1, A3 and A4 soil retention service, and the A4 soil retention service was more than the A1–A3 soil retention service. Thus, the change in the range of the soil retention service was 934.08–1240.56 ($\text{t ha}^{-1} \text{y}^{-1}$).

Figure 5. Spatial distribution of the average annual soil retention service and temporal tendency of the average annual soil retention based on four vegetation cover types and management factors (1982–2013). A1, average annual soil retention service based on C1 (1992–2013); A2, average annual soil retention service based on C2 (1982–2013); A3, average annual soil retention service based on C3 (1982–2013); A4, average annual soil retention service based on C4 (1982–2013).

3.4. Change Proportion of the Soil Retention Service

The pixel proportion of tendency shows the spatial distributions of soil retention service change (Figure 6). In Figure 6a, the pixels representing significant change only account for 1.62% of this area, with an area of $5.19 \times 10^4 \text{ km}^2$. Because the map was calculated based on the land cover type, this method also estimates the proportion of vegetation, for example, agriculture (26.65%), forest and shrub (16.46%), grassland (6.95%), and mixed vegetation (20.18%). It is obvious that the pixels representing significant change are distributed in the center of this study area. In Figure 6b–d, which are calculated based on the A2–A4 in Figure 5, the pixels representing a significant decrease or decrease account for 9.95%, 3.17%, and 3.77% of this area, with areas of 3.17×10^5 , 9.94×10^4 , and $3.77 \times 10^5 \text{ km}^2$, respectively. At the same time, the pixels representing significant increases or increases account for 3.77%, 2.37%, and 3.02% of this area, with areas of 1.18×10^5 , 7.42×10^4 , and $9.46 \times 10^4 \text{ km}^2$, respectively. From a regional perspective, the spatial distribution is obviously different among Figure 6a–d. Figure 6a shows the area of significant change at the junction of Sudan and Ethiopia. Figure 6b shows the areas of significant increases in Egypt and decreases in the southeast of Sudan. Figure 6c shows most of the significant increase area, with only $2.42 \times 10^4 \text{ km}^2$ showing a tendency to increase and $5.20 \times 10^4 \text{ km}^2$ showing a tendency to significantly decrease. For Figure 6d, it is similar to Figure 6c in the spatial distribution. From Figure 6a–d, we can see that the area ranges of pixels representing the significant increase and decrease in soil retention service are 1.31×10^4 – $1.94 \times 10^5 \text{ km}^2$ and 5.68×10^3 – $3.81 \times 10^4 \text{ km}^2$, respectively.

Figure 6. Temporal tendency and area percentages of the average annual soil retention service based on methods A1–A4 (1982–2013). (a) A1, tendency of soil retention service based on C1 (1992–2013); (b) A2, tendency of soil retention service based on C2 (1982–2013); (c) A3, tendency of soil retention service based on C3 (1982–2013); (d) A4, tendency of soil retention service based on C4 (1982–2013); (a%) area percentage based on (a); (b%) area percentage based on (b); (c%) area percentage based on (c); (d%) area percentage based on (d).

A soil retention service distribution with significant trends was found in the north and northeast areas. The significant increase area accounted for 13,067–194,016 km², and the significant decrease area accounted for 5684–38,082 km² and had a close relationship with the land cover type. An increasing tendency was observed from north to south. The temporal tendency showed a steady tendency from 1982 to 2013 in the Nile River Basin. In this study, soil retention service has only a slightly increasing tendency, which may indicate that this area still needs to take measures to prevent water erosion.

4. Discussion

4.1. Evolution of C Factor Methods

There are many methods of estimating the C factor based on land use and the NDVI. The different estimation methods could reduce the error of the impact of C factor overestimation or underestimation. Therefore, this study used six C factors to assess soil retention service, but the C5–C6 methods were not selected due to the errors in water erosion and the soil retention service and the similarity in the C factor values based on different land covers. The C1 method is commonly used on a large scale [24,33]. The C2 method has been used at the sub basin and sub country levels of this study [3,50,51]. For the C3–C4 methods, the water erosion and soil retention service values and the differences between the different features are reasonable for this study, and although the two methods are not used in this study, these methods can be used in future studies. When comparing the C1–C4 methods, the spatial distributions of the C1 and C2–C4 methods are clearly different because C1 is estimated by land cover types and C2–C4 are estimated by greenness. In the methods of C2–C4, the values of water and bare location are too high to estimate the C factor, which may make the result questionable; however, this study mainly assessed the soil retention service rather than the C factor, and the questionable result can be eliminated in the calculation process of the soil retention service. Thus, the C2–C4 methods are also reasonable for this study. In conclusion, the C factor methods selected in this study are found to be reasonable.

4.2. Evolution of Soil Retention Service

The assessment results of the soil retention service were in accordance with the statistical information from the Nile River Basin in some selected sub basins and sub countries where water erosion information was available (Table 4). This study selected water erosion information based on the different methods and sources of the white and blue river basins. It is difficult to compare the results of the soil retention service given the differences in the model and scale; however, the reasonableness of the results can be judged. For example, this study selected the locations of the white and blue basins to compare the water erosion with previous studies. This study found higher water erosion in the white basins and lower values in the previous research; as for the blue basins, the results of this study were in accordance with previous results [3]. Considering the differences, although the previous research was based on models of similar environmental constraint envelopes (SECEs) and RUSLE, the previous research only estimated the C factor with a method that was based on the NDVI and neglected the impact of land cover types. Therefore, this result can be regarded as an advancement that considers both the land cover types and the greenness at the same time. In addition, the water erosion ranges are from 227.21 to 524.12 t ha⁻¹ y⁻¹ in this study, and this result is similar to the result of the Nile River Basin, which was extracted from the estimation of global water erosion [34]. Moreover, we collected statistical information about water erosion from some countries in this study, such as Uganda, Ethiopia, Sudan, Tanzania and Kenya (Table 4). Due to the lack of information on Egypt, we only collected statistics on the water erosion information for these five countries; the range was 350 to 371 (t ha⁻¹ y⁻¹), which is similar to what we found in our study. Therefore, our research is in line with the public's perception.

Table 4. Average water erosion for different regions in the Nile River Basin by different studies.

Study Site	Water Erosion ($\text{t ha}^{-1} \text{y}^{-1}$)	The Source of Article
Nile River Basin	417	[34]
the Blue Volta	75 (NSL)	[3]
the White Volta	28 (NSL)	[3]
Ethiopia	185	[52]
Nyando catchment, Kenya	90	[53]
Uganda	10	[2]
Sudan	21–48	[54]
Upper Blue Nile River	27.5	[55]
Tanzania	10	[52]

Note average net water erosion (NSL).

Nevertheless, the impacts of land cover types and greenness on the soil retention service differed (Table 5). Obviously, the forest and shrub areas have the highest capacity to conserve soil in A1–A4, whereas the water/drainage and wetland areas have the lowest. However, the comparison between the barren area and the agricultural area is more controversial because the soil retention service is higher in the barren area than in the agricultural area in A1, whereas A2–A3 provide the opposite result. Many factors can cause this phenomenon (e.g., human activities, rainfall erosivity or the methods); thus, this issue warrants further study. The grassland and mixture areas have a moderate level of soil retention service. Accordingly, the estimation results obtained with A1–A4 in this study remind researchers that many factors should be considered in the estimation of the soil retention service. In conclusion, this study evaluates the statistics on the changes in soil retention service by land cover types based on A1–A4, but we cannot analyze in detail how soil retention service changes according to the land cover types based on the greenness. Thus, further research is still needed.

Table 5. Area percentages of the land cover types and A1–A4 soil retention service.

Land Cover Types	Percentages of Areas (%)	A1 (%)	A2 (%)	A3 (%)	A4 (%)
Agriculture area	26.67	10.32	16.55	14.76	14.70
Forest/Shrub	16.51	31.61	34.75	27.80	27.05
Grassland	6.95	11.13	7.74	9.66	9.88
Wetland	1.59	5.55	7.45	5.94	5.64
Built-up area	0.14	7.18	11.89	12.97	14.44
Water/Drainage	3.18	4.20	4.68	4.45	4.07
Barren Area	25.31	20.29	5.02	13.65	13.63
Mixture	19.65	9.71	11.91	10.76	10.60

Note: methods A1–A4 represent the average annual soil retention service values obtained based on C1–C4.

4.3. Uncertainties and Future Directions

Although uncertainty analysis is not the key component of soil retention service research on a large scale, it is still necessary to further explore the uncertainty and to improve the accuracy. Therefore, this study explores the uncertainty from the data source and the effect of the driving factors.

With respect to the data source, the use of data in an evaluation of the soil retention service is still worth exploring. This study estimated the C factor based on the NDVI and the land use and cover, in which the NDVI focused on the change in greenness and the land use and cover focused on the change in types. Thus, the spatial differences of the C factor based on greenness and type are our foci. Of course, the temporal mapping of soil retention service comes at the cost of reduced accuracy. First, if we only explore the spatiotemporal characteristics of soil retention service after 2000 or 2010, the Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI with a 1 km resolution can be applied in this study. However, the spatiotemporal characteristics are not obvious within a period of more than decade, so the GIMMS NDVI is regarded as a good choice when estimating soil retention

service for a period of over thirty years. Although the land cover types were annually continuous in 1992 and lacked data from 1982–1991, generally speaking, large changes in land cover types are difficult to evaluate during a period of less than a decade; thus, these are the only and longest term land cover data from 1992 to 2013 that can be used to explore the impact of the types on the C factor and soil retention service in this study.

From the effect of the driving factors, it is obvious that the distribution of the other factors for RUSLE changes is less uncertain than the crop and management C factor. For the rainfall erosivity factor R, which is calculated by the spatial interpolation of precipitation, the spatial interpolation can increase the uncertainty of the sample values. For the topographic factor LS, which is calculated according to slopes extracted by the 90 m DEM, it also increases the uncertainty of the accuracy of the soil retention service estimation. Because the value of the LS indicator would be largely reduced and distorted if the resolution of the elevation were coarser, when targeting a regional soil retention service estimation, a finer elevation resolution is recommended to calculate the LS indicator. For the erodibility factor K, which is calculated by the soil properties, it also increases the uncertainty due to the difference in soil types. To derive the appropriate P factor, although there is little impact on soil retention service with a value of one, the uncertainty would decrease if the P factor could be calculated with an approach similar to the calculation of the C factor.

With respect to the uncertainty analysis, it is important to make a careful judgment of the uncertainty factors when assessing soil retention service at a large scale. This study used four C factor methods to assess soil retention service from land cover types and greenness. However, whether we can assess soil retention service based on land cover in the future would make a great contribution to future research on soil retention service. For example, if we could establish a scenario that could maintain the balance of soil retention service according to the greenness change for the land cover types (e.g., first build an ecological security pattern, then simulate land and climate changes based on the pattern, and finally estimate soil retention service in this pattern), it would receive widespread attention. Further explorations can take the hydrological regime in the catchment into account, as assessed by Jiang [56,57]. Ito (2007) estimated that the uncertainty about the vulnerability of soils would increase due to the loss of more organic matter and mineral nutrients [44], which is also a possible research direction. In summary, this research scenario simulation is worth advancing and can provide guidance for the management of future soil retention service and the prevention of water erosion.

5. Conclusions

Water erosion is a serious threat in the Nile River Basin, and detailed spatiotemporal information of soil retention service is required. This study mapped the changes of water erosion and soil retention service based on the C factor variance estimated by land cover types and vegetation indices. The findings showed that, although the soil retention service has improved in recent years, water erosion is still at a relatively high level. In a summary, as a typical ecosystem service, the soil retention service is significant for human wellbeing and ecosystem health in the Nile River Basin. This study provides a reference for the selection of C factor methods and evidence for the change in water erosion and soil retention service in the Nile River Basin. In future studies, in order to improve the limitations of the mapping and water erosion and soil retention service, both more accurate datasets and more effective algorithms can play an important role for improving the mapping accuracy. In addition, some human activities such as land management measures and economic investment should be taken into account.

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