SECTION 2. POLLUTION

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Modeling of soil erosion by water in the provinces of Sikasso and Koulikoro (Republic of Mali)

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Abstract. Soil along water is arguably the most precious resource on the planet. In addition to its economic benefits, soil provides critical biological services [7]. Despite its pillar functions for society, soil is often overlooked and thus is subjected to degradation and erosion. Soil erosion represents a serious global threat to land, freshwater, and oceans [3]. In Western Africa, erosion is perceived as a critical threat to the livelihoods of millions of people. This study attempts to assess and map the potential annual soil loss in the provinces of Sikasso and Koulikoro (republic of Mali). Spatial modeling of soil loss by rainfall for the year 2018 was provided using rainfall data derived from the European Joint Research Center, the Soil Map of the World (FAO), digital elevation model (SRTM), vegetation activity (MODIS / Terra). Methods of calculation were based on the Remote Sensing and the Revised Universal Soil Loss Equation (RUSLE). The Geoinformation processing of the RUSLE subcomponents involved the use of the LS-factor algorithm of the System for Automated Geoscientific Analyses (SAGA) and the Raster calculator of the ArcGIS tool box. The potential soil loss within the area ranged from 0.02 ton/ha/year to 98.87 tons/ha/year with a mean of 1.63 ton/ha/year. The spatial pattern of the erosion showed a rate of 0.02 to 1 ton/ha/year for 39% of the territory, 1 to 3 tons/ha/year for 47.58%, while 0.01% experienced a rate of more than 50 tons/ha/year. This study despite its match with the result of the global soil loss by water established by Borreli et al (2020) [3], needs to be verified by direct measurements.

Key words: Soil Erosion, Soil Loss by Water, Revised Universal Soil Loss Equation (RUSLE), Geoinformation Processing, Remote Sensing, Raster Calculation

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РАЗДЕЛ 2. ТРАНСФОРМАЦИЯ ПРИРОДНОЙ СРЕДЫ

Оригинальная научная (исследовательская) статья
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Моделирование водной эрозии почв в провинциях Сикассо и Коуликоро (Республика Мали)

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Аннотация. Почва вместе с водой, возможно, являются самыми ценными ресурсами на планете. Помимо экономических выгод, почва обеспечивает жизненно важные биологические услуги. Несмотря на то, что почва является основной для общества, ей часто не уделяют должного внимания, и поэтому она подвержена деградации и эрозии. Эрозия почвы представляет собой серьезную глобальную угрозу не только суше, но и для пресноводных экосистем, а также для океана. В провинциях Западной Африки эрозия считается серьезной угрозой для жизни миллионов людей. В этом исследовании делается попытка оценить и составить карту потенциальной ежегодной потери почвы в провинциях Сикассо и Куликоро (республика Мали). Пространственное моделирование интенсивности эрозии почвы, вызванной дождем за 2018 год проведено при помощи данных о ливневых осадках, полученных из Европейского центра совместных исследований, глобальной почвенной карты (ФАО), открытых данных о рельефе (SRTM) вегетационной активности растительности (MODIS / Terra). Все расчеты проведены на основе пересмотренного универсального уравнения потерь почвы (RUSLE). Геоинформационная обработка подкомпонентов RUSLE включала использование алгоритма LS-фактора, системы автоматизированного геофизического анализа (SAGA) и калькулятора растра из набора инструментов ArcGIS. Потенциальная потеря почвы на территории колеблется от 0,02 тонн/га/год до 98,87 тонн/га/год, а среднее значение составляет 1,63 тонн/га/год. Для большей части изучаемой территории характерна сравнительно невысокая интенсивность эрозии. Так, уровень потерь почвы от 0,02 до 1 тонн/га/год

характерен для 39% территории; от 1 до 3 тонн/га/год для 47,58%. Максимальные темпы эрозии (более 50 тонн/га/год) отмечены лишь для 0,01% изучаемой территории. Наше исследование, в целом, совпадает с результатами глобального моделирования потерь почвы, обусловленных водной эрозией, установленным Borreli et al (2020) [3]. Однако, для применения на практике, результаты нашей работы необходимо верифицировать прямыми натурными измерениями.

Ключевые слова: водная эрозия почвы, потери почвы, пересмотренное универсальное уравнение потери почвы (RUSLE), геоинформационная обработка данных, дистанционное зондирование, растровые вычисления

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Introduction

Erosion remains one of the most important factors that has shaped the Earth's surface since it emerged. And for more than 7,000 years, humans have been fighting erosion to protect their land from the aggressiveness of rain and runoff [18]. Erosion corresponds to the accelerated removal of topsoil and can occur in many forms as a result of several causes. Anything that moves, including water, wind, glaciers, animals, and vehicles can be erosive [20]. Amongst different transporting agents, water remains however, one of the most serious threat. Water erosion has been recognized as the most severe hazard threatening the protection of soil as it reduces soil productivity by removing the most fertile topsoil [17].

Given its negative effects on soil productivity, nutrient loss, siltation in water bodies, and degradation of water quality, scientists, since 1960's have been trying to understand the driving forces behind soil erosion. They have developed a variety of models to assist in identifying critical components and interactions within the soil erosion system. Amongst different erosion models, the Universal Soil Loss Equation (USLE) and its family of models: Revised Universal Soil Loss Equation (RUSLE), the Revised Universal Soil Loss Equation version 2 (RUSLE2), and the Modified Universal Soil Loss Equation (MUSLE), remain the most widely used [1].

First released by US Department of Agriculture – Agricultural Research Service /USDA-ARS/ in 1992 with the aim to overcome the shortcomings of the USLE model, the RUSLE kept on the basis of the USLE and measures soil loss per unit area at an annual timescale [20]. It uses a simple equation as followed:

$A = R * K * LS * C * P$ (Equation 1) [1].

Where: A is the annual soil loss in ton/ha^{-1}yr^{-1}, R is the Erosivity factor in Mj. Mm/ (ha.hr. yr), K is the erodibility factor (t ha h ha^{-1} Mj^{-1} mm^{-1}), LS is the slope steepness and slope length factor (unitless), C is the land cover management factor (unitless) and P is the conservation practice management factor (unitless).

Erosion modelling in developing countries such as Mali is difficult because of the lack of data regarding soils, rainfall and management practices. It is difficult to obtain the key parameters of soil prediction models from direct measure. To remedy to this situation, indirect methods are applied to estimate them and make the study feasible.

Since Bennet (1939) father of soils' conservation, studies have been trying to assess soil loss at different level. First begun in the USA in the late 1930's with the U.S Soil Conservation Service (SCS), soil loss prediction models have been continuously refining [20]. At continental level, Van der Knijff et al. have quantified rill and inter-rill erosion in Europe in 2000 using the USLE [21]. At global scale, Borreli et al. in 2020 predicted the potential soil erosion by water from 2015 to 2070 [3]. In Tropical Africa however, studies on soil erosion remain sparse. If in 1950, the Institute of Rural Development (IRD) directed the first researches on soil erosion in Tropical Africa, these were particularly aiming at establishing classical hydrological parameters (flood hydrograph, runoff coefficient) and did not include any particular erosion measures [5]. In the Republic of Mali, researches directed on soil erosion by water measurement remain limited on the literature. Only Bishop, J. and Allan, J., in their study of on-site costs of soil erosion in Mali, provided a comprehensive investigation at the regional level [2]. Nowadays, in the Republic of Mali, there is some evidence of land resources degradation and thus the need for understanding the rate of this degradation and raising public awareness on the importance of the issue.

The present study attempts to estimate and map the potential soil loss for 2018 in the provinces of Sikasso and Koulikoro using remote sensing and Revised Universal Soil Loss Equation (RUSLE). This attempt is not only driven by scientific motive but also by economics one. In the Republic of Mali, natural resources at large and soil in particular represent a core mean of subsistence for most families. Across the country, rural populations depend on soil functions for the provision of their food, fodder for their animals, fuel for cooking, crops for market. In 2014, agriculture occupied more than 80% of the country's population and contributed 40% of the Gross Domestic Product [12]. To most rural people, land degradation is widely perceived as a critical threat to the economic development in a country where about 44% of the population lived less than $ 1 a day in 2010[13].

Materials and methods

Geographical settings. The study area covers 161 thousand km^2 and lies within the Sudanese and Sahelian zones between 10° 8' and 15° 30' north altitude and 4° 24' and 9° 7' west longitude.

The relief of the region is dominated by plains with an average altitude of about 300 – 400 m (fig.1. A / рис. 1. A). The plateaus Manding (with 808 m in Kati) and of Sikasso (with 591 m in Sikasso) remain the highest elevation in the area [9].

The climate of the provinces is largely dominated by the Sahelian domain which is marked in its northern limit by 200 mm isohyet while the rest belongs to the Sudanese zone limited by about 1300 mm isohyet [8]. The precipitation regime of the region is unimodal and controlled by the west African monsoon. The continentality of the region reinforces the seasonal contrast between a tropical rainy season lasting 3 to 5 months and a long absolute dry season of 9 to 7 months. The rains that result from isolated convective thunderstorms, occur during the boreal summer, starting between May and July and ending between September and October with a maximum in August. The annual rainfall fluctuates between 200 and 500 mm in the north (Sahelian zone) and 600 to 1300 mm in the south (Sudanese domain) [8]. The annual mean temperature regime in the region is influenced by the general atmospheric circulation and thus remains high (28 – 30^o C) with a maximum in May (42° C) and the minimum in January (22° C) [28].

The landscapes of the provinces are characterized by interfluves whose soils and their organization in landform and pedogenetic processes vary according to the climatic zones [4]. In the Sahelian zone, the influence of the shallow granito – gneissic substrate and the very low drainage index results in the formation of sodic and alkaline soils. Rich in swelling clays and very poorly permeable, they are very susceptible to erosion. Concerning the Sudanese domain, it presents soils rich in kaolinite and alterites, but modest in mineral. Soils in this zone, are subjected to serious risks of acidification and aluminium toxicity. Based on the FAO's Digital Soil Map of the World, fourteen soil Units: Ferric Acrisols (Af), Plinthic Acrisols (Ap), Eutric Cambisols (Be), Vertic Cambisols (Bv), Gleysols (G), Lithosols (I), Fluvisols (J), Ferric Luvisols (Lf), Gleyic Luvisols (Lg), Dystric Nitosols (Nd), Eutric Nitosols (Ne), Luvic Arenosols (Q1), Eutric Regosols (Re) and Chromic Vertisols (Vc) were found within the study area (fig.1. B / рис. 1. B) [24].

Hydrographically, our two provinces are crossed by the Niger river and its tributaries. With 4200 km (1780 km in Mali), the Niger begins its Malian journey in Kangaba then receives near Mopti, on its right side, its largest tributary in Mali: the Bani which is formed by the water of Baoulé, Banifing and Bagoé in the region of Sikasso. Sangarani remains another river in the region. The provinces are also home to several lakes and ponds (Wegnan, Ngoroma, Selingue, etc.).

The floristic composition of the region is dominated by savannas. Term designating a heterogeneous group of formations, the savanna according to the phytogeographic congress of Yangambi (1956) is a: "Grassy formation comprising a carpet of large grasses measuring, at the end of the growing season, at least 80 cm in height, with flat leaves at the base or on stubble, smaller grasses and herbaceous plants. These herbs are usually burnt every year; on this grassy carpet, trees and shrubs are generally found, which form a wooded savanna (trees and shrubs forming a clear cover allowing the light to pass through), a shrub savanna (shrubs only, on the grass carpet), a grassy savanna (trees and shrubs absent, only grass carpet)" [22]. Species such as: Andropogoneae, Combretum spp, Butyrospermum p, Detarium senegalense, Daniellia oliveri, etc. remain endemic in the region [10].

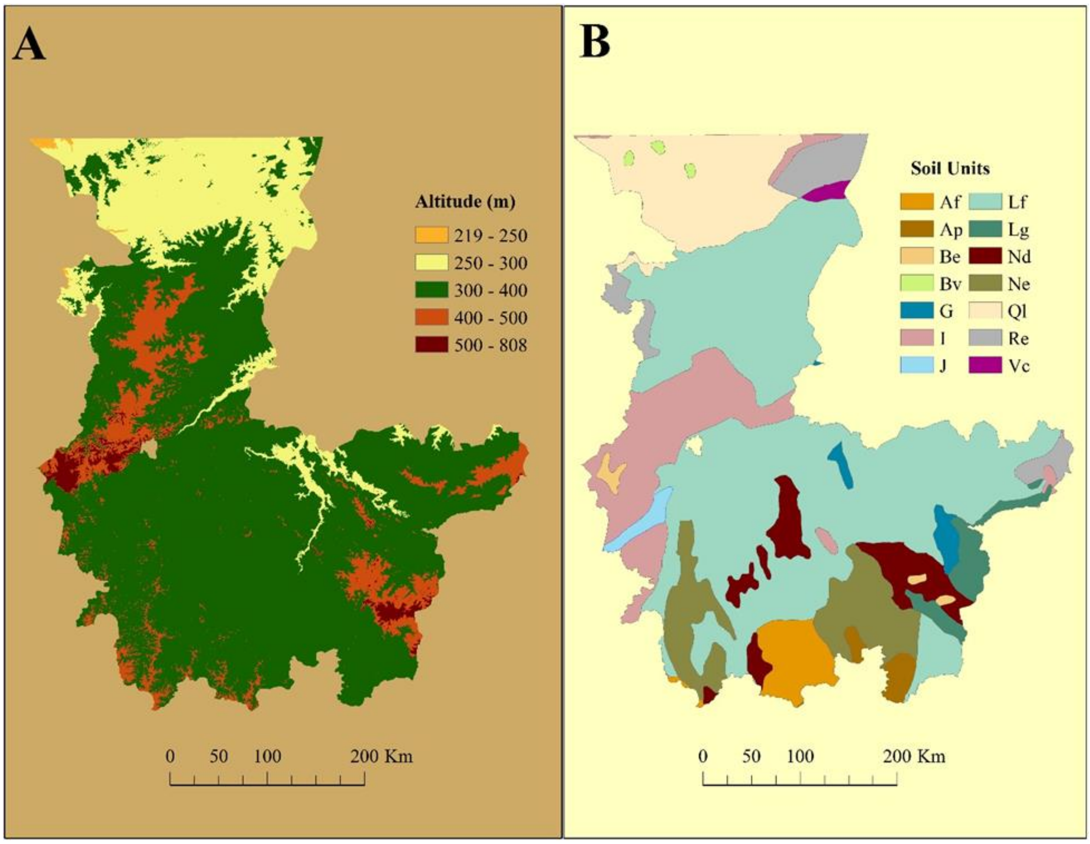

Fig. 1. Terrain and Soil Cover of the study area
A) Altitude B) Soil Units (FAO)

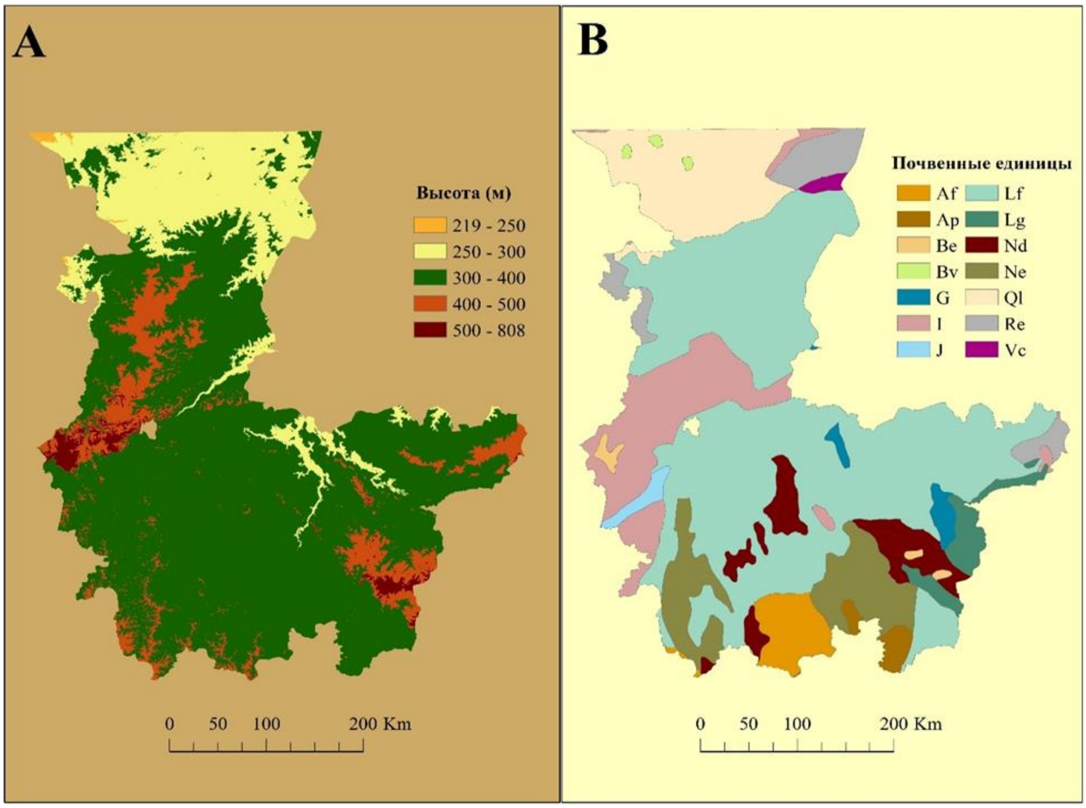

Рис. 1. Рельеф и почвенный покров изучаемой территории
А) Высоты над уровнем моря B) Почвенные единицы (ФАО)

Agriculture and breeding constitute the main activities of the region. Concentrating about 85% of the population, agriculture in the two provinces is the rain-fed type and produces primarily dry cereals, peanuts, sesame, cotton, etc. [11]. The farming system of the area is frequently simplified by resorting to plough for carrying out large-scale works. This practice, while stimulating the mineralization of humus by completely stumping cultivated plots, has many negative consequences. The mineral elements thus released are frequently washed away and can no longer be recycled on the surface. Concerning the breeding, it represents an important source of wealth around which rural people organize their lives. The increase national herd size since the 1992, has resulted in overgrazing, especially in the Sikasso region, which constitutes a transit area for Sahelian herders to the wetlands of Côte d'Ivoire and Guinea [11]. In addition to these threats, bushfires frequently used by both farmers and breeders as tool for managing their space, present serious consequences. By partially or totally destroying the woody and herbaceous vegetation, they expose the soils to the first storms of the rainy season.

Materials. To determine the soil loss within the study area, 26 bands of Shuttle Radar Topography Mission (SRTM 30m) [25], 5 NDVI 250 m MODIS/Terra Vegetation (MOD13Q1) covering the period from May 9th 2018 to September 14th 2018 [24], the annual Global Rainfall Erosivity dataset (30 arc seconds) [14] and the Digital Soil Map of the World [23] were used.

Methods. The different components of the RUSLE were computed using the ArcGIS toolbox and the System for Automated Geoscientific Analyses (SAGA) [26].

Rainfall Erosivity (R)

The R factor represents the effect that rainfall has on soil erosion and was included after observing sediment deposits after an intense storm [20]. The annual R factor is a function of the mean annual EI30 that is calculated from detailed and long-term records of storm kinetic energy (E) and maximum 30 min intensity (I30) [1]. The original Equation used to calculate R factor is:

$$\mathbf{R} = \frac{\sum_{i=I}^{j}(\mathbf{EI_{30}})\mathbf{i}}{\mathbf{N}}$$ (equation 2) [1].

$$\mathbf{EI_{30}} = \mathbf{E} * \mathbf{I_{30}}$$

$$\mathbf{E = 916 + 331 \times log10\ ^{I}}$$

Where: R is the rainfall and runoff factor – the rainfall erosion index plus a factor for any significant runoff from snowmelt (100 ft. ton. acre^{-1}yr $^{-1}$); I is the intensity (in h^{-1}); EI30i: EI30 for storm i; j is the number of storms in an N – year period.

This original method of computing R value requires extended pluviographic records over a period of 20 years at least, with temporal resolution less than or equal to 30 minutes [20]. Given the impossibility to obtain this, we used the annual Global Rainfall Erosivity dataset (30 arcsec) established by Panagos et al. (2017) to extract the R factor of the area. The annual global Rainfall Erosivity which derived from 3,625 stations covering 63 countries, was computed using the Rainfall Intensity Summarization Tool (RIST) software developed by the United States Department of Agriculture (USDA) [15].

Soil erodibility (K)

The K factor essentially represents the soil loss that would occur on the (R)USLE unit plot, which is a plot that is 22.1 m long, 1.83 m wide, and has a slope of 9% [1]. Higher K value indicates the soil's higher susceptibility to erosion. The original equation developed to compute K factor is expressed as followed:

$$\mathbf{K} = \frac{[\mathbf{2.1\ x\ M^{1.14}\ x\ (10^{-4})\ x\ (12-a)]+[3.25\ x\ (b-2)]+[2.5\ x\ (C-3)]}}{\mathbf{100}}$$

(equation 3) [1].

Where: K is the Soil Erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}); M is the particle-size parameter; a is the organic matter (%); b is the soil structure code used in soil classification and c is the profile permeability class.

Similar to R factor, studies have developed alternative methods to compute K factor. The K value of the study area was computed by applying the equation of Williams and Renard (1983) as cited in Benavidez. R et al. (2018) (equation 4) based on soil physical properties (texture and carbon content). This has been done by using the World Digital Soil Map of the FAO which is composed with the GIS shapefile and an attribute database that provides information about the composition of each soil mapping unit and standardized soil parameters for top and subsoil.

$$K = 0.2 + 0.3\exp(0.0256 * Sa * (1 - \frac{Si}{100})) * \left(\frac{Si}{Cl+Si}\right)^{03} * \left(1.0 - \frac{0.25 * C}{C+\exp(2.72-2.95C)}\right) * (1.0 - \frac{0.7 * SN}{SN+\exp(-5.51+22.9SN)}),$$ (Equation 4) [1].

Where: Sa = sand (%), Si = silt (%), Cl = clay (%), C = organic carbon, SN = 1 – (Sa/100). C = organic carbon.

NB: K value from (equation 4) is converted into SI units of metric ton hours per megajoules per millimeter by multiplying it by 0.1317.

Topographic factor (LS)

The LS factor represents the effect of the slope's length and steepness on sheet, rill, and inter-rill erosion by water, and it is the ratio of expected soil loss from a field slope relative to the original Universal Soil Loss Equation (USLE) unit plot [1]. The original method (equation 5) for estimating LS factor was applied at the unit plot and field scale, and the RUSLE extended this to the one-dimensional hill slope scale [1].

$$LS = \left(\frac{\lambda}{72.6}\right) m * [(65.41 * \sin^2\emptyset) + (4.56 * \sin\emptyset) + 0.065]$$(equation 5) [1].

Where: LS is the ratio of soil loss under a given slope steepness and slope length; λ is the slope length (ft), ∅ is the angle of slope, and m dependent on the slope (m = 0.2 to 0.5).

Further research extends the LS factor to topographically complex units using a method that incorporates contributing area and flow accumulation [16]. The LS factor of the area was estimated using one of the hydrology modules available in SAGA (the LS – factor) which contains the algorithm of the equation 6, proposed by Desmet and Govers (1983) as cited in Panagos et al. (2015) [27]. The input data to SAGA included the slope in gradient and the catchment of the area derived from the SRTM 30 m.

$LS = (m+1)\left(\frac{U}{L0}\right) m \left(\frac{Sin\beta}{S0}\right) n$ (equation 6) [1].

*Where: LS is the slope length and slope steepness; U is the flow accumulation * cell size; L0 is the length of the unit plot (22.1); S0 is the slope of unit plot (0.09); β is the slope; m (sheet) and n (rill) depend on the prevailing type of erosion (m = 0.4 to 0.6) and n (1.0 to 1.3).*

Cover management factor (C)

The C factor represents the ratio of soil loss under a given crop to that from bare soil [1]. The original method of computing C value which combines impacts of previous management, canopy cover, surface cover and roughness, requires extensive knowledge of the study area [6]. Further researches in Europe and Brazil computed C factor through the normalized difference vegetation index (NDVI) (equation 7). C value for the study area was estimated using (equation 8).

$\mathbf{C} = \mathbf{exp}\left(-\alpha * \frac{NDVI}{\beta - NDVI}\right)$ (equation 7) [21]

Where: C is the Cover management factor; NDVI is the Normalized Difference Vegetation Index; α = 1 and β = 2.

$Cr = (\frac{-NDVI+1}{2})$ (equation 8) [6].

Where: Cr is the rescaled C factor for tropical climate.

Practice management factor (P)

The P factor is defined as the ratio of soil loss under a specific soil conservation practice (e.g. contouring, terracing) to that of a field with upslope and downslope tillage [1]. P value ranges from 1 (no erosion control solution) to 0 (effective conservation practice). The P factor of the study area was estimated following the approach proposed by Shin et al. (1999) as cited in Sheikh and Alam (2011) which is based on the slope inclination [19].

Table 1

Cultivation method and slope classification, Shin (1999) as cited in [19]

Таблица 1

Эрозионная оценка методов сельскохозяйственной обработки земель при разных уклонах местности, Shin (1999) [19]

Practice management (P factor) estimation // Оценка сельскохозяйственных практик (P фактор)			
Slope % // Уклон %	Contouring // Контурная обработка почвы	Strip cropping // Прямые конечные полосы	Terracing // Террасирование
0.0 – 7.0	0.55	0.27	0.10
7.0 – 11.3	0.60	0.30	0.12
11.3 – 17.6	0.80	0.40	0.16
17.6 – 26.8	0.90	0.45	0.18
26.8 >	1	0.50	0.20

The annual soil loss (A)

In the ArcGIS toolbox, the annual soil loss was estimated using the raster layer of different sub components of the equation.

Results

Rainfall erosivity (R)

The R factor derived from the Global Rainfall Erosivity dataset varies between 1408 and 5084 MJ mm ha^{-1} h^{-1} $year^{-1}$ and shows a net decrease from south to north (fig. 2. A / рис. 2. A).

Soil Erodibility Factor (K)

The results also indicate that the soil erodibility factor (K) in the study area ranges from 0.04 to 0.1 t ha^{-1} MJ^{-1} mm^{-1}. The results presented in table 2 / таблица 2 show that the highest k value 0.10 is found in the clay-loam and loamy-sand whereas the smallest one (0.04) is found in the sandy soil. Also, 50.53% of the area belonging to sandy-loam have a k value of 0.08.

Topographic factor (LS)

The application of the method proposed by Desmet and Govers in the SAGA environment has resulted in the computation of the LS factor of the study area which varies between 0.03 and 21.26. About 94.11% of the area have a LS value comprised between 0.03 and 1. The highest LS value which ranges from 10 to 21.16 represents about 0.01% of the study area and are primarily found in the western part of the area (Kati) (fig. 2. B / рис. 2. B).

Cover management factor (C)

The C value of the study area was estimated using (the equation 8) and the NDVI 250 m MODIS acquired between May 9th and September 14th 2018. The estimated C value for the area ranges from 0.006 to 0.059 (fig 2. C / рис. 2. C). C value closer to 0 represents a denser vegetation coverage. About 86.6% of the area have a C value between 0.006 and 0.03. The highest C value 0.04 to 0.059 represents about 0.23% of the area of interest and are mainly located in the extreme northern part of the region (Nara).

Practique management factor (P)

Due to sparse information on specific land-use types and farming systems in the area, P value has been computed based on the slope inclination. This ranges from 0.55 to 1. It's important to note that about 89% of the territory have a P value of 0.55 (slope 0 to 7 %) whereas only 0.67% have a P value of 1 (slope greater than 26.8%).

Table 2

Soil types and soil erodibility in the study area

Таблица 2

Типы почв и характерные скорости эрозии в районе исследования

Soil erodibility (K factor) // Эрозионность почвы (К фактор)				
Soil Units (FAO) // Почвенные единицы (ФАО)	USDA Soil Textural class // Класс механического состава USDA	Organic Matter content (%) // Содержание органических веществ (%)	K-factor (t ha h ha^{-1} MJ^{-1} mm^{-1}) // К фактор (тонн га час $га^{-1}$ $Мдж^{-1}$ $мм^{-1}$)	Area th.ha (%) // Площадь, тыс. га (%)
Ferric Acrisols (Af)	Sandy-clay-loam // Супеси-суглинки	0.91	0.09	521.6 (3.21)
Plinthic Acrisols (Ap)	Loam // Суглинок	1.09	0.08	177.5 (1.09)
Eutric Cambisols (Be)	Clay-loam // Глинистый суглинок	1.07	0.10	85.9 (0.52)
Vertic Cambisols (Bv)	Clay // Глина	1.1	0.08	40.2 (0.24)
Gleysols (G)	Loam // Суглинок	2.02	0.07	175.7 (1.08)
Lithosols (I)	Loam // Суглинок	0.97	0.09	1850.8 (11.40)
Fluvisols (J)	Loam // Суглинок	1.32	0.09	123.8 (0.76)
Ferric Luvisols (Lf)	Sandy-loam // Супесчаный	0.39	0.08	8202.1 (50.53)
Gleyic Luvisols (Lg)	Clay // Глина	0.73	0.09	409.7 (2.52)
Dystric Nitosols (Nd)	Loam // Суглинок	1.57	0.07	802.2 (4.94)
Eutric Nitosols (Ne)	Clay // Глина	0.6	0.08	1315.3 (8.10)
Luvic Arenosols (Q1)	Sand // Супесь	0.2	0.04	1776.1 (10.94)
Eutric Regosols (Re)	Loamy-sand // Супесчаный	0.5	0.10	684.9 (4.21)
Chromic Vertisols (Vc)	Clay // Глина	0.69	0.09	63.9 (0.39)

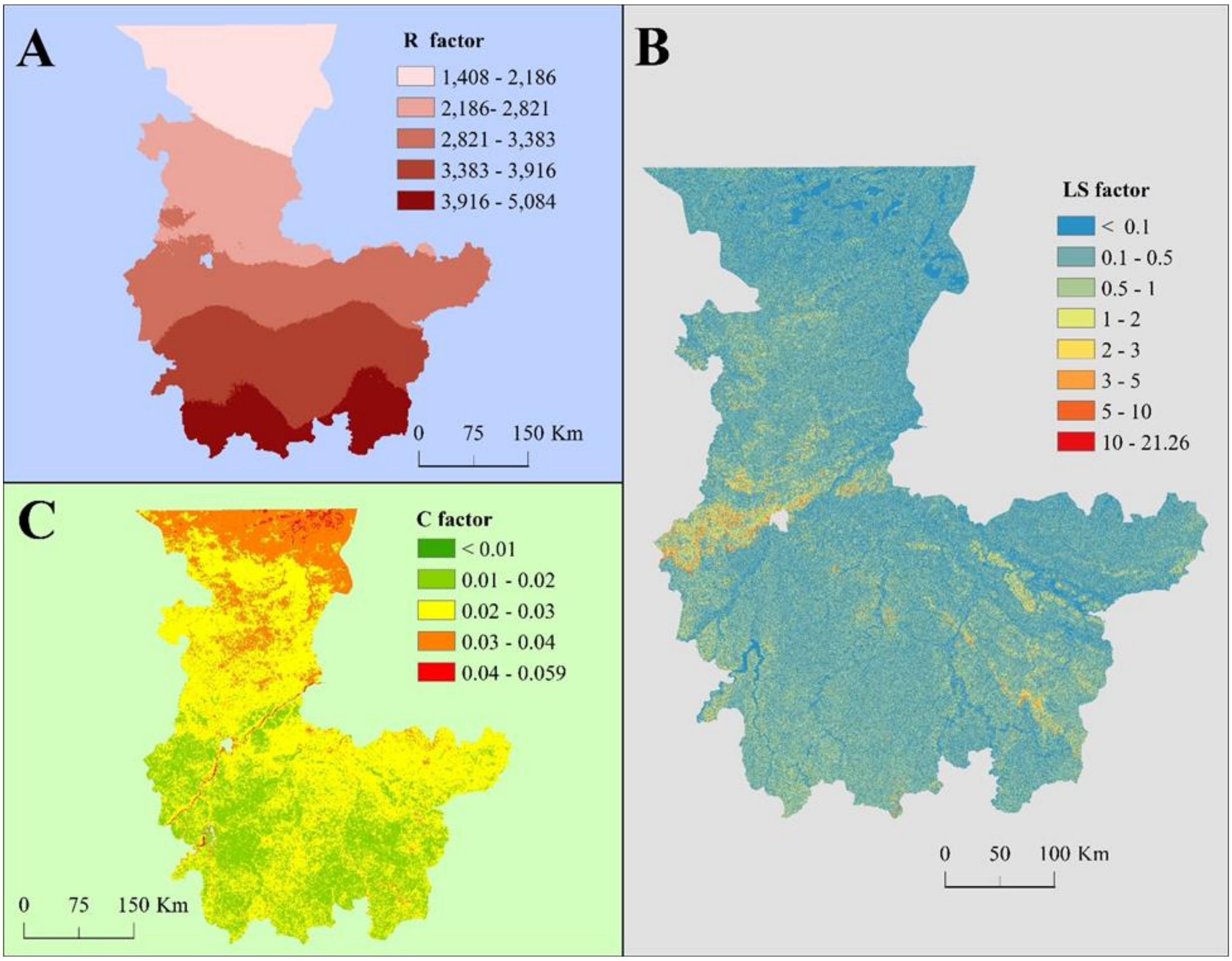

Fig. 2. Results of geoinformation processing of the RUSLE subcomponents
A) R factor B) LS factor C) C factor

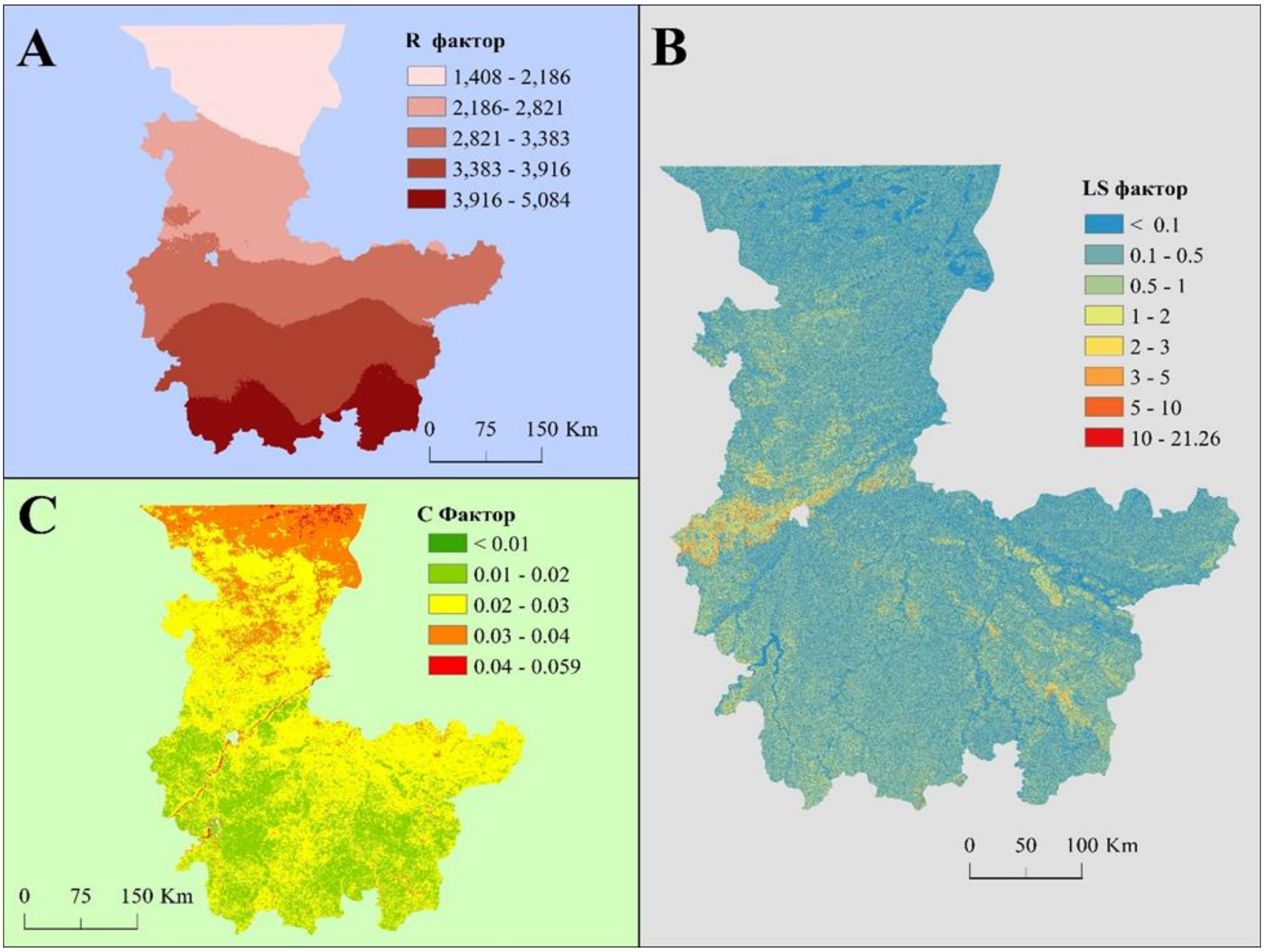

Рис. 2. Результаты геоинформационных расчетов субкомпонентов RUSLE
A) R фактор B) LS фактор C) C фактор

Potential annual soil loss (A)

To estimate the potential annual soil loss for the study area, we used the product of RUSLE's components (R, K, LS, C and P). In the ArcGIS toolbox (Spatial analyst), we run the RUSLE model by using the raster layers of different sub-factors. The potential soil loss in the region ranges from 0.02 to 98.86 tons/ha/year with an average of 1.63 tons/ha/year. The classification of this result into seven groups showed that 39% of the area has an erosion rate ranging from 0.02 to 1 ton/ha/year, 47.58% from 1 to 3 tons/ha/year and about 0.01% more than 50 tons/ha/year (table 3 / таблица 3). The spatial pattern of the potential soil erosion map indicated that the area with large erosion risk were located in the steeper slopes (fig. 3. A, B / рис. 3. A, B).

Table 3

Estimated soil loss for 2018 in the study area

Таблица 3

Рассчитанная скорость эрозии почв на изучаемой территории (2018 г.)

	A factor (The potential soil loss), tons/ha/year // A фактор (скорость потенциальных потерь почвы), тонн/га/год						
	0.02 – 1	1 – 3	3 – 5	5 – 10	10 – 20	20 – 50	>50
Area (th. ha) // Площадь, тыс. га	6285.33	7665.12	1550.95	431.48	137.93	35.95	2.03
Area, % // Доля площади, %	39	47.58	9.62	2.67	0.85	0.22	0.01

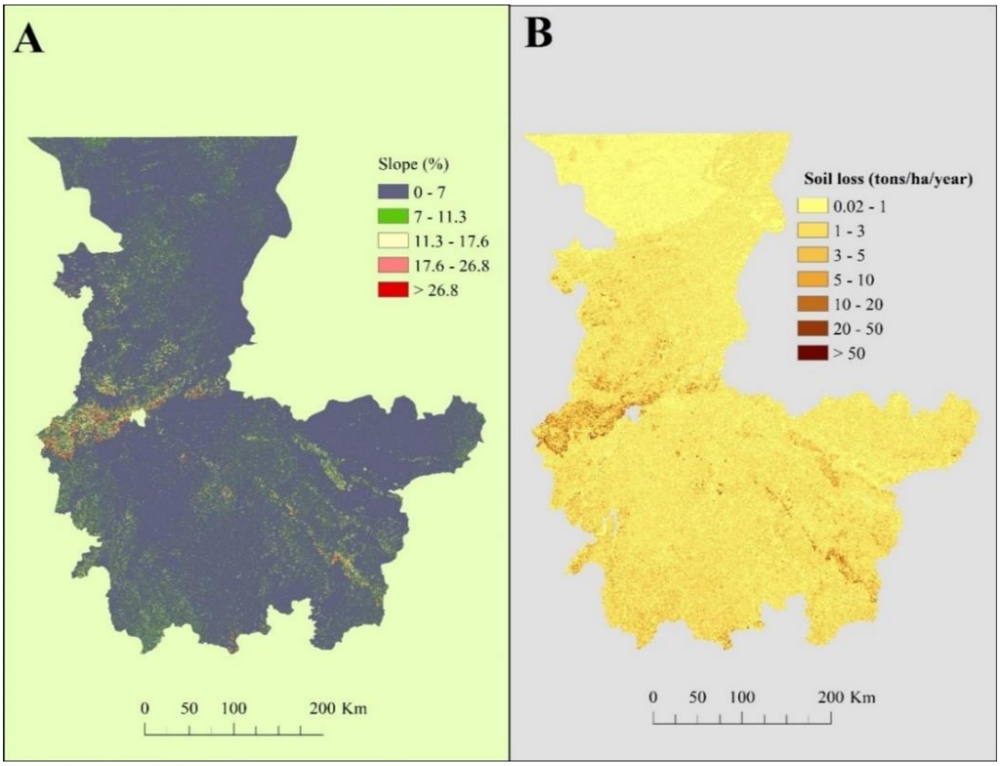

Fig. 3. Results of RUSLE subcomponents and RUSLE calculation
A) Slope B) Annual soil loss

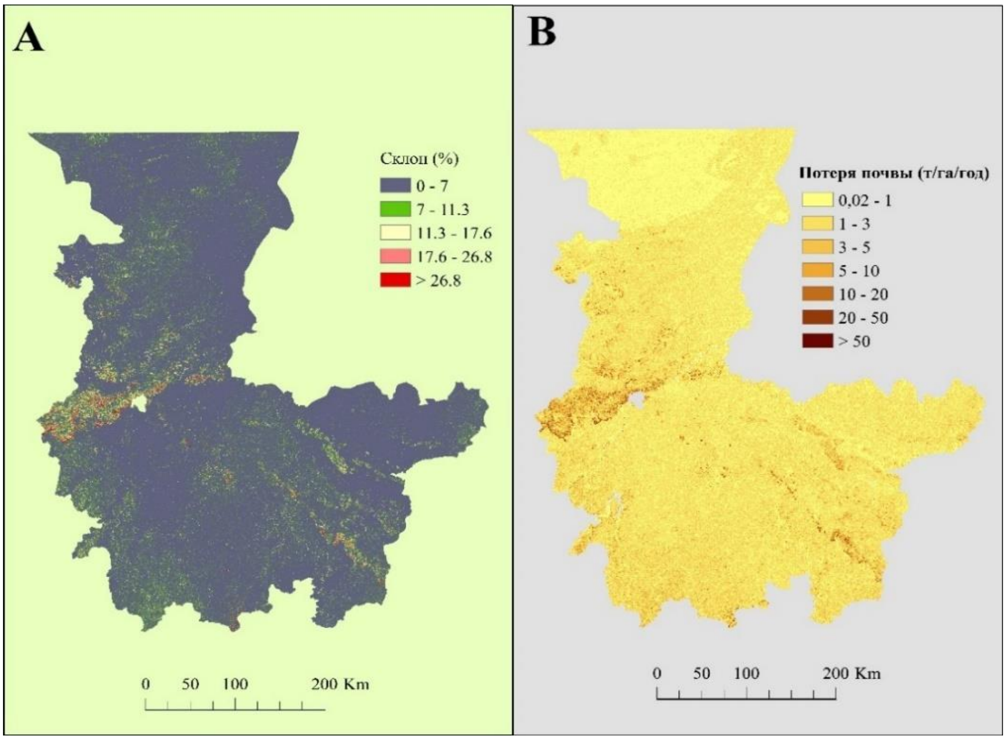

Рис. 3. Результаты геоинформационных расчетов
А) Уклоны местности В) Ежегодной потери почвы

Discussion

Regarding the validity of our estimates, they matched with the global soil loss map established by Borreli et al., which attributed in 2015, an erosion rate of 0 to 50 tons/ha/year to our study area [3]. It is however, useful to note that the use of the RUSLE under tropical climate has always been questioned. This is due to the fact that under this climate, the rainfall regime is more intense and the region subjects to gully erosion which is not taken into account by RUSLE.

The indirect estimation of the K value using the soil units derived from the small-scale global soil map of the world is due to the lack of detailed data on the texture and organic carbon content of soils in West Africa. A regional detailed data on soils will make this calculation much more detailed in the future. In addition to this, low resolution initial data precipitation (30 arc seconds) and NDVI (250 m) remain other limitations. Regarding the precipitation, any new data is likely to be expected in the near future due to the low rate of development of the representativeness and frequency of meteorological observations in Mali. For the calculation of the NDVI, much more detailed sources are available in the public domain. For example, Landsat 8 data is 30 m. However, their use is difficult due to the small width of the survey swath (185 km), which is not enough to fully cover all survey areas in one-day series of scenes.

These primary results are estimated at the annual timescale. Future researches will be focused on the different seasons of the year in order to understand the contribution of vegetation cover to seasonal soil loss and identify critical periods within the year when soil erosion is a risk.

Conclusion

The advance of Remote Sensing (RS) technology and GIS are making soil loss prediction much handy, cost effective, comprehensive and robust. This will be of particular importance for countries such as Mali where data regarding to soil, rainfall, management practices are sparse. Materials used for the present indirect measurement of potential soil loss in the provinces of Sikasso and Koulikoro included the Global Rainfall Erosivity Dataset (30 arc seconds), the Digital Soil Map of the World (1:5 000 000 scale), the SRTM (30m) and the NDVI MODIS (250 m).

The estimated components of the RUSLE equation range from 1408 to 5084 MJ mm ha^{-1} h^{-1} $year^{-1}$ for R factor, 0.10 to 0.04 t ha h ha^{-1} MJ^{-1} mm^{-1} for the erodibility factor (K), 0.03 to 21.26 for the topographic factor (LS), 0.006 to 0.05 for the cover management factor (C) and 0.55 to 1 for the practice management factor (P). The estimates potential soil loss for 2018 vary between 0.02 and 98.86 tons/ha/year with an average of 1.63 tons/ha/year. About 0.01% of the area experienced severe erosion rate (more than 50 tons/ha/year).

The estimation of the rainfall erosivity and the erodibility factors constituted the main limitation of this study. Like most of the meteorological patterns, rainfall regime is not static and varies widely from one season to another and thus its direct computation will be more accurate. Also, soil properties such as organic matter are subject to continually evolution and its data needs to be updated.

The rapid demographic growth of the Malian population will increase pressure on natural resources at large and on soil in particular. Since soils remain the core asset for most of the population, there is an urgent need of improving the accuracy and scale of their degradation. In this regard, establishing datasets relating to the rainfall, the soil property at the national level will make the forecasts of soil erosion by water more precise.

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