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Landscape pattern analysis using GIS and remote sensing to diagnose soil erosion and nutrient availability in two agroecological zones of Southern Mali

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Abstract

Background Soil is a basic natural resource for the existence of life on earth, and its health is a major concern for rural livelihoods. Poor soil health is directly associated with reduced agricultural land productivity in many sub-Saharan countries, such as Mali. Agricultural land is subjected to immense degradation and the loss of important soil nutrients due to soil erosion. The objective of the study was to diagnose the spatial distribution of soil erosion and soil nutrient variations under different land use in two agroecological zones of Southern Mali using the Geographical Information System (GIS) software, the empirically derived relationship of the Revised Universal Soil Loss Equation, in-situ soil data measurement and satellite products. The soil erosion effect on agricultural land productivity was discussed to highlight the usefulness of soil and water conservation practices in Southern Mali.

Results The results of the land use and land cover change analysis from 2015 to 2019 revealed significant area reductions in water bodies, bare land, and savanna woodland for the benefit of increased natural vegetation and agricultural land. There was significant variation in the annual soil loss under the different land use conditions. Despite recordings of the lowest soil erosion rates in the majority of the landscape (71%) as a result of field-based soil and water conservation practices, the highest rates of erosion were seen in agricultural fields, resulting in a reduction in agricultural land area and a loss of nutrients that are useful for plant growth. Spatial nutrient modelling and mapping revealed a high deficiency and significant variations ($p < 0.05$) in nitrogen (N), phosphorus (P), potassium (K), and carbon (C) in all land use and land cover types for the two agroecologies.

Conclusions The study highlighted the inadequacies of existing field-based soil and water conservation practices to reduce soil erosion and improve landscape management practices. The findings of the study can inform land management planners and other development actors to strategize and prioritize landscape-based intervention practices and protect catchment areas from severe erosion for the enhanced productivity of agricultural fields.

Keywords Soil erosion, Revised Universal Soil Loss Equation, Land use, Soil nutrient, Landscape, Southern Mali

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Background

Landscape patterns determine the physiographic characteristics that affect the rate of soil loss from agricultural fields. Land use and land cover play a major role in the soil nutrient cycle, specifically regarding the sources and sinks of carbon [1]. Studying their changes at any scale is critical to assess the impact of anthropogenic and natural changes on soil properties. Remote sensing data have been widely used for monitoring land use and land cover changes, and their use in combination with ground measurements provides a highly accurate view of the Earth's components, such as landscapes and hydrospheres [2]. Land use and land cover have detrimental effects on runoff and soil physical and chemical properties and hence significantly impact soil organic and macronutrients that are useful for plant growth [3, 4]. Land use and land cover also have an impact on the rate of soil erosion [5]. Studies [6–9] have highlighted an increase in soil erosion rates in areas, where natural vegetation has been converted into farms, settlements, and grasslands over time [10]. Excessive and uncontrolled erosion leads to the loss of important soil nutrients, such as nitrogen (N), phosphorus (P), and potassium (K), and consequently a decline in potential crop yield at the plot and farm levels [6].

Mali is a country with a high rate of population growth (2.9% in 2021 as per the World Bank Group report, while the data in sub-Saharan Africa was 2.6%). The southern region of Mali is the most populated area in the country exerting high pressure on land due to the physical expansion of urban and agricultural fields. This growth has resulted in an increased soil erosion rate over time [5]. The semiarid region of Southern Mali is characterized by intensive agricultural practices, land degradation, and extreme climatic variability. Traditional and less mechanical agricultural practices are applied to monocultures, intercropping, tillage, and agroforestry in most agroecological farm fields and landscapes. Maize (*Zea mays*), sorghum (*Sorghum bicolor*), cotton (*Gossypium spp*), groundnut (*Arachis hypogaea*), and millet (*Pennisetum glaucum*) are the main crops cultivated by applying a combination of manure and inorganic fertilizers. However, soil erosion has been a major problem affecting agricultural productivity, as it affects the whole landscape, and interventions to mitigate it at the farm level seldom have an effect.

Until recently, sustainable land management practices in most parts of Mali focused on reducing runoff and soil loss at the plot or farm level through soil and water conservation (SWC) practices, such as contour bunding [7]. Although important in its application at the plot or farm level, the efficiency of contour bunding is limited in addressing landscape degradation and the loss of crop productivity. Excessive soil erosion is usually caused by

accumulated runoff from farms, grazing areas, or bushlands. Landscape-level information about the processes of soil erosion, water infiltration, and the associated loss of valuable nutrients is often missing in most studies due to either insufficient data or methods of estimation [10]. The objective of the study was, therefore, to diagnose the spatial distribution of soil erosion and soil nutrient variations under different land use in two agroecological zones of Southern Mali using the Geographical Information System (GIS) software, the empirically derived relationship of the Revised Universal Soil Loss Equation, in-situ soil data measurement, and satellite products. Specifically, the study examined (i) land use changes between two different agroecologies over time, (ii) spatial factors that influenced soil erosion and nutrient loss, (c) variations in soil nutrients under different land use practices, and (d) usefulness of soil and water conservation practices on agricultural land productivity.

Methods

Study area

The study was conducted in the two agroecological zones of Southern Mali (Bougouni and Koutiala districts) (Fig. 1). The total land area of Bougouni district is estimated as 20,028 km² with a population of 458,546, and Koutiala district has an area of 8,740 km² and a population of 580,453 [13]. The ecosystem of Southern Mali is best defined as a Sudano-Guinean savanna [11] and an agricultural system characterized by rainfed, small-scale crop-livestock, and agro-pastoral farming systems [12]. The study area receives high rainfall in the range of 800 to 1200 mm and is considered the breadbasket of Mali [13]. In contrast, 34% of Mali's poor residents and 45% of Mali's food-poor residents live in the region [14, 15]. The major soil types in the study area are well-developed, weakly leached, ferruginous sand through loamy coarse sand to sandy clay loams and coarse textured. The sand content ranged from 250 to 890 kg ha⁻¹, with an average of 647 kg ha⁻¹. For silt, the range was from 40 to 620 kg ha⁻¹, with 221.1 kg ha⁻¹ on average, while the clay content ranged from 50 to 330 kg ha⁻¹, with an average of 131.1 kg ha⁻¹. The long-term (1970–2018) average monthly maximum and minimum air temperatures in the two districts are 33 and 22 °C in Bougouni and 34 and 23 °C in Koutiala, respectively [16].

Data and data sources

Data for land use/cover and the RUSLE model

Satellite-based information derived from Landsat 8 images was used to produce land use and land cover maps, and spatially derived crop management factors were used in the empirical model of the Revised Universal Soil Loss Equation (RUSLE) to estimate the annual

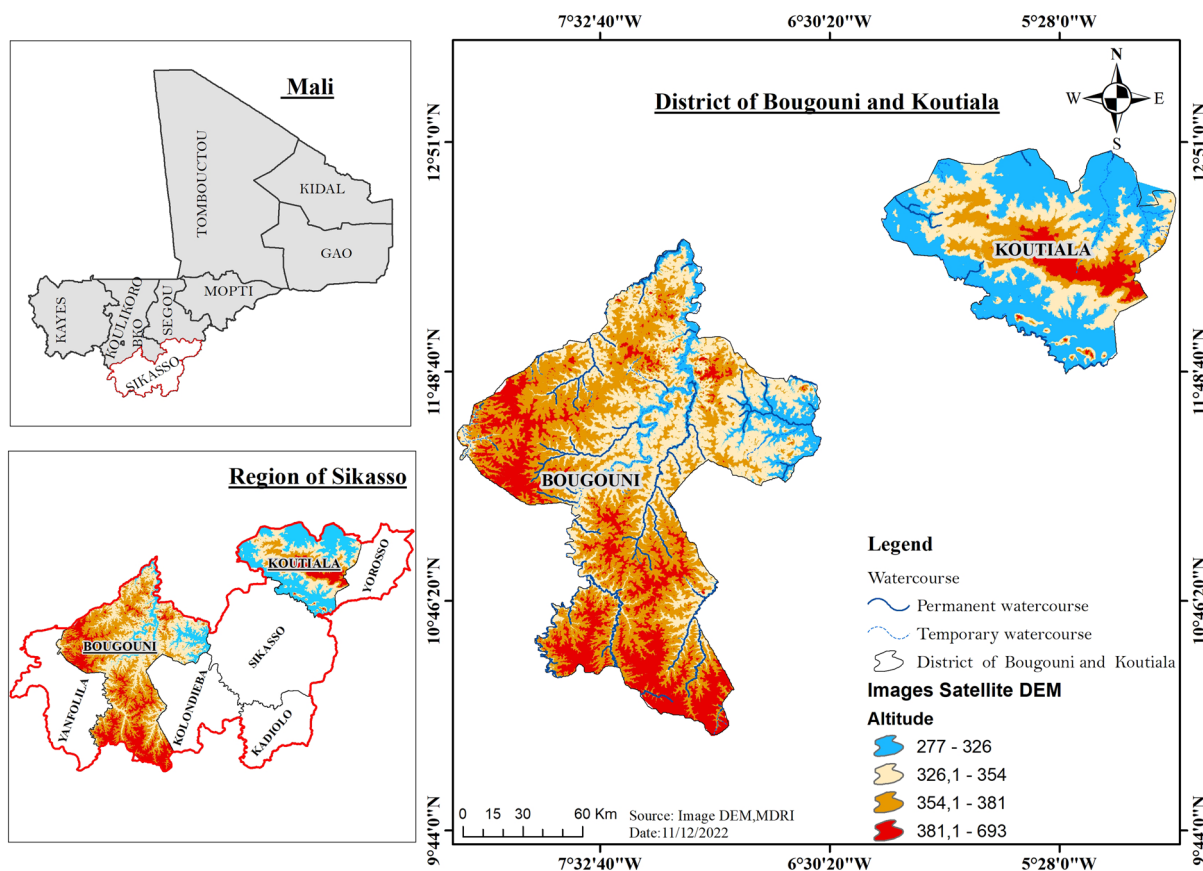


Fig. 1 Map showing the study area in the two districts of Bougouni and Koutiala (Sikasso region), Southern Mali

soil erosion loss. In addition, the digital elevation model (DEM) was derived from Landsat 8 images to determine the empirical parameters of the RUSLE.

Rainfall data from 2000 to 2019 were collected from national meteorological stations in both the Bougouni and the Koutiala districts. To obtain the spatial coverage of rainfall data, the study used gridded monthly precipitation data at a 1-km spatial resolution by the climatology at high resolution for the Earth’s land surface areas [17]. CHELSA climatological data have a higher accuracy in predictions of precipitation patterns than that of many other products [17]. CHELSA products are in a geographic coordinate system referenced to the World Geodetic System 1984 (WGS84) horizontal datum, with the horizontal coordinates expressed in decimal degrees. The data were in GeoTiff format, which can be viewed using GIS software.

Data for soil nutrients

The in-situ soil data were archived from a project named the “Africa Research In Sustainable Intensification for the Next Generation (Africa RISING)” database for Mali. The data were used to validate gridded

data from the African soil profile (<https://data.isric.org/geonetwork/srv/eng/catalog.search#/search>). In 2015, soil data were collected under the Africa RISING project from 350 sampling sites in 10 villages of the Bougouni and Koutiala districts of Southern Mali (Table 1). Sampling sites from each village were selected through a stratified random sampling technique. The strata included geographical location, availability of field-based soil and water conservation practices, mainly contour bunding (CB), food crop type and mixture, natural bush and/or grazing land, agroforestry or presence of forestland, presence of termitarium and oxen kraaling sites). From each village, a minimum of 29 composite soil samples were collected from depths of 0 to 15 cm with distribution across the strata. On a farmer’s field, samples were taken at five locations across two diagonal transects, and the coordinates at the midpoint were determined using hand-held Garmin GPS. Standard laboratory soil tests were employed to evaluate the fertility status of the soils, thereby mapping the erodibility and impact of land use on soil nutrients; carbon (C), nitrogen (N), phosphorus (P), and potassium (K) analyses were performed.

Table 1 Soil sample collection in ten villages in the districts of Bougouni and Koutiala

Village	Longitude	Latitude	Population	MAR* (mm)	N**
Madina	11.35	- 7.66	1582	1137	31
Dieba	11.51	- 7.931	1121	1139	29
Sibirila	11.43	- 7.77	929	1138	29
Flola	11.42	- 7.64	465	1102	29
Nampossela	12.33	- 5.34	2443	813	29
N'golonianasso	12.43	- 5.70	4383	849	30
M'pessoba	12.67	- 5.71	9862	800	33
Sirakele	12.52	- 5.47	4502	818	34
Kani	12.25	- 5.19	2488	944	33
Zanzoni	12.61	- 5.57	3463	842	31
Total					308

* MAR (Mean Annual Rainfall)

** N (Number of soil sampling locations)

Data analysis

Land use changes between two different landscapes over time

Land use changes between two different periods were evaluated based on percentage changes. A series of processes from data acquisition, data pre-processing, supervised classification, and post-classification were performed. Pre-processing was the first step conducted on Landsat 8 images [18]. Geometric correction, image enhancement, and topographical correction were performed for data pre-processing. The raw data were projected to the UTM WGS-84 projection system for supervised classification. An accuracy assessment was performed using ArcGIS software to determine the kappa coefficient of agreement (Eqs. 1–3):

$$KA = \frac{P_o - P_c}{1 - P_c} \quad (1)$$

$$P_o = \sum_{i=1}^r P_{ii} \quad (2)$$

$$P_c = \sum_{i=1}^r (P_{i+} * P_{+i}) \quad (3)$$

where r is the number of rows in the error matrix, P_{ii} is the proportion of pixels in row i and column i , P_{i+} is the proportion of the marginal total of row i , and P_{+i} is the proportion of the marginal total of column i .

Identification of factors that influence soil erosion and nutrient loss

Rainfall erosivity factor (R)

The rainfall erosivity factor (R) explains the variations in rainfall intensity at different locations within the landscape that can cause soil erosion. The R values for each agroecological zone were calculated using the CHELSA database and gridded data from 1979 to 2016 using Eq. 4. The formula has been used in many parts of Africa [19]:

$$Rfactor = -8.12 + 0.562 * P \quad (4)$$

where R is the rainfall erosivity factor in MJ mm ha⁻¹ h⁻¹ year⁻¹, and P is the mean annual rainfall in mm.

Soil erodibility factor (K)

Soil detachment and transport caused by the impact of raindrops and surface flow are represented by the K factor. Soil data on texture, structure, organic matter, and permeability were used to estimate the K factor as per Eq. 5 [20]. Data available in the Africa RISING database for Mali were used to validate the gridded data from the African soil profile (<https://data.isric.org/geonetwork/srv/eng/catalog.search>) and to adequately determine the soil erodibility factor (K).

$$Kfactor = \frac{\frac{\%sand + \%slit}{\%clay}}{100} \quad (5)$$

Slope length (L) and slope (S) factors

Slope steepness and slope length (LS-factor) were determined from a DEM. The Spatial Analyst Toolbox and the Map Algebra Raster Calculator in the ArcGIS environment were used to generating multiple slope maps and flow accumulation as well as to calculate and generate the topographic factor map. The flow accumulation was calculated from the Spatial Analyst Hydrology toolset of ArcMap in the ArcGIS environment. The slope of the study area as a percentage was calculated by the Slope tools in the Spatial Analyst Surface toolset of ArcMap from the DEM of the districts. The DEM data were downloaded from <https://lpdaacsvc.cr.usgs.gov/appeears/download/4d436aca-c5be-4011-981f-1e6020f37c79>. These data were used to determine and map the slope length and slope gradient of the topographic factors in the study area. The determination of the LS factor was performed using Eq. 6:

$$LS = Pow \left([flow\ accumulation] * \frac{resolution}{22.1, 0.4} \right) * Pow \left(\sin \left(\frac{[slope\ of\ DEM]}{0.0896, 1.4} \right) \right) * 1.4 \tag{6}$$

where flow accumulation denotes the accumulated upslope contributing area for a given cell, and LS is the combined slope length and slope steepness factor.

Crop management factor (C)

The crop management factor (C) was used to reflect the effect of cropping practices on erosion control in agricultural lands and vegetation covers. The C-factor is defined as the ratio of soil loss from land cropped under specific conditions to the loss from clean-tilled, continuous fallow. In the present study, the C values were determined based on the values presented in Table 2. Land use and cover maps were converted into polygons to estimate the spatial values of the C-factor based on the specific land use [9].

Conservation practice factor (P-factor)

In conservation practice, the P-factor values range from 0 to 1 depending on the land use/cover types. The highest value is assigned to areas with no conservation practice or with a high slope, while the minimum values correspond to built-up land and plantation area with strip and contour or small sloped areas. The P-factor values in Table 3 were based on the land cultivation method and slope [21]. The spatial values of the P-factor were determined from a DEM and GIS technique.

Revised Universal Soil Loss Equation (RUSLE)

The RUSLE was developed by Renard et al. [22] based on the modifications of the USLE [23]. There have been many studies on soil erosion worldwide [8, 9], and they have used RUSLE to predict annual soil loss, with results revealing that land use has an impact on the rate of soil erosion [24–26]. The RUSLE model uses five different raster layers processed by overlay analysis to generate

Table 2 Attribute values of vegetation cover (C-factor) [9]

Class	C-factor
Built-up land	0.003
Savanna woodland	0.004
Bare land	1
Waterbody	0
Agriculture	0.4
Natural vegetation	0.025

Table 3 Conservation practice factor (P)

Slope (%)	Contouring	Strip cropping	Terracing
0–7	0.55	0.27	0.10
7–11.3	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	0.50	0.20

the annual soil loss rate of each cell using the “raster calculator”. In the present study, soil erosion was estimated using the RUSLE (Eq. 4) based on the raster calculator technique in ArcGIS 10.7. The five factors (in the raster layer) used in the RUSLE model are erodibility (K), slope length (L), slope steepness (S), cropping system (C), and conservation practice (P):

$$A = R \times K \times (L \times S) \times C \times P \tag{7}$$

where A is the annual rate of soil loss (ton ha⁻¹ yr⁻¹), and R is the annual rainfall erosivity factor (MJ mm ha⁻¹ h⁻¹ yr⁻¹). K is expressed in tons ha yr. ha⁻¹ MJ⁻¹ mm⁻¹, and L, S, C, and P are dimensionless.

The five-factor layers used in the RUSLE were produced from various data sources with different spatial resolutions. Thus, all factor layers were previously spatialized and re-gridded to the same spatial resolution as shown in the flow chart (Fig. 2).

Statistical analysis

A T test was applied to compare the means of the samples in different years. Variations in the annual soil loss and soil nutrient loss among different land use types were evaluated at the 5% significance level in the two different

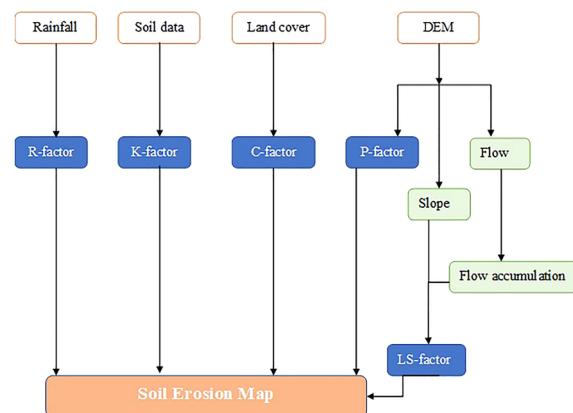


Fig. 2 Flow chart for the determination of annual soil loss

agroecological zones. The spatial difference ratio was used to detect land use change occurring between the two studied agroecologies.

Results

Land use and land cover change

Land use and land cover maps were classified into six classes, namely, agricultural land (AL), bare land (BL), water (W), settlements (S), savanna woodland (SW), and natural vegetation (NV). Percentage change analyses showed an increase in NV by 1151 km² at a rate of 230 km² per year, and AL increased by 1600 km² at a rate of 320 km² per year for Bougouni. This increase was a result of the introduction of new agricultural practices that converted forest areas into cashew plantations (commercial trees). Settlement areas increased at a rate of 0.5 km²/year, and in other land uses, SW and bare land showed a significant decline. In a similar mode, AL and NV areas increased over the studied period in Koutiala (Table 4). Land use and land cover change detection analysis between the two agroecologies showed that NV and agriculture areas increased at a higher rate in Bougouni than in Koutiala. Bougouni was more favourable to environmental development than Koutiala. However, the anthropogenic effects of agriculture and deforestation played major roles in land use changes in Bougouni.

Spatial factors influencing soil erosion and nutrient loss

Figure 3 and Table 5 show the variations in the spatial factors in the two agroecologies. The R values were higher in Bougouni than in Koutiala. The K values showed that erodibility was greater in Koutiala than in Bougouni, implying that soil in Bougouni resists erosion better than that in Koutiala (Fig. 4). The spatially mapped LS factors resulted in LS values ranging between 1.4 and 58 for Bougouni, while in Koutiala, the values ranged between 1.4

and 33. The value of the crop support practice factor (P) ranged between 0.55 and 1.

Spatial pattern of the annual soil loss

Table 6 shows the variation in the mean soil loss under different land uses across the two agroecologies. In Bougouni, in 2015, a higher mean value of soil loss was observed in bare land followed by agricultural land. Similar observations were made in the second period (2019), but agricultural land was more vulnerable than bare land. Similarly, in Koutiala, agricultural land was more vulnerable to land degradation in 2019. Considering the mean values of soil erosion loss, it was observed that the rate of land degradation vulnerability was greater in many of the agriculture fields.

Statistical analysis between the mean values indicated a significant difference in annual soil loss among the different land use types across locations for different periods ($p < 0.05$) (Table 7). The soil erosion loss in SW and the vegetation were not significant across the two agroecologies ($P > 0.05$). Significant soil erosion loss ($p < 0.05$) was observed across locations for agriculture, settlements, and bare land in the two periods. The relationship for bare land was stronger than that for agriculture (Table 7).

As shown in Table 8, the magnitude of soil erosion loss was classified into five categories ranging from low to severe. The results revealed that a low rate of soil erosion occurred in many agricultural fields in both districts. Over the period from 2015 to 2019, a decline in the soil erosion rate was observed in all classes except for the 'moderate rate'. This decline in erosion rates could be explained by the introduction of different cultural practices, such as contour bunding, afforestation, stone lines, and Zai, introduced by different projects in the two districts [6, 7, 12].

Table 4 Land use and land cover in 2015 and 2019

Land use and land cover	Bougouni					Koutiala				
	Area (2015)		Area (2019)		Change (%)	Area (2015)		Area (2019)		Change (%)
	Km ²	%	Km ²	%		Km ²	%	Km ²	%	
Settlements	44.0901	0.22	45.5643	0.23	0.01	66.79	0.70	68.68	0.72	0.02
Water	154.127	0.78	141.683	0.72	- 0.06	116.0976	1.21	16.30	0.17	- 1.04
SW*	2152.59	10.91	827.492	4.19	- 6.72	393.0814	4.09	205.65	2.14	- 1.95
Bare land	1788.99	9.06	373.638	1.89	- 7.17	561.5779	5.85	337.61	3.52	- 2.33
NV**	11,677.10	59.17	12,828.92	65.00	5.83	5137.06	53.49	5,633.94	58.66	5.17
Agriculture	3919.44	19.86	5519.02	27.96	8.10	3329.41	34.67	3,342.37	34.80	0.13

* SW Savannah Woodland

NV** Natural Vegetation

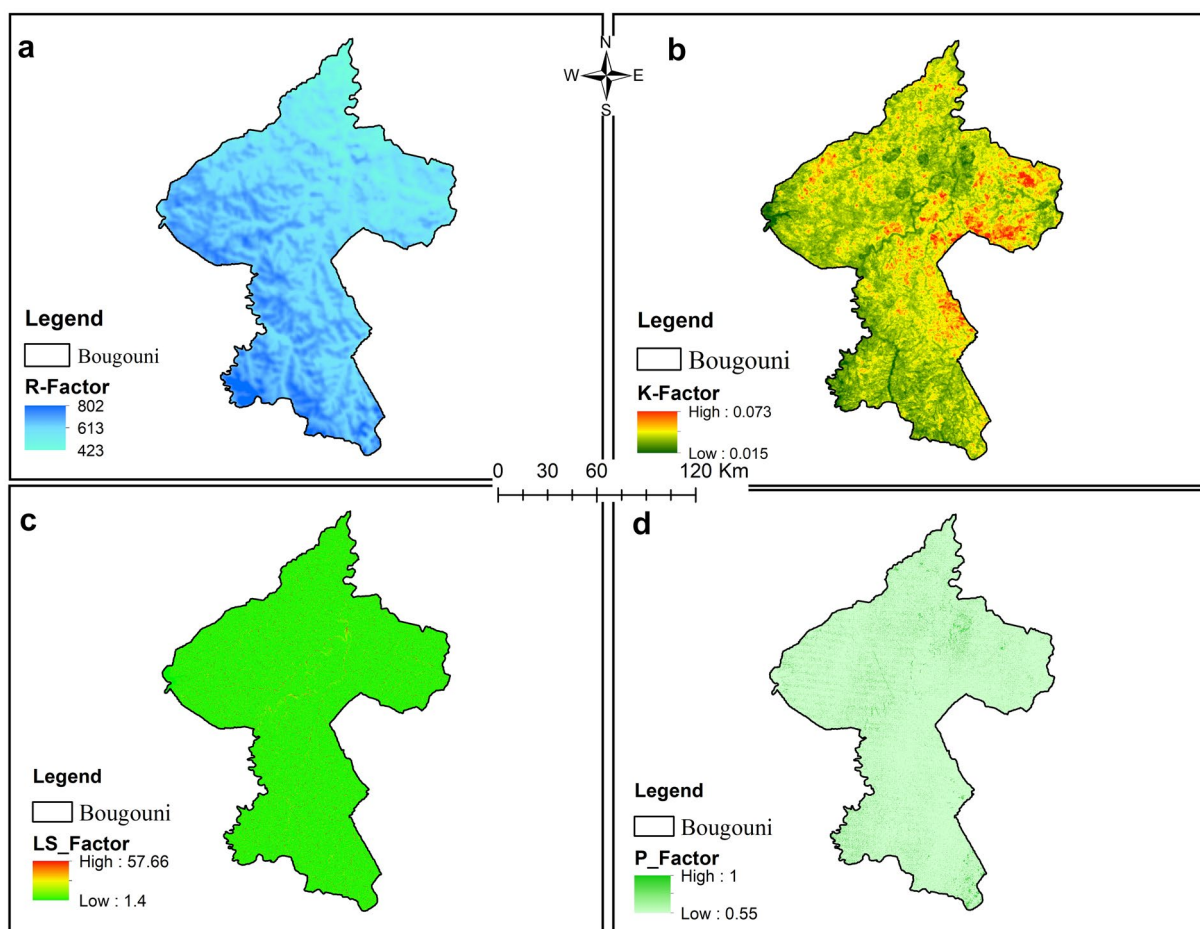


Fig. 3 Spatial pattern **a** R Factor, **b** K Factor, **c** LS Factor, **d** P Factor, in Bougouni

Table 5 Spatial factors influencing soil erosion and nutrient loss

District/ Agroecology	R	K	LS	P	C
Bougouni	683–180	0.073–0.015	1.4–58	0.55–1	Refer Table 2
Koutiala	477–226	1.4–33	1.4–33	0.55–1	Refer Table 2

R = Rainfall Erosivity in $MJmmha^{-1}h^{-1}y^{-1}$, K = Soil Erodibility (K) t.ha.h.
 $ha^{-1}MJ^{-1}mm^{-1}$, LS = Slope Length (L) and Slope (S) Factors, P = Crop Support Practice Factor, C = Cropping Management Factor

Spatial variation in C, N, P, and K under different land uses

Nitrogen (N), phosphorus (P), and potassium (K) are among the soil nutrients that are important for plant growth and development. Nitrogen (N) is a macronutrient that is required by crops in large quantities, and its deficiency restricts crop production in many agricultural fields. Plants need the same amount of potassium and nitrogen for growth. Phosphorus (P) is required by plants to increase yield. Soil organic carbon (C) improves soil’s physical and chemical properties. Table 9 shows the

variation in soil nutrients under different land use types. The results revealed that there were significant variations in N, P, K, and C across different land use categories in both the Bougouni and the Koutiala agroecologies ($P < 0.05$).

A comparison between soil nutrients in the two agroecologies highlighted that Bougouni had a higher concentration of nitrogen and a higher carbon content than Koutiala. The variance between these two districts was dependent on the land use types. Across the three land uses (agriculture, water, and bare land), phosphorus was higher in Bougouni than in Koutiala, but it was the opposite for the other land uses (settlements, natural vegetation, and savanna woodland) (Table 9).

Discussion

Soil erosion is the main driver of land degradation in many sub-Saharan agricultural fields. The study areas in Southern Mali are mostly covered by natural vegetation and agricultural fields. Over time, agricultural and

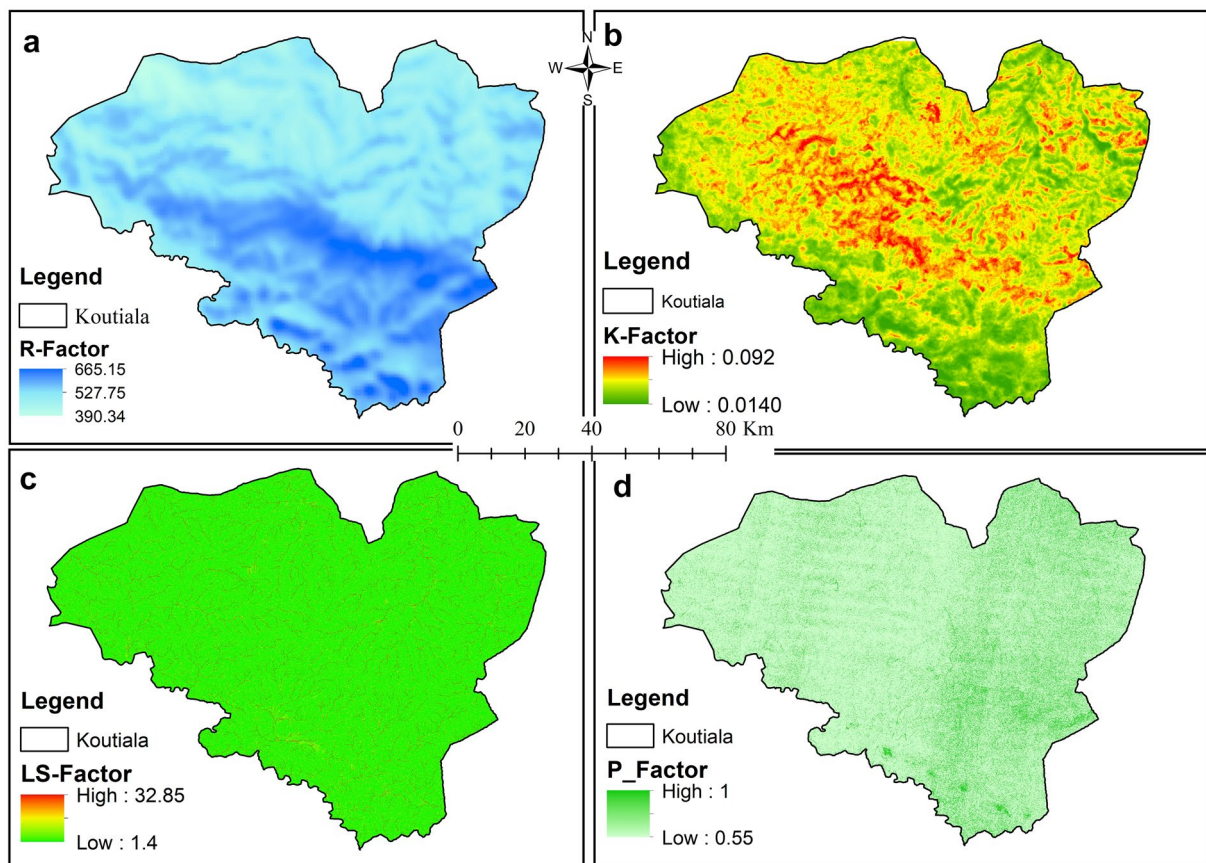


Fig. 4 Spatial pattern **a** R Factor, **b** K Factor, **c** LS Factor, **d** P Factor, in Koutiala

Table 6 Mean values of annual soil erosion loss under different land uses in t/ha/year

Landuse land cover	Bougouni				Koutiala				Erosion rate	
	2015		2019		2015		2019		Bougouni	Koutiala
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Mean
Agriculture	7.8	2.3	3.7	2.28	7.22	2.43	5.14	3.71	- 4.1	- 2.08
Settlements	0.21	1.09	2.61	3.24	0.04	0.01	1.38	2.46	2.4	1.34
SW	0.08	0.06	1.21	3.91	0.10	0.16	0.94	2.05	1.13	0.84
Bare soil	17.53	5.82	2.87	3.16	14.90	8.91	3.11	4.14	- 14.66	- 11.78
NV	0.42	0.1	0.79	1.6	1.82	4.19	0.38	0.09	0.37	- 1.43
Water	0.00	0.00	0.15	0.71	0.01	0.06	0.23	0.54	0.15	0.22

SW Savannah Woodland, NV Natural Vegetation

Table 7 Comparison between mean soil erosion rates

Period	Statistic	Agriculture	Settlements	SW	NV	Bare land
2015	p value	6.07e-05***	2.2e-16***	0.1013	0.1862	1.38e-06***
2019	p value	0.000219*	0.003478*	0.4961	0.4133	0.007281**

SW Savannah Woodland, NV Natural Vegetation; ***Significant across locations, **Significant between the years, *Significant across land uses

Table 8 Land area in the percentage of soil erosion loss rate for 2015 and 2019 in two agroecologies

Soil erosion rate (t/ha/year)	Bougouni			Koutiala		
	Area (2015) (%)	Area (2019) (%)	Change	Area (2015) (%)	Area (2019) (%)	Change
Low (<5)	71.70	69.67	− 2.04	64.29	65.45	1.16
Moderate (5–11)	17.02	26.64	9.62	26.74	26.80	0.06
High (11–25)	10.67	3.43	− 7.24	8.35	6.57	− 1.78
Very High (25–50)	0.54	0.23	− 0.30	0.54	1.12	0.58
Severe > 50	0.07	0.03	− 0.05	0.08	0.06	− 0.02

Table 9 Mean values and standard deviation of soil nutrient properties for different land uses in two agroecologies

Land use Land cover	Soil nutrient properties							
	Bougouni*				Koutiala*			
	Nitrogen (mg/kg)	Phosphorus (ppm)	Potassium cmol+/kg	Carbon (mg/kg)	Nitrogen (mg/kg)	Phosphorus (ppm)	Potassium cmol+/kg	Carbon (mg/kg)
Agriculture	591.82 ± 52.96	407.24 ± 84.44	102.93 ± 14.71	8.36 ± 2.67	479.04 ± 65.14	399.25 ± 117.19	101.13 ± 8.20	4.98 ± 1.38
Settlements	629.69 ± 69.48	469.34 ± 140.5	93.52 ± 13.13	6.78 ± 0.83	517.196 ± 47.11	520.88 ± 189.29	107.04 ± 8.59	6.14 ± 1.56
Water	796.75 ± 175.9	425.86 ± 99.49	108.42 ± 24.44	13.65 ± 4.95	675.97 ± 112.83	424.02 ± 87.73	114.98 ± 7.14	8.55 ± 2.18
SW	679.71 ± 75.45	376.87 ± 70.42	102.42 ± 12.22	9.88 ± 2.62	534.06 ± 69.95	418.64 ± 63.07	109.07 ± 9.46	5.68 ± 1.33
Bare land	682.77 ± 93.96	450.49 ± 128.9	104.15 ± 13.85	10.43 ± 2.66	515.087 ± 67.34	419.55 ± 91.63	103.40 ± 10.11	5.34 ± 1.22
NV	694.68 ± 62.34	385.95 ± 90.50	100.24 ± 13.41	9.30 ± 1.71	516.60 ± 66.00	411.19 ± 63.30	106.56 ± 8.50	5.01 ± 1.34
P Value	1.96E-49	2.34E-12	4.62E-10	1.06E-60	4.08E-84	3.09E-18	7.37E-34	7.13E-76

* Sample Size (N) = 112 for Bougouni and 122 for Koutiala, SW = Savanna Woodland, NV = Natural Vegetation

settlement areas have increased due to urban population growth and the need for more agricultural fields [27]. For instance, the increase in cashew plantations in Bougouni has led to the expansion of agriculture, leading to an increase in fallow areas. The decrease in water bodies was mainly due to gold mining activities and drought created by rainfall variability in a few landscapes. Land uses have an important impact on the soil's chemical and physical properties [28]. Previous studies have highlighted the influence of land use on soil management practices [29–31]. In addition, the importance of soil and water conservation in controlling soil erosion has been demonstrated by many studies conducted in the region [6, 7].

The findings of this study revealed the presence of low erosion rates in large landscapes in the studied areas, as established elsewhere [1, 27, 32]. Despite the low magnitude of runoff from the larger part of the Southern Mali landscapes, the runoff generated from many agricultural fields is severe and is the cause of land degradation as well as the loss of important soil nutrients. When forest and natural vegetation areas are the targets of human-induced activities, the rate of vulnerability to erosion increases over time [6].

Soil erosion vulnerability was reduced by the application of soil and water conservation (SWC) practices. The major SWC practices in the study area that have demonstrated a reduction in annual soil loss and an increase in farm-level soil nutrients are stone bunds, ridges, contour bunding, and tree plantations [6].

In this study, the highest values of N, K, and C were recorded in water bodies, and a greater amount of P was noted in settlement areas with P in vegetation covers (natural vegetation and savanna woodland). These findings corroborate well with previous assessments of soil fertility variation in different land uses and management practices [27, 28, 33].

The economy of Mali is mainly based on rainfed agriculture, and hence, any depletion in soil nutrients may cause food insecurity and poverty for smallholder farming systems. As soil erosion has a significant impact on agricultural productivity, land management practices should be considered a priority by decision-makers for agricultural-led economic growth. The current land management practice in Mali may be the reason for the varying erosion risk rather than natural conditions, as explained by Rousseva et al. [35]. Based on the findings

of this study and recommendations from previous studies [6, 7, 34], soil nutrient loss could be controlled by applying appropriate soil and water conservation practices integrated with good agronomic practices. The most common SWC practices recommended in the study area include a combination of constructing contour bunding, planting trees, stone bunds, and terracing. This study calls for increased efforts by all stakeholders to implement the needed intervention at the landscape scale and boost agricultural productivity in the region.

Conclusion

Through spatial modelling and empirical relations, soil loss was estimated for 2015 and 2019 using soil loss parameters and the RUSLE. The results revealed that the dominant portion of land use and land cover was characterized by erosion risks leading to land degradation. High deficiencies in soil nutrients (N, P, K, and C) were observed in the landscapes. Many of these nutrients were found in the water bodies as a result of the increased rate of soil erosion from the landscape over time, thus leaving only a small amount on the agricultural fields. The implementation of a few SWC and restoration practices, such as contour bunding and cashew plantation, seemed to contribute to reduced soil erosion risk over the studied period (2015 to 2019).

The results of this study are useful in providing guided information about the importance of controlling soil erosion at the landscape level and retaining important plant growth parameters in agricultural fields. Mapping soil erosion risk at the landscape level helps identify vulnerable areas and protect them at a priority level. Land planners, government extension services, and local NGOs can, therefore, use the results of this study to develop informed natural resource conservation strategies and prioritize intervention measures to protect soil loss from many agricultural farms. This study strongly recommends scaling up the implementation of SWC practices at the landscape scale and integrating other sustainable land management practices, such as afforestation and crop management strategies, for the health of the ecosystem and improved agricultural productivity.

Abbreviations

GIS	Geographic Information System
RUSLE	Revised Universal Soil Loss Equation
SE	Soil Erosion
SWC	Soil and Water Conservation
N	Nitrogen
P	Phosphorus
K	Potassium

AL	Agricultural Land
SW	Savanna Woodland
NV	Natural Vegetation
DEM	Digital Elevation Model
Africa RISING	Africa Research in Sustainable Intensification for the Next Generation
CB	Contour Bunding
C	Organic carbon
GPS	Global Positioning System

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Author contributions

KS and BZB developed the outline and wrote the different sections of the manuscript. SS and AB contributed to the scientific content and review of the findings. All authors have read and accepted the final version of the manuscript. All authors read and approved the final manuscript.

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