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Effects of Land Use and Land Cover Change on Soil Nutrient Loss in the Rwagitugusa Watershed

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ABSTRACT

Soil nutrient loss is a critical issue affecting agricultural productivity and ecosystem sustainability, particularly in regions experiencing rapid land use and land cover (LULC) changes. This study investigates the Effects of Land Use and Land Cover Change on Soil Nutrient Loss in the Rwagitugusa Watershed, employing a combination of remote sensing, Geographic Information System (GIS) analysis, and soil sampling techniques. Using Landsat satellite imagery from 2017, 2018, 2019 and 2020, LULC changes over the past two decades were analyzed to identify shifts in land use patterns. The study focused on key nutrients such as nitrogen (N), phosphorus (P), potassium (K), Calcium, Magnesium (Mg), Sodium (Na), pH, and Electrical Conductivity (EC) which are crucial for plant growth and agricultural productivity. Soil samples were collected from representative sites across different land use categories to assess nutrient levels and loss rates. The results revealed that the change in Nitrogen (N) varied from 0.18 to 2.99 $g.kg^{-1}$, Phosphorus (P) varied from 6.44 $g.kg^{-1}$ to 17.48 $g.kg^{-1}$, and potassium (K) varied from 0.98 $g.kg^{-1}$ to 5.08 $g.kg^{-1}$. The key findings also showed that the change in pH and EC within the LULC types was also presented and discussed. The results revealed that the change in pH varied from 5.28 to 7.84 while the change in EC ranged from 34.63µS/cm to 148.55 µS/cm respectively. The SOM change varied from 9.96 $g.kg^{-1}$ to 55.13 $g.kg^{-1}$, the Calcium change ranged from 1.393$g.kg^{-1}$ to 1.393 $g.kg^{-1}$, the Magnesium (Mg) change ranged from 0.7233 $g.kg^{-1}$ to 1.233 $g.kg^{-1}$ while the Sodium (Na) change varied from 0.625 $g.kg^{-1}$ to 0.85 $g.kg^{-1}$ respectively. Results indicate significant alterations in LULC patterns over the study period, characterized by the expansion of agricultural land, urbanization, and deforestation, leading to changes in soil nutrient dynamics. Furthermore, soil nutrient loss was found to be exacerbated by factors such as improper land management practices, including excessive fertilizer application, monoculture cropping systems, and inadequate soil conservation measures. Steep slopes and erosion-prone areas experienced higher rates of nutrient loss, further compromising soil fertility and agricultural sustainability. In conclusion, the findings provide valuable insights into the complex interplay between LULC dynamics and soil nutrient loss processes in the Rwagitugusa Watershed. The study highlights the urgent need for integrated land use planning and agricultural policies that promote soil conservation, nutrient management, and sustainable farming practices to safeguard soil fertility and ensure long-term agricultural productivity and ecosystem resilience in similar regions facing similar challenges.

Keywords: Land Use Land Cover (LULC), Soil Nutrients Loss, Watershed, Geographical Information System and Remote Sensing

1. Introduction

Land use land cover changes can have significant effects on soil nutrient loss [1]. The study found that soil nitrogen (N) and potassium (K) loss were observed in croplands, while there was a positive phosphorus (P) balance [2]. High soil nutrient uptake and loss due to erosion and leaching were identified as the main causes of nutrient loss [3]. The spatial variations in nutrient balance were influenced by various factors such as soil nutrient stocks, erosion, elevation, rainfall, soil texture, and soil bulk density [4]. To address soil nutrient loss, it is recommended to prioritize soil and water conservation measures and increase soil nutrient inputs [5]. In the case of the Rwagitugusa watershed, the current soil nutrient balance and its spatial variation were assessed. Implementing integrated soil fertility management practices and conservation-based production systems are also suggested. These findings highlight the importance of managing land use and cover to mitigate soil nutrient loss in the Rwagitugusa watershed [6].

It is crucial to assess and understand the nutrient losses originating from agricultural fields as well as their underlying causes. This is necessary for accurately gauging the extent of nutrient enrichment in water bodies and formulating appropriate management approaches [7]. Field-level monitoring will accurately predict nutrient movement. However, it requires more manpower, time, and money. Due to the scarcity of data, the methods will become ineffective on a larger scale [8]. The complexity and expensive nature of laboratory and field observations has necessitated the application of models in predicting the hydrology and nutrient movement at the watershed level [9]. Watershed models capture the dynamic hydrological processes and clearly understand the association between land, water and management practices in a watershed [10]. The most recently developed models are freely available, efficient in time, explicit, comprehensive and user-friendly in simulating nutrients and sediment. Non-point source pollution models are widely used to assess pollutant loads, simulate runoff and soil loss and learn better management practices to address non-point source pollution [11]. Many hydrological models have proved their efficiency at the watershed scale for the prediction of non-point source pollution. The models can also predict the impact of land-use changes on watershed hydrology and nutrient movements [12].

In Rwanda, Land Use Land Cover (LULC) change in Rwanda, coupled with soil erosion, has contributed to soil nutrient loss. Studies have shown that half of Rwanda's farmland suffers from moderate to severe erosion, with the highest soil loss rates in the steeper and rainier northern and western highlands [2]. The estimated mean annual soil losses in Rwanda were 48.6 t/ha/year in 2000 and 39.2 t/ha/year in 2015, resulting in total nationwide losses of approximately 110 and 89 million tons, respectively [13]. Changes in LULC have also played a role, with 34.6% of the evaluated LULC types changing over a 15-year period [14]. The conversion of grassland to forestland has resulted in the highest mean soil loss, while grassland converting to cropland has a lower soil loss rate [15]. These changes in LULC, combined with soil erosion, have led to the

depletion of soil nutrients, including nitrogen, phosphorus, and potassium, in Rwanda's agricultural lands [16]. Soil erosion, triggered by LULC changes, intensifies nutrient loss through several mechanisms. Firstly, erosion physically removes the topsoil layer, which is rich in organic matter and nutrients. Secondly, erosion disrupts soil structure and reduces water infiltration capacity, leading to increased surface runoff and nutrient leaching. Finally, eroded sediments often carry significant amounts of nutrients, pesticides, and fertilizers into water bodies, resulting in nutrient pollution and eutrophication [17]. Overall, the combination of LULC changes and soil erosion in Rwanda has resulted in the loss of soil nutrients, which has detrimental effects on agricultural productivity, water quality, and ecosystem health [18]. Effective land management strategies, including afforestation, soil conservation practices, agroforestry, and sustainable agricultural practices, are essential to mitigate soil erosion, preserve soil fertility, and promote long-term environmental sustainability in the region. Thus the present study of Land Use Land Cover Effects on Induced Soil Nutrient Loss: Case of Rwagitugusa Watershed is taking up in Rwanda to close the knowledge gap.

2. Study area and data acquisition

The study was conducted in Rwagitugusa Agricultural wetland of the Upper Akagera Catchment which has the Akagera water body. Rwagitugusa Wetland is located in Eastern of Rwanda, particularly in both the Mutenderi sector and the Gahara sector. Occupying an area of 551.5507 Ha with a perimeter of 34,633.5923 meters, the Rwagitugusa Wetland is a site proposed by RAMSAR with exploitation under conditions of national importance and vegetation of Papyrus. It is bounded by Akagera among wetlands and Rwakaganze wetlands all are tributaries of Lake Rweru (**Fig. 1**) and (**Fig . 2**).

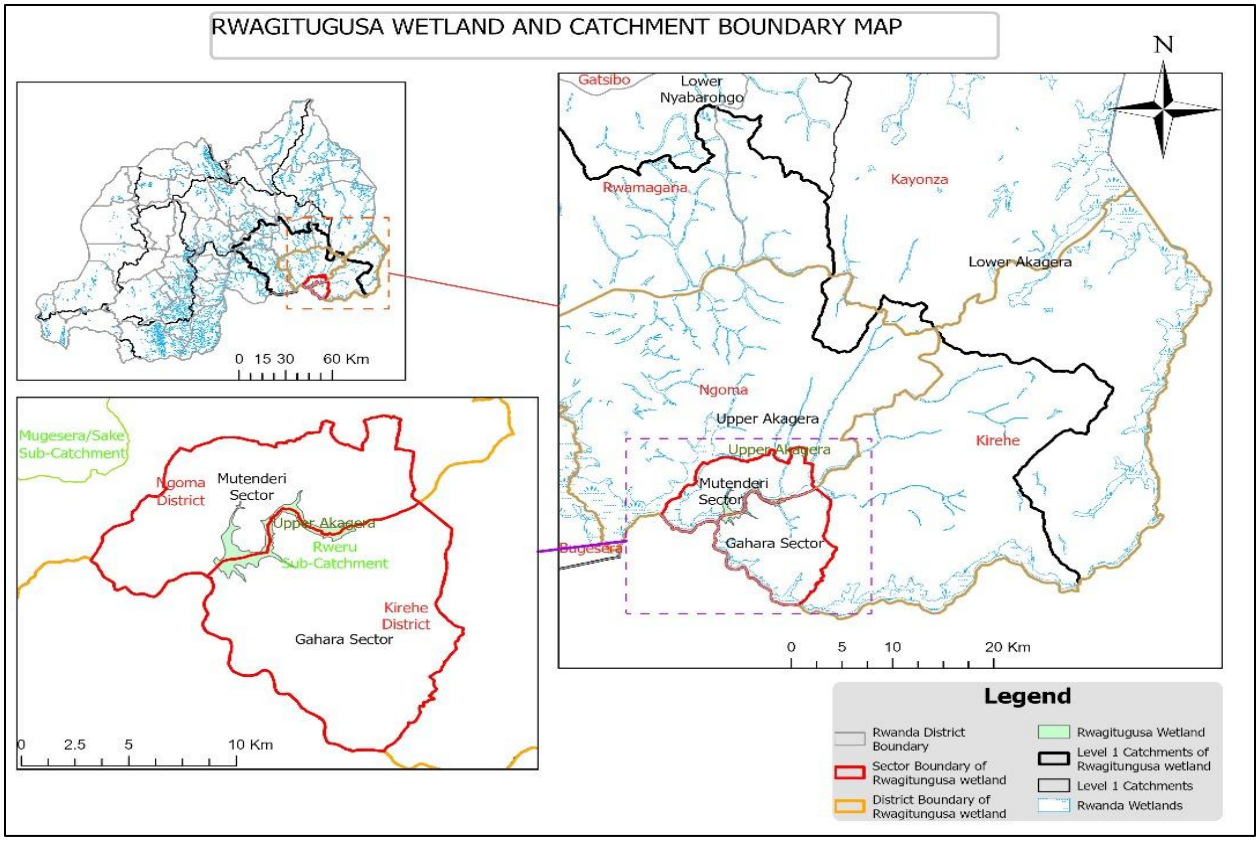


Figure 1: Location of Rwagitugusa in Upper Akagera catchment of Rwanda water bodies

Source: Application of GIS & RS, 2024

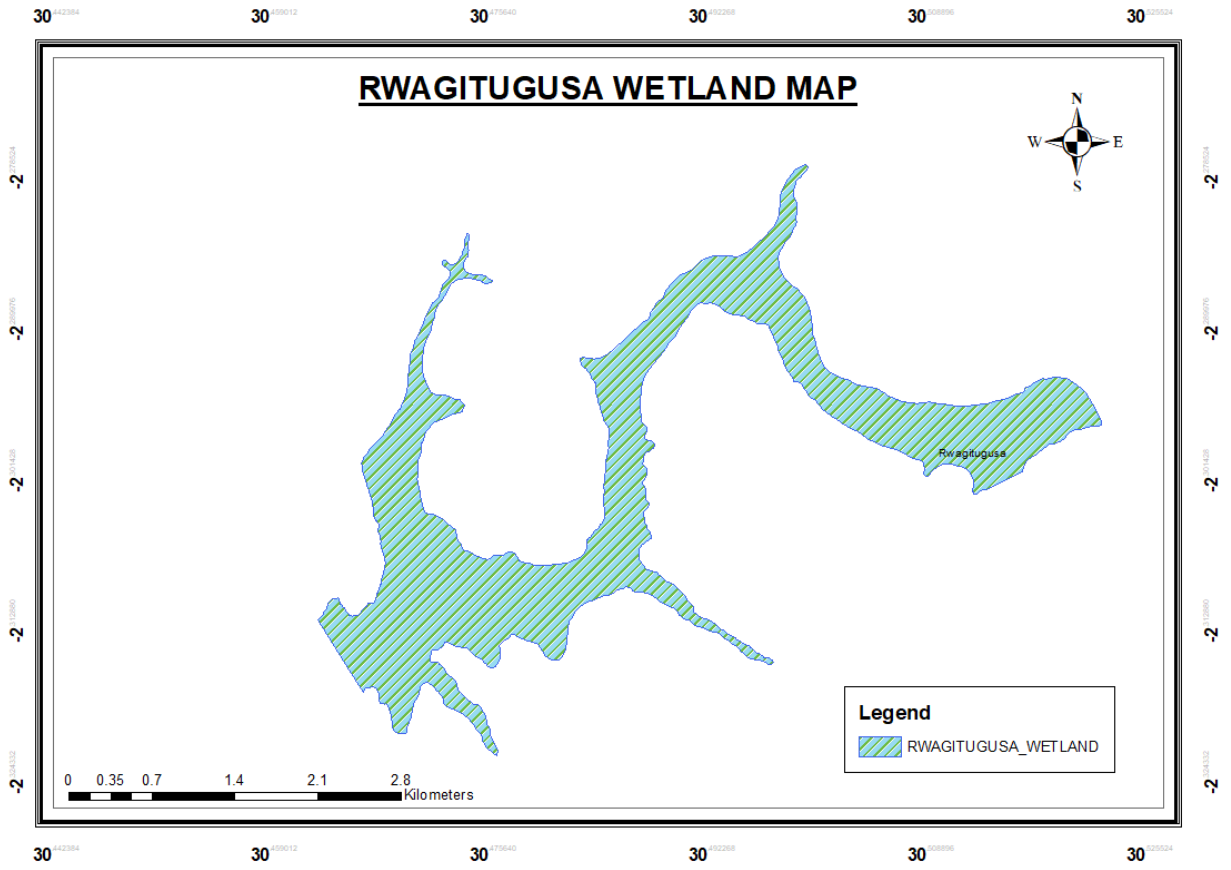


Figure 2: Geographical location of Rwagitugusa wetland for vegetable crops production

Source: Application of GIS & RS, 2024

2.2 Rwagitugusa Watershed Delineation Process

Watershed delineation involves identifying the area of land that drains runoff to a common outlet, such as a stream outlet or basin point. It is an essential step in water resource management, land use planning, and environmental conservation. To delineate the Rwagitugusa Watershed, several key steps were carried out using ArcGIS 10.8 and associated GIS tools and datasets. These steps included importing a Digital Elevation Model (DEM) of the study area, followed by preprocessing operations such as filling sinks, and generating flow direction and flow accumulation grids. A crucial step was the identification of outlet points, which represent locations where water exits the watershed, such as stream junctions, reservoirs, or river confluences. Finally, the watershed boundary was defined using the ArcGIS watershed tool, which utilizes the flow direction and flow accumulation data together with the specified outlet points to generate the delineated watershed.
. The watershed was delineated based on the existing agricultural lands like Rwagitugusa wetland and its named river. It has a total area of 84.86 km^2. It is geographically situated between 2°23’0’’S - 2°14’0’’S to 30°26’30’’E - 30°33’00’’ (**Fig.3**);

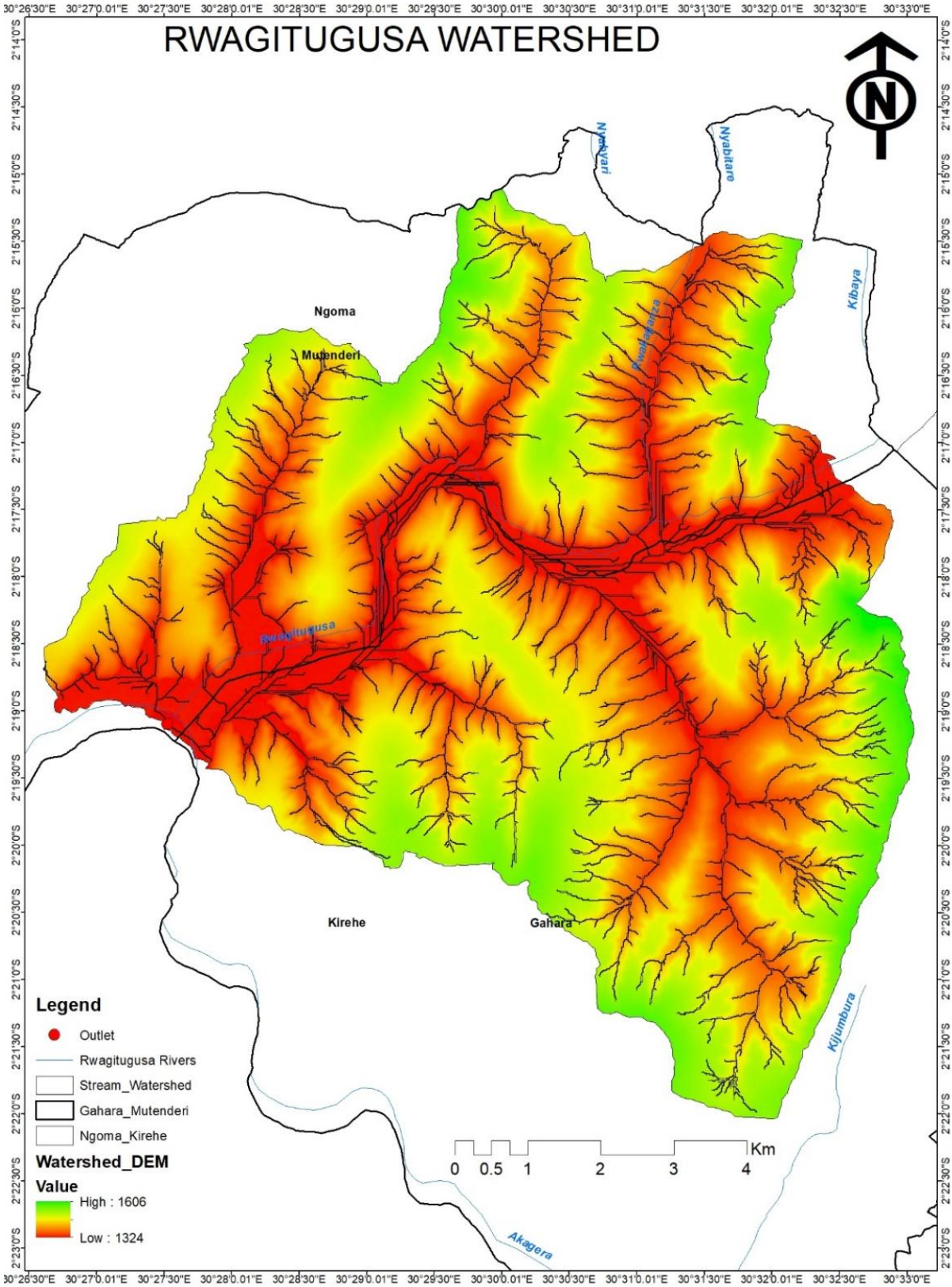


Figure 3: Rwagitugusa Watershed delineation

And has an altitude of 1324 m to 1606 m above sea level. The climate of the valley is moist temperate. Summers are moderate and winters are extremely cold with heavy snow and frost. The valley of Rwagitugusa has borders with the Akagera Rivers and Rwakaganze wetland of Lake Rweru. Monthly Average temperatures in summers range from 19.81 - 21°C in general and the monthly average rainfall varies from 980 – 1,100 mm (**Fig.3**).

2.1 Methods

2.1.1 Site selection

The study area comprises a total of 18 soil samples that were experimentally selected based on the land uses i.e. densely forested, moderately forested and agricultural land (Figure 4). This map indicated the 18 soil samples sampled from crops (3), Rangeland (4), Trees/ Forest (4), Built- Up area (3) and Flooded Vegetation (4) (**Fig. 4**)

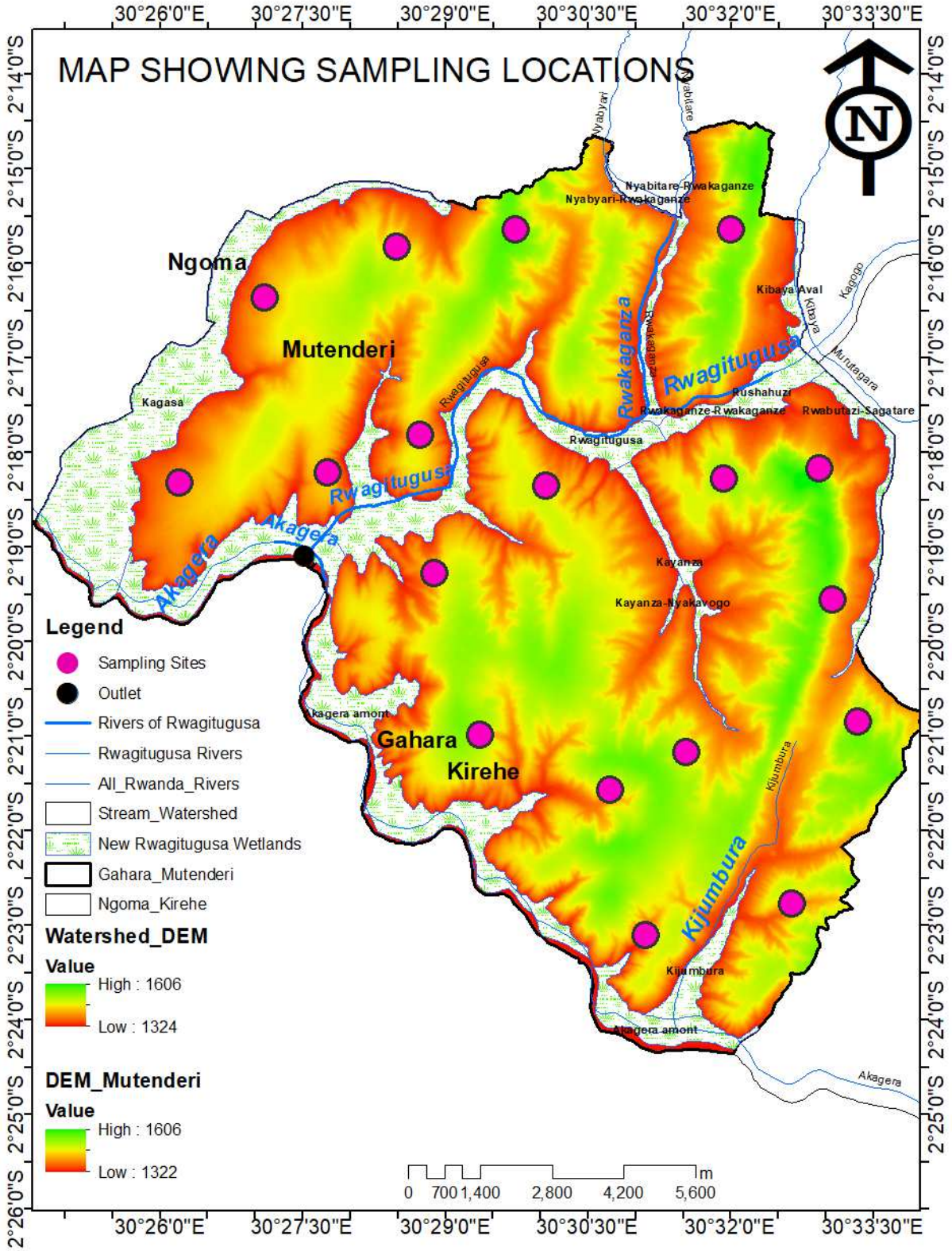


Figure 4: Sampling location/ sites by LULC types of Rwagitugusa Wetland

2.2.2 Soil sampling

In August 2023, soil samples were collected from five (5) different land use types using an auger, applying a stratified random sampling approach. At each site, three samples were taken and combined to form a single composite sample. The samples were carefully packed, labeled, and transported to the soil laboratory at Rwanda Polytechnic, Kigali College. After air drying, the samples were sieved through a 2 mm mesh following the removal of stones and plant debris, and then stored in a cool, dry environment prior to analysis. Laboratory tests were conducted to determine the levels of Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Sodium (Na), as well as pH and Electrical Conductivity (EC).

2.2.3 Land use/land cover (LULC)

Landsat 8 multi-temporal images from 2017, 2018, 2019, and 2020 were utilized to assess changes within the study area. The data underwent preprocessing, including atmospheric correction, and digital numbers (DN values) were converted into reflectance. These reflectance images were then classified using a supervised classification approach to identify different LULC categories. Spectral signatures for each class were carefully selected for each respective year to improve classification accuracy. Following classification, post-classification processing, including Maximum Likelihood classification, was applied. The resulting classified maps were then overlaid to detect and quantify changes in LULC categories over time.

2.2.4 Laboratory analysis

The processed soil samples were analyzed for various chemical properties using standard laboratory procedures, including the measurement of soil pH with a pH meter.
(Inolab WTW Series pH 720) [4], electrical conductivity by EC meter [19], organic matter [20], AB-DTPA (ammonium bicarbonate diethylene Triamine Penta acetic acid) extractable P and K [21] and total Nitrogen by Kjeldahl digestion [22].

Soil pH and electrical conductivity were measured using the 1:1 soil-to-water ratio method, a simple and cost-effective approach that requires minimal materials while providing a reliable estimate of field salinity. This method, like other salinity assessment techniques, involves the use of an instrument to measure electrical conductivity. Soil pH was determined directly with a pH meter equipped with a glass electrode immersed in the soil solution, which produces a voltage proportional to the hydrogen ion concentration and converts it into pH values. The other soil nutrients were analyzed using the respective laboratory methods summarized below:

Table1: Methods to be used to analyse soil nutrients from Rwagitugusa Watershed

SNO	Parameters	Unit	Methods to be used
1	pH	Unitless	Hanna portable Tester
2	Nitrogen (N)	mg/L/ ppm	UV spectrophotometer
3	Sodium (Na)	mg/L/ ppm	Flame photometer
4	Calcium (Ca)	mg/L/ ppm	Standard Titration
5	Magnesium (Mg)	mg/L/ ppm	Standard Titration
6	Potassium (K)	mg/L/ ppm	Flame photometer
7	Phosphorus (P):	mg/L/ ppm	Mehlich-3 Method
8	Soil Organic Matter (SOM)	$g.kg^{-1}$	Loss on Ignition method

2.2.5 Statistical analysis

Land Use Land (LULC) classification was performed by ArcGIS 10.8 computer software to indicate decrease and increase in soil loss. The various soil parameters like pH, electrical conductivity, organic matter, nitrogen, phosphorus, potassium, were analyzed statistically and presented through descriptive and Analysis of Variance (ANOVA) techniques as suggested by [23]. Time series data presentation with Minitab 21 software was used to indicate the change in soil nutrients

2.2.6 Nutrient loss through sediment

The quantity of each nutrient lost through sediment was calculated using the following equation: $N = n.s$ (1), where N represents the total mass of each nutrient lost in the collected sediment (g), nnn is the total mass of the collected soil sediment (g), and sss denotes the concentration of the specific nutrient in the sediment (g/g)[24].

2.2.7 Enrichment Ratio (ER)

Soil erosion not only impacts the location where it originates but also influences surrounding soils and ecosystems beyond the eroded area. At deposition sites, accumulated sediments and nutrients can alter soil properties. The enrichment ratio (ER) refers to the extent to which eroded materials are concentrated in fine soil particles and plant nutrients compared to the soil that remains at the erosion source[25]. The enrichment ratio exceeds one when the sediments contain higher nutrient concentrations than the original soil. ER = Nutrients concentration in sediment (g/kg)/ Nutrients concentration in the parent soil (g/kg) [24].

3. Results and Discussion

3.1 Land use/land cover

The Landsat images from 2017, 2018, 2019, and 2020 were categorized into four land use and land cover classes (Figure 4). Table 1 presents the observed changes in soil nutrients across these LULC categories. The distribution of these classes such as water, forest, urban areas, agriculture, barren

land, and pasture illustrates the land use and land cover patterns within the Rwagitugusa Watershed.
(**Fig 5**).

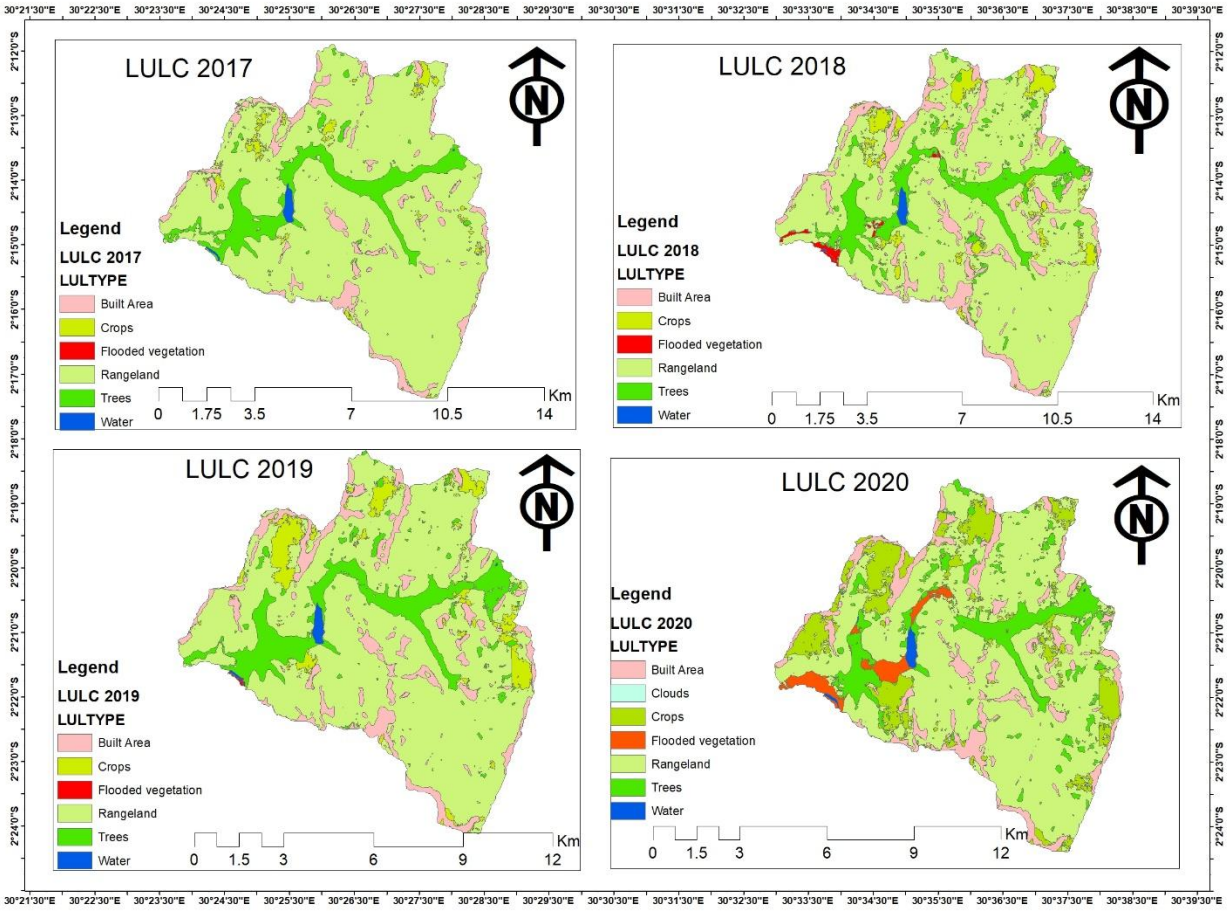


Figure 5: Land Use Land Cover of Rwagitugusa Watershed (2017-2020)

Table 2 presents the distribution of Land Use and Land Cover (LULC) types for 2017, 2018, 2019, and 2020 in the Rwagitugusa watershed, including percentage changes between consecutive years. The area under crop cultivation increased consistently over the study period, with a marked rise between 2017 and 2019 and a more moderate increase from 2019 to 2020, resulting in an overall gain of 12.76%. In contrast, rangeland declined from 2017 to 2019, followed by a slight recovery in 2020, yet it still recorded an overall reduction of 18.23%. Tree cover showed minor fluctuations but experienced a modest overall increase of 1.11% during the four-year period. Built-up areas expanded steadily, particularly between 2017 and 2018, leading to a total increase of 3.63%. Water bodies remained relatively stable, with only slight variations and a small overall increase. Flooded vegetation was minimal in 2017, 2018, and 2019 but rose significantly between 2018 and 2019 and continued to increase in 2020, resulting in a total rise of 2.62%. These LULC changes indicate notable transformations within the watershed. The expansion of cropland and urban areas, coupled

with a reduction in forested land, reflects pressures from population growth and economic development. Such changes may adversely affect water resources and hydro-morphological processes, influencing rainfall–runoff dynamics, water availability, and flood risks. Future projections suggest that these trends will persist, with cropland expected to expand further in the western part of the watershed alongside declining grassland, while the eastern region may experience the opposite pattern.

[26].

Table 2: Land Use Land Cover change (2017 to 2020) of Rwagitugusa Watershed

LULC Types	2017		2018		2019		2020		2017/ 2018	2018/ 2019	2019/ 2020	2017/ 2020
	Area (Km^2)	% LULC	Area (Km^2)	% LULC	Area (Km^2)	% LULC	Area (Km^2)	% LULC	% LULC Change			
Crops	1.64	1.93	4.35	5.12	5.06	5.95	10.84	12.76	3.19	0.84	6.80	10.83
Rangeland	68.06	79.95	59.62	70.17	60.14	70.78	52.45	61.72	-9.79	0.62	-9.06	-18.23
Trees	8.62	10.12	10.08	11.87	10.29	12.11	9.55	11.23	1.74	0.24	-0.88	1.11
Built Area	6.38	7.50	9.96	11.72	9.02	10.62	9.46	11.13	4.23	-1.11	0.52	3.63
Water	0.42	0.50	0.39	0.46	0.41	0.49	0.45	0.53	-0.04	0.03	0.04	0.03
Flooded vegetation	0.00	0.00	0.56	0.66	0.04	0.05	2.23	2.62	0.66	-0.61	2.57	2.62
Clouds	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total (Km^2)	85.13	100	84.97	100	84.97	100	84.97	100	0.00	0.00	0.00	0.00

Referred on results presented in table 2, the LULC changes observed from 2019 to 2020 in the Rwagitugusa Watershed suggest potential impacts on soil nutrient loss, including increased erosion and nutrient runoff associated with expansion of agriculture and urban areas, as well as potential mitigation of soil nutrient loss through the expansion of flooded vegetation areas. Further detailed analysis and monitoring would be necessary to fully understand and manage the implications of these LULC changes on soil nutrient dynamics in the watershed

3.2 Soil nutrients loss

Soil loss and nutrient loss due to Land Use and Land Cover (LULC) changes are critical factors in environmental degradation and agricultural productivity. LULC changes refer to alterations in the way land is used or covered, often as a result of human activities such as urbanization, deforestation, agriculture, and infrastructure development.

Table 3: Statistics of Soil Nutrients change by Land Use Land Cover types

Variable	LULC Types	Total Count	Mean	SE Mean	SD	CV	Min	Max
N	Crops	3	1.974	0.572	0.991	50.18	1.019	2.997
	Rangeland	4	1.497	0.477	0.954	63.71	0.808	2.908
	Trees/ Forest	4	1.796	0.448	0.897	49.94	1.019	2.979
	Built- Up area	3	1.604	0.202	0.349	21.80	1.329	1.997
	Flooded Veg.	4	1.341	0.589	1.178	87.80	0.179	2.979
P	Crops	3	9.70	1.63	2.83	29.16	6.44	11.46
	Rangeland	4	10.78	1.69	3.38	31.34	7.44	14.48
	Trees/ Forest	4	10.975	0.898	1.796	16.36	8.482	12.755
	Built- Up area	3	13.47	1.00	1.74	12.91	11.46	14.48
	Flooded Veg.	4	9.98	1.21	2.43	24.32	7.48	12.76
K	Crops	3	2.56	1.26	2.18	85.04	1.24	5.08
	Rangeland	4	3.105	0.891	1.783	57.43	0.981	4.617
	Trees/ Forest	4	2.330	0.526	1.052	45.17	1.365	3.805
	Built- Up area	3	1.233	0.252	0.436	35.38	0.981	1.737
	Flooded Veg.	4	2.814	0.602	1.204	42.79	1.365	3.805
pH	Crops	3	7.173	0.203	0.352	4.91	6.780	7.460
	Rangeland	4	6.920	0.562	1.125	16.25	5.280	7.840
	Trees/ Forest	4	6.807	0.314	0.628	9.23	6.140	7.460
	Built- Up area	3	6.3267	0.0467	0.0808	1.28	6.2800	6.4200
	Flooded Veg.	4	7.130	0.282	0.563	7.90	6.460	7.710
EC	Crops	3	93.1	13.7	23.8	25.56	78.5	120.6
	Rangeland	4	83.47	4.46	8.91	10.68	70.54	90.18
	Trees/ Forest	4	118.2	18.2	36.5	30.85	67.6	148.6
	Built- Up area	3	66.3	26.4	45.7	68.90	34.6	118.6
	Flooded Veg.	4	74.0	18.8	37.7	50.89	38.5	120.5
SOM	Crops	3	26.75	5.86	10.14	37.93	16.53	36.82
	Rangeland	4	43.3	10.2	20.4	47.16	12.8	55.1
	Trees/ Forest	4	18.66	5.76	11.52	61.73	9.96	35.62
	Built- Up area	3	26.3	13.9	24.0	91.33	10.9	53.9
	Flooded Veg.	4	37.00	4.88	9.75	26.36	25.38	47.27
Ca	Crops	3	1.330	0.379	0.656	49.30	0.630	1.930
	Rangeland	4	1.340	0.258	0.515	38.44	0.720	1.970
	Trees/ Forest	4	1.393	0.204	0.408	29.33	0.870	1.840
	Built- Up area	3	1.477	0.273	0.472	32.00	0.940	1.830
	Flooded Veg.	4	1.100	0.175	0.349	31.74	0.880	1.620
Mg	Crops	3	1.233	0.393	0.680	55.14	0.560	1.920
	Rangeland	4	0.895	0.266	0.532	59.39	0.360	1.630
	Trees/ Forest	4	1.132	0.336	0.672	59.33	0.540	1.940
	Built- Up area	3	0.7233	0.0384	0.0666	9.21	0.6500	0.7800

	Flooded Veg.	4	1.008	0.214	0.428	42.52	0.650	1.630
Na	Crops	3	0.8933	0.0817	0.1415	15.84	0.7300	0.9800
	Rangeland	4	0.625	0.170	0.340	54.33	0.190	0.950
	Trees/ Forest	4	1.320	0.252	0.503	38.11	0.880	1.980
	Built- Up area	3	1.173	0.280	0.484	41.27	0.850	1.730
	Flooded Veg.	4	0.850	0.300	0.599	70.48	0.170	1.630

Noted: N (Nitrogen, g/Kg); P (Phosphorus, g/Kg), K (Potassium, g/Kg), pH (Indicate acidity or basicity), EC (Electrical conductivity, µS/cm), SOM= Soil Organic Matter (g/Kg), Ca (Calcium, g/Kg), Mg (Magnesium, g/Kg) and Na (Sodium, g/Kg

3.2.1 Nitrogen (N), Phosphorus (P) and Potassium (K) Change by Land Use/Land Cover

Land Use and Land Cover (LULC) changes have significant impacts on N, P and K cycling in ecosystems. Nitrogen (N), Phosphorus (P) and Potassium (K) Change are a crucial nutrients for plants growth and are essential for various biological processes. However, human activities associated with land use changes can disrupt the natural N, P and K Change cycle, leading to environmental problems such as nutrient pollution, ecosystem degradation, and biodiversity loss. Figure 5 depicts the change of N, P and K Change by type of Land Use Land Cover in the Rwagitugusa Watershed (**Fig. 6**).

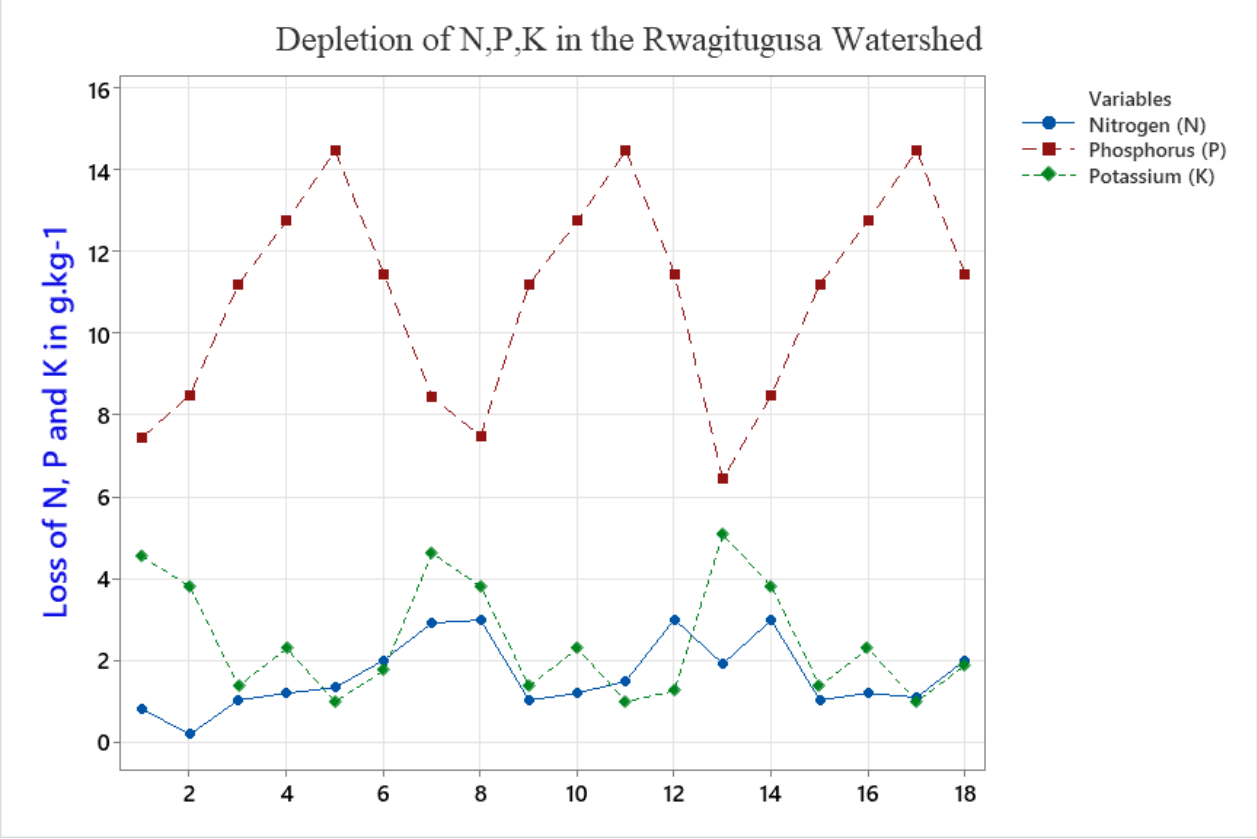


Figure 6: Change of N, P and K in the Rwagitugusa Watershed by LULC types

The figure illustrates variations in nitrogen (N), phosphorus (P), and potassium (K) losses across different Land Use and Land Cover (LULC) types, highlighting those with the lowest and highest mean values. Built-up areas generally exhibit the lowest nutrient losses, particularly for nitrogen, due to limited vegetation cover and reduced agricultural activity. This results in minimal nitrogen inputs and restricted nutrient cycling, largely influenced by impermeable surfaces and reduced soil exposure. In contrast, cropland areas show significantly higher nitrogen losses, mainly due to intensive agricultural practices such as fertilizer application. While nitrogen supports crop productivity, excessive use can contribute to environmental challenges, including water pollution and ecosystem degradation. Similarly, phosphorus loss is lowest in built-up areas, reflecting limited phosphorus cycling and controlled discharges, often supported by wastewater management systems in urban environments. On the other hand, forested areas tend to show higher phosphorus losses, which may be associated with soil erosion and surface runoff. These losses can be intensified by deforestation and land use changes, potentially leading to environmental degradation and reduced ecosystem stability.

For potassium, built-up areas again record the lowest losses, indicating limited potassium inputs and cycling due to the absence of natural vegetation and organic matter. In contrast, rangelands including shrubs, grasslands, and pastures exhibit higher potassium losses. This is often attributed to soil erosion, grazing pressure, and land degradation, which negatively affect soil fertility and nutrient retention. Understanding these differences in nutrient loss across LULC types is essential for promoting sustainable land management practices. Implementing appropriate conservation strategies can help reduce nutrient depletion while maintaining ecosystem health. Results from Table 3 and Figure 6 further indicate that nitrogen levels ranged from 0.18 to 2.99 g kg^{-1}, phosphorus from 6.44 to 17.48 g kg^{-1}, and potassium from 0.98 to 5.08 g kg^{-1}. These variations suggest that changes in land use and land cover significantly influence soil nutrient availability. Moreover, increased runoff linked to LULC changes can intensify soil erosion and flood risks, ultimately contributing to greater nutrient loss within the watershed[27].

3.2.2 Relationship between pH and EC by LULC types in Rwagitugusa watershed

To determine which type of Land Use Land Cover (LULC) has the lowest and highest values of pH and Electrical Conductivity (EC) loss, plot time series was used to examine the mean values for each LULC type and their implications (**Fig.7**).

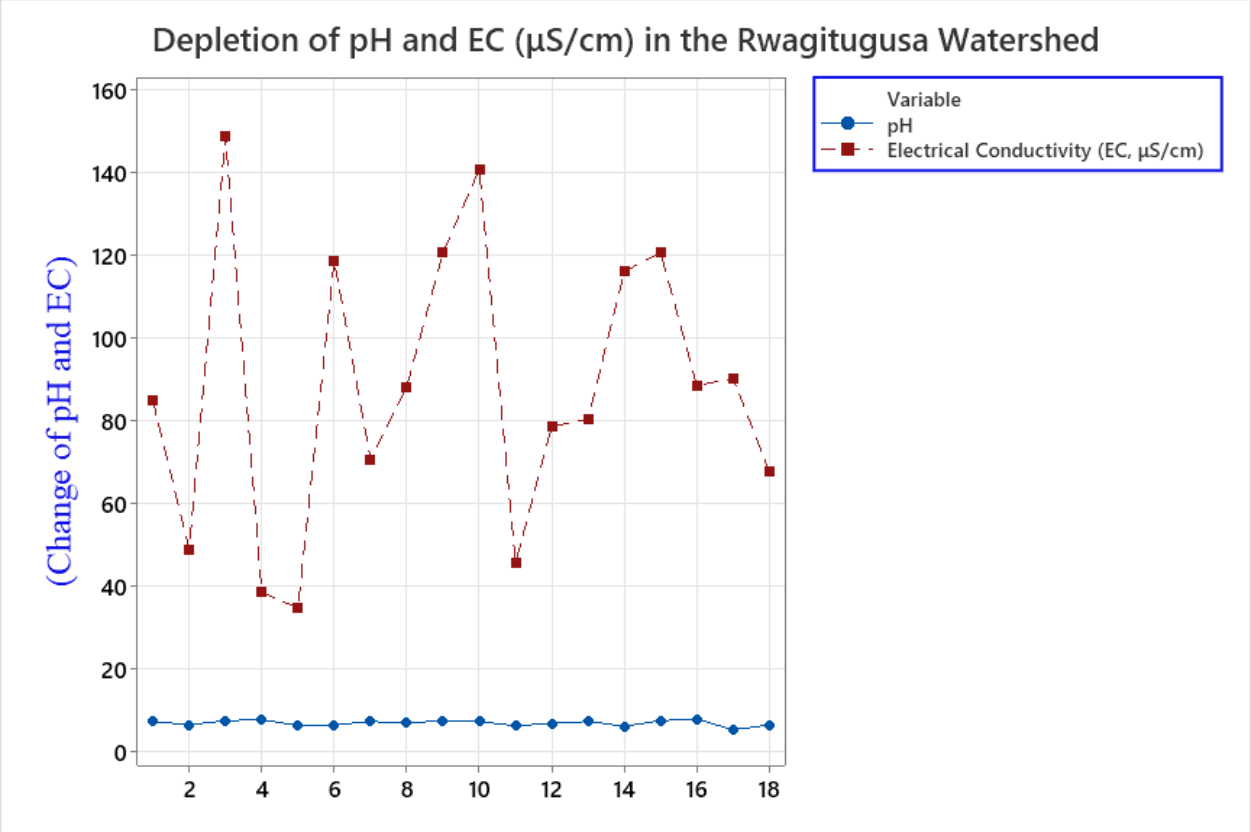


Figure 7: Loss of pH and EC (µS/cm) at the Rwagitugusa Watershed

The results indicate that built-up areas exhibit the lowest mean values, with a pH of 6.33 and electrical conductivity (EC) of 66.3 µS/cm, highlighting the influence of urbanization on soil properties. In contrast, cropped and forested lands show higher values, with pH reaching 7.17 and EC up to 118.2 µS/cm, reflecting the effects of agricultural activities and natural ecosystem processes. These variations in pH and EC across different land cover types are important for land management decisions. Lower pH levels in built-up areas are likely associated with urban activities such as construction, pollution, and alterations in soil composition, which can negatively affect soil health, plant growth, and urban ecosystem functioning. On the other hand, higher pH values in cropland may result from practices such as liming and the application of alkaline fertilizers, both of which are essential for maintaining soil conditions favorable for crop production by improving nutrient availability and microbial activity. Similarly, the relatively low EC observed in built-up areas may be linked to limited organic matter, reduced mineral content, and decreased salt movement compared to other land cover types. In contrast, higher EC values in forested areas are influenced by natural processes such as organic matter decomposition, mineral weathering, and active nutrient cycling. However, excessively high EC levels may indicate salinity issues, which can adversely affect plant growth and ecosystem health. Overall, changes in land use and land cover significantly affect soil pH and EC by altering soil properties and processes. For example, in the study by [28], it was found that the conversion of rice paddy fields to other land uses resulted

in significant changes in soil pH and EC levels [29]. Similarly, the study by [29] showed that land use change, such as the conversion of cropland to garden, can lead to changes in soil pH [30]. Additionally, the study by [31] found that different land use categories, such as vineyards, can have varying effects on soil acidity [28].

3.2.3 Soil nutrients loss of SOM, Ca, Mg and Na in the Rwagitugusa watershed

Soil nutrients loss refers to the reduction or depletion of essential nutrients from the soil, which can occur due to various natural and anthropogenic factors. These nutrients are vital for sustaining soil fertility, supporting plant growth, and maintaining ecosystem health. Several key soil nutrients are commonly studied in the context of soil nutrient loss, including Soil Organic Matter (SOM), Calcium (Ca), Magnesium (Mg), and Sodium (Na). Understanding soil nutrient loss is crucial for sustainable land management and agricultural practices to mitigate adverse effects on soil quality and productivity (**Fig.8**).

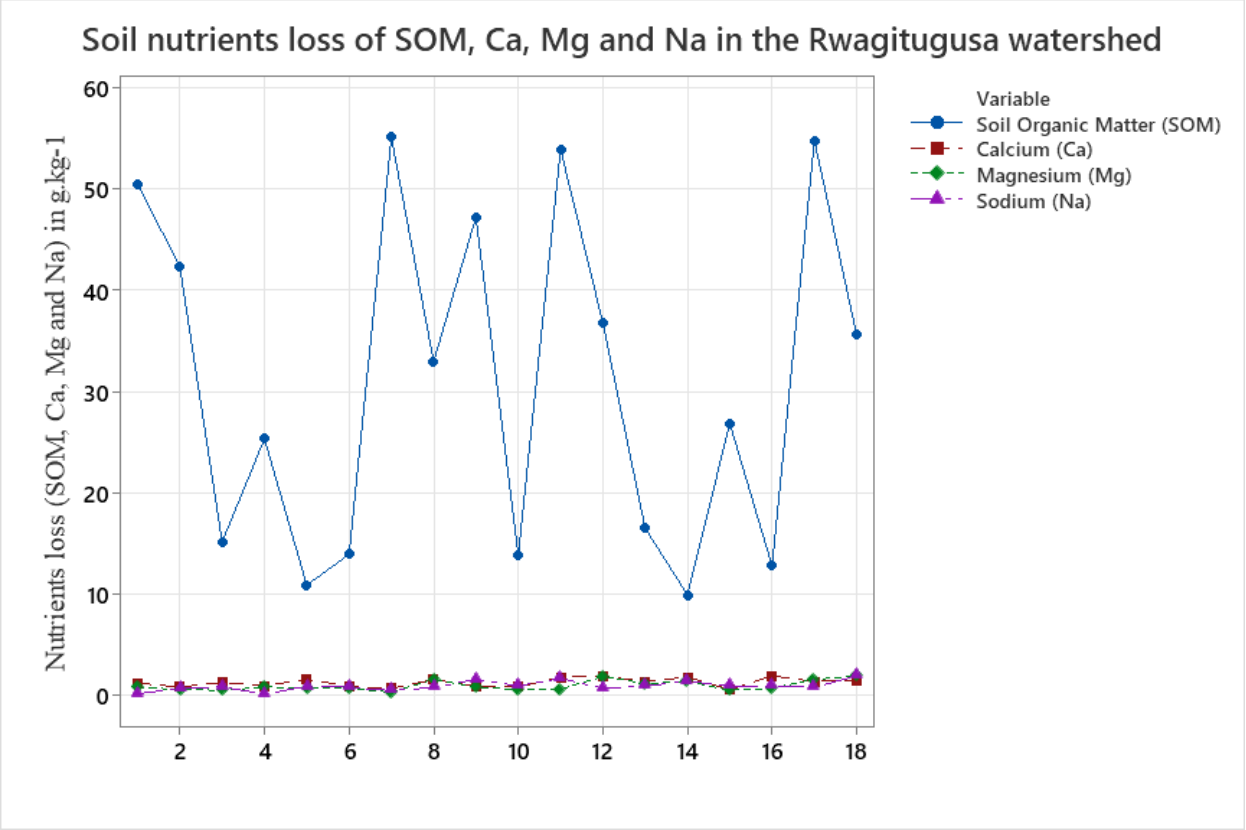


Figure 8: Loss of SOM, Ca, Mg and Na by LULC types of Rwagitugusa watershed

The assessment of Land Use and Land Cover (LULC) types focused on identifying those with the lowest and highest losses of Soil Organic Matter (SOM), Calcium (Ca), Magnesium (Mg), and Sodium (Na) based on their mean values, along with their implications. The findings revealed that rangeland areas recorded the highest SOM value of 43.3 g kg^{-1}, likely due to the presence of natural

vegetation and limited human disturbance, which promote organic matter accumulation, improve soil fertility, and enhance moisture retention. In contrast, the lowest SOM value of 18.66 g kg^{-1} was observed in forested areas, possibly influenced by factors such as decomposition rates, vegetation type, and soil disturbance, which affect nutrient cycling and microbial activity. Similarly, the lowest calcium content, 1.393 g kg^{-1}, was found in forested areas, likely due to natural processes such as leaching and weathering, which are controlled by soil pH and vegetation characteristics. Conversely, higher calcium levels recorded in built-up areas may be attributed to human activities, including the addition of construction materials, waste disposal, and urban runoff, all of which can alter soil chemistry and nutrient availability. The analysis of magnesium showed that built-up areas had the lowest value (0.7233 g kg^{-1}), which may result from soil degradation, reduced organic inputs, and the effects of urbanization on soil processes. On the other hand, cropland areas exhibited the highest magnesium level (1.233 g kg^{-1}), likely linked to agricultural practices such as fertilizer use and crop residue incorporation, which enhance soil nutrient content. In the case of sodium, lower values (0.625 g kg^{-1}) were recorded in rangeland areas, reflecting limited human influence and the effects of natural processes like leaching and weathering. Higher sodium levels (0.85 g kg^{-1}) were observed in areas with flooded vegetation, which may be influenced by irrigation practices, saline water intrusion, or wetland soil conditions that affect soil quality and plant growth. Overall, these results demonstrate that changes in land use and land cover significantly affect soil properties, including SOM, calcium, magnesium, sodium, and pH. The conversion of forest to other land uses leads to a decrease in SOM content [32], and this change also affects the physicochemical properties of the soil, including a decrease in total soil porosity and permeability rate, as well as an increase in soil bulk density [33]. However, there is an increase in soil P-availability, cation exchange capacity (CEC), and exchangeable Ca and Na [34]. In another study, it was found that the shift from thick forests to thin forests or arable lands can increase phosphorus (P) losses and disturb the associated soil-plant nutrient status like Ca, Mg and Na [29].

4. Conclusion and Recommendations

4.1 Conclusion

Based on the key findings, the following are conclusion points drawn. The study demonstrated that significant changes in land use and land cover (LULC) between 2017 and 2020 have markedly influenced soil nutrient dynamics in the Rwagitugusa watershed. Cropland expanded by 12.76%, while rangeland decreased by 18.23% and built-up areas increased by 3.63%, indicating intensified agricultural activities and urbanization. These changes were closely associated with variations in soil nutrient loss, where nitrogen ranged from 0.18 to 2.99 g kg^{-1}, phosphorus from 6.44 to 17.48 g kg^{-1}, and potassium from 0.98 to 5.08 g kg^{-1}, showing substantial spatial variability across LULC types. Built-up areas recorded relatively low nutrient losses, with mean nitrogen (1.604 g kg^{-1}) and potassium (1.233 g kg^{-1}), alongside the lowest pH (6.33) and EC (66.3 µS/cm), reflecting limited biological activity and nutrient cycling. In contrast, cropland exhibited higher nitrogen levels (1.974 g kg^{-1}), indicating the influence of fertilizer inputs, while rangeland showed the highest soil

organic matter (43.3 g kg^{-1}) and potassium (3.105 g kg^{-1}), suggesting stronger nutrient retention under natural vegetation. Forest areas displayed moderate nutrient values but recorded lower SOM (18.66 g kg^{-1}), reflecting ongoing ecological processes. Furthermore, soil chemical properties varied significantly, with pH ranging from 5.28 to 7.84 and EC from 34.63 to 148.55 µS/cm, indicating the combined effects of land use practices and environmental factors. Essential base cations also showed variability, with magnesium ranging from 0.7233 to 1.233 g kg^{-1} and sodium from 0.625 to 0.85 g kg^{-1}. Therefore, the findings confirm that LULC changes significantly affect soil fertility through nutrient depletion, driven by agricultural intensification, urban expansion, and erosion processes, highlighting the need for integrated land management strategies to sustain soil productivity.

4.2 Recommendations

Land management practices have a significant influence on soil physical and chemical properties, as well as overall nutrient status. A comparative evaluation of different land use types shows that agricultural land, often characterized by intensive cultivation and limited inputs, tends to degrade soil quality and reduce nutrient levels. In contrast, forested areas demonstrate improved soil conditions and higher nutrient availability, largely due to the accumulation of organic matter. This organic matter plays a crucial role in enhancing soil structure and maintaining favorable physical properties. In agricultural lands, increased rainfall can accelerate nutrient loss through leaching and erosion, further reducing soil fertility. These findings highlight the critical role of vegetation cover in preserving soil nutrients and maintaining soil health. Both climatic factors, particularly rainfall, and human activities such as land use change and intensified farming practices in the Rwagitugusa Watershed are key contributors to alterations in soil properties. Addressing the impacts of these changes, especially soil erosion, remains a major challenge for sustainable land management. Improving soil quality requires integrated approaches, including the addition of organic matter and the appropriate use of inorganic fertilizers to ensure sufficient availability of essential nutrients, including micronutrients.

Authors Contribution

Ideation and conceptualization: M.M.C & J.N.N.; Literature review: J.N.N., S.H, G.G.A & R.N; Data collection and analysis: M.M.C & J.N.N.; Methodology: M.M.C, D.E.B & J.N.N.; Writing original draft: M.M.C, S.H & J.N.N.; Review, editing & proof reading: M.M.C & J.N.N., G.G.A, D.E.B & R.N.

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Declarations

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Data availability
The authors are willing to supply the datasets utilized and/or analyzed in the current work upon reasonable request (**cmusinga@gmail.com**) or at URL: **10.6084/m9.figshare.29425451**

Declarations

Ethics approval and Consent to participate
This study was conducted in strict adherence to ethical principles governing research involving human participants. Approval was granted by the Institutional Ethics and Research Committee of the Institute of Young Researchers in Rwandan Agriculture (IYRRA), under the Youth in Agroecology and Business Learning Track Africa (YALTA) Rwanda initiative, with approval number 0572/2023. The committee ensures compliance with national research standards and promotes responsible practices among young agricultural researchers. Prior to data collection, informed consent was obtained from all participants after clearly explaining the study objectives, voluntary participation, and their right to withdraw at any stage. All data were collected, stored, and analyzed with confidentiality, and participant anonymity was maintained throughout the research process.

Ethics Statement
This study was conducted in accordance with established ethical standards for environmental and geospatial research. It relied solely on secondary data, including satellite imagery and hydrological model outputs, with no involvement of human or animal subjects. All data sources were properly acknowledged, analyses were conducted objectively, and results were reported transparently to support sustainable land and water resource management.

Consent for publication
Not applicable

Competing interests: The authors declare no competing interests.

Clinical trial number: Not applicable.

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