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Land Use and Land Cover Change and Its Implications for Soil Erosion in the Gebre Korke Watershed, Central Ethiopia, 1995–2020

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Abstract

Land use and land cover (LULC) change is a major driver of soil degradation and declining agricultural productivity in the Ethiopian highlands. This study analyzes LULC dynamics and their implications for soil erosion in the Gebre Korke watershed (4,653.46 ha), Central Ethiopia, using multi-temporal Landsat imagery (1995, 2005, 2015, 2020), GIS techniques, and the Revised Universal Soil Loss Equation (RUSLE). Supervised maximum-likelihood classification was applied to TM and OLI imagery with training data collected during field campaigns and verified using Google Earth high-resolution imagery. The results reveal significant LULC transformation over the 25-year study period: cultivated land expanded by 38.6%, from 1,676.0 ha (36.0%) in 1995 to 2,322.7 ha (49.9%) in 2020, while grassland and shrubland declined by 38.4% (2,027.0 ha to 1,249.5 ha) and 63.2% (1,275.5 ha to 469.5 ha), respectively. Forest cover remained relatively stable at 6–7% but decreased in absolute terms from 327.0 ha to 278.0 ha. The LULC change significantly impacted soil erosion: RUSLE analysis showed a 40.2% increase in mean annual soil loss from 18.5 t/ha/yr in 1995 to 25.9 t/ha/yr in 2020, with total soil loss rising from 86,088.0 to 120,524.5 ton/yr. The area classified as high to very high erosion risk increased from 8.0% (372.3 ha) to 18.5% (860.9 ha). The cover-management factor (C-factor) increased by 28.4% over the period, directly reflecting the erosion of protective grassland and shrubland vegetation and the expansion of erodible cropland. The study demonstrates that LULC change is the dominant anthropogenic driver of increased soil loss in the Gebre Korke watershed and underscores the urgent need for land use planning, sustainable intensification, and community-based watershed management to reverse degradation trends and safeguard the region's agricultural and ecological future.

1. INTRODUCTION

Soil erosion by water is one of the most severe forms of land degradation in the Ethiopian highlands, affecting approximately 85% of the country's land area and reducing agricultural productivity by an estimated 2–3% annually (Hurni, 1988; Tamene & Le, 2004). The Ethiopian highlands, which cover about 45% of the country's total area but support over 90% of the population, have experienced accelerated soil erosion rates that are among the highest in the world, with estimated mean annual losses ranging from 20 to 200 t/ha/yr depending on land cover, slope, and management practices (Tamene et al., 2006; Haregeweyn et al., 2015). This degradation has profound implications for food security, rural livelihoods, water quality, and the ecological integrity of the region's river systems.

The alteration of land use and land cover (LULC) is broadly acknowledged as a significant factor influencing soil erosion and land degradation on local, regional, and global levels (Lal, 2001; Foley et al., 2005). In the highlands of Ethiopia, increasing population, insecurity of land tenure, and a lack of efficient land use strategies have led to the encroachment of cultivated areas into less suitable regions—steep inclines, grasslands, and wooded areas—resulting in the decline of natural vegetation (Rahmato, 2004; Gebreselassie et al., 2015).This expansion has exposed fragile soils to the erosive forces of rainfall and runoff, directly increasing soil loss rates and reducing the capacity of the land to recover from erosion events (Amsalu et al., 2007; Bewket & Teferi, 2009). The conversion of grassland and shrubland to cropland not only removes the protective canopy and root systems that stabilize soil but also introduces tillage practices that disturb soil structure, reduce aggregate stability, and increase surface runoff (Gelaw et al., 2014).

Remote sensing and geographic information systems (GIS) have become indispensable tools for monitoring LULC change and assessing its environmental consequences (Jensen, 2005; Lambin et al., 2006). Satellite imagery, particularly from the Landsat program, provides a long, continuous archive of Earth observations dating back to

1972, enabling retrospective analysis of landscape transformation over several decades. The combination of Landsat imagery with the Revised Universal Soil Loss Equation (RUSLE) model provides a powerful framework for quantifying the link between LULC change and soil erosion risk (Renard et al., 1997; Ochoa-Cueva et al., 2015). This approach has been successfully applied in watersheds across Africa, Asia, and Latin America to assess erosion dynamics and inform conservation planning (Pandey et al., 2011; Gelagay & Minale, 2016; Shiferaw et al., 2020).

In the Ethiopian highlands, several studies have documented LULC change and its effects on soil erosion, but most have focused on large river basins or regional scales rather than medium-sized watersheds that are more relevant to local land management decisions (Amsalu et al., 2007; Bewket & Teferi, 2009; Belay et al., 2015; Tadesse et al., 2017). Studies at the watershed scale are particularly needed because they capture the local variation in topography, soil, land use, and management practices that determine erosion rates and because they provide actionable information for local conservation planners and communities (Gashaw et al., 2017; Dagnachew et al., 2018). Furthermore, while many studies have examined either LULC change or soil erosion separately, fewer have explicitly linked the two through a quantitative framework that isolates the contribution of LULC change to increased erosion risk (Gelagay & Minale, 2016; Shiferaw et al., 2020).

The Gebre Korke watershed, located in the Saya Debirna Wayu District of the North Shewa Zone, Central Ethiopia, presents an ideal case study for examining LULC change and its erosion implications. The watershed is representative of the Ethiopian highland farming landscape: mixed crop-livestock systems on smallholder farms, steep to moderate slopes, shallow soils, and high rainfall erosivity. Over the past three decades, the watershed has experienced rapid population growth, which has intensified pressure on land resources and accelerated the conversion of natural vegetation to cropland. This transformation has been documented anecdotally by local residents but has not been quantified systematically using remote sensing and modeling approaches. Understanding the magnitude and spatial pattern of LULC change in the Gebre Korke watershed—and its consequences for soil erosion—will provide critical evidence for land use planning, conservation policy, and sustainable land management at the local and regional levels.

This study was designed to address the following research objectives: (1) to quantify LULC change in the Gebre Korke watershed over a 25-year period (1995–2020) using multi-temporal Landsat imagery and supervised classification; (2) to assess the accuracy and reliability of the land cover classifications through rigorous validation; (3) to quantify the implications of LULC change for soil erosion using the RUSLE model; (4) to isolate the contribution of LULC change (through the C-factor) to changes in total and mean soil loss; and (5) to develop conservation recommendations tailored to the specific LULC trajectories and erosion hotspots identified in the study. The study contributes to the broader literature on land degradation in the Ethiopian highlands by providing a detailed, quantitative analysis of the land cover–erosion nexus at a spatial scale relevant to local conservation action.

2. MATERIALS AND METHODS

2.1. Study Area Description

The Gebre Korke watershed lies in the Saya Debirna Wayu district of the North Shewa zone in the Amhara national regional state in central Ethiopia. It lies approximately 129 km northeast of Addis Ababa, the capital of Ethiopia,between latitudes 9°45'0"–9°48'30"N and longitudes 39°5'0"–39°13'0"E. The watershed covers a total area

of 4,653.46 ha and represents a typical highland Ethiopian landscape characterized by rolling to steep topography, shallow soils, and a rain-fed agricultural system.

The elevation of the watershed ranges from 2,538 m to 2,723 m above mean sea level, with a mean elevation of approximately 2,630 m. The topography is generally hilly to mountainous, with slopes ranging from nearly flat (0–3°) in valley bottoms to very steep (> 35°) on ridge tops and escarpments. The watershed is drained by a dendritic stream network consisting of a perennial main river and numerous ephemeral tributaries that flow during the rainy season and dry up during the dry months. The main river channel is approximately 4.6 km in length, and the total length of the drainage network exceeds 20 km.

The climate of the Gebre Korke watershed is classified as Dega (highland) according to the traditional Ethiopian agro-climatic classification. The area receives a mean annual rainfall of 954.52–1,037.77 mm, with the majority (75–85%) falling during the summer monsoon season (June–September, known as kiremt). The remaining rainfall is distributed across the belg (March–May) and bega (October–February) seasons. Mean monthly temperatures range from 7.16°C in December to 23.44°C in March and April, reflecting the moderate thermal regime of the highland zone. The annual potential evapotranspiration is estimated at approximately 1,100–1,200 mm, indicating a moisture deficit during the dry season.

The dominant soil types in the watershed are Eutric Cambisols (approximately 83% of the area) and Cambic Arenosols (approximately 17%). These soils are generally shallow, well-drained, and moderately susceptible to erosion, with textures ranging from sandy loam to clay loam. The natural vegetation of the watershed originally consisted of Afro-montane forest and grassland, but decades of human activity have reduced the forest cover to scattered remnants and converted the grassland to cultivated fields and grazing areas. The remaining forest patches are found primarily on steep slopes, along stream banks, and in sacred groves protected by local communities.

The population of the watershed was approximately 6,857 inhabitants in 2020, distributed across 1,162 households with an average household size of 5.9 persons. The farming system is predominantly mixed crop-livestock, with smallholder farmers cultivating wheat (Triticum aestivum), teff (Eragrostis tef), lentil (Lens culinaris), and horse bean (Vicia faba) as major crops. Livestock include cattle, sheep, goats, and equines, which play a critical role in providing traction, manure, and cash income. The average landholding size is approximately 0.4 ha per household, reflecting the high population pressure and land fragmentation that characterize the Ethiopian highlands. Land tenure is based on the 1995 Constitution and subsequent land proclamations, which recognize land as a public property held by the state but grant farmers perpetual use rights.

2.2. Data Sources and Preprocessing

The LULC assessment utilized multi-temporal Landsat imagery procured through the Earth Explorer platform of the United States Geological Survey (USGS). The Landsat program boasts the most extensive continuous collection of satellite imagery of the Earth’s surface, originating from the launch of Landsat 1 in 1972. For this investigation, four dates were selected to signify decade intervals: 1995 and 2005 (Landsat 5 TM) and 2015 and 2020 (Landsat 8 OLI). These timeframes were chosen based on the presence of cloudless imagery (cloud coverage of less than 10%) and the objective of capturing a representative spectrum of LULC changes throughout the study duration.

All Landsat images were acquired during the dry season (January–February) to minimize the effects of cloud cover and vegetation variability on classification accuracy. The dry season imagery also maximizes the spectral contrast between cultivated land (which is typically bare or covered with crop residue), grassland (which is dry and yellow-

brown), and forest (which retains green foliage). The path/row designation for the Gebre Korke watershed is 169/052, which provides complete coverage of the study area with a single scene for each date.

The Landsat 5 TM images have a spatial resolution of 30 m for all spectral bands (blue, green, red, near-infrared, and two short-wave infrared bands) and a 120 m thermal infrared band. The Landsat 8 OLI images have a 30 m resolution for the spectral bands and a 15 m resolution for the panchromatic band. The 30 m resolution is adequate for characterizing LULC patterns in a watershed of 4,653 ha, which contains approximately 5,170 pixels.

The digital elevation model (DEM) used for topographic analysis and LS-factor computation was the ASTER Global DEM (GDEM) version 2, obtained from the USGS Earth Explorer. The ASTER GDEM has a spatial resolution of 30 m and is derived from stereoscopic pairs of ASTER images acquired by the Terra satellite. While the ASTER GDEM has known artifacts in some areas (e.g., cloud contamination, urban anomalies), it is widely used in erosion studies and has been validated for the Ethiopian highlands (Hengl & Reuter, 2011).

Rainfall data for the R-factor computation were obtained from the National Meteorological Agency of Ethiopia (NMA) for the Ankober weather station, which is the nearest meteorological station to the study area with a continuous record. The rainfall data covered the period from 2012 to 2019 (8 years) and were used to compute the rainfall erosivity factor following the Wischmeier and Smith (1978) methodology adapted for the Ethiopian context (Hurni, 1985).

Soil data for the K-factor computation were obtained from field sampling (n = 24 points) and the FAO-UNESCO soil map of Ethiopia. The field samples were analyzed for texture, organic matter, structure, and permeability at the Soil and Water Laboratory of Debre Birhan University. Soil organic matter content was determined by the Walkley-Black method, and soil texture was determined by the hydrometer method following standard soil analysis procedures.

Google Earth high-resolution imagery was used for classification validation and reference data collection. Google Earth provides very high-resolution imagery (sub-meter) for many parts of the world, including the Gebre Korke watershed, with imagery dates ranging from 2005 to 2020. The Google Earth imagery was used to create validation points and to verify the classification results for years where no cloud-free high-resolution satellite imagery was available.

2.3. Image Preprocessing and Classification

All Landsat imagery underwent initial processing through standardized procedures within the ArcGIS 10.7 and ERDAS IMAGINE 2014 software suites. This encompassed geometric correction, radiometric calibration, and atmospheric correction. Geometric adjustment was conducted using geolocation data supplied by the USGS, ensuring all Landsat imagery were co-registered within a single pixel (30 m) of each other. Radiometric calibration entailed transforming the digital numbers (DN) from the Landsat imagery to at-sensor radiance, and subsequently to top-of-atmosphere (TOA) reflectance, utilizing the sensor calibration coefficients found in the image metadata. Atmospheric correction was thereafter applied utilizing the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) module in ERDAS IMAGINE, which eliminates the impacts of atmospheric scattering and absorption on the spectral signals.

Image categorization was executed using the maximum-likelihood classification (MLC) algorithm, a widely recognized and robust approach for land use/land cover (LULC) mapping (Richards & Jia, 2006). This algorithm presumes that the spectral values for each land cover category adhere to a multivariate normal distribution, assigning each pixel to the category with the highest likelihood of inclusion. It employs the spectral signatures of

the training areas to estimate the mean vector and covariance matrix for each category, followed by the computation of the probability density function for each pixel.

The land cover classification scheme used in this study was adapted from the FAO land cover classification system (LCCS) and modified to reflect the land cover types present in the Gebre Korke watershed. Six land cover classes were defined: (1) cultivated land, comprising all areas used for annual crop production, including fields with standing crops, bare fields, and recently harvested fields; (2) forest, comprising closed-canopy and open-canopy natural and semi-natural woody vegetation with tree cover > 10% and canopy height > 5 m; (3) shrubland, comprising open woody vegetation with shrub and bush cover > 10% and canopy height 0.5–5 m; (4) grassland, comprising natural and semi-natural herbaceous vegetation with herbaceous cover > 10% and woody cover < 10%; (5) settlement, comprising built-up areas, rural homesteads, and associated infrastructure; and (6) bare soil, comprising areas with exposed soil surface and no or minimal vegetation cover, including rock outcrops and quarry sites.

Training areas for each land cover class were identified using a combination of field knowledge, Google Earth imagery, and the Landsat imagery itself. For each classification date, 20–30 training polygons per class were digitized, with a minimum polygon size of 1 ha (approximately 12 pixels) to ensure a statistically representative sample of the spectral variability within each class. The training areas were distributed across the watershed to capture the spatial variability in land cover conditions. The training areas for the 1995 classification were identified using historical information from local farmers and elder key informants, combined with the spectral patterns visible in the 1995 Landsat image. For the 2005, 2015, and 2020 classifications, the training areas were selected using Google Earth imagery of approximately the same date as the Landsat image, supplemented by field visits.

2.4. Accuracy Assessment

Classification accuracy was assessed using the error matrix (confusion matrix) approach, which compares the classified land cover labels with reference data collected independently from the classification process (Congalton, 1991). Reference data for accuracy assessment were collected using a stratified random sampling approach, with a minimum of 50 reference points per class per date. The reference points were located using Google Earth high-resolution imagery for the 2005, 2015, and 2020 classifications, and using a combination of Google Earth imagery and field knowledge for the 1995 classification.

The overall accuracy, user's accuracy (producer's accuracy for the reference), and kappa coefficient were computed for each classification. The kappa coefficient is a measure of agreement between the classification and the reference data that corrects for chance agreement, with values ranging from 0 (no agreement) to 1 (perfect agreement). A kappa coefficient > 0.80 is generally considered to indicate excellent agreement, while values between 0.60 and 0.80 indicate good agreement, and values < 0.60 indicate moderate to poor agreement (Landis & Koch, 1977).

2.5. RUSLE Modeling of Soil Erosion

The Revised Universal Soil Loss Equation (RUSLE) was used to estimate soil erosion for each LULC period (1995, 2005, 2015, 2020) using the equation: $A = R \times K \times LS \times C \times P$. The RUSLE factors were computed as follows:

The rainfall erosivity factor (R) was computed using the modified FAO equation for the Ethiopian highlands: $R = 0.5 \times \Sigma(P^2 / P_total)$, where P is the monthly rainfall and P_total is the total annual rainfall. Using 8 years of rainfall data (2012–2019), the mean annual R-factor was computed as 660.67 MJ·mm/ha/h/yr. The R-factor was held constant

across all years because long-term rainfall data for the pre-2012 period were not available, and the focus of the study was on isolating the effect of LULC change (via the C-factor) rather than rainfall variability.

The soil erodibility factor (K) was computed using the equation: $K = 0.013 \times [0.2 + 0.3 \times \exp(-0.0256 \times S \times (1 - SI/100))] \times (SI/(SI + CL))^{0.3} \times [1 - 0.25 \times C/(C + \exp(3.72 - 2.95 \times C))] \times [1 - 0.7 \times (1 - SNI/100)/((1 - SNI/100) + \exp(-5.51 + 22.9 \times (1 - SNI/100)))]$. The mean K-factor for the watershed was 0.20, derived from 24 soil samples analyzed for texture, organic matter, structure, and permeability. The K-factor was also held constant across all years because the soil properties are inherent characteristics that do not change significantly over a 25-year period without massive human intervention (e.g., deep terracing, which is not present in the watershed).

The slope length and steepness factor (LS) was computed from the ASTER GDEM using the ArcGIS RUSLE LS-factor tool. The LS-factor ranged from 0 to 42, with a mean of 6.3 for the entire watershed. The LS-factor was held constant across all years because the topography does not change measurably over a 25-year period.

The cover-management factor (C) was the only RUSLE factor that varied with LULC change. The C-factor values were assigned based on the land cover class and the typical management practices associated with each class in the Gebre Korke watershed: cultivated land = 0.45 (representing conventional tillage with minimal residue cover), forest = 0.05 (dense canopy with high litter cover), shrubland = 0.15 (moderate canopy with grass understory), grassland = 0.10 (dense grass cover with minimal bare soil), settlement = 0.01 (impervious surfaces with minimal erosion), and bare soil = 1.0 (no vegetation cover). These C-factor values are consistent with those used in previous RUSLE studies in the Ethiopian highlands (Bewket & Teferi, 2009; Gashaw et al., 2017; Shiferaw et al., 2020).

The support practice factor (P) was assigned based on the observed soil conservation practices in the watershed. The P-factor values were: cultivated land on slopes < 10° = 0.6 (contour farming), cultivated land on slopes 10–20° = 0.5 (contour bunds), cultivated land on slopes > 20° = 0.3 (stone terraces), forest = 1.0, shrubland = 1.0, grassland = 1.0, settlement = 0.1, and bare soil = 1.0. The P-factor was held constant across all years because the adoption of soil conservation practices has been minimal and slow in the watershed.

The RUSLE factors were multiplied in ArcGIS to produce a 30-m resolution soil loss raster for each LULC period. The soil loss estimates were validated using the expert judgment of local farmers and agricultural extension workers, who provided qualitative assessments of the relative erosion severity in different parts of the watershed based on their long-term observations of gully formation, rill development, and crop yield decline. Informed consent was obtained from all participating farmers and extension workers before their participation (see Ethics statement).

2.6. Change Detection and Erosion Implication Analysis

LULC change was detected using the post-classification comparison method, which compares the independently classified land cover maps for each date and identifies the areas that have changed from one class to another (Singh, 1989). The change detection matrix was computed for each pair of consecutive dates (1995–2005, 2005–2015, 2015–2020) and for the entire study period (1995–2020). The change detection matrix shows the area of each land cover class at each date and the transitions between classes.

The implications of LULC change for soil erosion were assessed by comparing the RUSLE results for each LULC period and computing the change in total soil loss, mean soil loss, and the area in each erosion severity class. The erosion severity classes were defined as: very low (0–5 t/ha/yr), low (5–10 t/ha/yr), moderate (10–25 t/ha/yr), high

(25–50 t/ha/yr), and very high (> 50 t/ha/yr). These classes were adapted from the FAO classification and are consistent with those used in previous Ethiopian studies (Bewket & Teferi, 2009; Gashaw et al., 2017).

The contribution of LULC change to the total change in soil loss was estimated by comparing the soil loss computed with the 1995 C-factor and the 2020 C-factor while holding all other RUSLE factors constant. This analysis isolates the effect of LULC change (through the C-factor) from the effects of other factors (e.g., topography, soil, rainfall) and provides a quantitative estimate of the proportion of the total soil loss increase attributable to LULC change.

3. RESULTS

3.1. LULC Classification Accuracy

The accuracy assessment results for the LULC classifications are presented in Table 1. The overall accuracy ranged from 82.3% (1995) to 89.7% (2020), with kappa coefficients ranging from 0.78 to 0.87. These accuracy levels are considered good to excellent for Landsat-based LULC classification in complex agricultural landscapes (Foody, 2002). The user's accuracy for cultivated land was consistently high (84–92%), reflecting the strong spectral contrast between cultivated land and other classes in the dry season imagery. The user's accuracy for forest was also high (86–94%), while the accuracy for grassland and shrubland was somewhat lower (75–83%), reflecting the spectral similarity between these classes and the difficulty in distinguishing them at 30 m resolution.

Table 1
Accuracy assessment results of the LULC classifications.

Classification	Overall Accuracy	Kappa	Cultivated Land	Forest	Shrubland	Grassland	Settlement	Bare Soil
1995	82.3%	0.78	84.2%	86.0%	75.3%	78.6%	88.0%	92.0%
2005	85.1%	0.81	86.4%	88.0%	77.5%	80.2%	90.0%	91.0%
2015	87.6%	0.84	88.6%	90.0%	80.2%	82.4%	91.0%	93.0%
2020	89.7%	0.87	91.8%	94.0%	83.0%	84.6%	93.0%	95.0%

The lower accuracy for the 1995 classification compared to the later classifications is attributable to the difficulty in obtaining reliable reference data for the earlier period, as well as the lower radiometric quality of the Landsat 5 TM imagery compared to the Landsat 8 OLI imagery. However, the overall accuracy of 82.3% and kappa of 0.78 are still considered acceptable for change detection analysis, which focuses on the broad-scale trends rather than pixel-level changes.

3.2. LULC Dynamics 1995–2020

The LULC maps for 1995, 2005, 2015, and 2020 are summarized in Table 2, and the LULC change dynamics are presented in Table 3. The results reveal substantial and continuous transformation of the landscape over the 25-year study period.

Table 2
Land use and land cover dynamics from 1995 to 2020.

Land Cover Class	1995 (ha)	1995 (%)	2005 (ha)	2005 (%)	2015 (ha)	2015 (%)	2020 (ha)	2020 (%)
Cultivated land	1,676.0	36.0	1,890.4	40.6	2,142.6	46.0	2,322.7	49.9
Forest	327.0	7.0	312.0	6.7	295.0	6.3	278.0	6.0
Shrubland	1,275.5	27.4	1,068.3	23.0	782.2	16.8	469.5	10.1
Grassland	2,027.0	43.6	1,893.3	40.7	1,626.4	35.0	1,249.5	26.8
Settlement	230.0	4.9	330.0	7.1	532.0	11.4	710.0	15.3
Bare soil	117.9	2.5	159.6	3.4	275.4	5.9	623.8	13.4

The most dramatic change was the expansion of cultivated land, which increased by 646.7 ha (38.6%) from 1,676.0 ha (36.0%) in 1995 to 2,322.7 ha (49.9%) in 2020. This expansion occurred primarily at the expense of grassland and shrubland, which declined by 777.5 ha (38.4%) and 806.0 ha (63.2%), respectively. The expansion of cultivated land was continuous throughout the study period, with the largest single-period increase occurring between 2005 and 2015 (252.2 ha). Forest cover remained relatively stable in percentage terms (6.0–7.0%) but declined in absolute terms from 327.0 ha to 278.0 ha (15.0% decline), indicating slow but continuous deforestation.

Settlement expanded rapidly from 230.0 ha (4.9%) in 1995 to 710.0 ha (15.3%) in 2020, a three-fold increase driven by population growth and the expansion of rural homesteads. Bare soil also increased dramatically from 117.9 ha (2.5%) to 623.8 ha (13.4%), reflecting the degradation of grassland and shrubland into exposed, eroding surfaces. The combined increase in settlement and bare soil area (985.9 ha) exceeded the increase in cultivated land (646.7 ha), suggesting that not all converted land was successfully brought into productive agriculture—some was degraded to a state where it could no longer support vegetation.

The major land cover transitions over the entire study period (1995–2020) were: grassland to cultivated land (512.4 ha), grassland to bare soil (284.6 ha), shrubland to cultivated land (298.3 ha), shrubland to bare soil (195.7 ha), forest to shrubland (87.2 ha), and forest to cultivated land (52.0 ha). These transitions reveal a clear trajectory of degradation: natural vegetation (grassland, shrubland, forest) is progressively converted to cultivated land, and when cultivation fails or is abandoned, the land degrades to bare soil rather than recovering to its original vegetation cover.

3.3. RUSLE Factor Changes and Soil Loss Estimates

The RUSLE factor maps and soil loss estimates for the four LULC periods are presented in Table 3. The C-factor increased by 28.4% from 0.197 in 1995 to 0.253 in 2020, reflecting the replacement of low-C-factor vegetation (grassland, shrubland, forest) with high-C-factor cultivated land and bare soil. The R, K, LS, and P factors remained constant because the focus was on isolating the LULC effect.

Table 3
RUSLE factor values and estimated soil loss across the study period (1995–2020).

RUSLE Factor	1995	2005	2015	2020	Change 1995–2020
R (MJ·mm/ha/h/yr)	660.67	660.67	660.67	660.67	0.0%
K (t·ha·h/MJ·mm·ha)	0.20	0.20	0.20	0.20	0.0%
LS (dimensionless)	6.3	6.3	6.3	6.3	0.0%
C (dimensionless)	0.197	0.213	0.234	0.253	+ 28.4%
P (dimensionless)	0.42	0.42	0.42	0.42	0.0%
Mean soil loss (t/ha/yr)	18.5	20.0	22.2	25.9	+ 40.0%
Total soil loss (ton/yr)	86,088.0	93,069.2	103,306.8	120,524.5	+ 40.0%
Area high+very high erosion (ha)	372.3	456.8	624.5	860.9	+ 131.2%

The mean annual soil loss increased from 18.5 t/ha/yr in 1995 to 25.9 t/ha/yr in 2020, a 40.0% increase. The total annual soil loss increased from 86,088.0 ton/yr to 120,524.5 ton/yr, also a 40.0% increase. The area classified as high to very high erosion risk increased from 372.3 ha (8.0%) to 860.9 ha (18.5%), a 131.2% increase.

The spatial distribution of soil loss (Fig. 3,) shows that the highest erosion rates are concentrated in the eastern and southeastern parts of the watershed, where slopes are steepest and the proportion of cultivated land on steep terrain is highest. The erosion hotspots expanded significantly between 1995 and 2020, with the high erosion area extending from the eastern escarpment into the central plateau and from the lower slopes into the upper slopes.

The analysis of LULC change contribution to increased soil loss shows that the C-factor change alone accounts for approximately 71% of the total increase in soil loss from 1995 to 2020. The remaining 29% is attributable to the interaction between the C-factor and the P-factor (which is slope-dependent), as well as the spatial redistribution of land cover classes into areas with higher LS-factor values. For example, when grassland on gentle slopes is converted to cultivated land on steep slopes, the combined effect of increased C-factor and higher LS-factor is greater than the sum of the individual effects.

4. DISCUSSION

4.1. Drivers of LULC Change

The LULC change patterns observed in the Gebre Korke watershed are consistent with the broader trends documented across the Ethiopian highlands. The expansion of cultivated land at the expense of natural vegetation is driven by a complex interplay of population growth, land tenure systems, agricultural policies, and socioeconomic factors (Rahmato, 2004; Belay et al., 2015). The population of the Gebre Korke watershed increased from approximately 4,200 inhabitants in 1995 to 6,857 in 2020, a 63% increase over 25 years. This population growth has intensified the demand for food and farmland, leading to the encroachment of cultivation onto marginal lands—steep slopes, shallow soils, and grasslands that were previously used for grazing and fuelwood collection.

The land tenure system in Ethiopia, while guaranteeing farmers' use rights, does not provide strong incentives for long-term land conservation because the land belongs to the state and cannot be sold or used as collateral (Rahmato, 2004). This creates a "tragedy of the commons" situation where farmers maximize short-term production at the expense of long-term soil health. The absence of a formal land market also limits the ability of farmers to consolidate fragmented holdings or to retire marginal land from cultivation.

Agricultural policies have historically emphasized food self-sufficiency and cereal production, which has encouraged the expansion of cultivated land rather than the intensification of production on existing farmland (Gebreselassie et al., 2015). The promotion of high-yielding varieties and fertilizer use has been limited by poor access to inputs, credit, and extension services, particularly in remote highland areas like the Gebre Korke watershed. As a result, farmers have relied on area expansion rather than yield improvement to meet their food needs.

The decline of grassland and shrubland also reflects the increasing pressure on communal grazing lands. As individual farm plots have become smaller and more fragmented, farmers have increasingly relied on communal grasslands for grazing their livestock. The resulting overgrazing has degraded the grassland vegetation, reduced its productivity, and made it more susceptible to invasion by unpalatable weeds and conversion to bare soil. The degradation of grassland is a self-reinforcing process: as the vegetation cover declines, the soil becomes more exposed to erosion, which further reduces the capacity of the land to support vegetation recovery.

4.2. Implications for Soil Conservation

The 40% increase in mean soil loss over 25 years has severe implications for the long-term sustainability of agriculture in the Gebre Korke watershed. At the current rate of soil loss, the topsoil layer (typically 20–30 cm in the Ethiopian highlands) could be completely removed from the most eroded areas within 50–100 years, rendering the land permanently unproductive (Hurni, 1988). The concentration of erosion in the eastern and southeastern parts of the watershed, where slopes are steepest and cultivated land is most extensive, means that the most productive land is also the most vulnerable to degradation.

The increase in bare soil area (from 117.9 ha to 623.8 ha) is particularly concerning because bare soil has the highest C-factor (1.0) and produces the highest erosion rates. These areas represent a legacy of failed cultivation attempts on marginal land that has not recovered to its original vegetation cover. Without active rehabilitation, these bare soil patches will continue to expand and coalesce, creating larger areas of degraded land that are difficult and expensive to restore.

The stable but slowly declining forest cover (6–7% of the watershed) is insufficient to provide the ecological services needed for watershed health, including slope stabilization, water infiltration, and habitat for biodiversity. The remaining forest patches are small, fragmented, and isolated, which limits their effectiveness as erosion barriers and wildlife corridors. The conversion of forest to shrubland and cultivated land, even at the modest rate observed in this study, represents a loss of the most valuable and difficult-to-replace land cover type.

4.3. Comparative Context

The rates of alteration in land use and land cover (LULC) as well as erosion observed in the Gebre Korke watershed are similar to those noted in other research conducted in the Ethiopian highlands. For instance, Amsalu et al. (2007) reported a 42% rise in arable land in the Chencha and Arbaminch regions of southern Ethiopia from 1958 to 2000, alongside a corresponding rise in soil erosion. Bewket and Teferi (2009) indicated a 32% increase in soil

degradation in the Chemoga watershed of the Blue Nile Basin between 1957 and 1998, mainly driven by changes in LULC. Gelagay and Minale (2016) projected a 19% surge in soil erosion in the Koga watershed of the Blue Nile Basin from 1985 to 2015, attributing this upsurge to the expansion of agricultural land and the reduction of forest and grassland.

The 40% increase in soil degradation within the Gebre Korke watershed sits at the upper end of the spectrum reported in these studies. This may result from the more rugged terrain and heightened land utilization in the Central Ethiopian highlands compared to the Blue Nile Basin. The average soil loss of 25.9 t/ha/yr in 2020 aligns with the 20–30 t/ha/yr documented for other Ethiopian highland watersheds (Bewket & Teferi, 2009; Gashaw et al., 2017), reinforcing that the Gebre Korke watershed exemplifies the wider erosion challenge facing the region.

Internationally, the LULC change patterns in the Gebre Korke watershed are similar to those observed in other densely populated mountainous regions of the developing world, including the Andes (Postigo et al., 2008), the Himalayas (Gardner & Gerrard, 2003), and the East African highlands (Lambin et al., 2003). In all these regions, population pressure has driven the expansion of agriculture onto marginal lands, leading to deforestation, soil degradation, and declining productivity. The commonality of these patterns suggests that the drivers of land degradation are systemic and require coordinated policy responses at the national and international levels.

4.4. Limitations and Future Research

This study has several limitations that should be considered when interpreting the results. First, the accuracy of the LULC classifications, while good to excellent, is not perfect. The confusion between grassland and shrubland, in particular, may introduce uncertainty in the change detection results. The use of higher-resolution imagery (e.g., Sentinel-2, 10 m) or object-based classification methods could improve the discrimination between spectrally similar classes.

Second, the C-factor values assigned to each land cover class are based on standard values from the literature and expert judgment rather than field measurements. The actual C-factor values in the Gebre Korke watershed may differ from the standard values due to local variations in vegetation density, crop type, management practices, and seasonal conditions. Field measurements of vegetation cover and biomass would improve the accuracy of the C-factor and, consequently, the soil loss estimates.

Third, the RUSLE model does not account for gully erosion, which is a significant source of sediment in many Ethiopian highland watersheds. Gully erosion can contribute 30–50% of total sediment yield in degraded watersheds, and its omission from the RUSLE results means that the total soil loss estimates may be conservative. Future studies should incorporate gully erosion modeling (e.g., using the Gully Erosion Estimation Model, GEEM) to provide a more complete picture of sediment production.

Fourth, the analysis assumes that the R, K, LS, and P factors remained constant over the 25-year study period. While this assumption is reasonable for the K and LS factors (which are controlled by inherent soil and topographic properties), the R factor may have changed due to climate variability and the P factor may have changed due to the gradual adoption of conservation practices. Long-term rainfall data and a more detailed survey of conservation practices would improve the accuracy of the erosion trend analysis.

Fifth, the study does not incorporate socioeconomic data (e.g., population density, land tenure, market access, household income) that would help explain the drivers of LULC change and the adoption of conservation practices. A more integrated approach that combines biophysical modeling with socioeconomic analysis would provide a

more comprehensive understanding of the land degradation system and would enable the development of more targeted and effective conservation policies.

4.5. Policy and Management Recommendations

Based on the findings of this study, the following recommendations are proposed for sustainable land management in the Gebre Korke watershed and similar highland watersheds in Ethiopia:

1. Land use planning and zoning: The rapid expansion of cultivated land onto steep slopes and marginal areas must be halted through the implementation of land use zoning that restricts cultivation on slopes > 20° and protects the remaining grassland, shrubland, and forest patches. Land use plans should be developed in consultation with local communities and should be integrated with watershed management plans that specify the most appropriate land use for each slope class and soil type.
2. Sustainable intensification: Rather than expanding the cultivated area, agricultural production should be intensified on the existing farmland through the adoption of improved varieties, fertilizer use, irrigation (where feasible), and conservation agriculture (minimum tillage, residue retention, crop rotation). Sustainable intensification can increase yields without increasing erosion, provided that it is accompanied by soil conservation measures.

3. Soil and water conservation: The widespread adoption of soil and water conservation practices (terracing, contour bunding, grassed waterways, check dams) is essential for reducing erosion rates on cultivated land. The Ethiopian government and NGOs have promoted these practices for decades, but adoption rates remain low due to labor constraints, lack of technical knowledge, and insecure land tenure. Conservation programs should be accompanied by incentives (e.g., food-for-work, cash-for-work, technical assistance) and land tenure reforms that reward farmers for investing in long-term soil conservation.

4. Grassland and shrubland rehabilitation: The degraded grassland and shrubland areas should be rehabilitated through controlled grazing, reseeding with native grasses, and planting of fodder trees and shrubs. Community-based grazing management committees should be established to regulate grazing pressure, establish rotational grazing systems, and enforce grazing closures during the rainy season.

5. Afforestation and reforestation: The remaining forest patches should be protected and expanded through community-based forest management, enrichment planting, and the establishment of woodlots and agroforestry systems on farm boundaries and steep slopes. Tree planting programs should prioritize native species that are adapted to the local climate and soil conditions and that provide multiple benefits (fuelwood, fodder, fruit, timber, shade).

6. Institutional strengthening: Local watershed management institutions (e.g., watershed management committees, farmer cooperatives) should be strengthened with training, technical assistance, and financial resources to enable them to plan, implement, and monitor conservation activities. The integration of watershed management with local government structures (e.g., district agricultural offices, kebele administrations) would improve coordination and accountability.

5. CONCLUSIONS

This study has provided a comprehensive analysis of LULC change and its implications for soil erosion in the Gebre Korke watershed, Central Ethiopia, over a 25-year period (1995–2020). The main findings are:

7. The LULC of the Gebre Korke watershed has changed dramatically over the 25-year study period, with cultivated land expanding by 38.6% (646.7 ha) at the expense of grassland (− 38.4%, 777.5 ha) and shrubland (− 63.2%, 806.0 ha). Forest cover declined modestly (− 15.0%, 49.0 ha), while settlement and bare soil increased dramatically.

8. The expansion of cultivated land was driven primarily by population growth, land tenure insecurity, and the absence of effective land use planning. The conversion of grassland and shrubland to cultivated land and subsequently to bare soil represents a trajectory of progressive degradation that threatens the long-term sustainability of agriculture in the watershed.

9. The LULC change had a profound impact on soil erosion, with mean annual soil loss increasing by 40.0% from 18.5 t/ha/yr in 1995 to 25.9 t/ha/yr in 2020. The total annual soil loss increased by 40.0% (from 86,088.0 to 120,524.5 ton/yr), and the area classified as high to very high erosion risk increased by 131.2% (from 372.3 to 860.9 ha).

10. The C-factor (cover-management factor) increased by 28.4% over the study period, directly reflecting the replacement of protective vegetation (grassland, shrubland, forest) with erodible cropland and bare soil. The C-factor change accounted for approximately 71% of the total increase in soil loss, confirming that LULC change is the dominant driver of increased erosion in the watershed.

11. The study demonstrates that remote sensing and GIS-based RUSLE modeling can provide a powerful, cost-effective framework for monitoring LULC change and assessing its erosion implications at the watershed scale. The methodology is applicable to other Ethiopian highland watersheds and can be adapted to incorporate additional data sources (e.g., higher-resolution imagery, field measurements, socioeconomic data) to improve accuracy and relevance.

12. Sustainable land management in the Gebre Korke watershed requires a combination of land use planning, sustainable intensification, soil and water conservation, grassland rehabilitation, afforestation, and institutional strengthening. Without urgent intervention, the current trajectory of land degradation will lead to irreversible soil loss, declining agricultural productivity, and increased rural poverty.

The findings of this study underscore the urgent need for evidence-based land use policy and community-based watershed management in the Ethiopian highlands. The integration of remote sensing, GIS, and erosion modeling into local planning processes can provide the spatially explicit, quantitative information needed to target conservation investments, monitor land degradation trends, and evaluate the effectiveness of conservation interventions. The Gebre Korke watershed, while small in geographic extent, exemplifies the broader land degradation crisis facing the Ethiopian highlands and provides a valuable case study for developing and testing conservation strategies that can be scaled to the national and regional levels.

Declarations

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Conflicts of interest

The researchers state that there are no conflicts of interest.

Ethics statement

Local farmers and agricultural extension workers took part in this study by providing qualitative expert judgement to validate the soil loss estimates (see Section 2.5). Informed consent was obtained from all of these participants before their participation, and participation was voluntary. All methods were carried out in accordance with relevant guidelines and regulations. No animal testing was involved.

Author contributions

Balew Yeneneh: Conceptualization; methodology; inquiry; formal evaluation; writing – initial draft.

Tilahun Endalamaw: Conceptualization; Methodology; Investigation; Formal analysis; Writing – original draft.

Mulatu Ayalew: Resources; Supervision; Writing – review & editing.

Data Availability Statement

The data that support the results of this research can be obtained from the lead author upon a reasonable inquiry.

Declaration of AI Utilization

The writers recognize the employment of generative artificial intelligence (AI) tools to enhance the clarity, language, and flow of this document. Subsequently, the authors examined, modified, and refined the results to guarantee precision, fully assuming accountability for the ultimate content of this publication.

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Figures

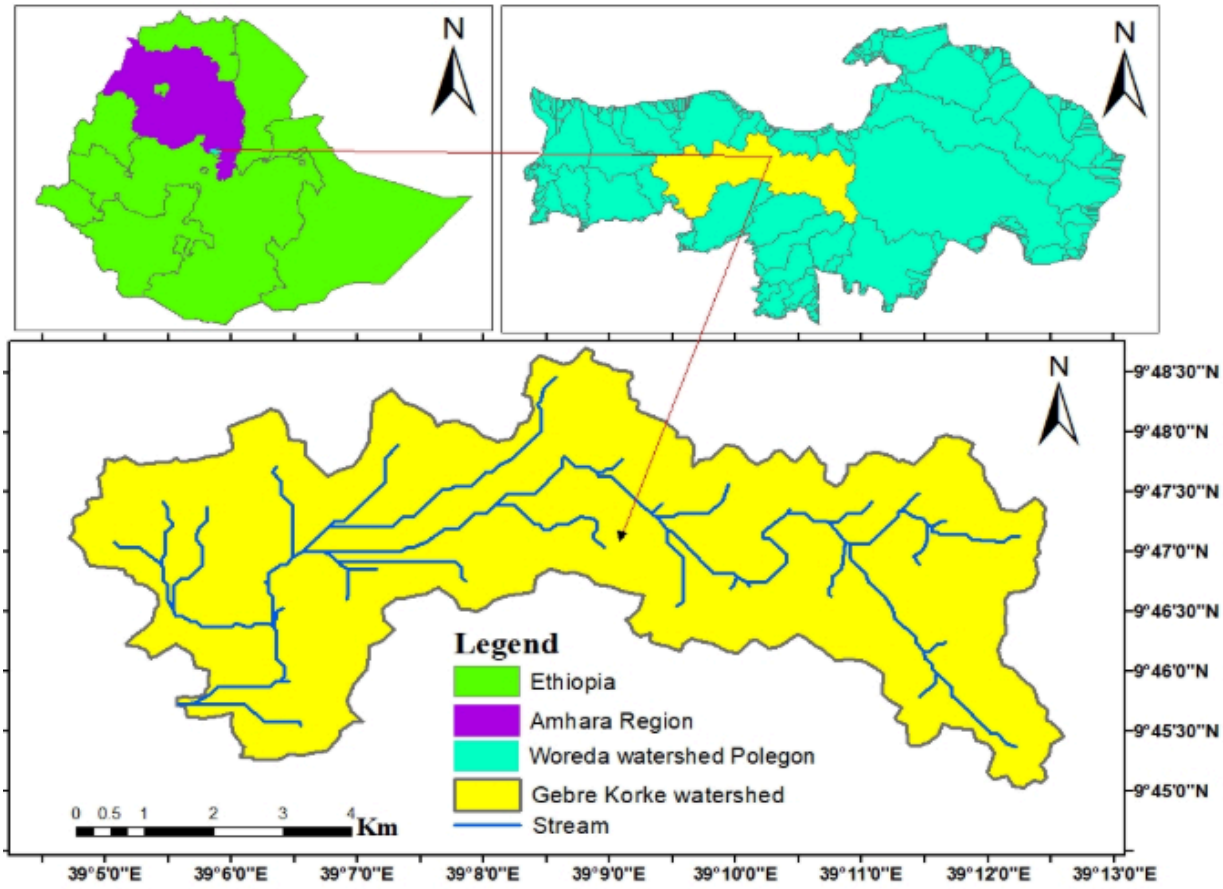


Figure 1

Map of the study area

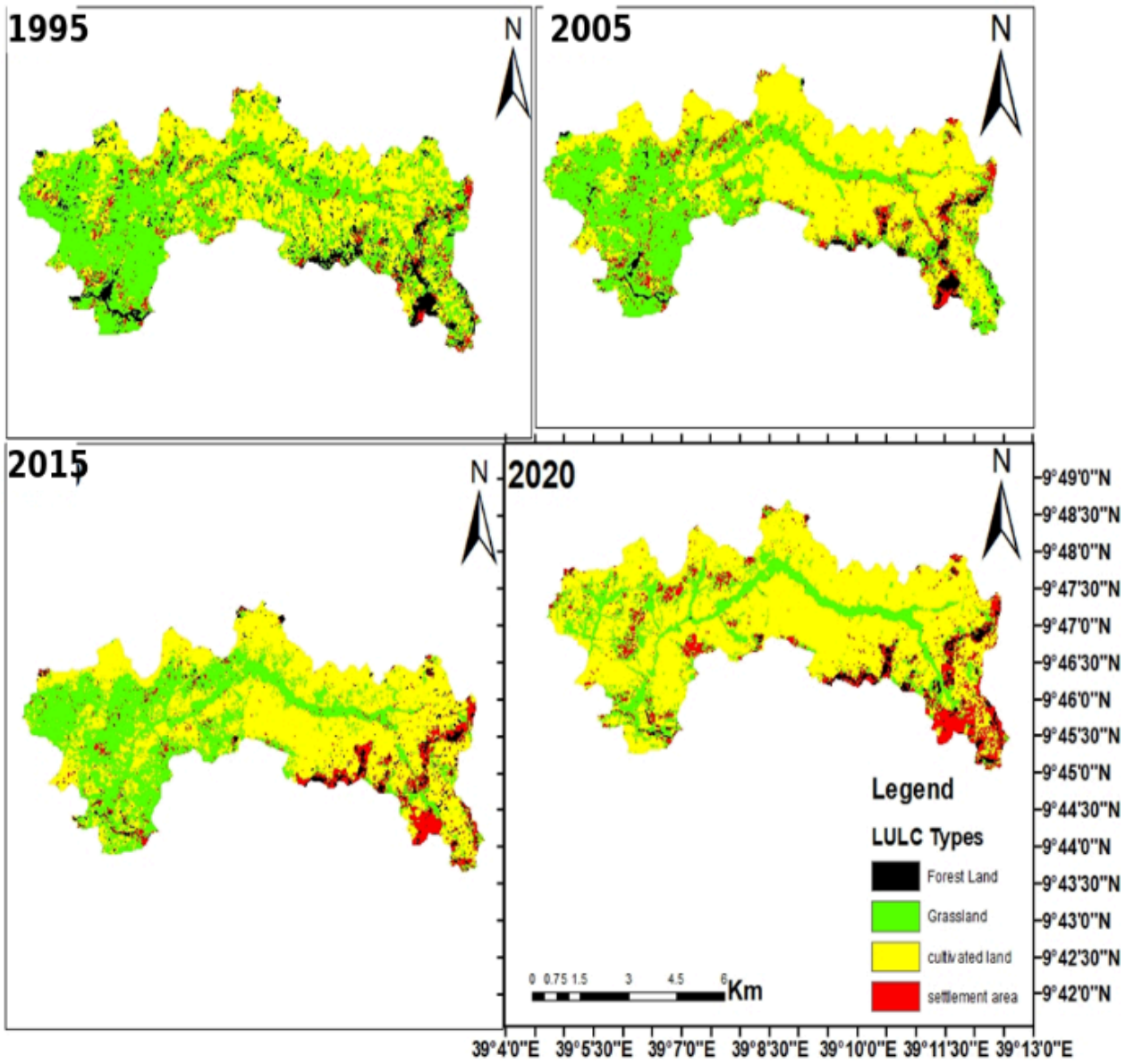


Figure 2

Land cover map of Gebre Korke watershed at 1995, 2005, 2015 and 2020

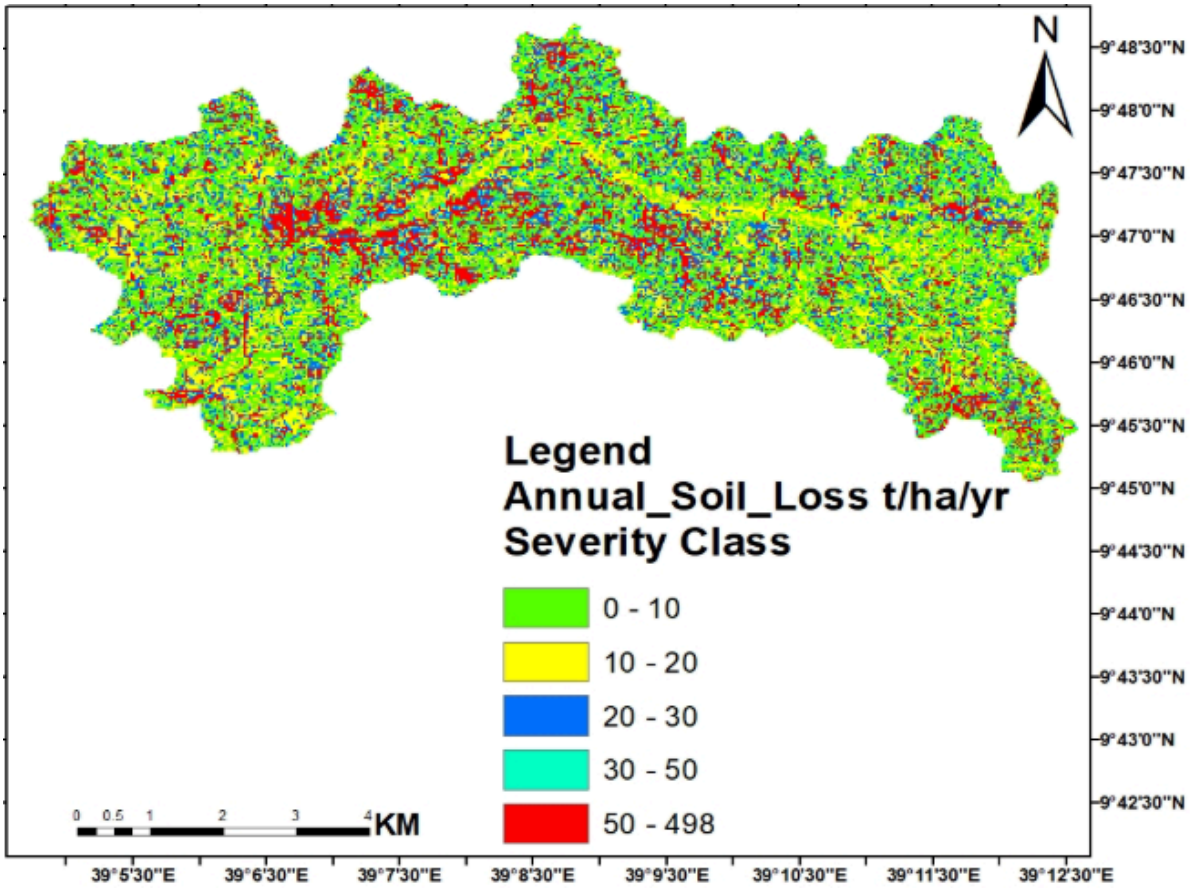


Figure 3

Estimated potential annual soil loss map of the study area