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Impact of land-use and land-cover change on soil erosion using the RUSLE model and the geographic information system: a case of Temeji watershed, Western Ethiopia

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ABSTRACT

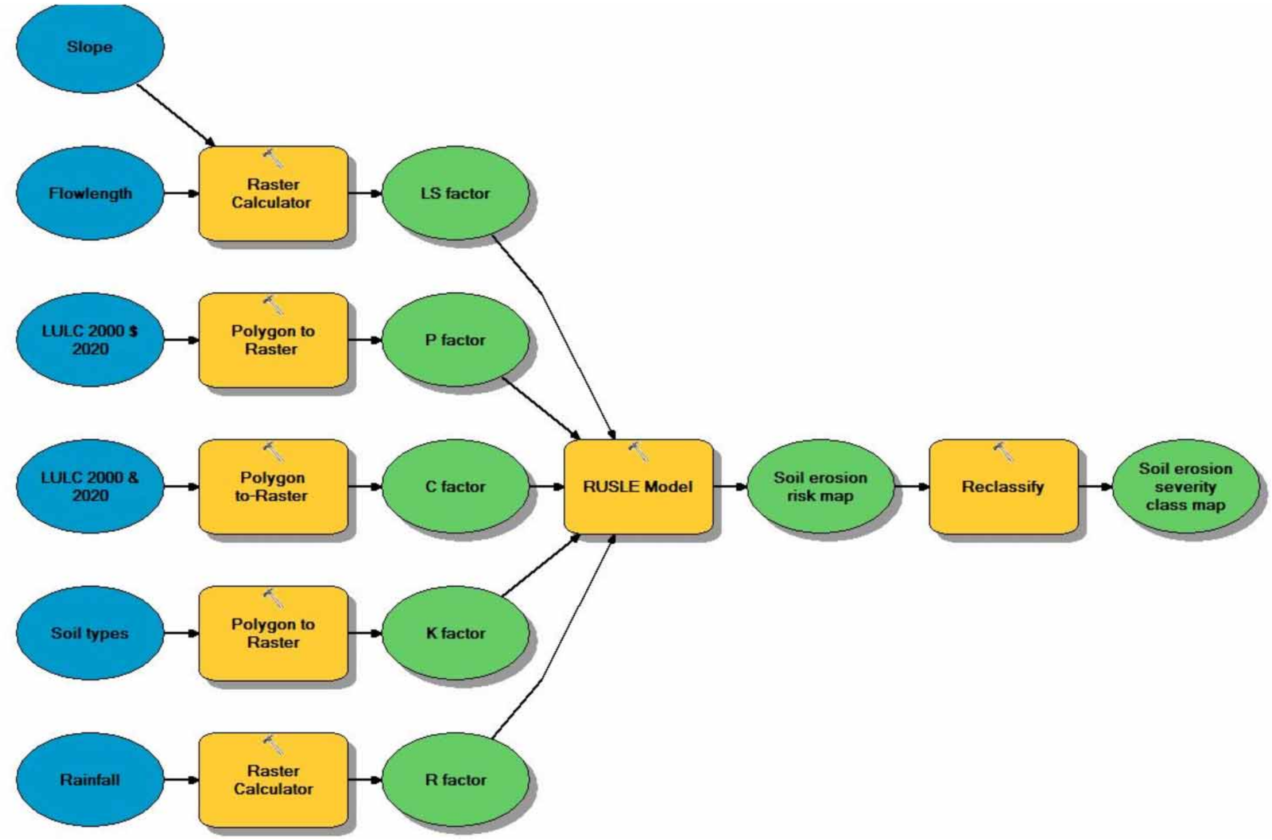
The impact of land-use land-cover (LULC) change on soil resources is getting global attention. Soil erosion is one of the critical environmental problems worldwide with high severity in developing countries. This study integrates the Revised Universal Soil Loss Equation model with a geographic information system to estimate the impacts of LULC conversion on the mean annual soil loss in the Temeji watershed. In this study, LULC change of Temeji watershed was assessed from 2000 to 2020 by using 2000 Landsat ETM+ and 2020 Landsat OLI/TIRS images and classified using supervised maximum likelihood classification algorithms. Results indicate that the majority of the LULC in the study area is vulnerable to soil erosion. High soil loss is observed when grassland and forest land were converted into cultivated land with a mean soil loss of 88.8 and 86.9 t/ha/year in 2020. Results revealed that about 6,608.5 ha (42.8%) and 8,391.8 ha (54.4%) were categorized under severe classes in 2000 and 2020, respectively. Accordingly, the soil loss severity class is directly correlated with the over-exploitation of forest resources and grasslands for agricultural purposes. These results can be useful for advocacy to enhance local people and stakeholder's participation toward soil and water conservation practices.

Key words: GIS, LULC, remote sensing, RUSLE, soil loss

HIGHLIGHTS

- The integration of the Revised Universal Soil Loss Equation model and geographic information system is highly applicable to estimate the impacts of LULC conversion on the mean annual soil loss.
- LULC and topography are the main key factors that influence soil erosion in the highland areas.
- Agricultural encroachment to forest and grassland is the major factor that aggravates soil erosion.
- There is a direct relationship between slope length and erosion rate.

GRAPHICAL ABSTRACT



LISTS OF ABBREVIATIONS

GIS	Geographic information systems
LS	Slope length and steepness
LULC	Land use land cover
LUTM	Land use transfer matrix
OWWDSE	Water Work Design and Supervision Enterprise
RUSLE	Revised Universal Soil Loss Equation

INTRODUCTION

Soil erosion is a critical environmental problem worldwide (Li *et al.* 2014; Ganasri & Ramesh 2016). At the global level, 75 billion metric tons of soil are removed from the land each year by erosion (Dabral *et al.* 2008). Soil erosion severity is influenced by the land-use land-cover (LULC) type and the cumulative effects of LU and management. For instance, a study by Benaud *et al.* (2020) confirmed that inappropriate land management can enhance soil erosion. Human-dominated landscape is more vulnerable to soil erosion than other landscape. A study by Han *et al.* (2020) indicates that agricultural land experienced more severe erosion than forest and grassland cover. Amounts of rainfall, slope and soil types are the fundamental factors that determine the severity of soil erosion (Kiani-Harchegani *et al.* 2019; Quan *et al.* 2020). These factors are measured using the Revised Universal Soil Loss Equation (RUSLE) model and the geographic information system (GIS). The RUSLE model is recommended for soil loss estimation due to its flexibility and compatibility with GIS (Pandey *et al.* 2021). This model is also compatible with the digital elevation model (DEM) and remote sensing data for the assessment of soil erosion (Kouli *et al.* 2009). This model has been widely used worldwide to estimate soil loss. Soil erosion is very high in the highland areas of Ethiopia, characterized by steep slopes, and intensive rainfall (Hailu *et al.* 2015; Welde 2016; Moges & Taye 2017).

There are different empirical models for soil loss measurements such as Soil and Water Assessment Tool (Halecki *et al.* 2018; Shi & Huang 2021), erosion potential method (Refahi & Nematti 1995; Tangestani 2006), the Universal Soil Loss Equation (Wischmeier & Smith 1978; Ferro 2010; Meinen & Robinson 2021) and pan-European soil erosion risk assessment (Fernandez & Vega 2016), which are highly applicable for large geographical areas. From the existing empirical models, we have chosen the RUSLE due to its effectiveness in highland areas (Hurni 1985; Marondedze & Schutt 2020), and more operational to estimate the amount of soil loss on annual basis with less field data (Renard *et al.* 1997; Fernandez & Vega 2016). Moreover, the RUSLE model is applicable at the watershed scale. It is obvious that RUSLE values have uncertainty due to environmental conditions like cover management and topography. In order to minimize the expected uncertainty from the RUSLE model through well parameterization of topographic and cover management factors while avoiding severe soil loss by targeting soil conservation practices in areas where both factors interact and enhance soil loss following (Estrada-Carmona *et al.* 2017).

So far, substantial studies have been conducted to analyze the impacts of LULC on soil erosion by using the RUSLE model in Ethiopia (e.g. Tadesse *et al.* 2017; Kassawmar *et al.* 2018; Kidane *et al.* 2019; Alemu & Melesse 2020; Aneseyee *et al.* 2020; Belihu *et al.* 2020; Desta & Fetene 2020; Gashaw *et al.* 2020; Woldemariam & Harka 2020). However, detailed information on soil loss from each LU category is uncertain in several places. Soil loss estimation during LU conversion from one type to another was not well studied yet. Adequate information on soil loss hazard and LULC change is limited for the Temeji watershed. Moreover, there is limited information on the extent of soil loss at the watershed level. Information and knowledge dissemination on the impact of LULC change on soil loss at the watershed level can be useful for promotion to convince the public and decision-making organs toward nature conservation. Therefore, this study is aimed to analyze the impact of LULC conversion on soil erosion with special emphasis on land conversion by applying the land use transfer matrix (LUTM) method. This work identifies the severity of erosion at the watershed level and gives appropriate suggestions on possible conservation strategies.

MATERIALS AND METHODS

Description of the study area

The Temeji watershed is located in the Abay river basin. The study area lies between 9°27′30″ and 9°36′50″N and 36°57′40″ and 37°4′40″E. Administratively, the Temeji watershed is located in Horo district of Horo Guduru Wollega Zone of Oromia National Regional State in Western Ethiopia (Figure 1). The altitude of the study area varies from 1,839 to 3,174 above mean sea level. It covers an area of about 15,434 ha.

Soil types

There are three soil types existed in the study area, i.e. chromic cambisols, cystic nitisols and Leptosols. Among these, dystric nitisols and chromic cambisols are more dominant in the study area.

Best soil conservation practices

Due to high demand for agricultural practices driven by rapid population growth, little attention was given to soil conservation practices in the Temeji watershed. However, some people are protecting their land by planting trees, check dams, terracing and soil bund to minimize the rate of soil loss.

Agricultural crop types and cropping pattern

Crop production is the major agricultural practice in the Temeji watershed. The major crops are wheat, barley, beans, maize and teff. Crop rotation, intercropping and mixed cropping are the major existing cropping patterns in the study area.

Methods

In the present study, the RUSLE model integrated with GIS technology has been used to analyze the impact of LULC on soil erosion in the Temeji watershed. Similar studies have been conducted using RUSLE model and GIS technology to analyze the impact of LULC on soil erosion (Millward & Mersey 1999; Prasannakumar *et al.* 2012; Galagay & Minale 2016; Ganasri & Ramesh 2016; Gashaw *et al.* 2017; Ostovari *et al.* 2017; Zerihun *et al.* 2018; Kidane *et al.* 2019; Mohammed *et al.* 2020; Olorunfemi *et al.* 2020). The RUSLE model combines various parameters, which were acquired from different sources (Table 1). The methodological framework for soil loss estimation in this study is presented in Figure 2.

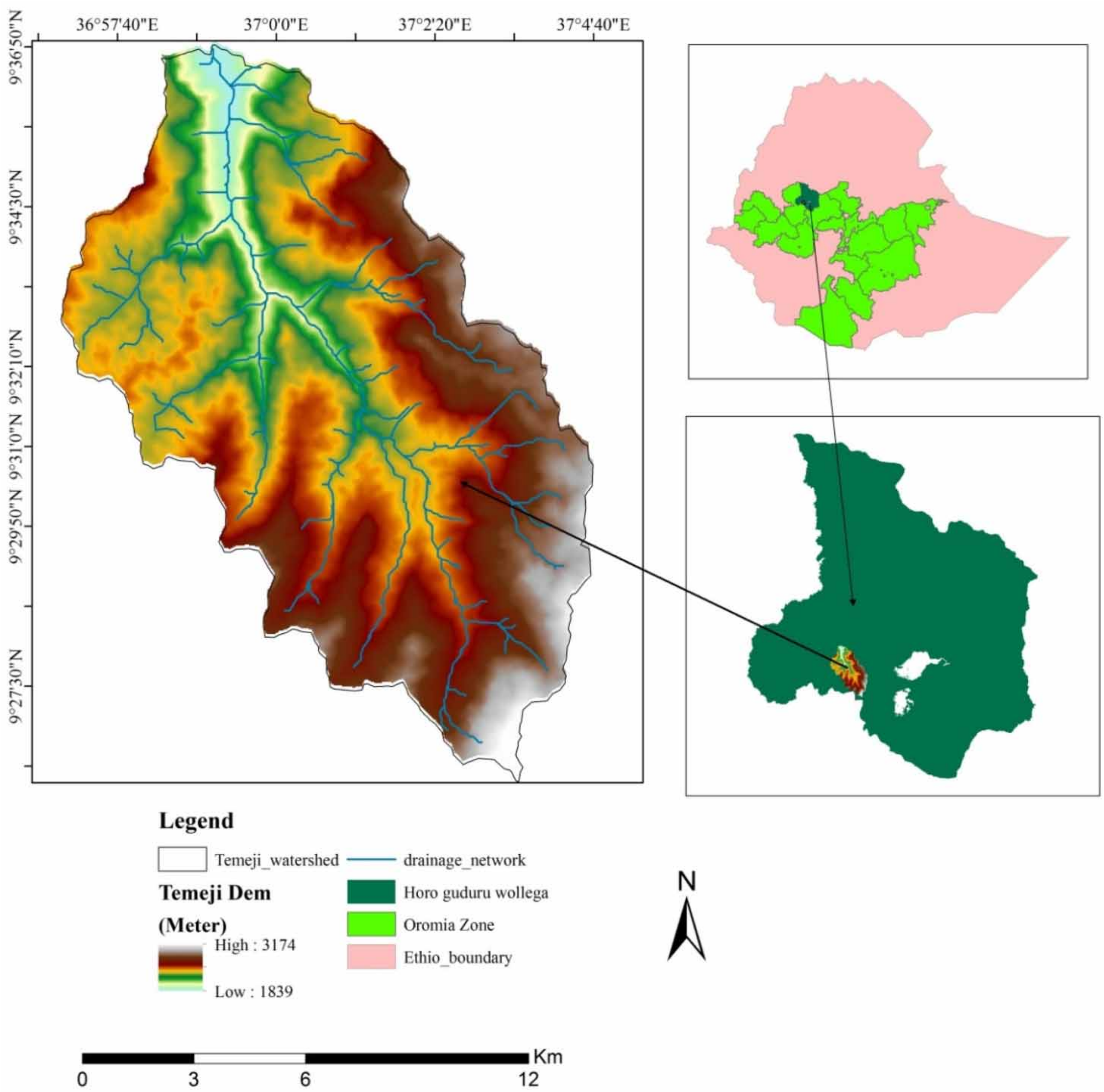


Figure 1 | Location map of Temeji Watershed.

Annual soil loss estimation method

The RUSLE model (Renard *et al.* 1997) was adopted to estimate the annual soil loss on field slopes. This model is recommended by various researchers due to its compatibility with GIS technology (Jasrotia & Singh 2006; Prasannakumar *et al.* 2012) and overcome the problem of data availability (Belayneh *et al.* 2019). This model was widely used to estimate the mean annual soil loss worldwide (Renard *et al.* 1997; Kidane *et al.* 2019; Yesuph & Dagnaw 2019; Woldemariam & Harka 2020). The total annual soil loss was estimated by raster grid spatial analysis of the six parameters (Wischmeier & Smith 1978; Hurni 1985; Renard *et al.* 1997). The mean soil loss (A) due to erosion per unit area per year soil erosion prediction using RUSLE for central Kenyan highland conditions was quantified by the RUSLE model (Renard *et al.* 1997) using the following equation:

$$A = R * K * LS * C * P \quad (1)$$

Table 1 | The types, sources and descriptions of RUSLE input data used in this study

Data type	Data source	Descriptions	Purpose
Landsat ETM+ (2000) and OLI/TIRS (2020)	USGS	30 m resolution	*C*- and *P*-factors
ASTER GDEM	USGS	30 m resolution	To derive *LS*-factor
Soil map	OWWDSE	1:1,000,000	To derive *K*-factor
Rainfall data	NMA of Ethiopia	20 years monthly data	To derive *R*-factor

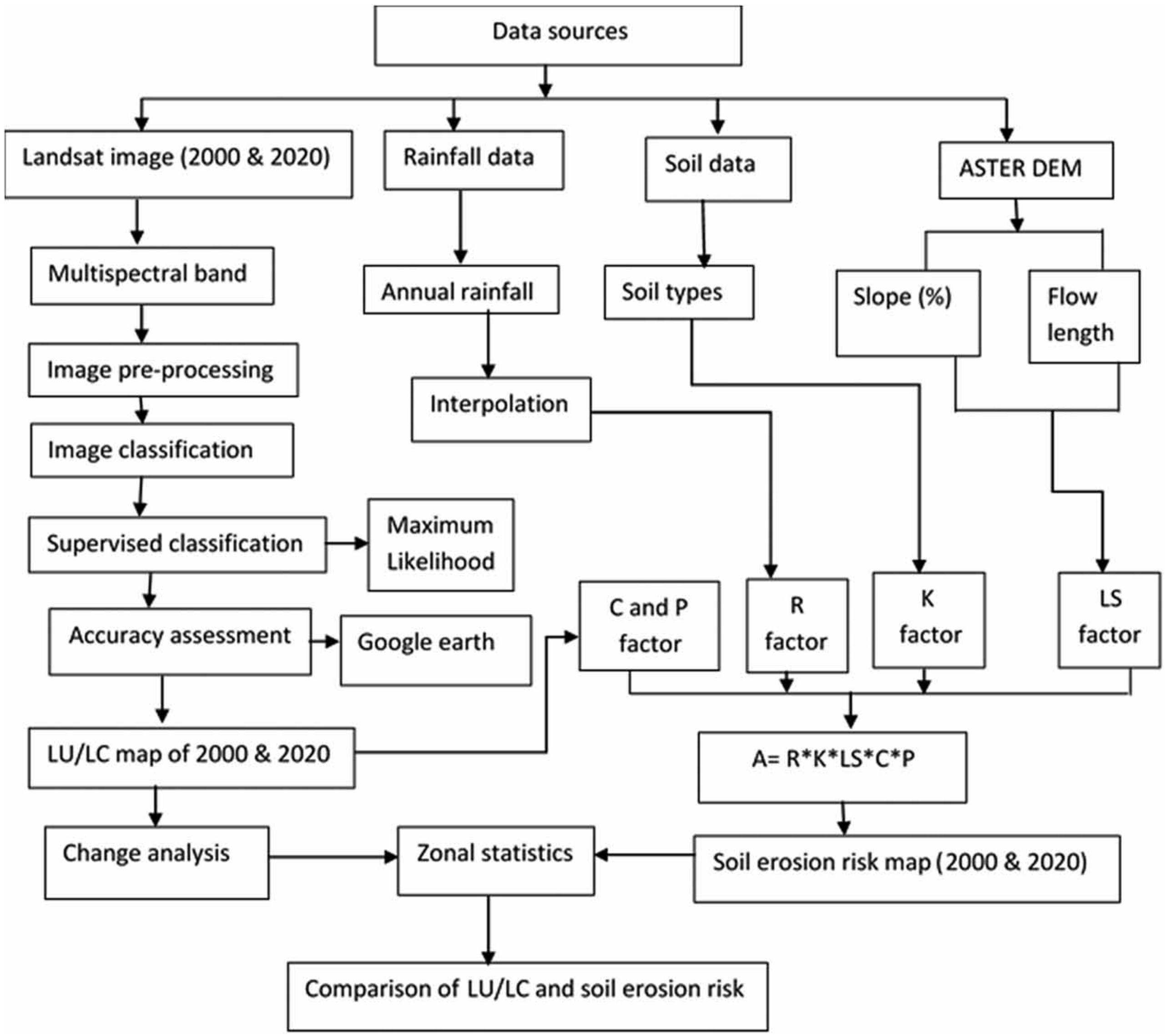


Figure 2 | Methodological flowchart.

where A is annual soil loss in t/ha/year, R is the rainfall–runoff erosivity factor in (MJ/mm/ha/year), LS is the slope length and slope steepness factor, C is the cover and management factor and P is the conservation practice factor.

Rainfall erosivity (*R*) factor

Rainfall–runoff erosivity is the primary factor causing soil erosion and accounts for about 85% of land degradation in the world (Angima *et al.* 2003). The *R*-factor quantifies the impact of rainfall on erosion rate (Kayet *et al.* 2018). Geo-statistical interpolation was used to develop continuous raster grids of the long year average annual rainfall. Mean historical rainfall data (20 years) was collected from Ethiopian National Meteorology Agency (Table 2). Using 20 years of precipitation data, the *R*-factor (Figure 3) in MJ/mm/ha/year was calculated in ArcGIS raster calculator as indicated in the following equation:

$$R = -8.12 + (0.562*P) \tag{2}$$

where *R* is the rainfall erosivity factor, and *P* is the mean annual rainfall (mm).

Soil erodibility factor

Soil erodibility (*K*) factor shows the mean long-term soil and soil profile response to the erosive power associated with rainfall and runoff (Millward & Mersey 1999). *K*-factor indicates the sensitivity of soil to erosion (Kayet *et al.* 2018). Soil types for the Temeji watershed were obtained from Oromia Water Work Design and Supervision Enterprise (OWWDSE) to associated soil types and color (Table 3), and the *K*-values were adapted from Hurni (1985). For each soil type, *K*-value were assigned and

Table 2 | Mean annual rainfall and *R*-value (computed from 20 years data)

Station name	*X*-coordinate	*Y*-coordinate	Elevation (m)	Mean annual rainfall
Haro	205,402	1,089,701	1,993	1,765.9
Shambu	290,840	1,058,428	2,553	1,791.7
Anger Gutin	232,890	1,058,349	1,391	1,575.9
Nekemte	230,537	1,005,760	2,119	2,181
Sibu sire	265,668	9,99,901	1,821	1,510

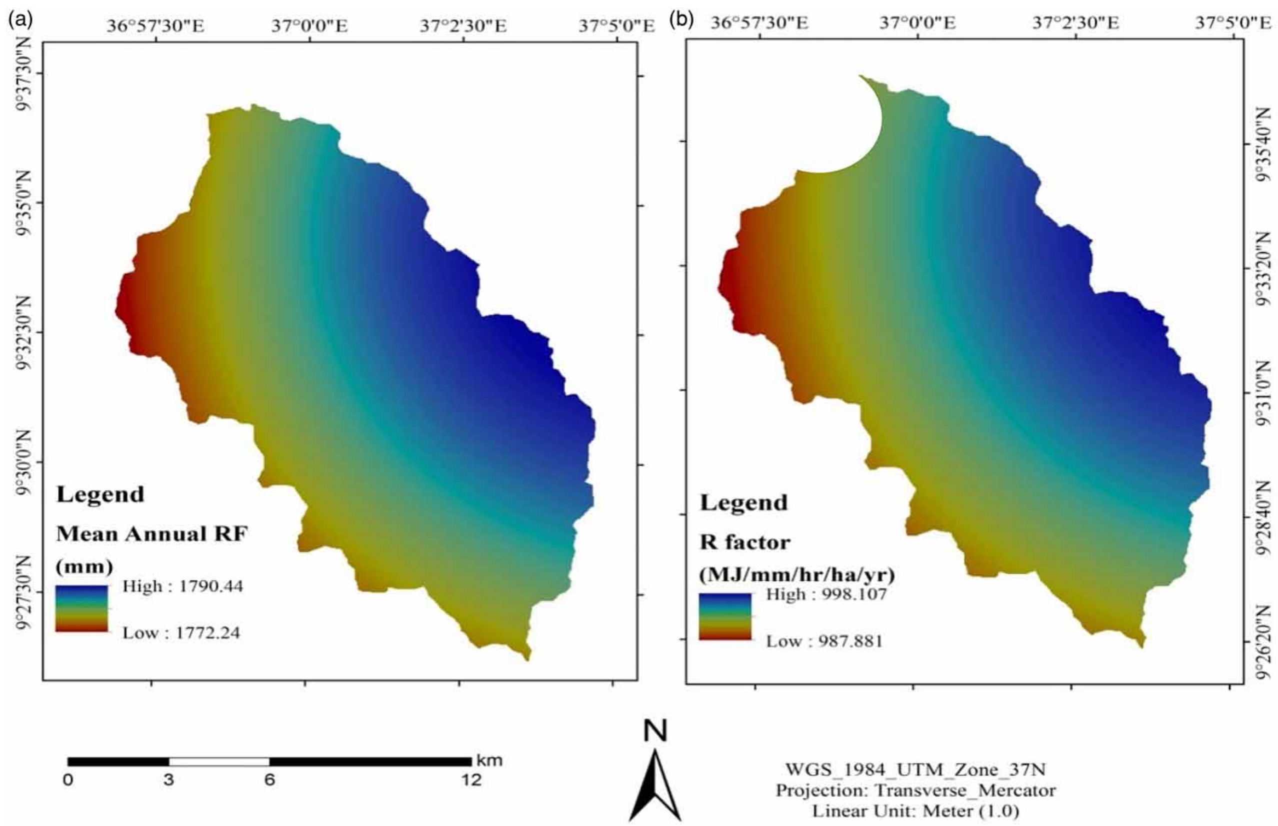


Figure 3 | (a) Mean annual rainfall and (b) *R*-factor of the study area.

Table 3 | Soil type, color and erodibility value of Temeji watershed (adapted from Hurni 1985)

S/No	Soil types	Area (ha)	Soil color	*K*-factor
1	Chromic cambisols	6,768.2	Brown	0.2
2	Dystric nitisols	5,734.9	Red	0.25
3	Leptosols	2,931.1	Yellow	0.3

converted to raster grid in ArcGIS environment. A 1:1,000,000 scale map of the soil was used within ArcGIS environment to determine the erodibility (K) values for each soil type (Figure 4).

Slope length and steepness factor

The slope length and steepness (LS) factor indicates the impact of topography on the soil erosion process. It is the combined effects of slope length (L) factor and the slope steepness (S) factor (Figure 5). There is a direct relationship between slope length and erosion rate (Wischmeier & Smith 1978). To prove this direct correlation, we assess the extent of soil loss across different slope lengths in the study area. For this purpose, we used a freely available DEM-ASTER from the US Geological Survey with 30-m resolution. The LS is the ratio of observed soil loss related to the soil loss of standardized plot (22.13) as indicated in Schmidt *et al.* (2019). The LS-value is considered to have values between 0.02 and 48 for the Ethiopian condition (Hurni 1985), and the study area is ranging from 0 to 21.32. The LS-factor was calculated with the support of ArcGIS software spatial analysis using the DEM and slope developed by Moore & Burch (1986) and used by Ostovari *et al.* (2017),

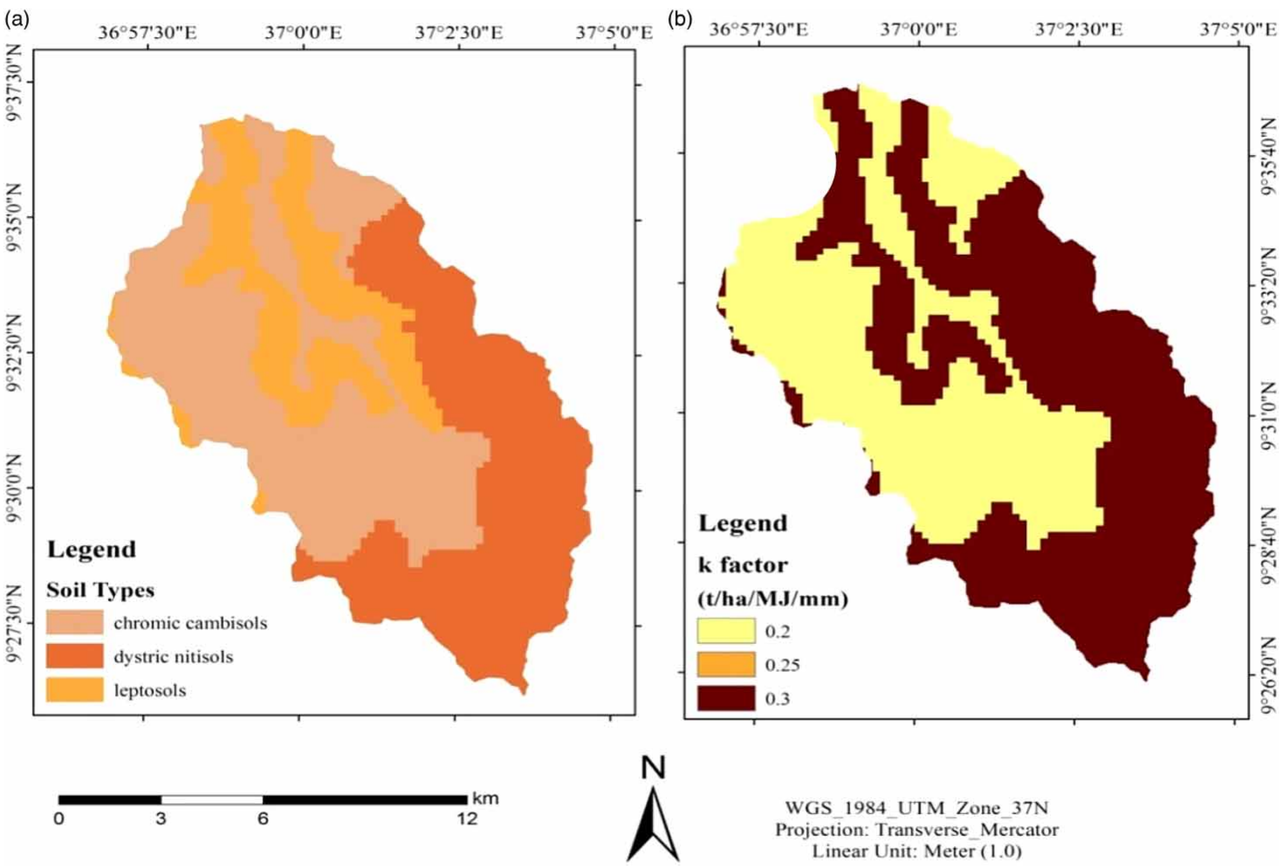


Figure 4 | (a) Soil types and (b) *K*-factor of the study area.

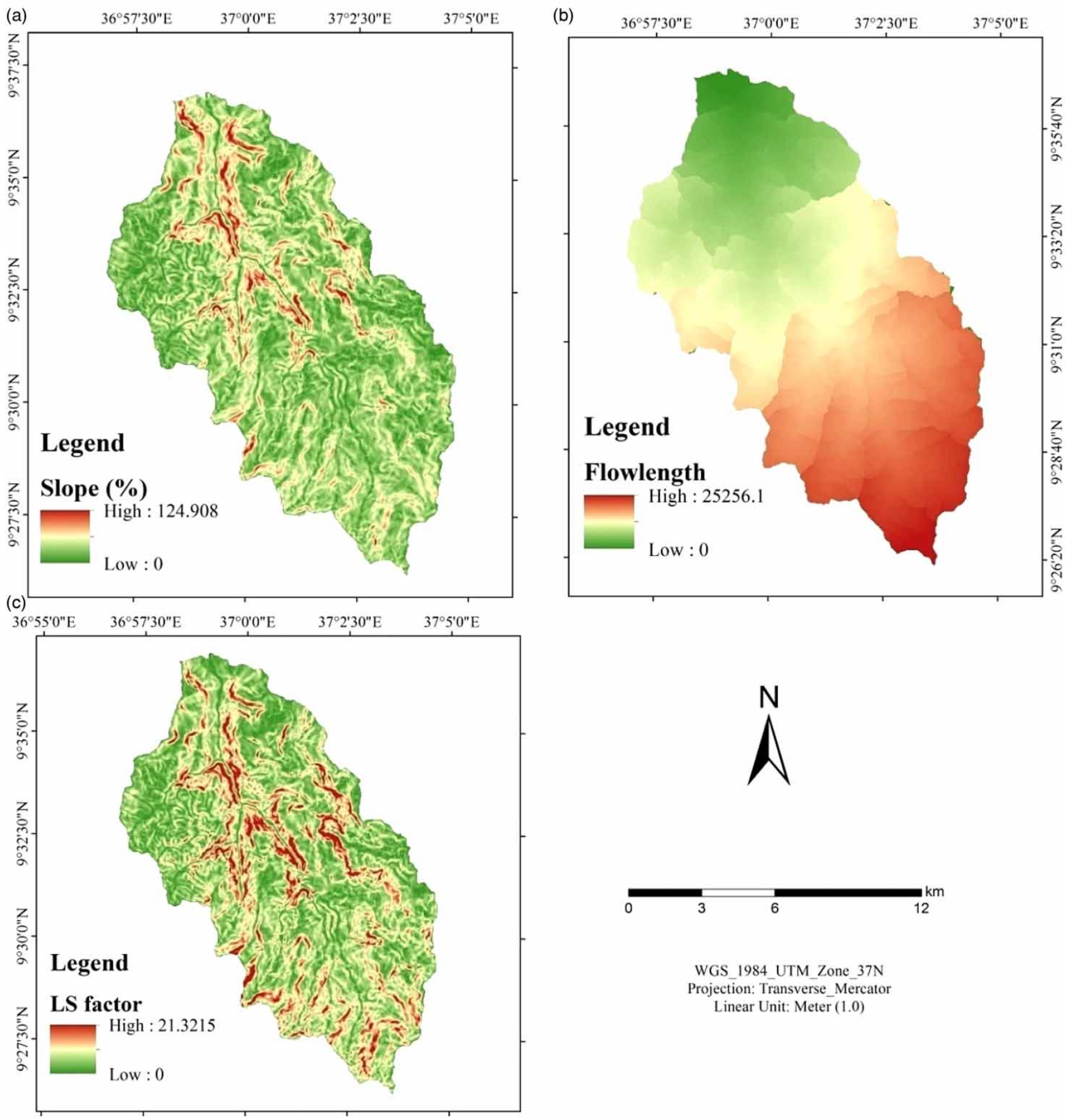


Figure 5 | (a) Slope, (b) flow length and (c) *LS*-factor of the study area.

Kidane *et al.* (2019) and Mohammed *et al.* (2020) in the following equation:

$$\mathrm{LS} = \left(\text{Flow accumulation} * \frac{\text{Cell size}}{22.13}\right)^{0.4} * \left(\frac{\sin \text{Slope}}{0.0896}\right)^{1.3} \quad (3)$$

where LS is the slope length and the slope steepness factor, cell size is the size of the grid cell and the sin slope is the slope degree value in sin.

Table 4 | *C*- and *P*-factors of the study area

S/No.	LU/LC types	*C*-factor	*P*-factor
1	Bare land	0.05	0.73
2	Cultivated land	0.18	0.9
3	Forest	0.001	0.53
4	Grassland	0.05	0.63
5	Settlement	0.05	0.63

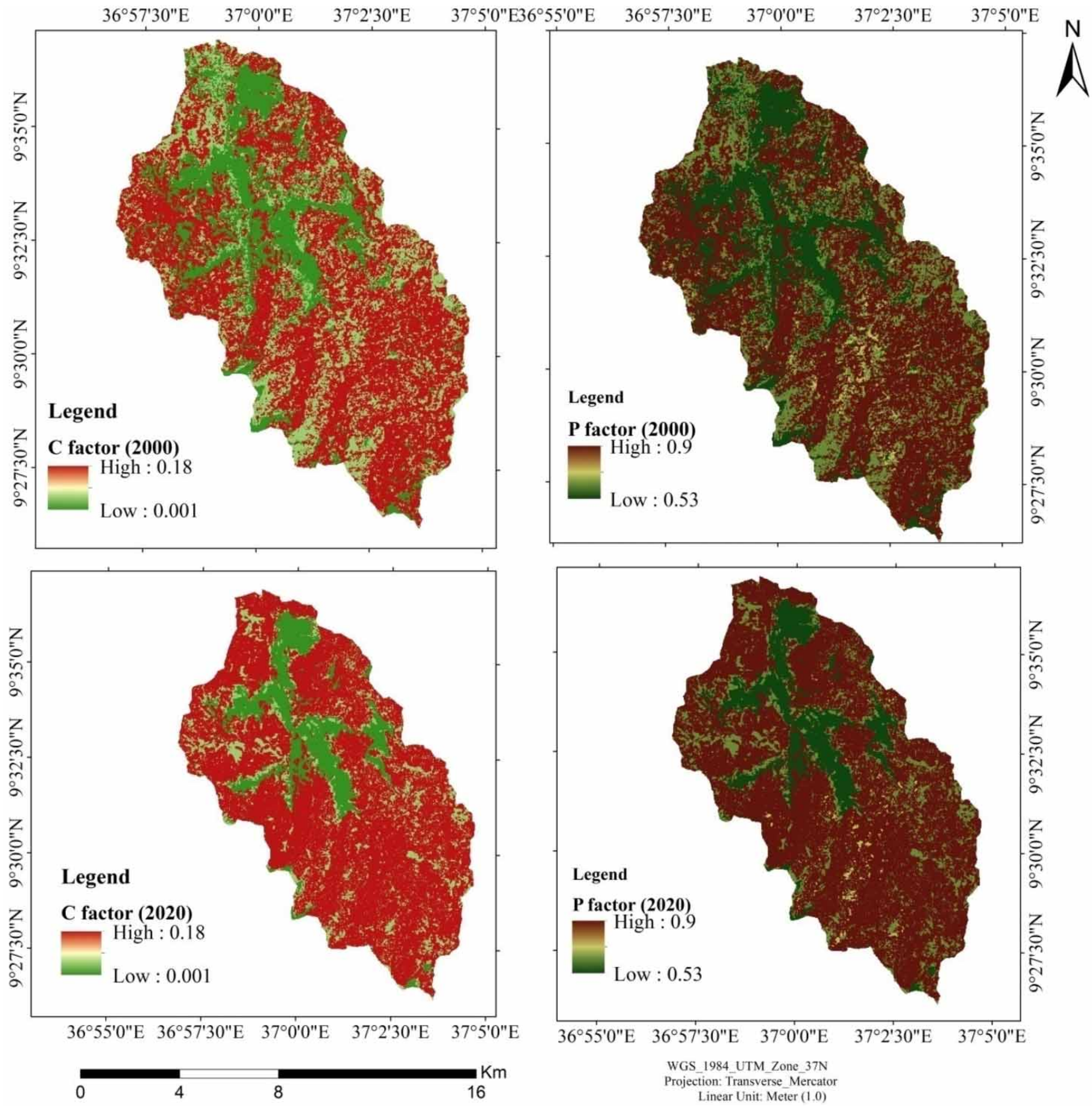


Figure 6 | *C*-factor (left) and *P*-factor (right) of the study area.

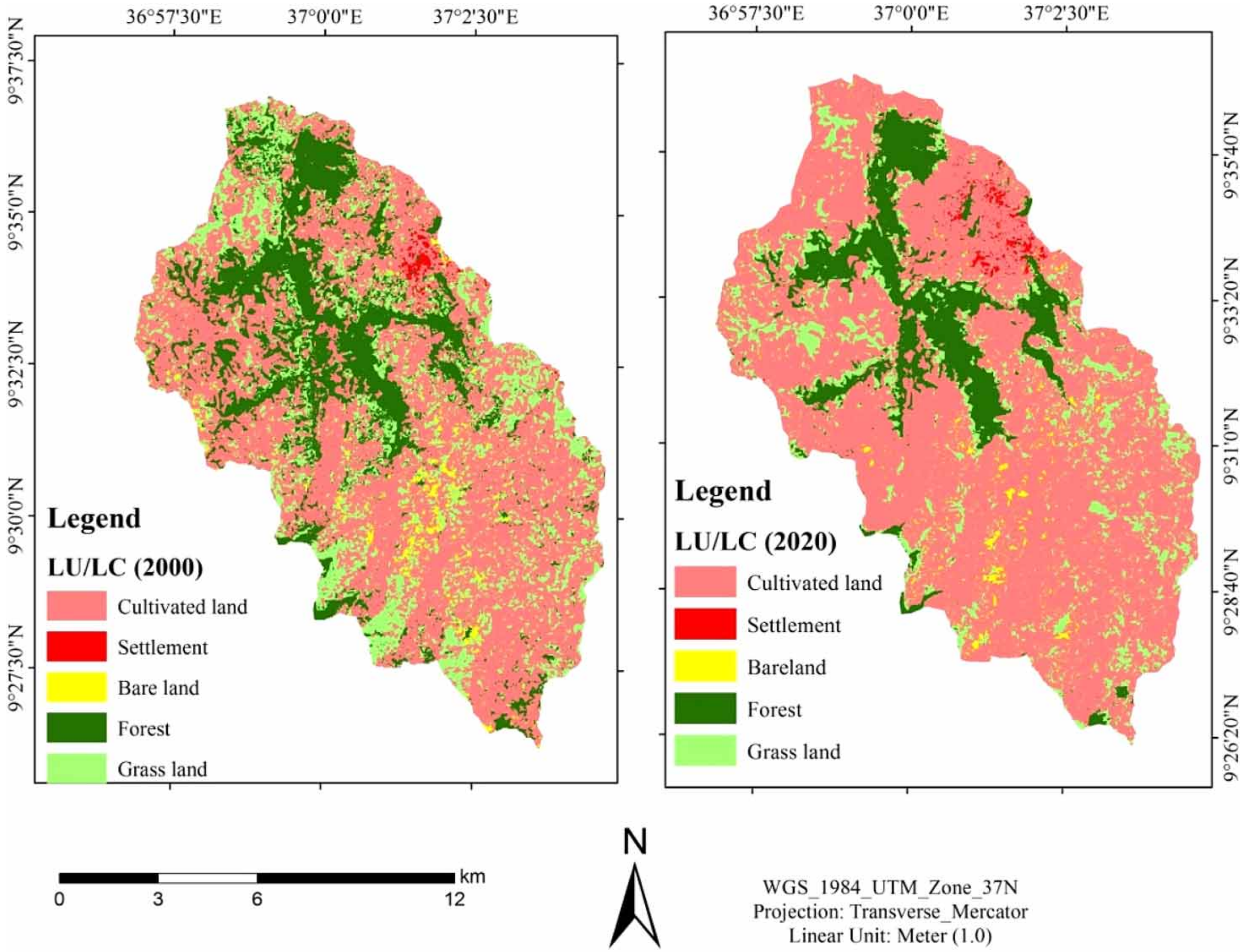


Figure 7 | LU/LC map of the study area.

Table 5 | Magnitude and trends of LU/LC change during 2000 and 2020

		Area in 2000		Area in 2020		LU/LCC (2000–2020)	
S/No.	**LU/LC types**	**(ha)**	**(%)**	**(ha)**	**(%)**	**(ha)**	**(%)**
1	Bare land	209.4	1.4	239.7	1.6	30.3	0.2
2	Cultivated land	8,805.9	57.1	11,181.0	72.4	2,375.1	15.3
3	Forest	3,174.4	20.6	2,000.5	13.0	−1,173.9	−7.6
4	Grassland	3,175.9	20.6	1,916.2	12.4	−1,259.6	−8.2
5	Settlement	68.3	0.4	96.6	0.6	28.2	0.2
Total		15,434.0	100.0	15,434.0	100.0		

Cover management factor

The cover management (C) values for each LULC type were assigned based on the works of Belayneh *et al.* (2019) and Kidane *et al.* (2019) as indicated in Table 4. The LULC map of the watershed was classified using 30-m resolutions of Landsat7ETM+ and 8 OLI/TIRS satellite images taken in March 2000 and 2020 downloaded from the USGS website (http://earthexplorer.usgs.gov), respectively. In the RUSLE model, the C-factor shows the effect of vegetation/crop cover and management practices on soil erosion rate (Renard *et al.* 1997; Millward & Mersey 1999; Ostovari *et al.* 2017). The C-factor

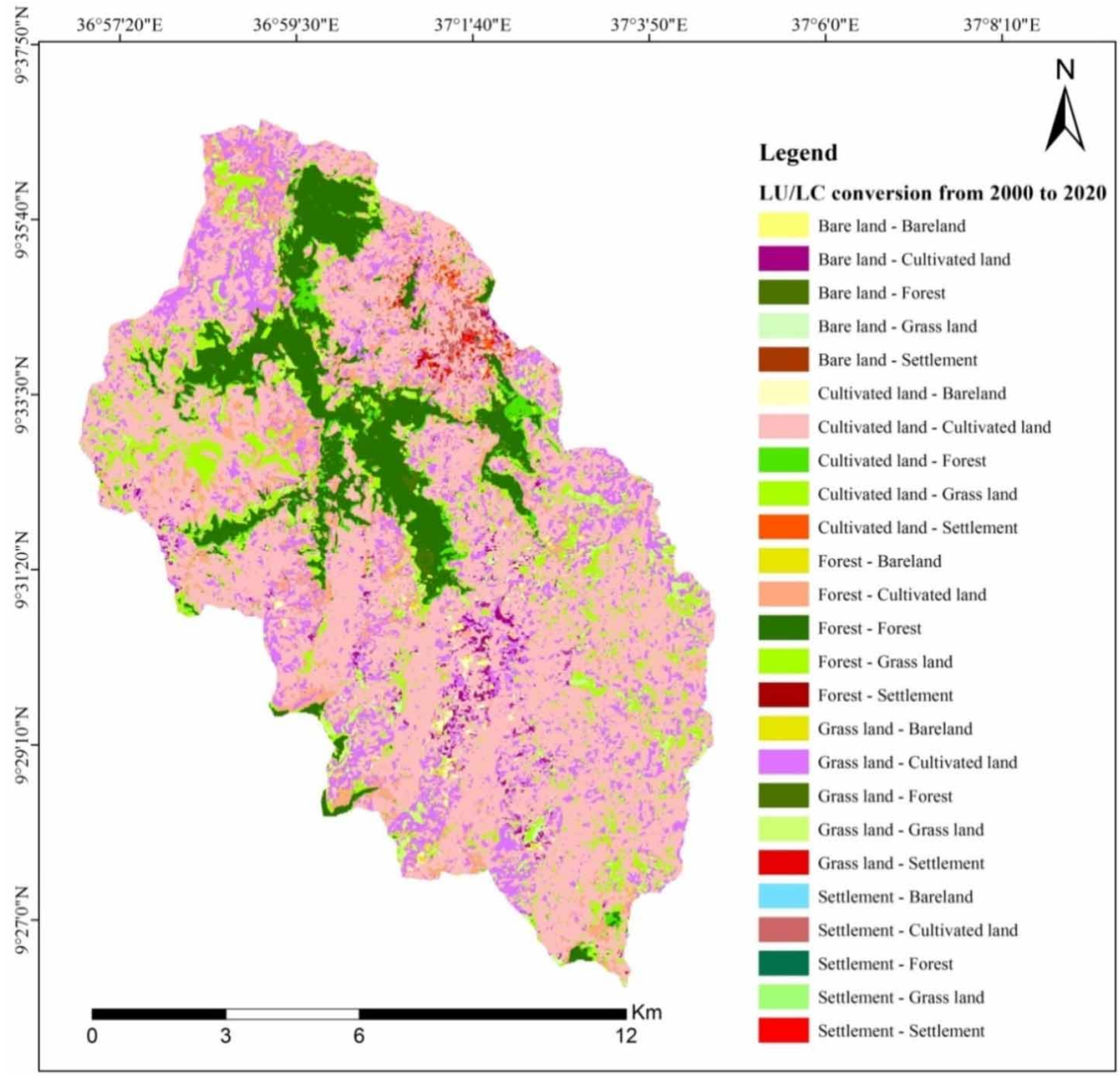


Figure 8 | LU/LC conversion from 2000 to 2020.

ranges between 0 (no susceptibility to soil erosion due to well protected and managed land) to value 1, which depicts high susceptibility to erosion due to lack of protective cover (Ganasri & Ramesh 2016; Mohammed *et al.* 2020; Olorunfemi *et al.* 2020).

Support practices factor

The support practices (*P*) factor is the ratio of soil loss with specific support practice to the corresponding soil loss with up and down cultivation (Wischmeier & Smith 1978; Millward & Mersey 1999). Similar to *C*-values, the *P*-values ranges from 0 to 1, whereby the value 0 indicates a good conservation practice and erosion resistance facility and the vale 1 indicates poor conservation practice and no manmade erosion resistance facility (Renard *et al.* 1997; Ganasri & Ramesh 2016; Olorunfemi *et al.* 2020). Because of lack of conservation practice-related data in the study watershed, the *P*-factor values were taken from the literature review, which varies between 0.53 and 0.9 (Figure 6). The P-values were estimated based on conservation practices, slope and LULC types as used by Kidane *et al.* (2019).

Table 6 | LU/LC conversion and mean annual soil loss of the study area

No.	LU/LC conversion (2000–2020)	Mean (t/ha/year)	No.	LU/LC conversion (2000–2020)	Mean (t/ha/year)
1	Bare land to bare land	34.1	14	Forest to grassland	18.2
2	Bare land to cultivated land	66.1	15	Forest to settlement	38.3
3	Bare land to forest	1.6	16	Grassland to bare land	33.0
4	Bare land to grassland	24.9	17	Grassland to cultivated land	88.8
5	Bare land to settlement	26.6	18	Grassland to forest	3.6
6	Cultivated land to bare land	27.5	19	Grassland to grassland	25.5
7	Cultivated land to cultivated land	83.8	20	Grassland to settlement	30.2
8	Cultivated land to forest	7.7	21	Settlement to bare land	10.7
9	Cultivated land to grassland	24.1	22	Settlement to cultivated land	75.4
10	Cultivated land to settlement	34.0	23	Settlement to forest	7.1
11	Forest to bare land	27.3	24	Settlement to grassland	11.1
12	Forest to cultivated land	86.9	25	Settlement to settlement	36.7
13	Forest to forest	1.3			

RESULTS AND DISCUSSION

LULC change

The spatial extent of different LULC is presented in Figure 7 (2000 and 2020). The LU/LC of the study area was classified into five major classes: bare land, cultivated land, forest, grassland and settlement. Among the existing LU, cultivated land constituted the largest coverage, which is about 8,805.9 ha (57.1%) and 11,181.0 ha (72.4%) in 2000 and 2020, respectively. The LULC analysis shows that the cultivated land spatial coverage is increasing over time. Similar results are obtained by Negassa *et al.* (2020), which report that cultivated land is increased by 50.8% around Komto protected forest priority in the East Wollega zone. The cultivated land increases at a rate of 118.75 ha/year. The agricultural land expansions were at expense of forest and grasslands. This finding is supported by other studies (Shang *et al.* 2019; Belihu *et al.* 2020). The forest and the grassland cover are the 2nd and 3rd coverage both in the years 2000 and 2020 (Table 5).

The declining trends of forest and grassland in the study resulted in land degradation predominantly soil erosion. Reduction of forest and grassland area resulted in an increase in surface runoff (Shang *et al.* 2019). Deforested lands are exposed to the potential impacts of raindrops, which accelerate the detachment, removal and transportation of soil particles (Kidane *et al.* 2019). Additionally, rapid population growth enhances the over-exploitation of forest resources for agricultural activities that contributes to land degradation particularly on steep slopes. The use of forest products for energy consumptions and house construction is another factor that accelerates the declining of forest coverage in the study area.

LULC change matrix

In this study, the LUTM (post-classification) method was used to detect LULC change from 2000 to 2020. The LUTM method is derived from the quantitative description of state transition system analysis (Figure 8). The LULC matrix was produced by overlaying two LULC maps of the same area to show probability that one particular LULC category changed into another LC category. From the five LULC classes, cultivated land is the most vulnerable, while the forest LU class is the least vulnerable to soil erosion (Table 6). Soil is highly eroded, especially when another LULC is converted into farmland. The result is in line with findings of Negassa *et al.* (2020).

Analysis of soil erosion

The estimated mean annual soil loss of Temeji watershed is presented in Table 6. The mean annual soil loss was determined by a cell-by-cell analysis of the soil loss surface by multiplying the RUSLE factors. In this study, we evaluated the impact of LULC change on soil erosion for the years 2000 and 2020. The result of soil erosion map of each LULC for the two periods is presented in Figure 9.

More than 50% of the total area of the watershed is grouped under severe category, i.e. the majority of the LULC of the study area is highly vulnerable for soil erosion (Table 7). This result has a reasonable agreement with Haregeweyn *et al.* (2017) and Belayneh *et al.* (2019). The high vulnerability of Temeji watershed to soil erosion is associated with agricultural encroachment to forest and grassland. Similar research finding was reported by Kidane *et al.* (2019) in the West Shewa zone of Oromia National Regional State in Ethiopia, which report that the local communities continue to expand their cultivated land to more erosion-prone areas. The conversions of the original forest cover into farmlands and grassland caused a decline in forest cover. Similarly, grassland cover reductions were driven by the expansions of farmlands (Esa *et al.* 2018). The result indicated that the conversions of various LULC classes to cultivated land were the most detrimental to soil erosion, while forest was the most effective barrier to soil loss (Sharma *et al.* 2011).

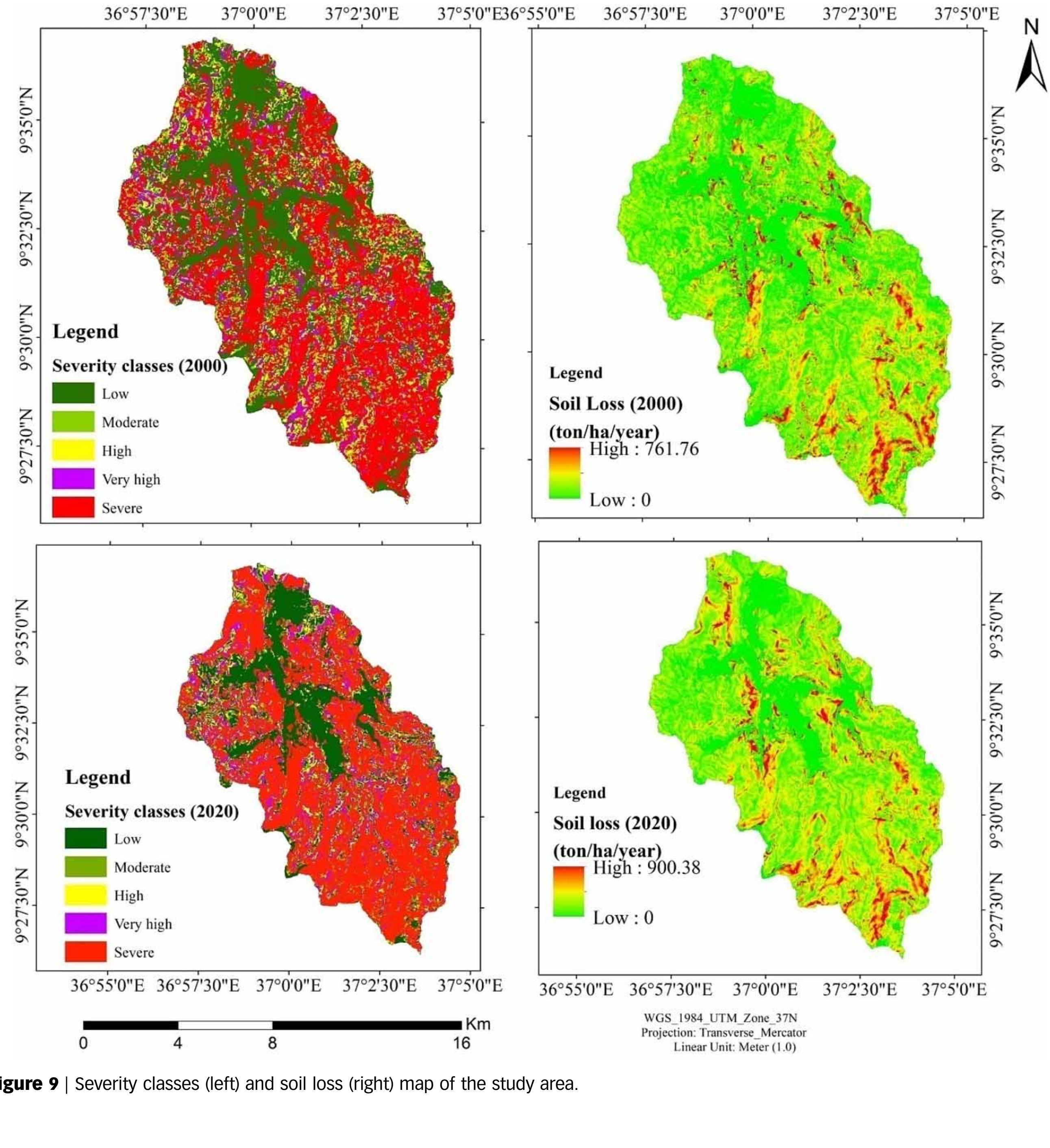


Figure 9 | Severity classes (left) and soil loss (right) map of the study area.

Table 7 | Severity range and classes of soil loss of the study area

S/No.	Severity range	Severity classes	2000 Area (ha)	2000 Area (%)	2020 Area (ha)	2020 Area (%)
1	0–10	Low	4,428.8	28.7	2,927.1	19.0
2	10–20	Moderate	1,584.6	10.3	1,162.2	7.5
3	20–30	High	1,139.7	7.4	1,056.5	6.8
4	30–50	Very high	1,672.4	10.8	1,896.3	12.3
5	>50	Severe	6,608.5	42.8	8,391.8	54.4
–	Total	–	15,434.0	100.0	15,434.0	100.0

Soil and water conservation strategies

Physical soil and water conservation strategies have been practiced by the local communities in the Temeji watershed. These conservation strategies have two common goals: (1) to protect the loss of topsoils and (2) to enhance agricultural yields. Even though the soil and water conservation measures in the watershed are very poor, some mechanical and biological soil and water conservation measures have been implemented by the local community. Among the mechanical measures, terracing (hillside and farmland), check dams, stone bunding and cutoff drains construction are practices in some places. From biological soil and water conservation measures, the uses of Agro-forestry systems, horticulture and agronomic practices, and planting trees on hillside are rarely practiced in the study area. During field observation for the validation of RUSLE results, we confirmed that the participation of the local community in biological soil and water conservation practices is considerably lower. This is the major factor that aggravated the problem of soil erosions in the Temeji watershed, which requires further intervention by the government as well as the public.

CONCLUSIONS

This paper reveals the application of empirical soil erosion model such as RUSLE integrated with GIS to assess the impact of LULC on soil erosion in the Temeji Watershed, Western Ethiopia. An effort has been made to analyze the impact of LULC change, climate (rainfall and temperature), soil types and color, as well as slope length on soil erosion. The results highlight that LULC and topography are the main key factors that influence soil erosion, particularly in the highland country like Ethiopia. Due to the topographic nature of the study area and people's dependence on agriculture, the problem of soil erosion in the Temeji watershed is very high. Our results show that about 6,608.5 ha (42.8%) and 8,391.8 ha (54.4%) were categorized under severe classes in 2000 and 2020, respectively. This research concludes that the severity of soil loss may increase as slope length increases, and vice versa. The quantitative indication obtained through interpretation of satellite images indicated that the majority of the LULC of the study area is highly vulnerable for soil erosion, particularly cultivated land is the most susceptible LULC for soil erosion. Soil is highly eroded, especially when another LULC is converted into farmland. Thus, decision-making organ should advocate the importance of mechanical and biological soil and water conservation measures. To minimize the anticipated impacts of soil erosion, sustainable mechanical and biological soil and water conservation practices should be promoted by the government. Lastly, further research should be conducted on the dynamics of LULC changes in and around big cities by using high spatial resolution satellite images.

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AUTHOR CONTRIBUTIONS

M.B.M. was involved in research design, data collection, data analysis and draft manuscript. D.A.N. and B.B.M. were involved in data analysis. D.O.G. works on literature, data analysis and re-wrote the manuscript to the journal style. All authors read and approved the final manuscript.

CONSENT FOR PUBLICATION

The authors agreed to publish the manuscript in Journal of Water and Climate Change.

CONFLICT OF INTEREST

The authors declared that they have no competing interests.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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