Impact of Land Use and Land Cover Change on Soil Erosion Using Rusle Model And Gis: A Case of Temeji Watershed, Western Ethiopia

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Research

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Abstract

Background

The impact of Land Use/Land Cover (LULC) conversion on soil resources is getting global attention. Soil erosion is one the critical environmental problems worldwide with high severity in developing countries due to land degradation. This study integrates the Revised Universal Soil Loss Equation (RUSLE) model with a Geographic Information Systems (GIS) to estimate the impacts of LU/LC conversion on the mean annual soil loss in Temeji watershed. In this study, LU/LC change of Temeji watershed were 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

Results indicates that majority of the LU/LC in the study area is vulnerable to soil erosion. Our findings show that cultivated land had the highest average soil loss rate in Temeji watershed. High soil loss is observed when grass and forest land were converted into cultivated land with mean soil loss of 88.8t/ha/yr and 86.9t/ha/yr in 2020. Results revealed that about 6608.5ha (42.8%) and 8391.8ha (54.4%) were categorized under severe classes in 2000 and 2020, respectively.

Conclusions

The results can definitely support policy makers and environmental managers in implementation of soil and water conservation practices and erosion risk prevention and mitigation strategies in Temeji watershed.

Background

Soil erosion is a critical environmental problem worldwide (Li et al. 2014; Ganasri and Ramesh 2016). At global level, 75 billion tons of soil is removed and 20 million hectares of land lost 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 land use and management. For instance, 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. Study by Han et al. (2020) indicates that agricultural land experienced more severe erosion than forest and grass land cover. The amount of rainfall, slope and soil types are the fundamental factors determining the severity of soil erosion (Quan et al. 2020; Kiani-Harchegani et al. 2019). These factors are measured using the Revised Universal Soil Loss Equation (RUSLE) model and Geographic Information Systems (GIS). Soil erosion is very high in the highland areas of Ethiopia; characterized by steep slopes, and intensive rainfall (Moges and Taye 2017; Welde 2016; Hailu et al. 2015).

So far, substantial studies have been conducted recently to analyze the impacts of LU/LC on soil erosion in Ethiopia (e.g.;(Alemu and Melesse 2020; Aneseyee et al. 2020; Belihu et al. 2020; Desta and Fetene 2020; Gashaw et al. 2020; Woldemariam and Harka 2020; Kidaneet al. 2019; Kassawmar et al. 2018; Tadesse et al. 2017). However, detail information on soil loss from each land use category is uncertain in several places. Moreover, soil loss estimation during land use conversion from one type to another was not well studied yet. Adequate information on soil loss hazard and LU/LC change is limited for Temeji watershed. Therefore, this study was aimed at analyzing the impact of LU/LC on soil erosion with special emphasis on land conversion though applying Land Use Transfer Matrix (LUTM) method.

Materials And Methods

Description of the study area

Temeji watershed is located in the Abay river basin. The study area lies between $9^0$27'30" and $9^0$36'50" N and $36^0$57'40" and $37^0$4'40" E. Administratively, Temeji watershed is located in Horo district of Horo Guduru Wollega Zone of Oromia National Regional State in Western Ethiopia (**Fig.1**). The altitude of the study area varies from 1839-3174 above mean sea level. It covers an area of about 15,434ha.

Methods

The integration of RUSLE model and GIS technology was used following (Mohammed et al. 2020; Olorunfemi et al. 2020; Kidaneet al. 2019; Zerihunet al. 2018; Gashaw et al. 2017; Ostovar et al. 2017; Ganasri and Ramesh 2016; Galagay and Minale 2016; Prasannakumar et al. 2012) to determine the impact of LULC on soil erosion in Temeji watershed. The RUSLE model combines various parameters which were acquired from different sources (**Table 1**). The overall methodology flowchart for this study was indicated in (**Fig. 2**).

Annual soil loss estimation method

The RUSLE model (Renard et al. 1997) was adopted to estimate the annual soil loss on field slopes. The RUSLE model is highly recommended to soil loss estimation due to its compatibility suitability with GIS technology (Jasrotia and Singh 2006; Prasannakumar et al. 2012) and applicability in limited data conditions (Belayneh et al. 2019). This model was widely used to estimate the mean annual soil loss at worldwide (Woldemariam and Harka 2020; Kidane et al. 2019; Yesuph and Dagnaw 2019; Renard et al. 1997). The total annual soil loss was estimated by raster grid spatial analysis of the six parameters (Renard et al. 1997; Hurni 1985; Wischmeier and Smith 1978). 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 RUSLE model (Renard et al. 1997) using Eq.1.

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

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 slop 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% 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 following (Kidane et al. 2019). Mean historical rainfall data (20 years) was collected from Ethiopian National Meteorology Agency (**Table 2**). Using 20 years precipitation data, the R factor (**Fig. 3**) in MJ mm ha^{-1} h^{-1} per year was calculated in ArcGIS raster calculator as indicated in Eq.2.

$$R = -8.12 + (0.562 * P) \qquad (2)$$

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

Soil erodibility (K) factor

Soil erodibility factor shows the mean long-term soil and soil profile response to the erosive power associated with rainfall and runoff (Millward and Mersey 1999). K factor indicates the sensitivity of soil to erosion (Kayet et al. 2018). For soil erodibility estimations, soil type and color method were adapted from Hurni (1985) as indicated in (**Table 3**). Soil types for Temeji watershed were obtained from Oromia Water Work Design and Supervision Enterprise (OWWDSE) to associated soil types and color. For each soil type, K value were assigned and converted to raster grid in ArcGIS environment. A 1:1,000,000 scale map of the soil was used withing ArcGIS environment to determine the erodibility (K) values for each soil type (**Fig 4**).

Slope length and steepness (LS) factor

The LS factor indicates the impact of topography on soil erosion process. It is the combined effects of slope length (L) factor and the slope steepness (S) factor (**Fig 5**). There is a direct relationship between slope length and erosion rate (Wchmeier and Smith 1978). As a result, erosion increases as slope length increases. This study used the DEM-ASTER at 30-meter resolution downloaded from US Geological survey. 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 0.02-48 for Ethiopian condition (Hurni 1985) and the study area is ranging from 0-21.32. The length slope (LS) factor was calculated with the support of ArcGIS software spatial analysis using the DEM and slope following equations developed by Moore and Burch (1986) and used by (Mohammed et al. 2020; Kidaneet al. 2019; Ostovari et al. 2017) using Eq.3.

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

Where

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

Cover management (C) factor

In the RUSLE model, the C-factor show the effect of vegetation/crop cover and management practices on soil erosion rate (Ostovar et al. 2017; Millward and Mersey 1999; Renard et al. 1997). The C factor ranges between zero (no susceptibility to soil erosion due to well protected and managed land) to value one (1), which depict high susceptibility to erosion due to lack of protective cover (Mohammed et al. 2020; Olorunfemi et al. 2020; Ganasri and Ramesh 2016). The C values for each LU/LC types were assigned (**Table 4**). The LU/LC map of the watershed was classified using 30*30 m cloud free Landsat7ETM+ and 8 OLI/TIRS satellite images taken in March 2000 and 2020 downloaded from USGS website (http://earthexplorer.usgs.gov), respectively.

Support practices (P) 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 (Millward and Mersey 1999; Wischmeier and Smith 1978). Similar to C-values, the P-values ranges from Zero to One, whereby the value zero indicates a good conservation practice and erosion resistance facility and the vale One indicates poor conservation practice and no manmade erosion resistance facility (Olorunfemi et al. 2020; Ganasri and Ramesh 2016; Renard et al. 1997). Because of lack of conservation practices related data in the study watershed the p-factor values were taken from literature review which varies between 0.53 to 0.9 (**Fig. 6**). The p-values was estimated based on conservation practices, slope and land use land cover types as used by (Kidane *et al*. 2019).

Results And Discussion

Land use/land cover (LU/LC) change

The spatial extents of different LU/LC are presented in **Fig 7** (2000 and 2020). The LU/LC of the study area was classified into five major classes: Bare land, cultivated land, forest, grass land, and settlement. Among the existing land use, cultivated land constituted the largest coverage, which is about 8805.9ha (57.1%) and 11181.0ha (72.4%) in 2000 and 2020 respectively. The LU/LC analysis show that the cultivated land spatial coverage is increasing overtime. Similar results are obtained by Negassa et al. (2020), which reports that cultivated land is increased by 50.8% around Komto protected forest priority in East wollega zone. The cultivated land increase with rate of 118.75ha/year. The agricultural land expansions were at expense of forest and grasslands. This finding is supported by other studies (Belihu et al. 2020; Shang et al. 2019). The forest and the grass land cover are the 2nd and 3rd coverage both in the year 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 grass land area resulted in an increase in surface runoff (Shang et al. 2019). Deforested lands are exposed to the potential impacts of rain drops, which accelerate the detachment, removal and transportation of soil particles (Kidane et al. 2019). Additionally, rapid population growth enhances the over-exploitation forest resources for agricultural activities that contributes land degradation particularly on steep slopes. The use of forest products for energy consumptions and house construction are another factor that accelerates the declining of forest coverage in the study area.

Land use transfer matrix (LUTM) analysis

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

Analysis of soil erosion using RUSLE model

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 LU/LC change on soil erosion for the year 2000 and 2020.The result of soil erosion map of each LU/LC for the two periods was presented (**Fig. 9**).

More than 50% of the total area of the watershed is grouped under severe category i.e., majority of the LU/LC of the study area is highly vulnerable for soil erosion (**Table 7**). This result has a reasonable agreement with (Haregeweyn *et al.* 2017; Belayneh *et al*. 2019). The high vulnerability of Temeji watershed to soil erosion is associated with agricultural encroachment to forest and grass land. Similar research finding was reported by (Kidane et al. 2019) in 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 grass land caused a decline in forest cover. Similarly, reduction in grassland covers was largely caused by the conversion of its initial extent into farmlands (Esa et al. 2018). The result indicated that the conversions of various LU/LC classes to cultivated land was the most detrimental to soil erosion, while forest was the most effective barrier to soil loss (Sharma et al. 2010).

Conclusions

This paper reveals the application of empirical soil erosion model such as RUSLE integrated with GIS to assess the impact of LU/LC on soil erosion in Temeji Watershed, Western Ethiopia. An effort has been made to analyze the impact of change in LU/LC on soil erosion. The quantitative indication obtained through interpretation of satellite images indicated that majority of the LU/LC of the study area is highly vulnerable for soil erosion particularly; cultivated land is the most susceptible land use/land cover for soil erosion. Soil is highly eroded especially, when other land use /land cover is converted in to farm land. Thus, soil and water conservation measures should be undertaken in the study area to minimize the loss of soil through erosion.

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

Declarations

Ethics approval and consent to participate: Not applicable

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Author contributions

MBM involved in research design, data collection, data analysis, and draft manuscript. DAN and BBM involved in data analysis. DOG works on literature, data analysis and re-wrote the manuscript to the journal style. All authors read and approved the final manuscript.

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Tables

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 factor
ASTER GDEM	USGS	30 m resolution	To derive LS factor
Soil map	OWWDSE	1:1000,000	To derive K factor
Rainfall data	NMA of Ethiopia	20yrs monthly data	To derive R factor

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	205402	1089701	1993	1765.9
Shambu	290840	1058428	2553	1791.7
Anger Gutin	232890	1058349	1391	1575.9
Nekemte	230537	1005760	2119	2181
Sibu sire	265668	999901	1821	1510

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	6768.2	Brown	0.2
2	Dystric nitisols	5734.9	Red	0.25
3	Leptosols	2931.1	Yellow	0.3

Table 4: C and P factor 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	Grass land	0.05	0.63
5	Settlement	0.05	0.63

Table 5: Magnitude and Trends of LU/LC change during 2000 and 2020

S/No	LU/LC Types	Area in 2000		Area in 2020		LU/LCC (2000 to 2020)	
		(ha)	(%)	(ha)	(%)	(ha)	(%)
1	Bare land	209.4	1.4	239.7	1.6	30.3	0.2
2	Cultivated land	8805.9	57.1	11181.0	72.4	2375.1	15.3
3	Forest	3174.4	20.6	2000.5	13.0	-1173.9	-7.6
4	Grass land	3175.9	20.6	1916.2	12.4	-1259.6	-8.2
5	Settlement	68.3	0.4	96.6	0.6	28.2	0.2
Total		15434.0	100.0	15434.0	100.0		

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

No.	LU/LC Conversion (2000-2020)	Mean (t/ha/yr)	No		Mean (t/ha/yr)
1	Bare land to Bare land	34.1	14	Forest to Grass land	18.2
2	Bare land to Cultivated land	66.1	15	Forest to Settlement	38.3
3	Bare land to Forest	1.6	16	Grass land to Bare land	33.0
4	Bare land to Grass land	24.9	17	Grass land to Cultivated land	88.8
5	Bare land to Settlement	26.6	18	Grass land to Forest	3.6
6	Cultivated land to Bare land	27.5	19	Grass land to Grass land	25.5
7	Cultivated land to Cultivated land	83.8	20	Grass land to Settlement	30.2
8	Cultivated land to Forest	7.7	21	Settlement to Bare land	10.7
9	Cultivated land to Grass land	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 Grass land	11.1
12	Forest to Cultivated land	86.9	25	Settlement to Settlement	36.7
13	Forest to Forest	1.3			

Table 7: Severity range and classes of Soil loss of the study area

S/No	Severity range	Severity classes	2000		2020	
			Area(ha)	Area (%)	Area (ha)	Area (%)
1	0-10	Low	4428.8	28.7	2927.1	19.0
2	10_20	Moderate	1584.6	10.3	1162.2	7.5
3	20_30	High	1139.7	7.4	1056.5	6.8
4	30_50	Very high	1672.4	10.8	1896.3	12.3
5	>50	Severe	6608.5	42.8	8391.8	54.4
__	Total	___	15434.0	100.0	15434.0	100.0

Figures

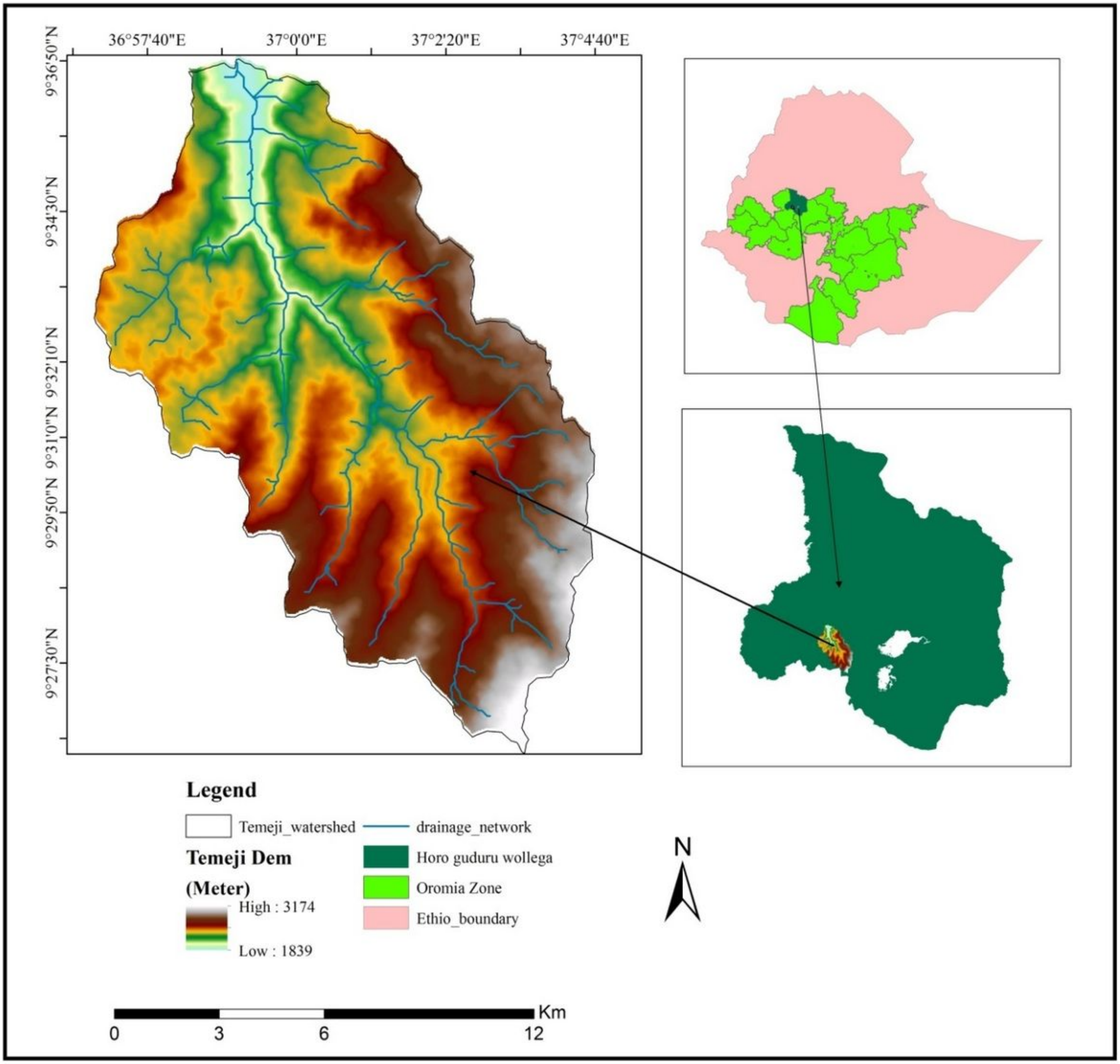
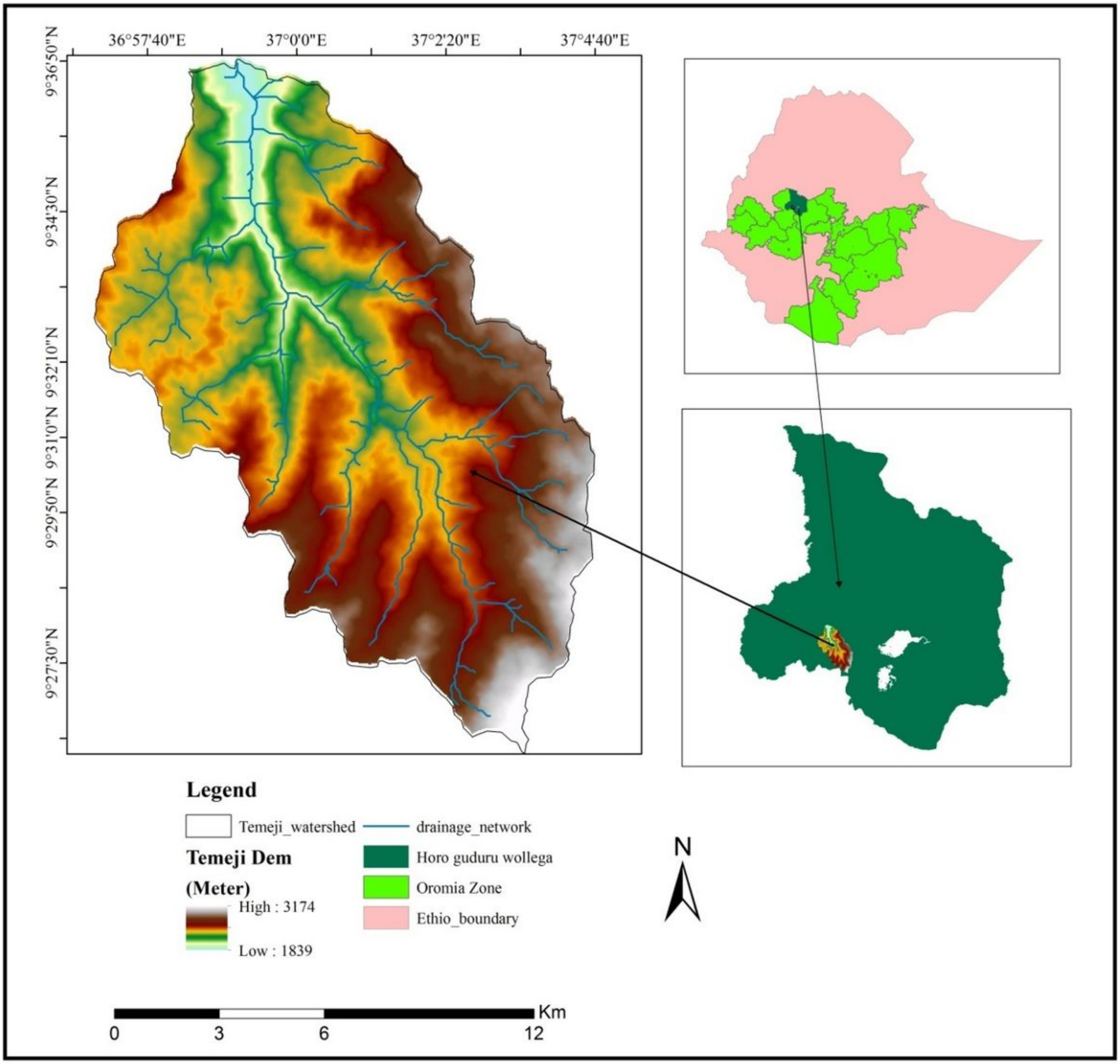


Figure 1

Location map of Temeji Watershed. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



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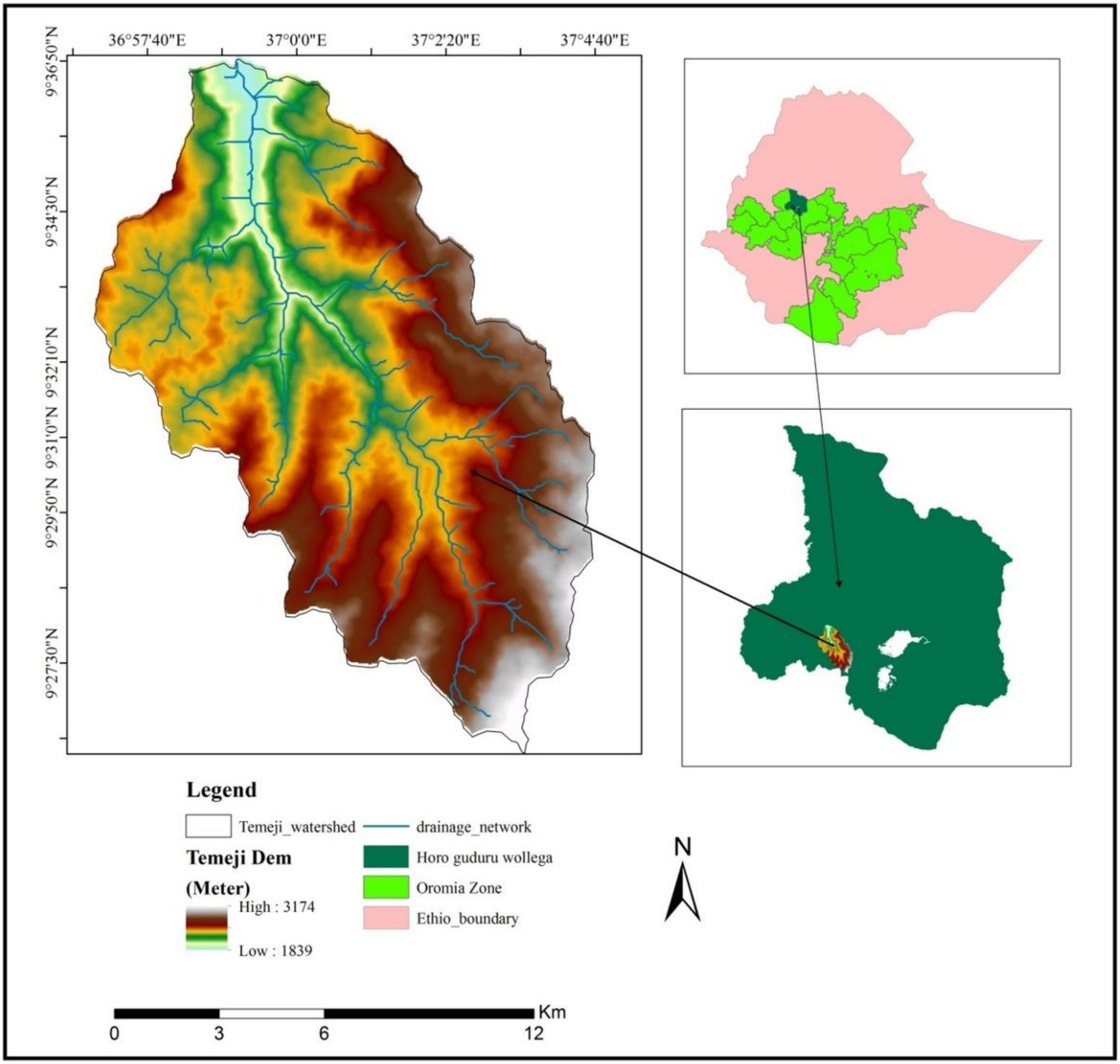

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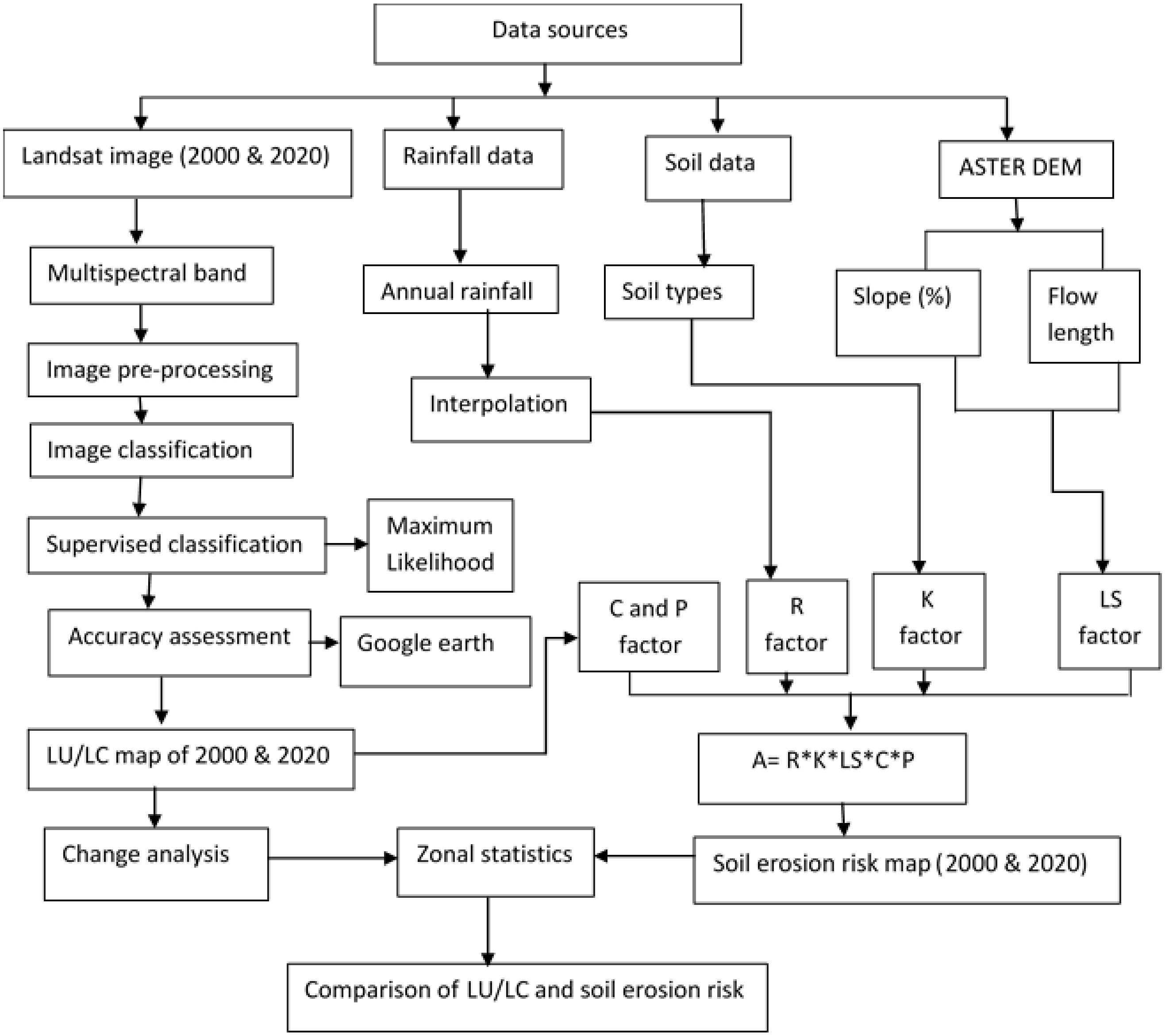
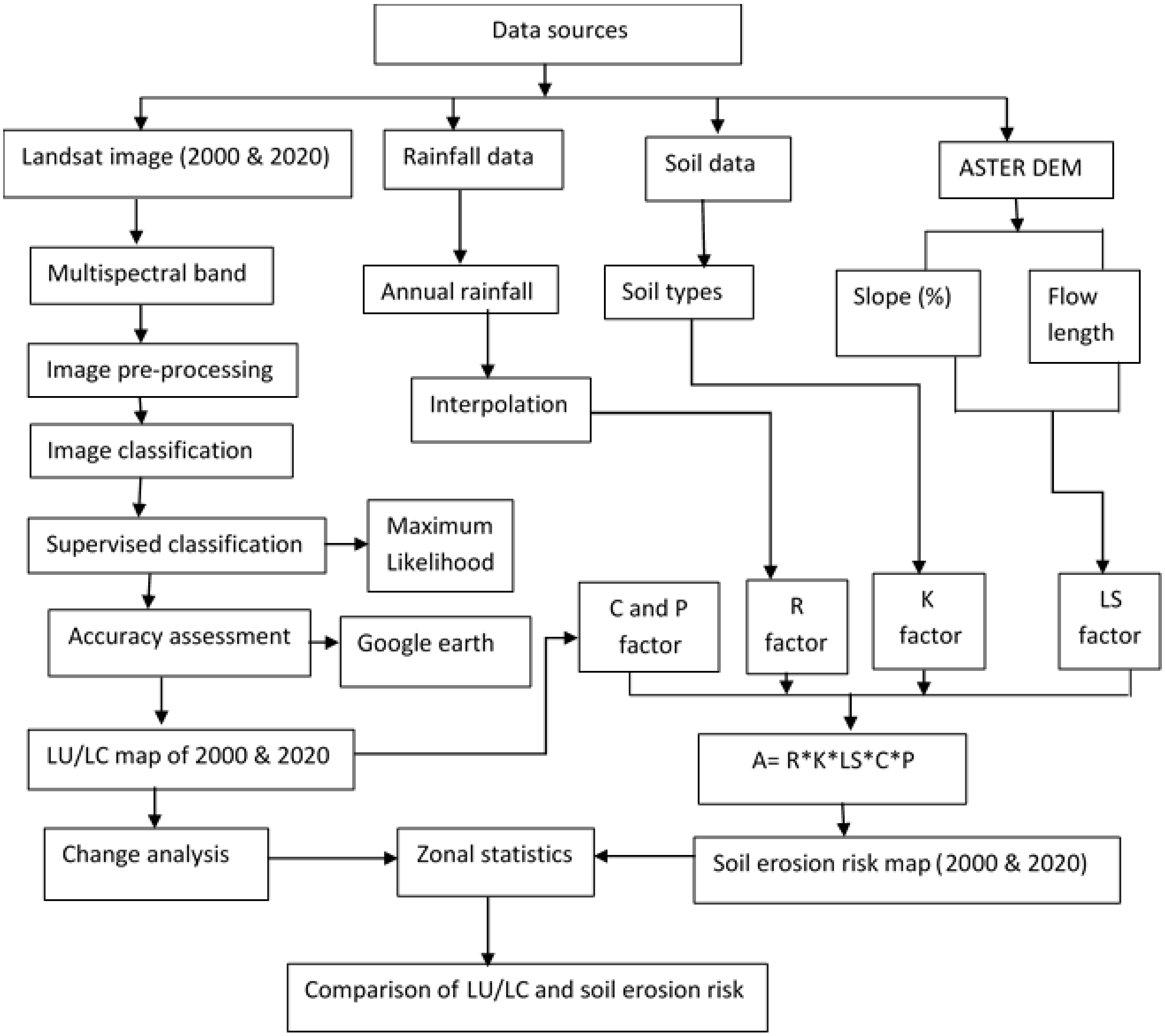


Figure 2

Methodological flowchart



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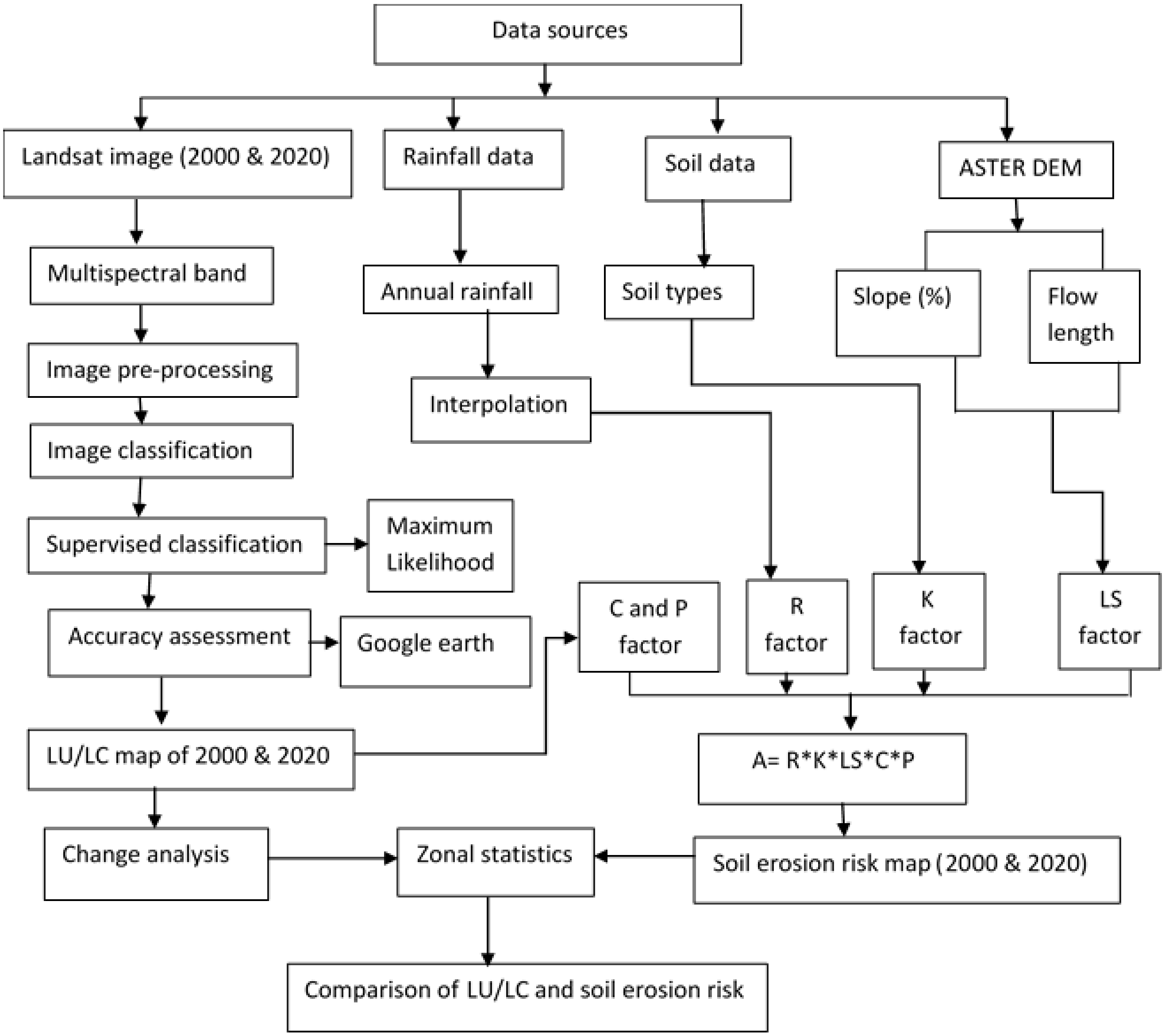

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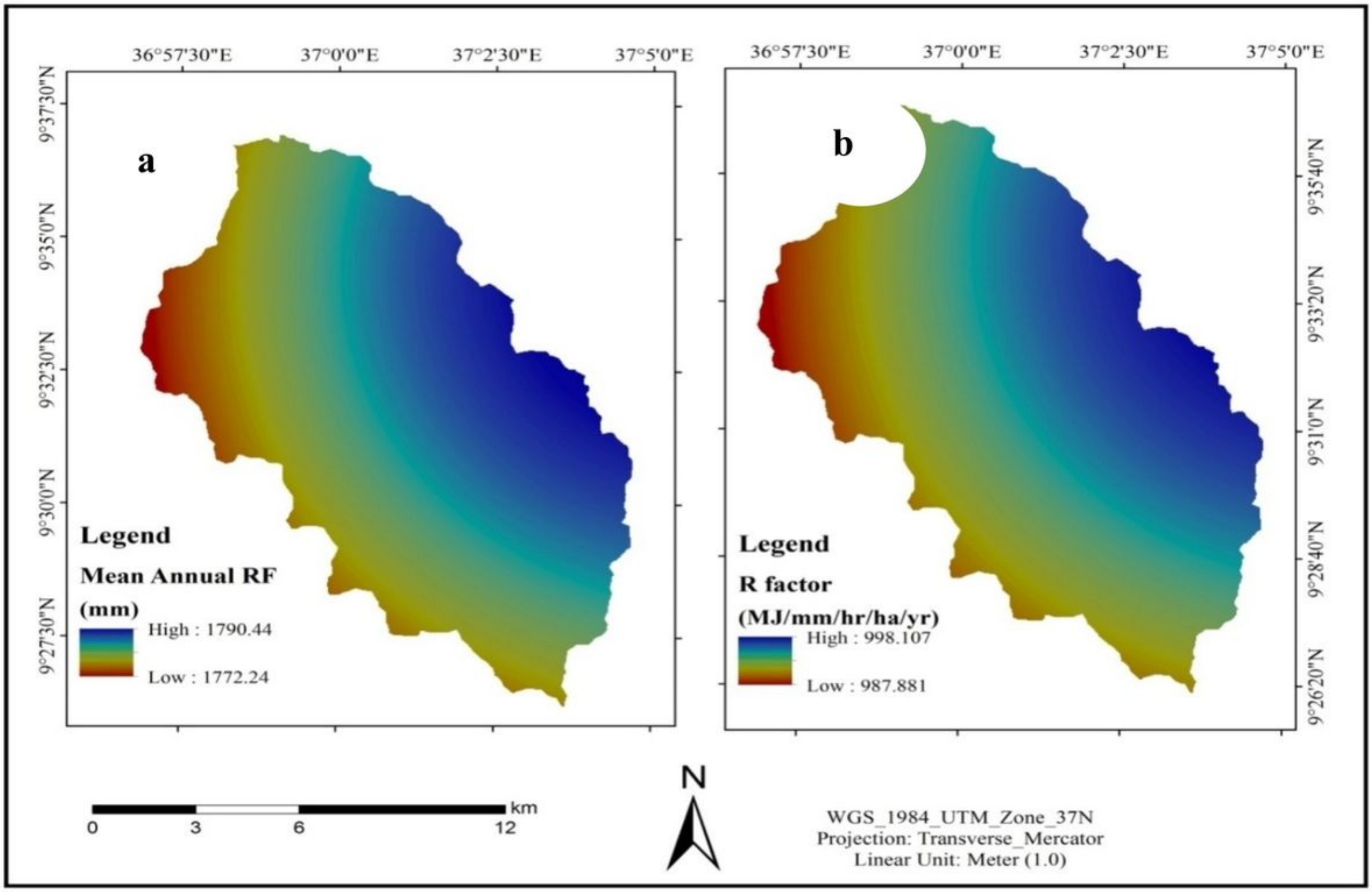
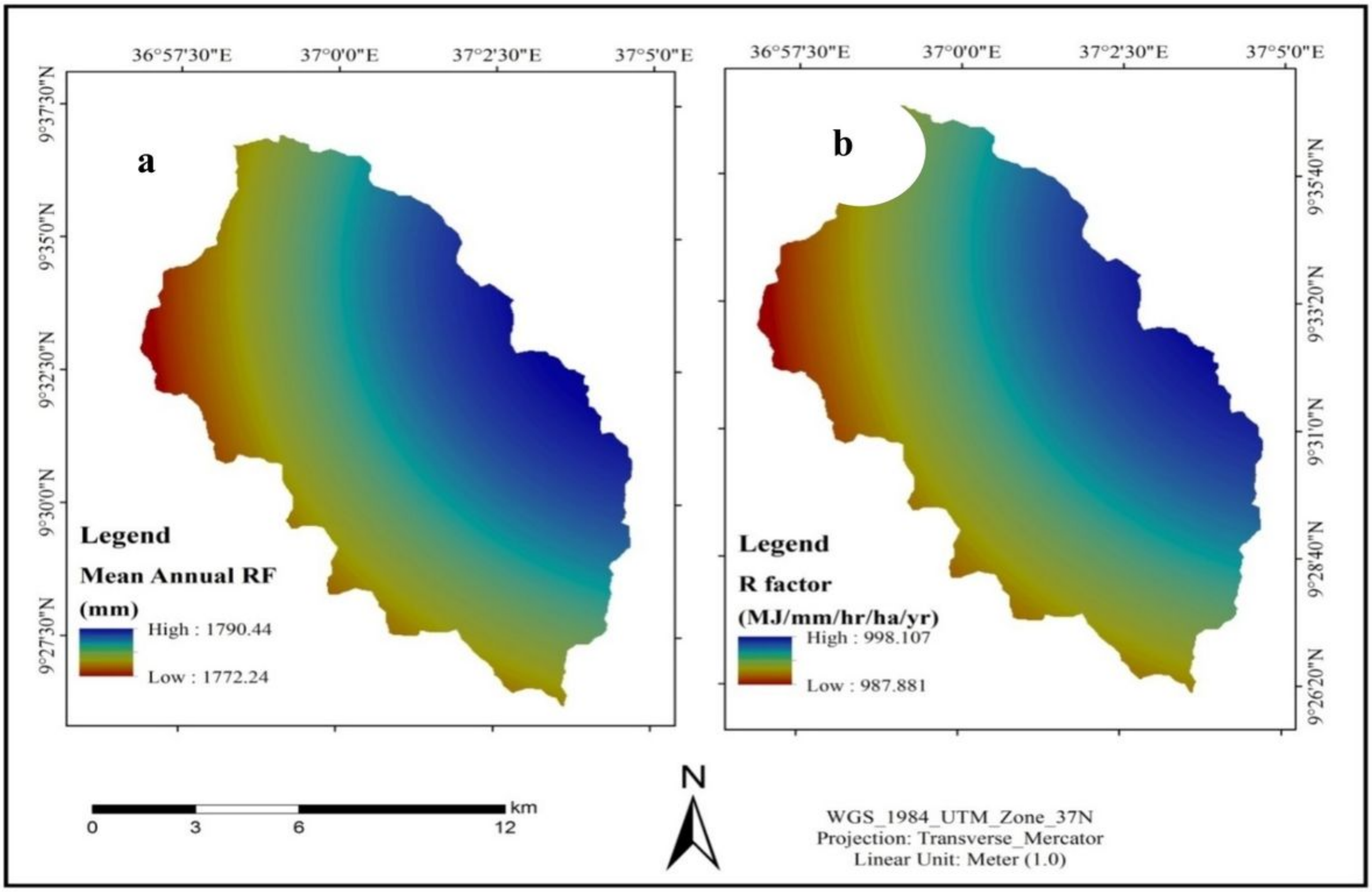


Figure 3

:(a) Mean annual rainfall and (b) R factor of the study area



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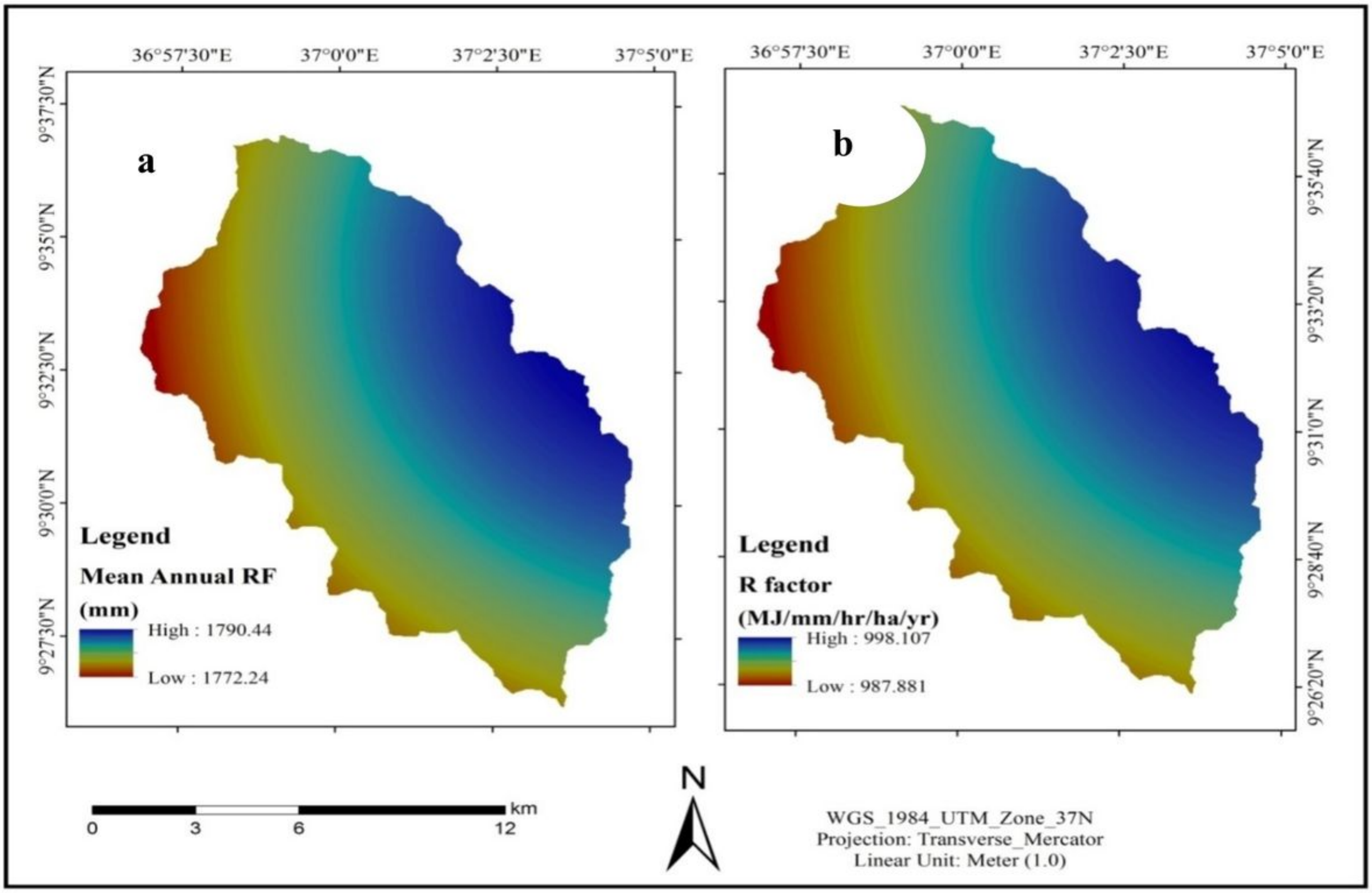

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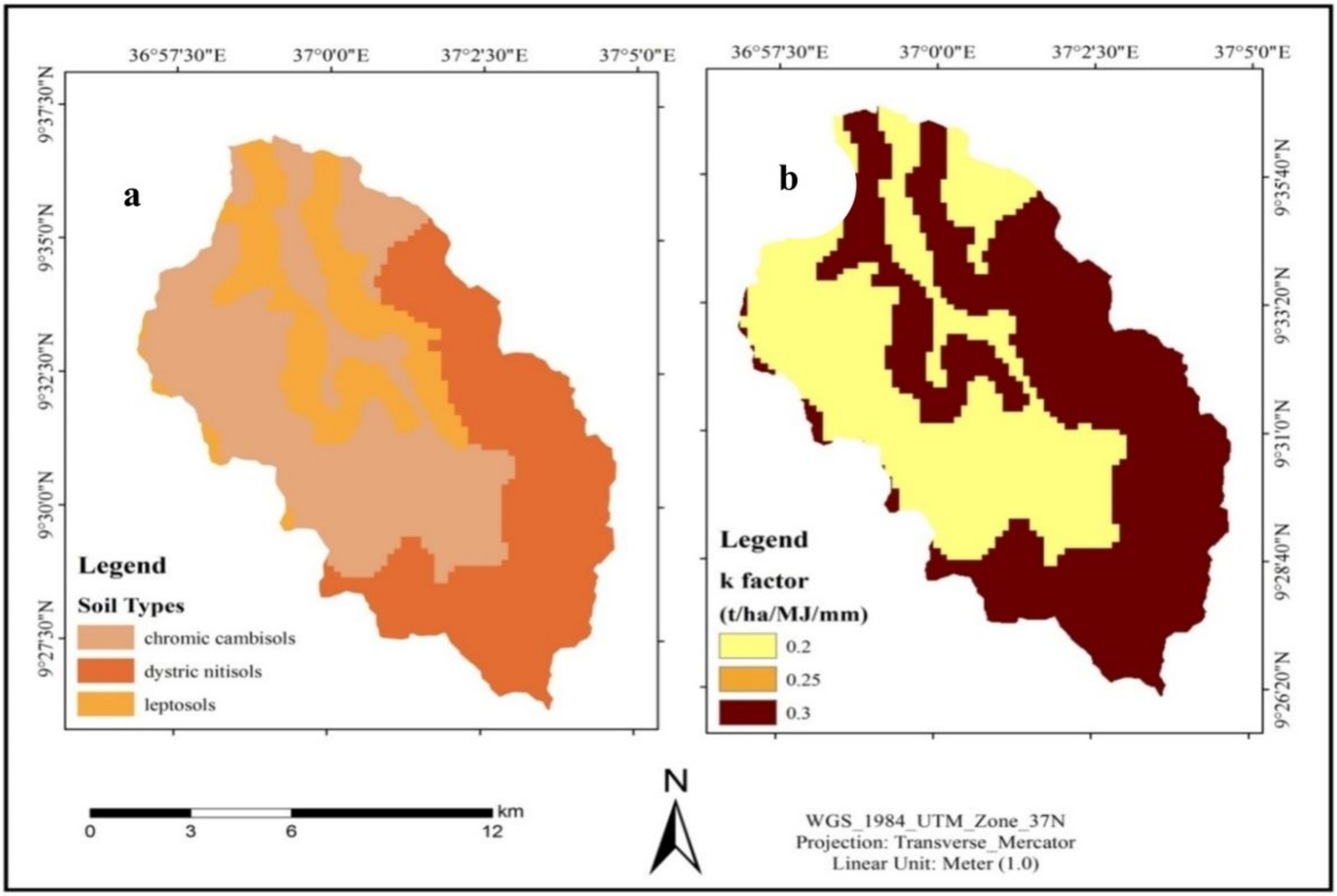
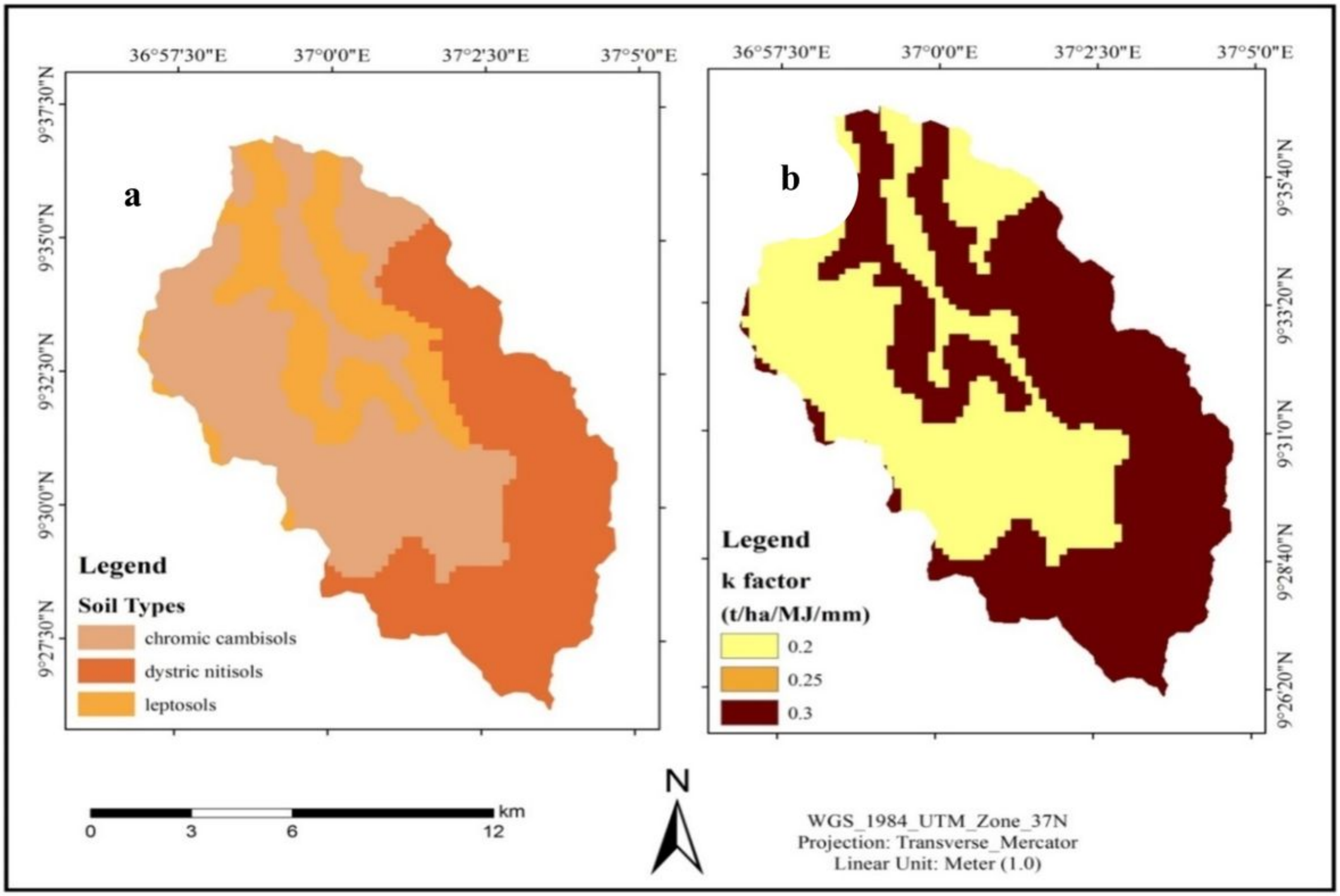


Figure 4

(a) Soil Types and (b) K factor of the study area



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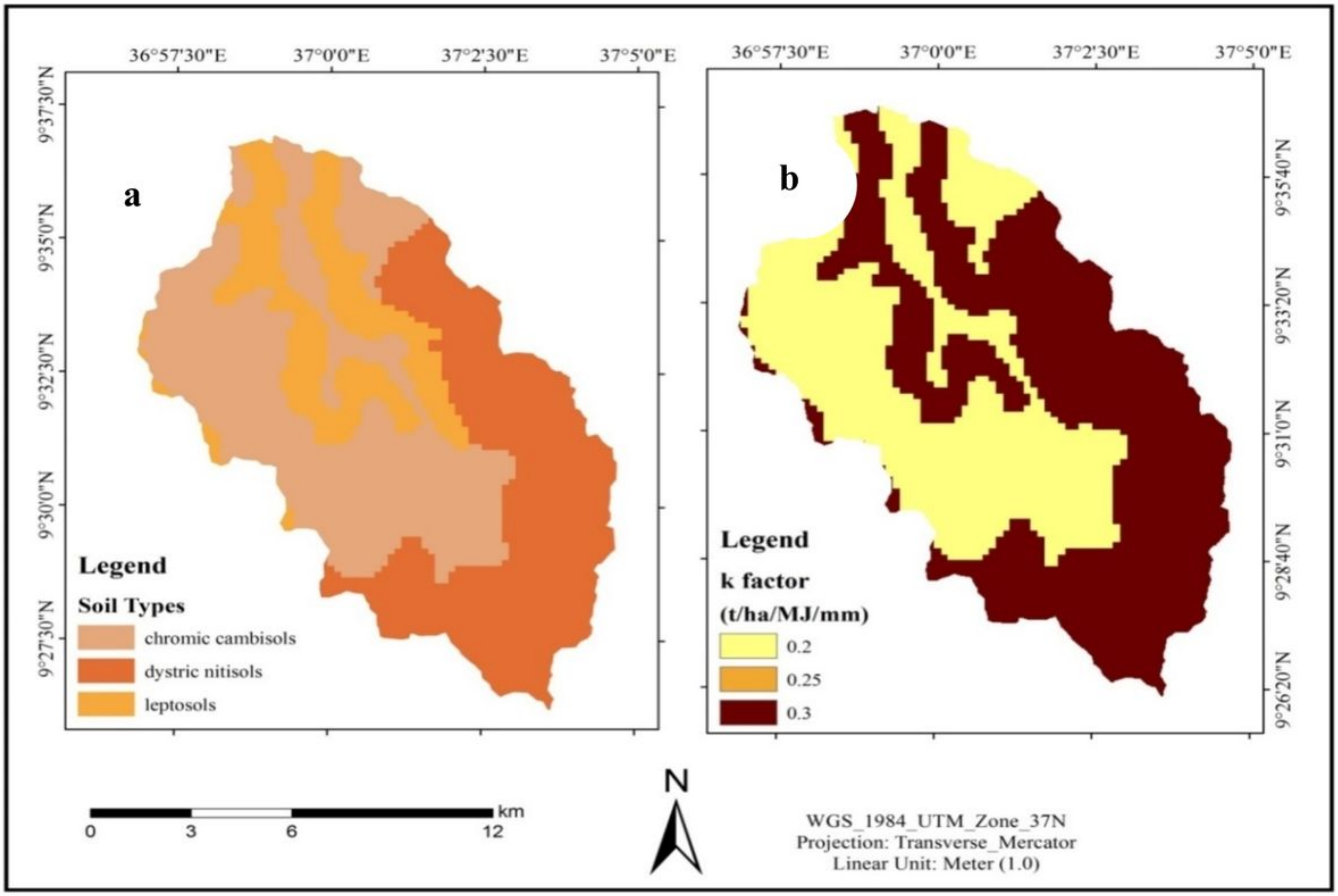

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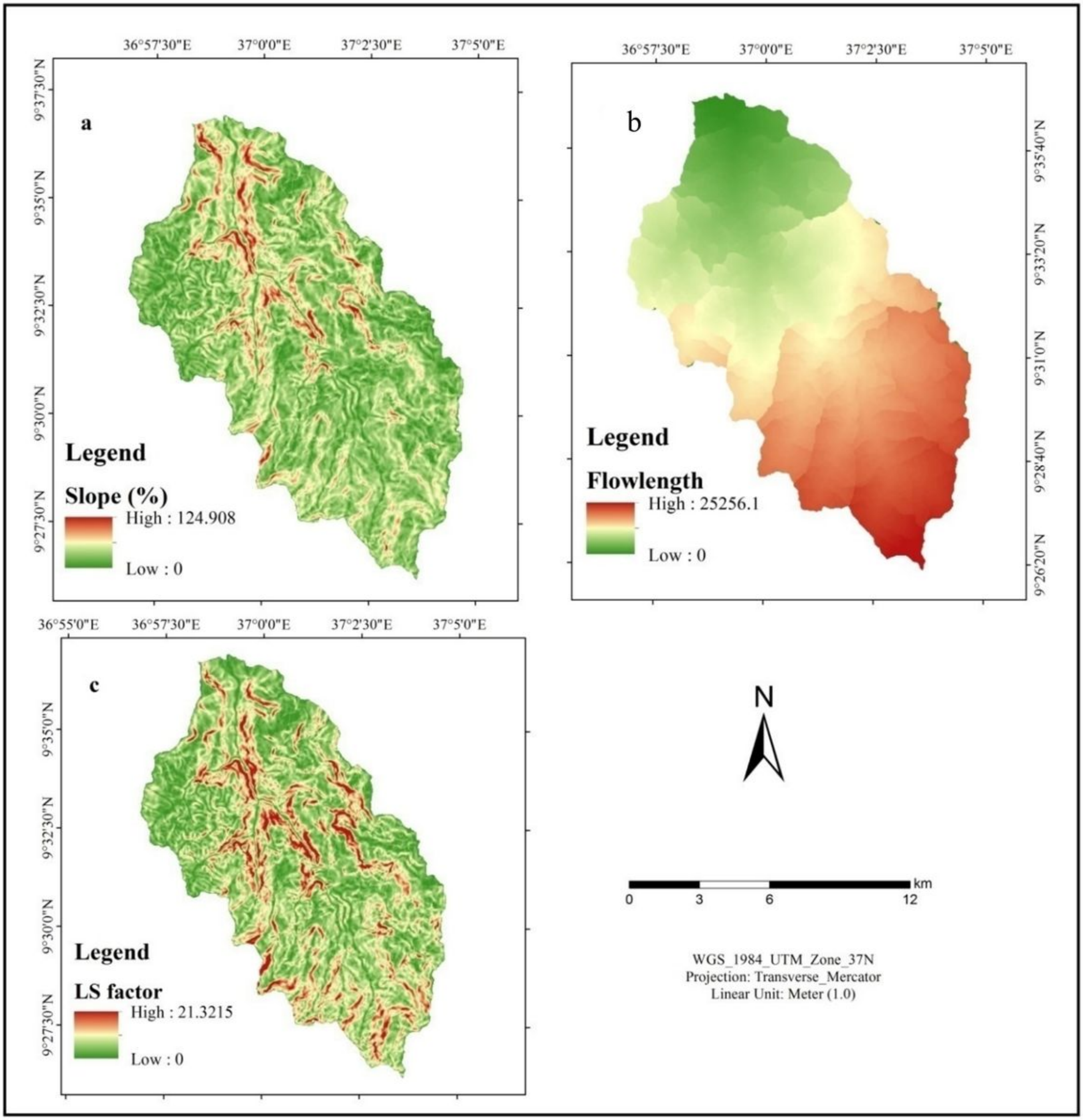
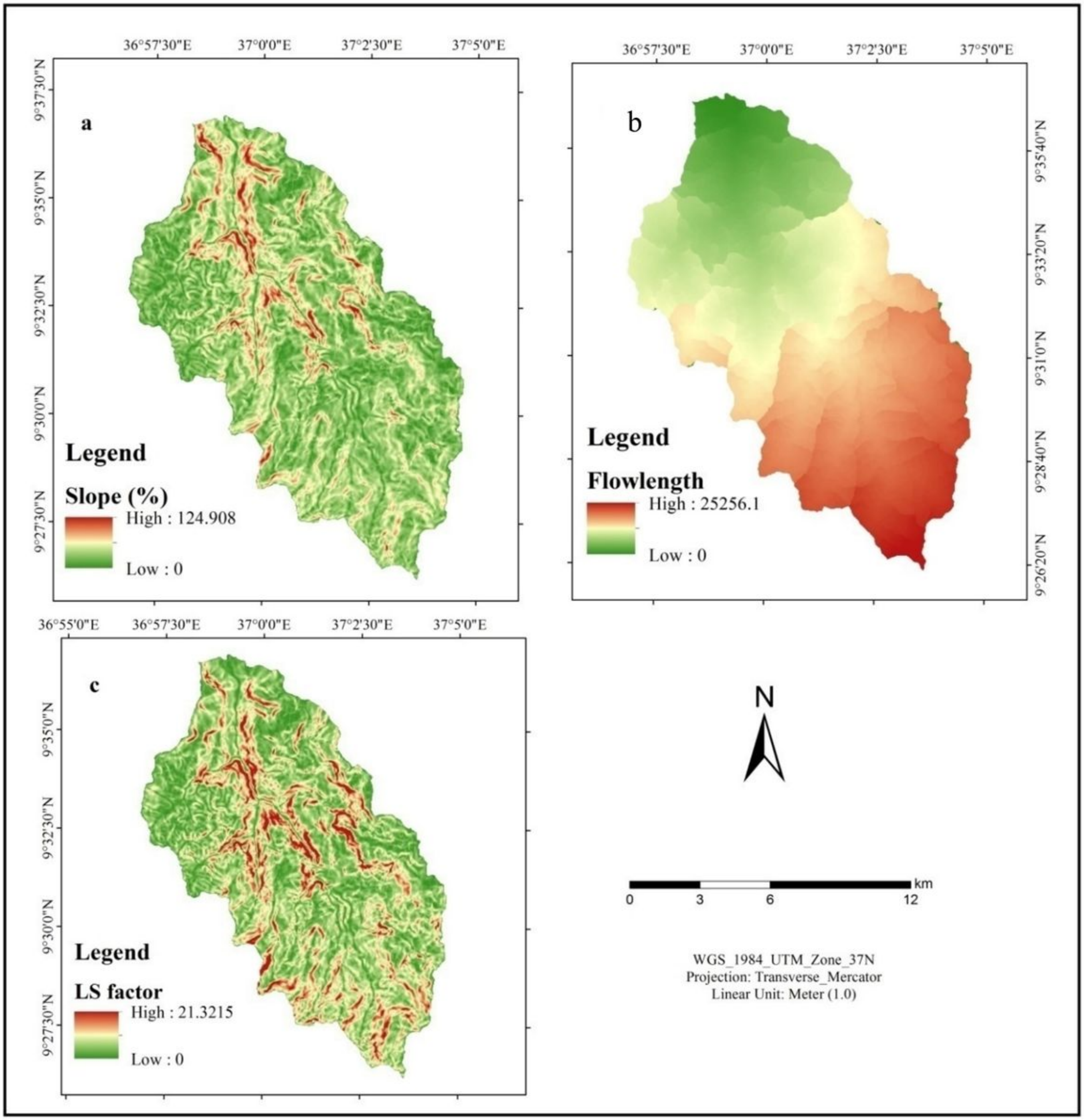


Figure 5

(a) Slope, (b) Flow length and (c) LS factor of the study area



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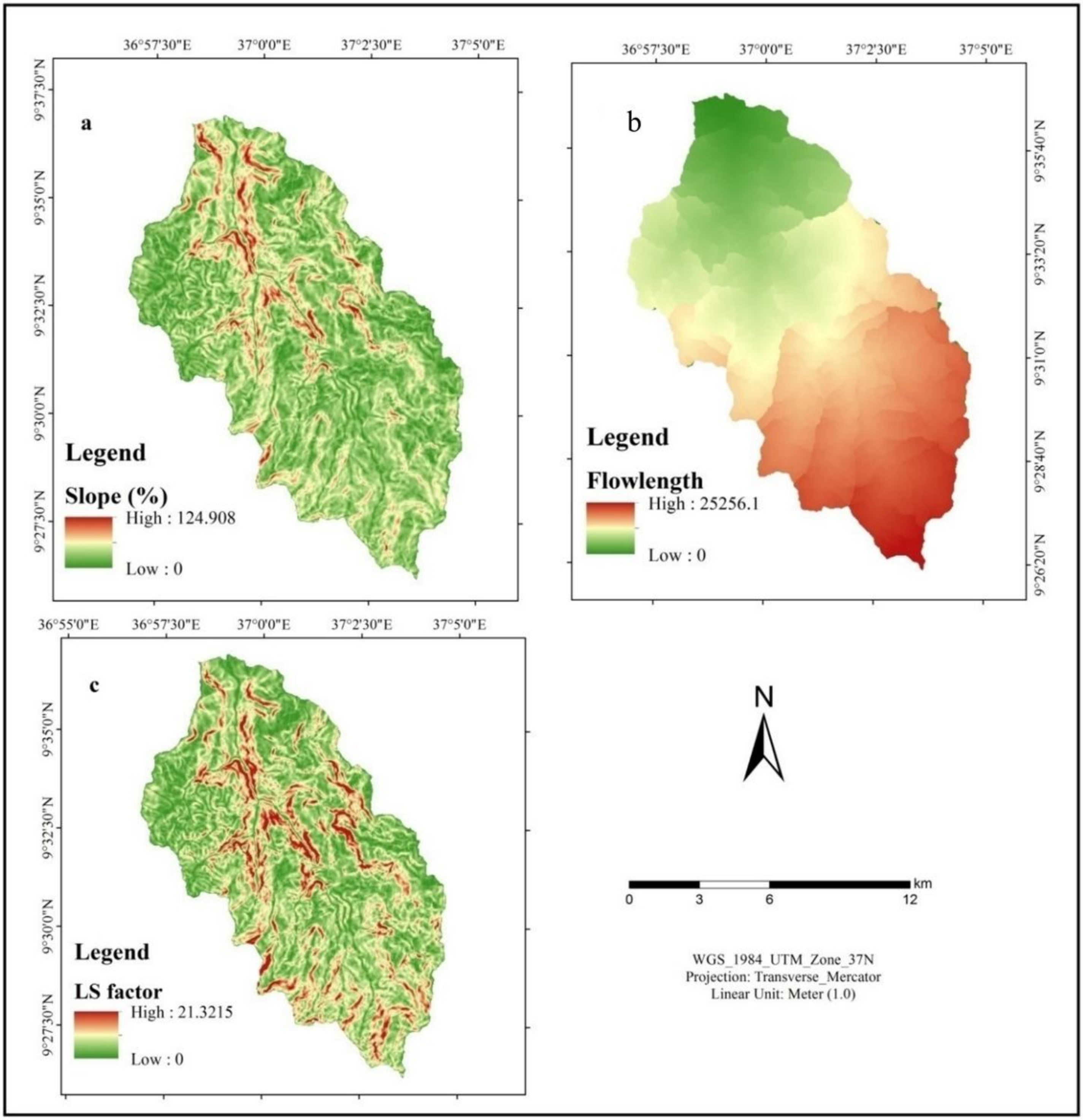

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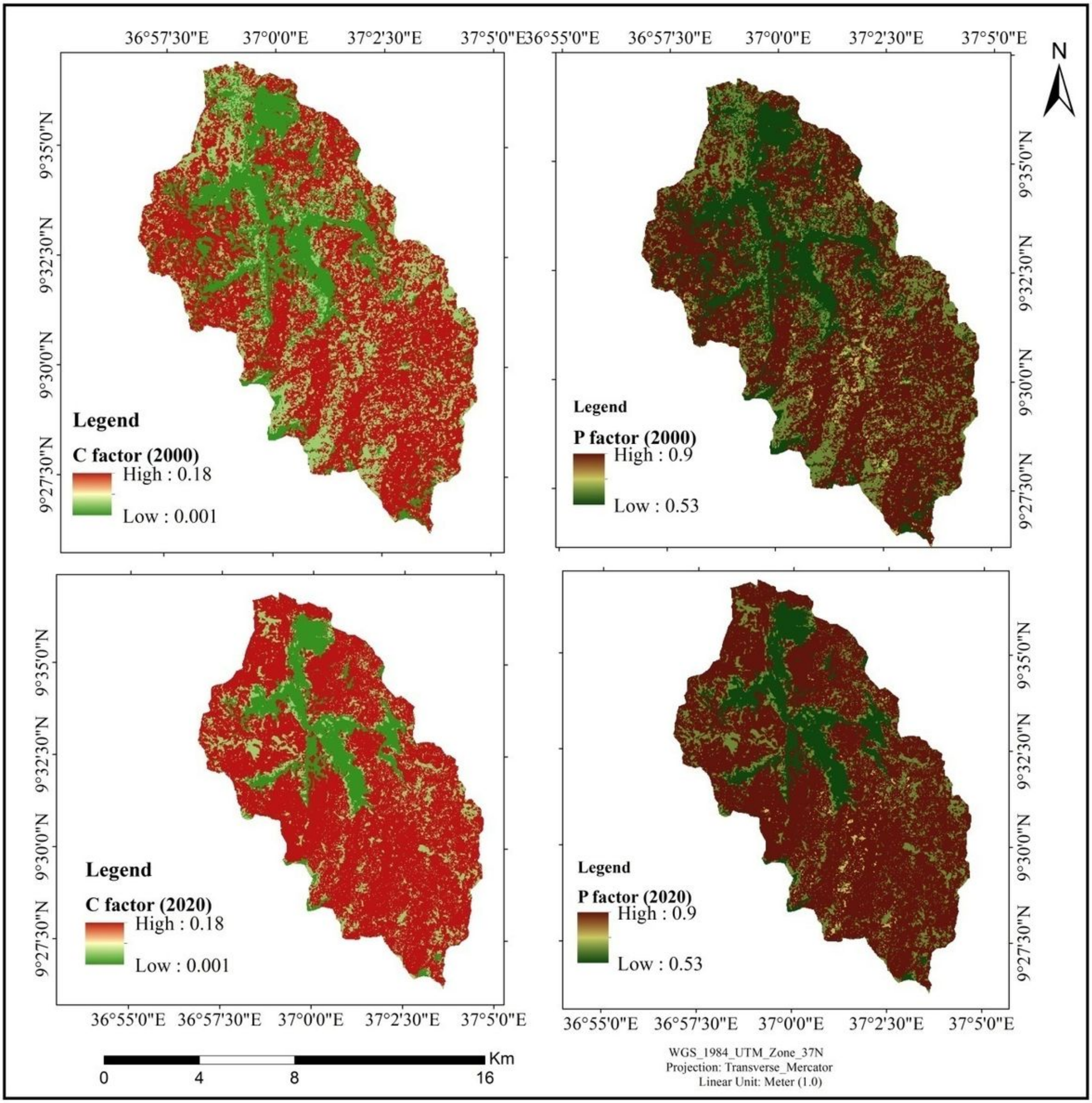
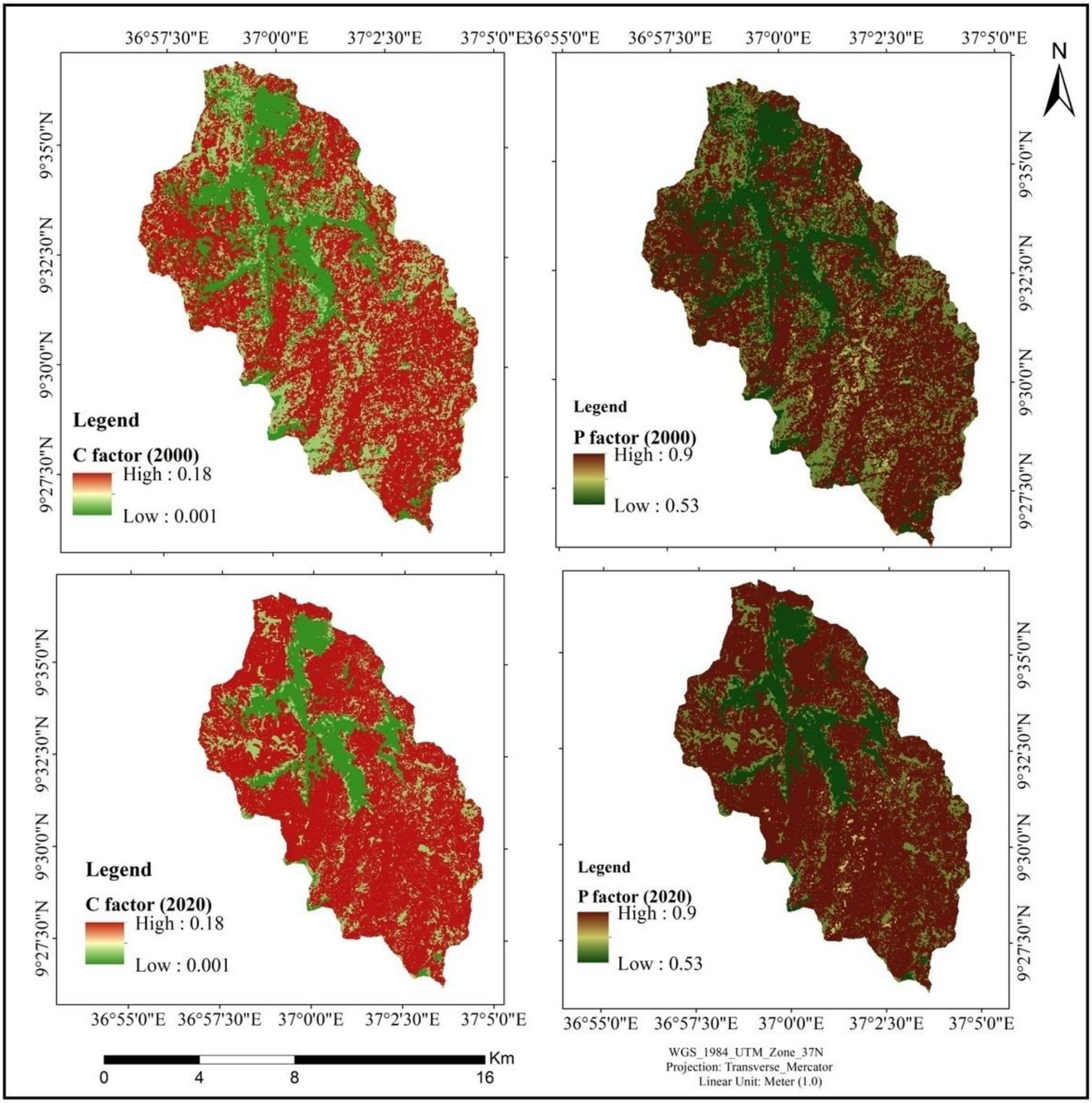


Figure 6

C (left) and P (right) factors of the study area



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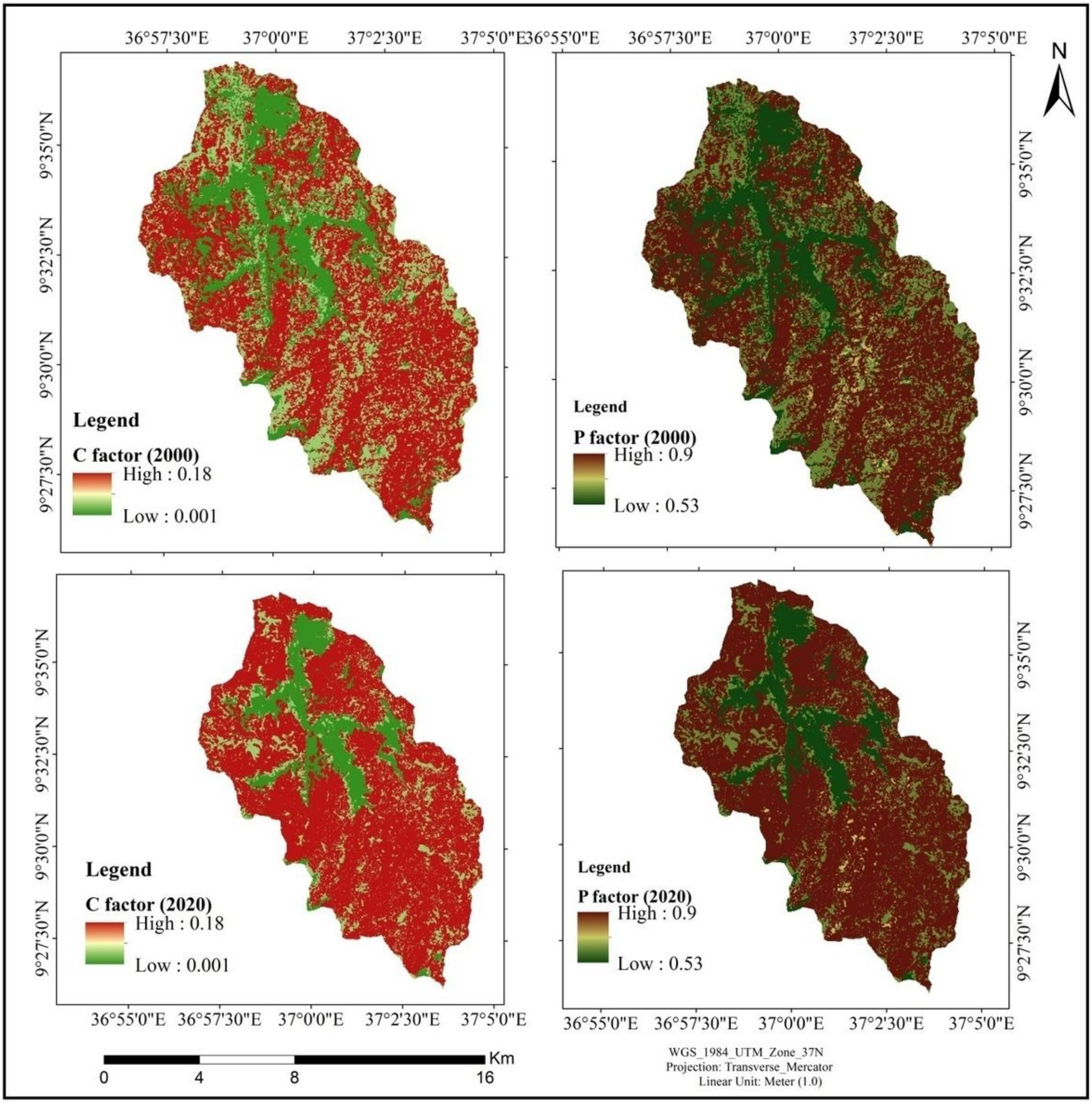

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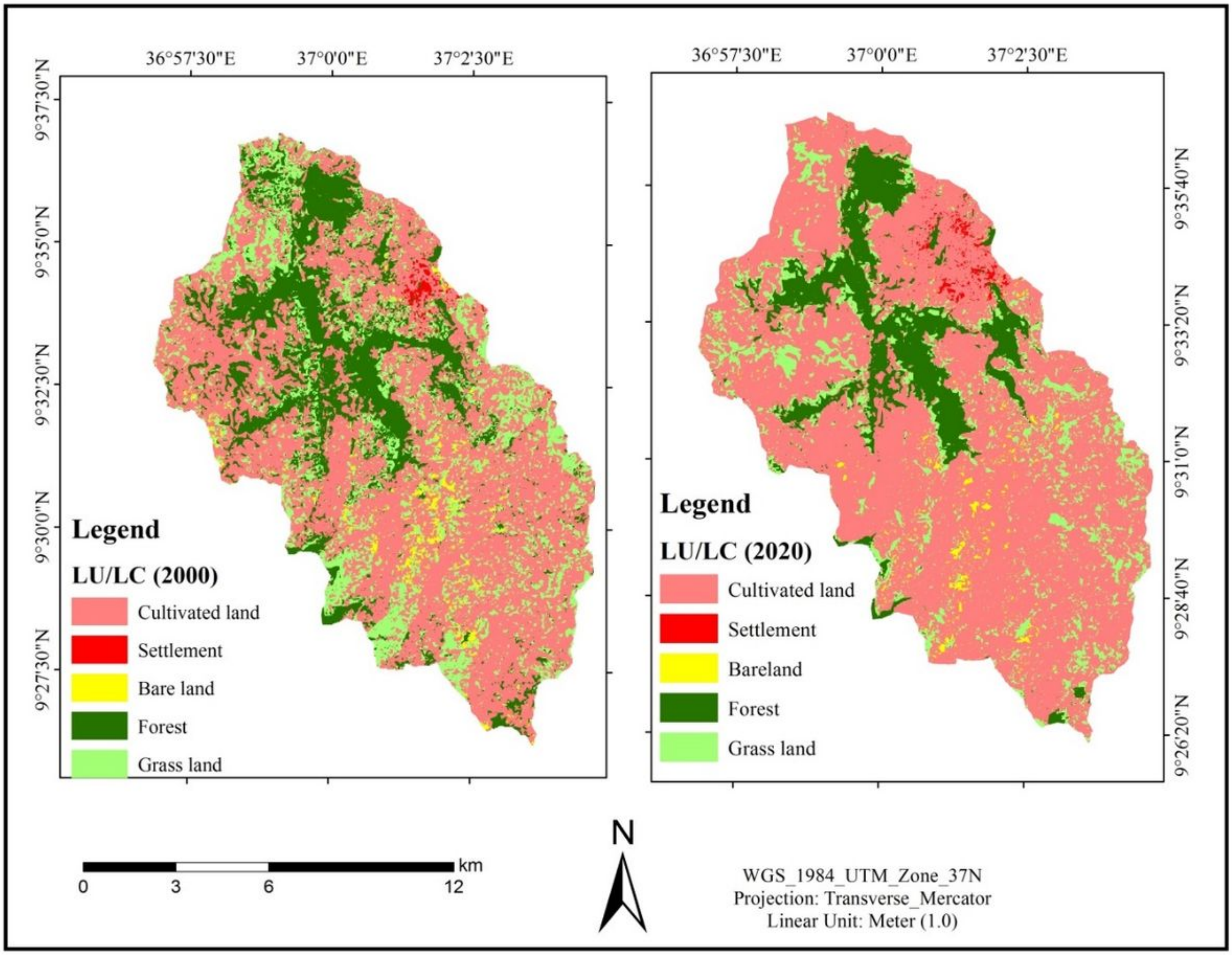
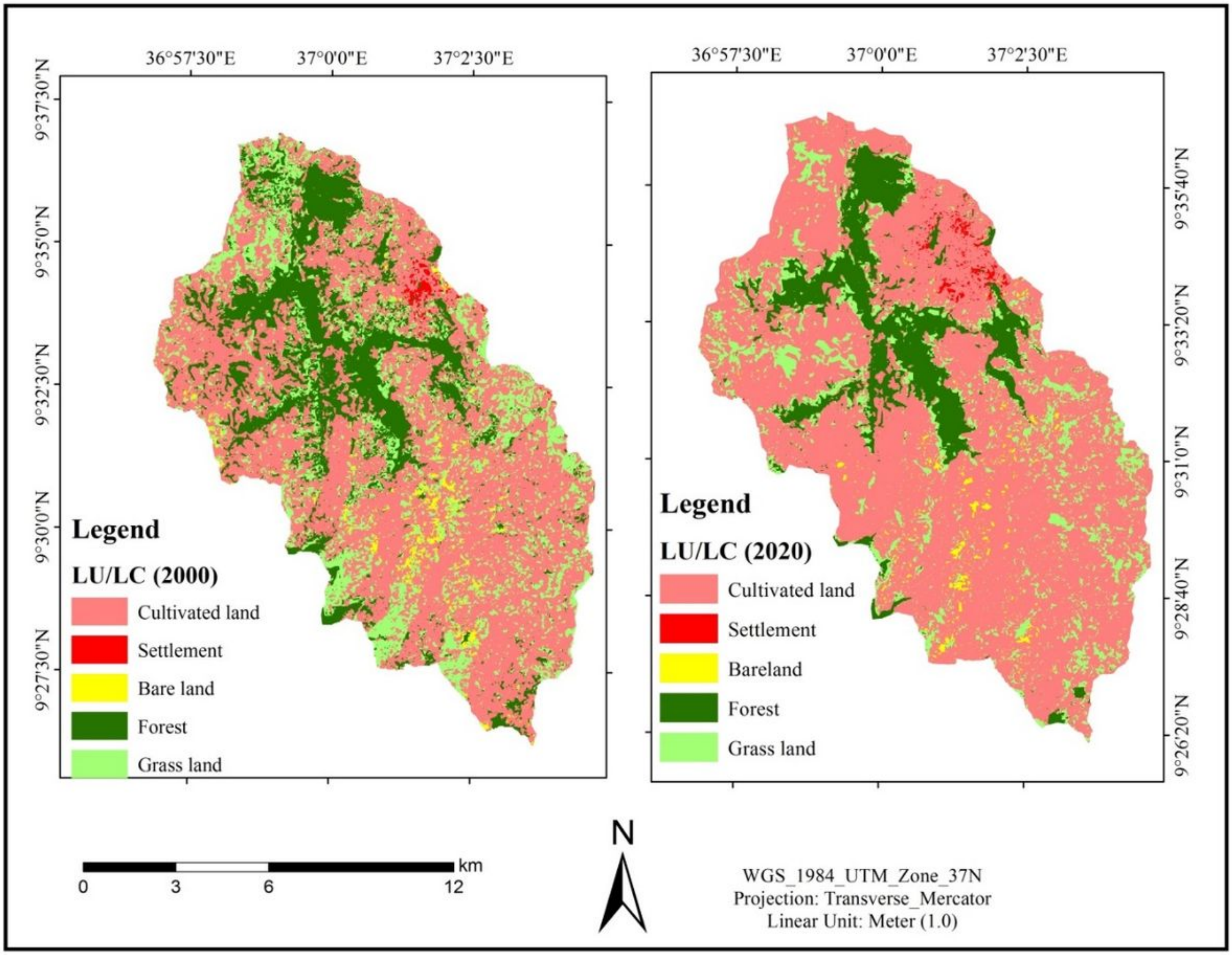


Figure 7

Land use/Land cover map of the study area



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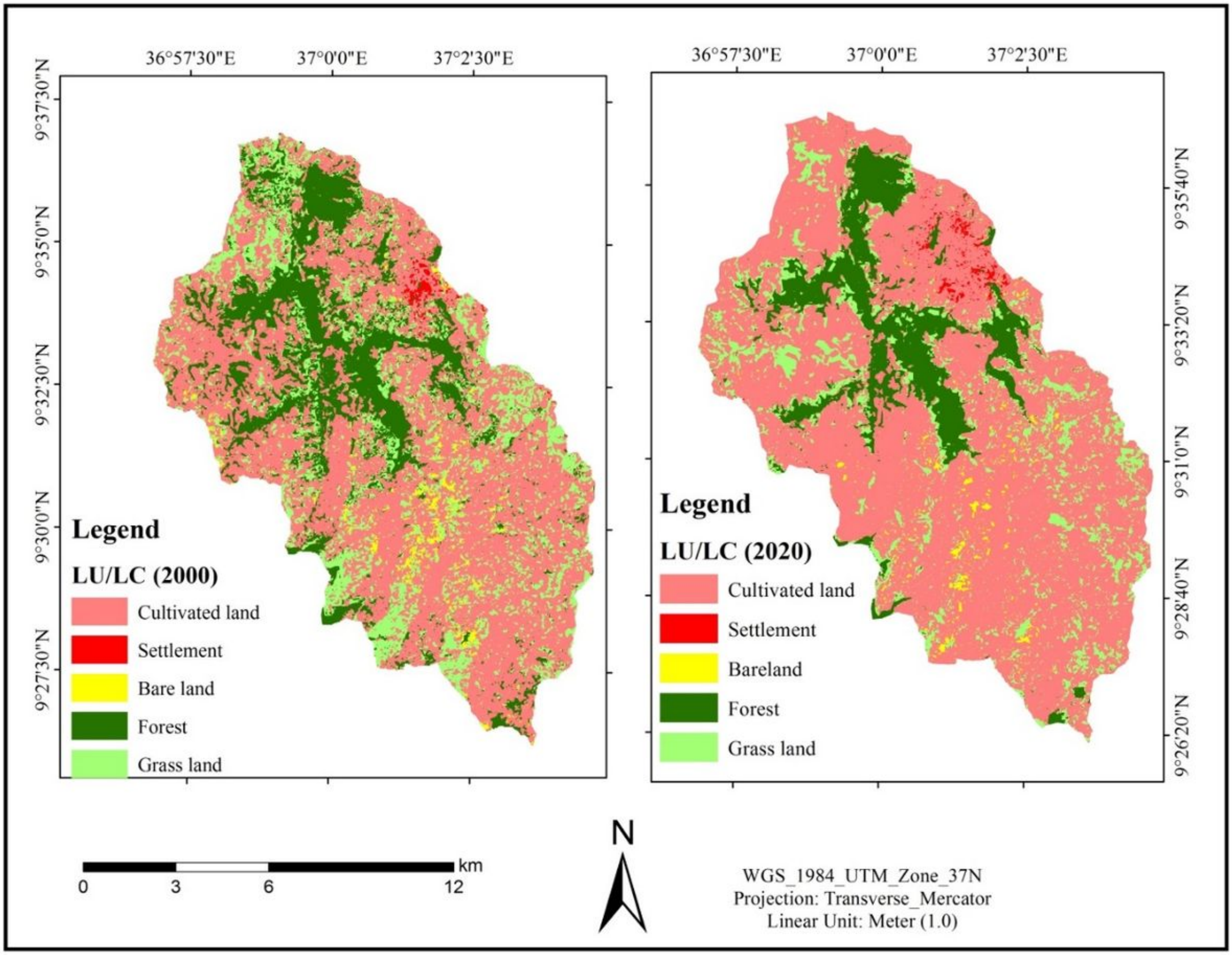

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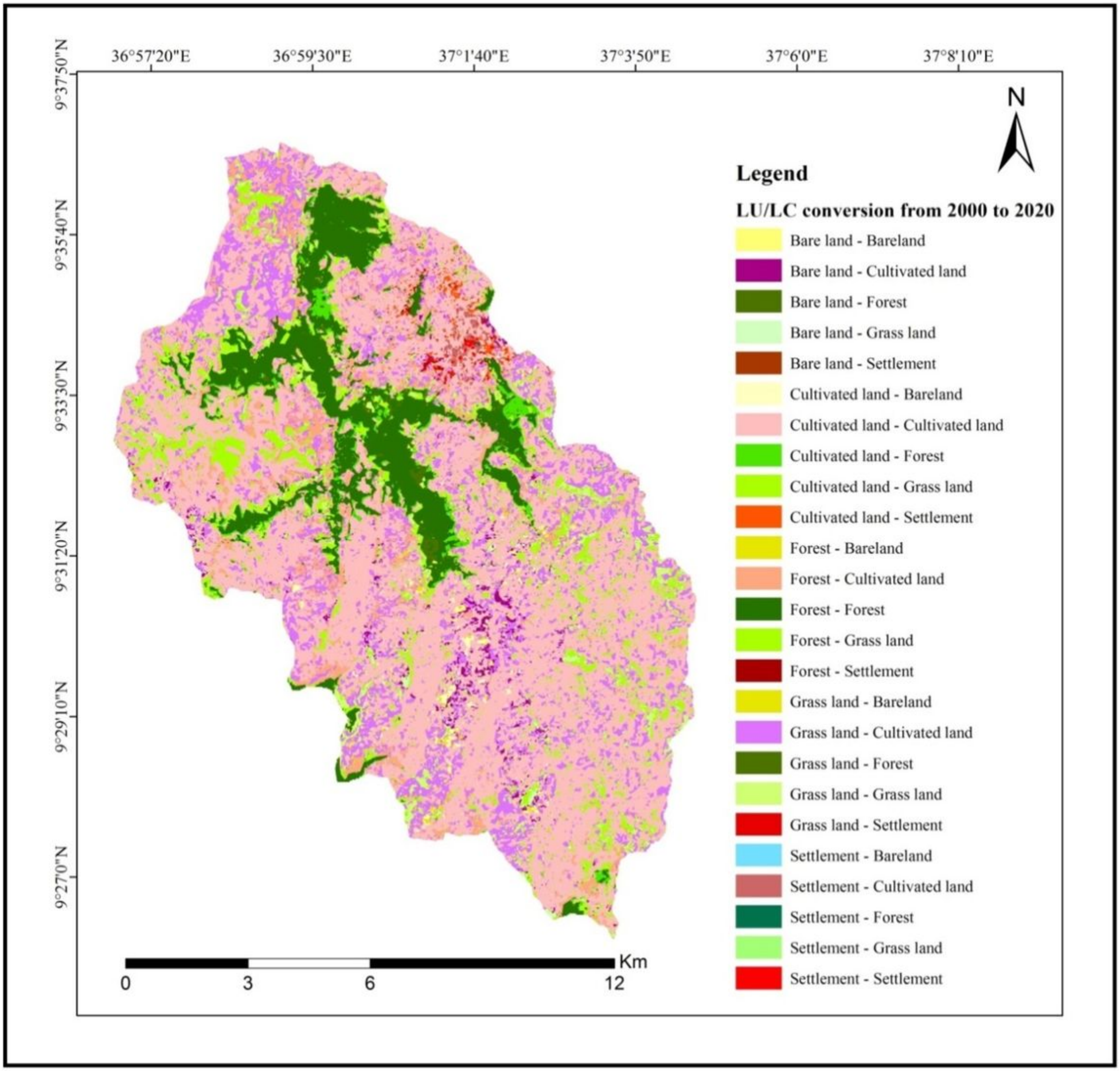
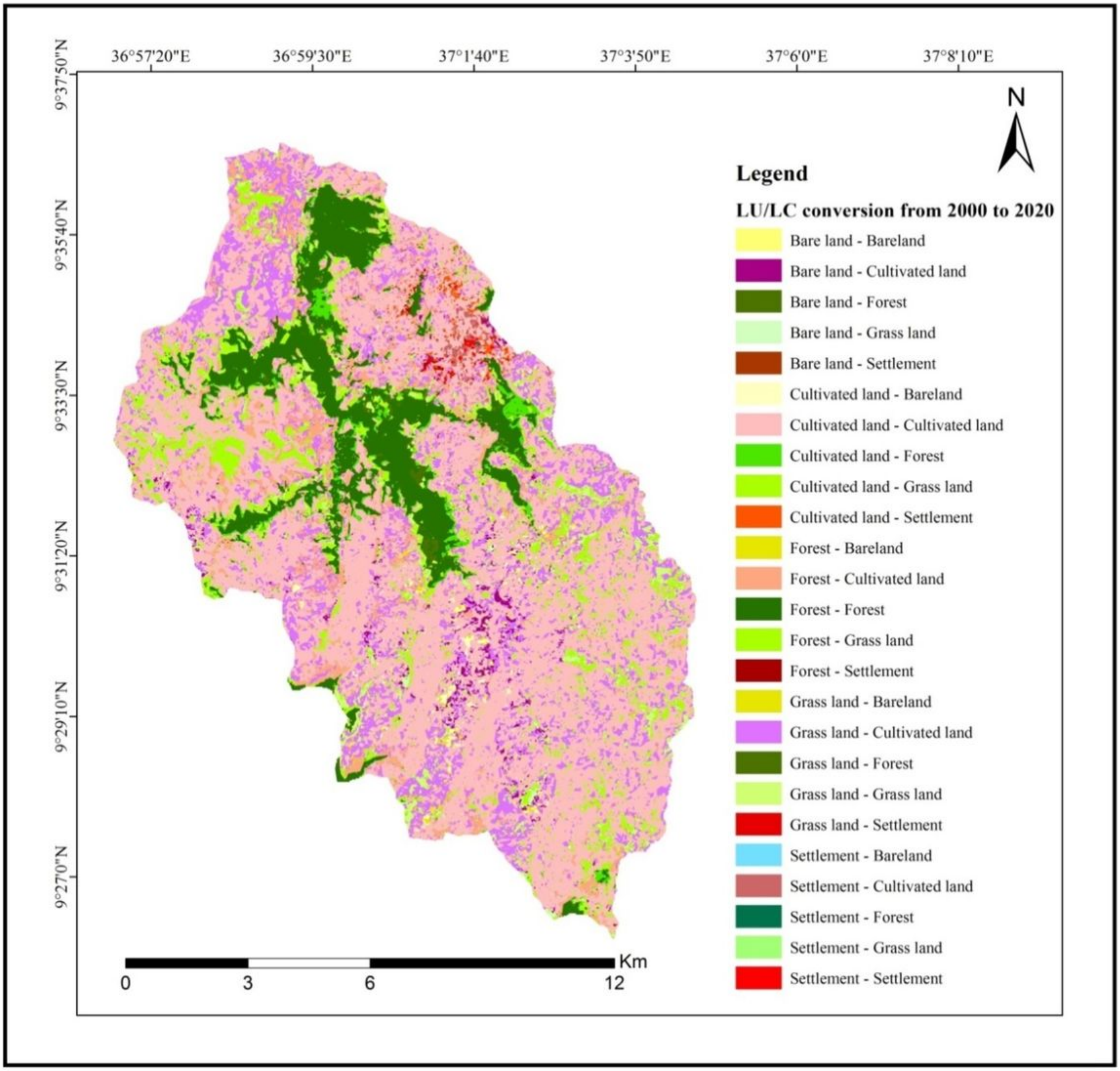


Figure 8

Land use/Land cover conversion from 2000 to 2020



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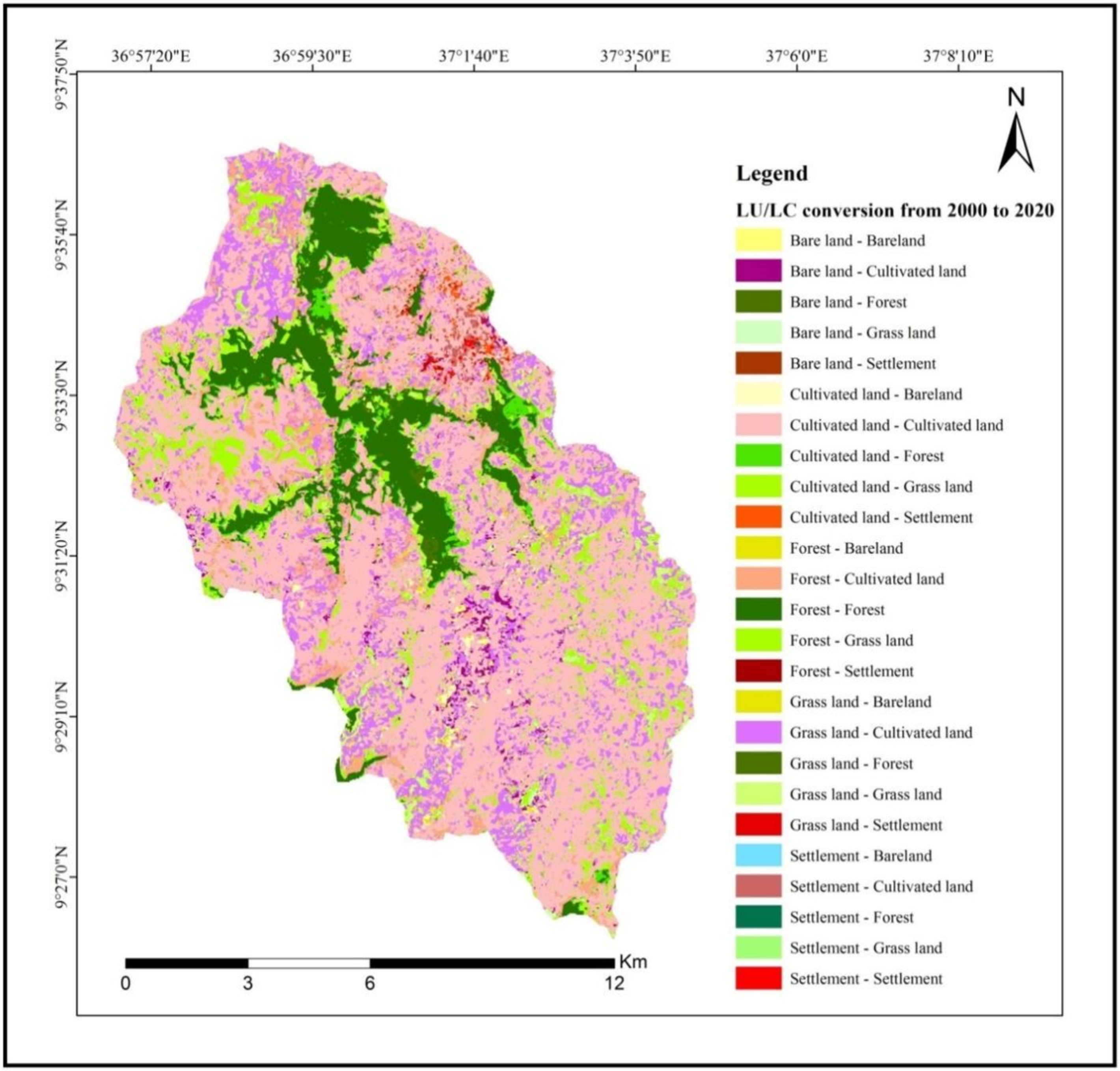

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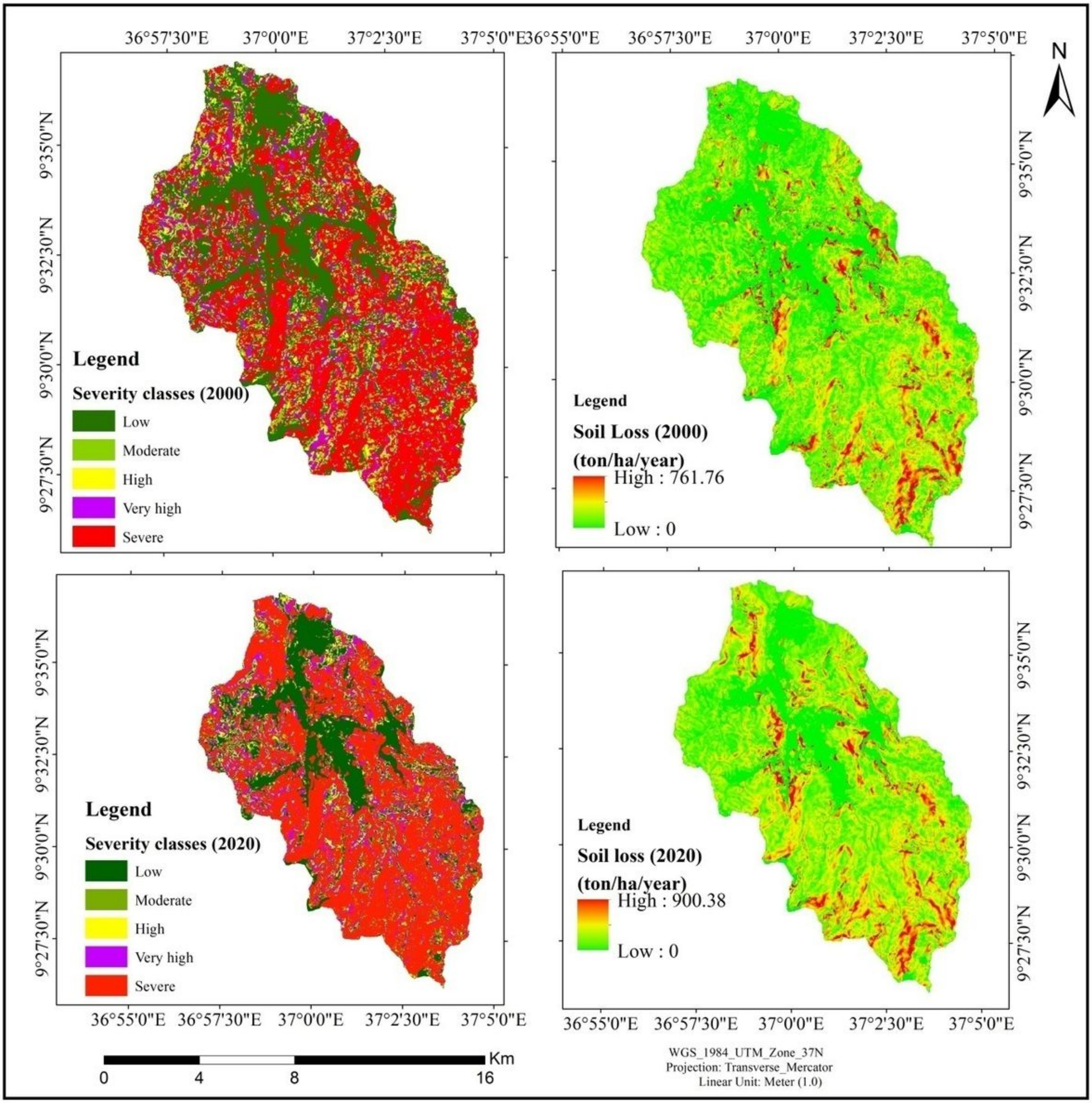
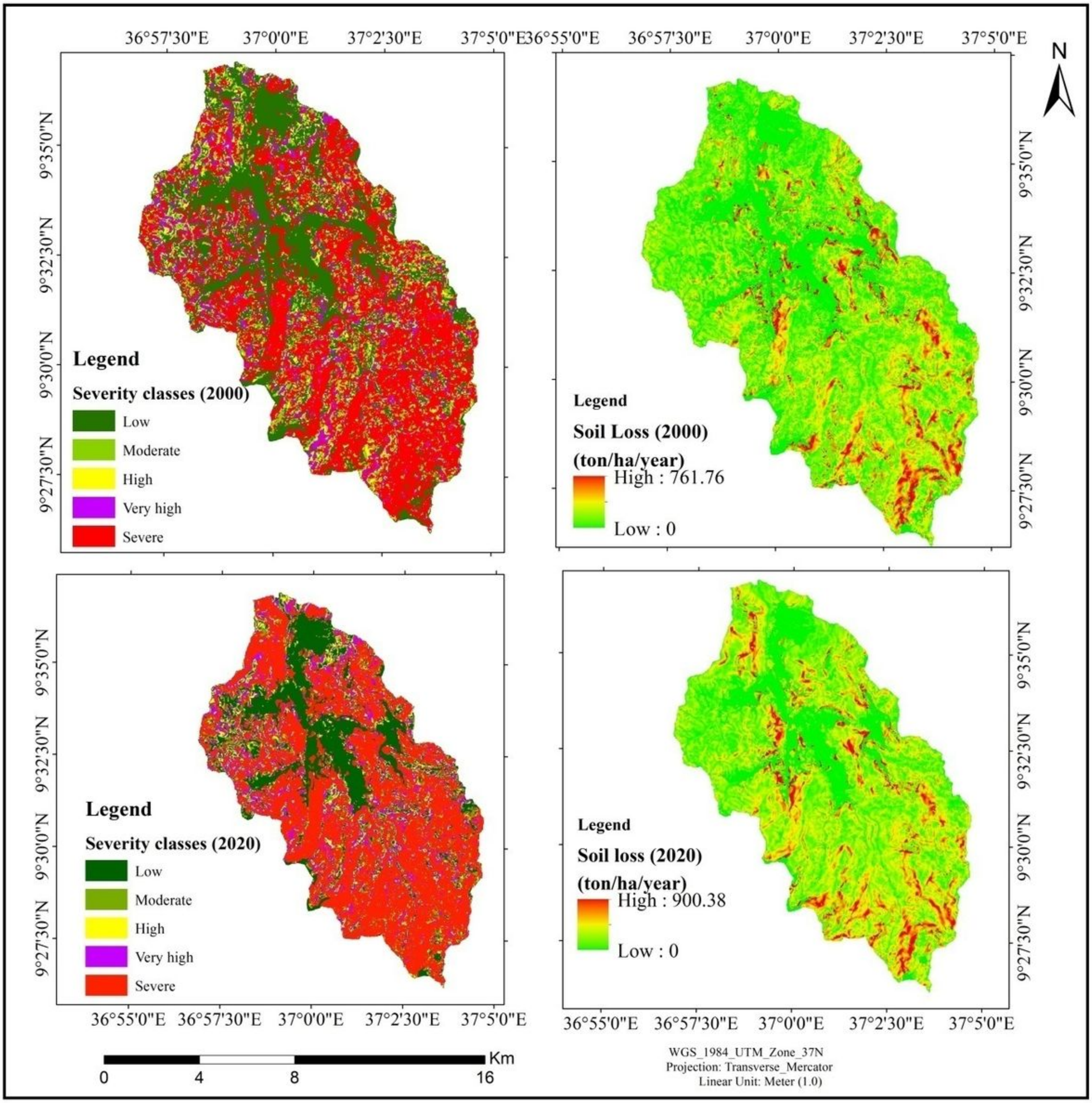


Figure 9

Severity classes (left) and Soil loss (right) map of the study area



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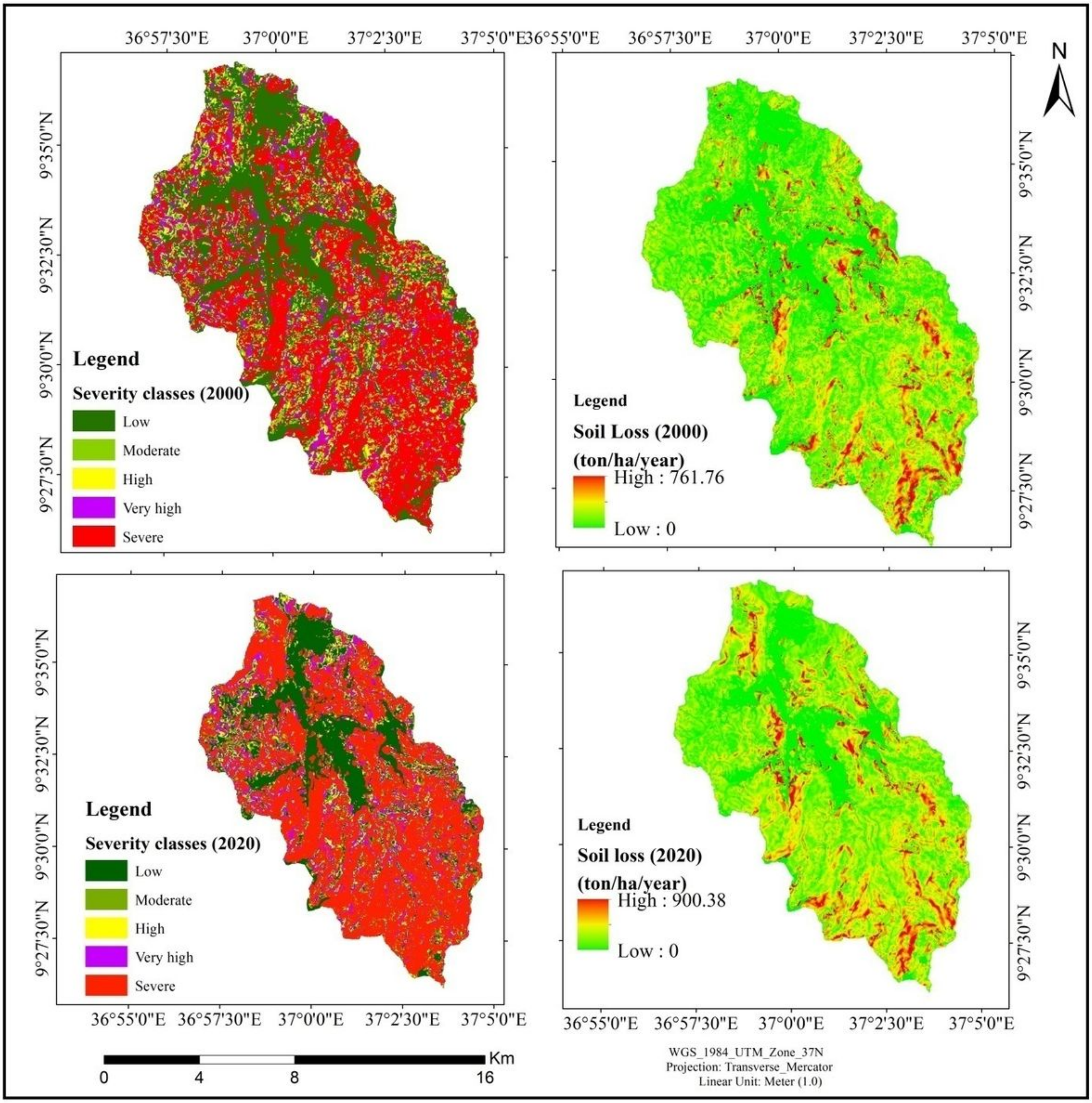

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