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Research Article

Impacts of Land Cover and Greenness Change on Soil Loss and Erosion Risk in Damota Area Districts, Southern Ethiopia

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Soil erosion is a key problem in Ethiopia in view of tropical climate, lack of vegetation, and landscape relief. Therefore, soil and water conservation (SWC) measures have been practiced, but their impacts on soil loss have not been estimated adequately. The RUSLE modeling was applied using satellite imageries, ASTER GDEM, rainfall, and soil data to estimate total annual soil loss for a 100 km^2 hilly and highly populated area in Ethiopia. Soil loss decreased in the Damota districts from 21 to 13 million tons from 2000 to 2020. Similarly, the average annual soil loss decreased by 36%. Very slight-risk areas ($< 5\,t\,ha^{-1}\,yr^{-1}$) increased from 42.66 to 53.72%, and very high-risk areas ($> 50\,t\,ha^{-1}\,yr^{-1}$) decreased from 12 to 5%. Soil and water conservation measures showed an important implication against soil erosion through improved land cover and landscape greenness. However, still, the rate of soil erosion is high compared to the soil loss tolerance of 1–6 $t\,ha^{-1}\,yr^{-1}$ for the Ethiopian highlands.

1. Introduction

Soil erosion is an important form of land degradation globally [1]. The loss of fertile surface soil through erosion is fundamental for successful agricultural, pastoral, and forestry practices [2]. Soil erosion is among the most challenging and continuous environmental problems and has a significant impact on potential land productivity and food security in many highland regions of Ethiopia [3, 4]. Over the twenty-first century, natural events and anthropogenic factors favored risks of soil erosion [5]. In Ethiopia, the existing strong soil erosion is associated with anthropogenic causes such as high population growth coupled with cultivation of marginal land, overgrazing, land cover degradation, steep-slope cultivation, and poor soil management [6–9].

Cultivated lands are the main areas of severe soil erosion or very high runoff and soil losses [8, 10]. Because it is an activity of making the soil more vulnerable for erosion through tilling and removes the natural cover of the land that can strongly increase soil erodibility. Besides, the severity of the problem in Ethiopia can be better explained by steep topography, overgrazing, and continuous cultivation with poor agricultural technology [11]. Due to a shortage of farmland resulted from population pressure, steep-slope areas (including a slop >30%) have been cultivated without appropriate conservation measures [12]. Lands with a slope gradient of >15% are not suitable for cultivation [13] and susceptible to water erosion [7, 8, 10]. For instance, studies indicated that cultivated land contributes 80% of the total soil loss [14] and 54% of runoff [7]. As a result, soil erosion in sheet, rills, and gullies are prevalent in the Ethiopian highlands [15].

The Damota area of southern Ethiopia is characterized by high population density, erosive rainfall, rugged topography, and intensively cultivated land for a long period. Erosive rainfall is rainfall with a cumulative value of greater than 12.7 mm [44]. Because of these and other related factors, the area has been experiencing high soil erosion. These are noticeable by erosion features in the area particularly during the rainfall periods, although the rate and spatial variation has not been studied and documented so far.

Soil erosion results in multifaceted negative effects on humans and the environment. It causes an increased runoff from more impermeable subsurfaces, displaces nutrient-rich topsoil [16, 17], limits vegetation growth and productivity, and disturbs biodiversity [16]. The rate of soil loss in Ethiopia reached mostly as high as five times the maximum soil loss tolerance [8, 18, 19]. Zeleke and Hurni [12] estimated to lose ~9 million tons of soil from rain-fed cultivated fields. Besides, it reduces cultivated lands such as area damage by gully erosion and stream bank expansion [13]. By these, serious environmental degradation has occurred, and the livelihood of two-thirds of households has been critically affected in Ethiopia [12, 20]. It is therefore a foremost threat to subsistence agriculture [21], sustainability of production [22], and the national economy [23].

Soil and water conservation measures are acknowledged as the best method to control and minimize further soil erosion and rehabilitation of degraded landscapes. Conservation measures are local-level activities that maintain or enhance the productive capacity of the land in areas affected by or prone to degradation (World Overview of Conservation Approaches and Technologies (WOCAT)) [24]. In this regard, for the past 2–4 decades, SWC activities were performed in most parts of the Ethiopian highlands [10, 11]. Similarly, large-scale watershed management activities were practiced in the Damota districts mainly in the past two decades.

However, several researches reported the limited effectiveness of conservation practices [25]. Indeed, soil erosion is still very high [8, 18, 19, 23]. This is mostly related to the lack of site-specific, evidence-based implementation and maintenance of conservation measures [8]. Particularly, in the Damota area, the SWC practices have not been performed based on quantified soil erosion data. Quantitative data of soil erosion and hotspot area identification are considered a foundation for watershed management initiatives [26]. Planning and implementation of conservation measures need an understanding of the extent, risk, and spatial variation of soil loss [19]. On the other hand, analyzing the effect of improved land cover and greenness as a result of SWC measures is vital to learn lessons from past conservation efforts because conservation measures primarily increase the density, greenness, and health of vegetation through increased infiltration and reduction of soil loss.

Both soil erosion quantification can be reasonably estimated using GIS and remote sensing-based RUSLE modeling [8, 19, 27, 28]. It is a recommended method in areas lacking data for model calibration and validation and is effectively implemented [7, 19, 27]. Thus, this study employed the RUSLE model adopted in the Ethiopian condition [27]. The objectives of this study were to: (1) estimate soil erosion rate and spatial distribution and (2) evaluate the impacts of land cover and greenness changes on soil erosion in the past two decades in the Damota area districts.

2. Methods and Materials

2.1. The Study Area. Damota area comprising Bolosso Sore, Damot Gale, and Soddo Zuriya districts lies between 6° 44′ 30″ to 7° 9′49″ Latitude and 37° 34′ 47″ to 37° 98′ 58″ Longitude in the Wolaita zone of the Southern Nations, Nationalities, and Peoples region (Figure 1). It is located 395 km south of Addis Ababa, the capital city of Ethiopia. It covers an area of 97,600 hectares. Damota area districts are dominated by rugged and elevated topography particularly in the central part formed by tectonic and volcanic activity. According to the agroclimate classification system, the area is classified as Dega and Woina Dega zones with an altitude ranging from 1,480 to 2,855 meters above sea level (Figure 1).

Dystric Cambisols, Chromic Vertisols, Chromic Luvisols, Pellic Vertisols, Vitric Andosols, Eutric Nitrosols, Orthic Acrisols, and Lithosols soil types dominate the Damota area. The mean monthly minimum and maximum temperatures are 14 and 20°C, respectively (Figure 2). The area receives a long-term average annual rainfall of approximately 1,200 mm in a bimodal rainfall pattern. The main rainfall season is from June to September (locally called *Kiremt*) and a small rainfall season from February to March (locally called *Belg*).

Cropland is the dominant land use type in the study area followed by shrub woodlands, grasslands, forestland, bare land, and settlement land. Small-scale subsistence mixed farming is the main livelihood system in the area. The most commonly cultivated crops are barley (*Hordeum vulgare*), wheat (*Triticum Vulgare*), maize (*Zea mays*), teff (*Eragrostis tef*), horse bean *(Pisum sativum)*, and chickpeas (*Cicer arietinum*). Damota area districts are among the highly populated parts of Ethiopia. For instance, according to 2007 census data, the rural population density of the area varied from 167 persons km^{-2} in the midlands to 746 persons km^{-2} in the highlands [30].

2.2. Model Input Data Types, Quality, and Sources. The RUSLE model primarily uses five main factors (climate (rainfall), soil, topography, land use/cover, and land management) as an input to estimate the annual soil loss. Therefore, the rainfall data was collected from the National Meteorology Agency of Ethiopia. Soil data of the study area with 1:250, 000 scale was collected from the Ministry of Water, Irrigation, and Energy of Ethiopia. The ASTER GDEM 1-arc second data from United Nations Geological Survey (USGS) website (http://earthexplorer.usgs.gov) was used to compute the topographic information (slope length and steepness). Besides, USGS was also consulted for satellite imageries of 2000 (Enhanced Thematic Mapper Plus, ETM+) and 2020 (Operational Land Imager, OLI) at a path of 169 and row of 55 with 30 m spatial resolution to generate the land use/cover and conservation practice information.

2.3. Method of Soil Loss Estimation. The Universal Soil Loss Equation (USLE) first developed by Wischmeier and Smith [31] and later revised [32] in an integrated form with GIS and remote sensing was used. Unlike other methods of soil erosion modeling (such as SWAT), the applicability of RUSLE in data-poor areas that validation and calibration of model estimation are not possible is good [26], but still, some input data are not available enough as the quality

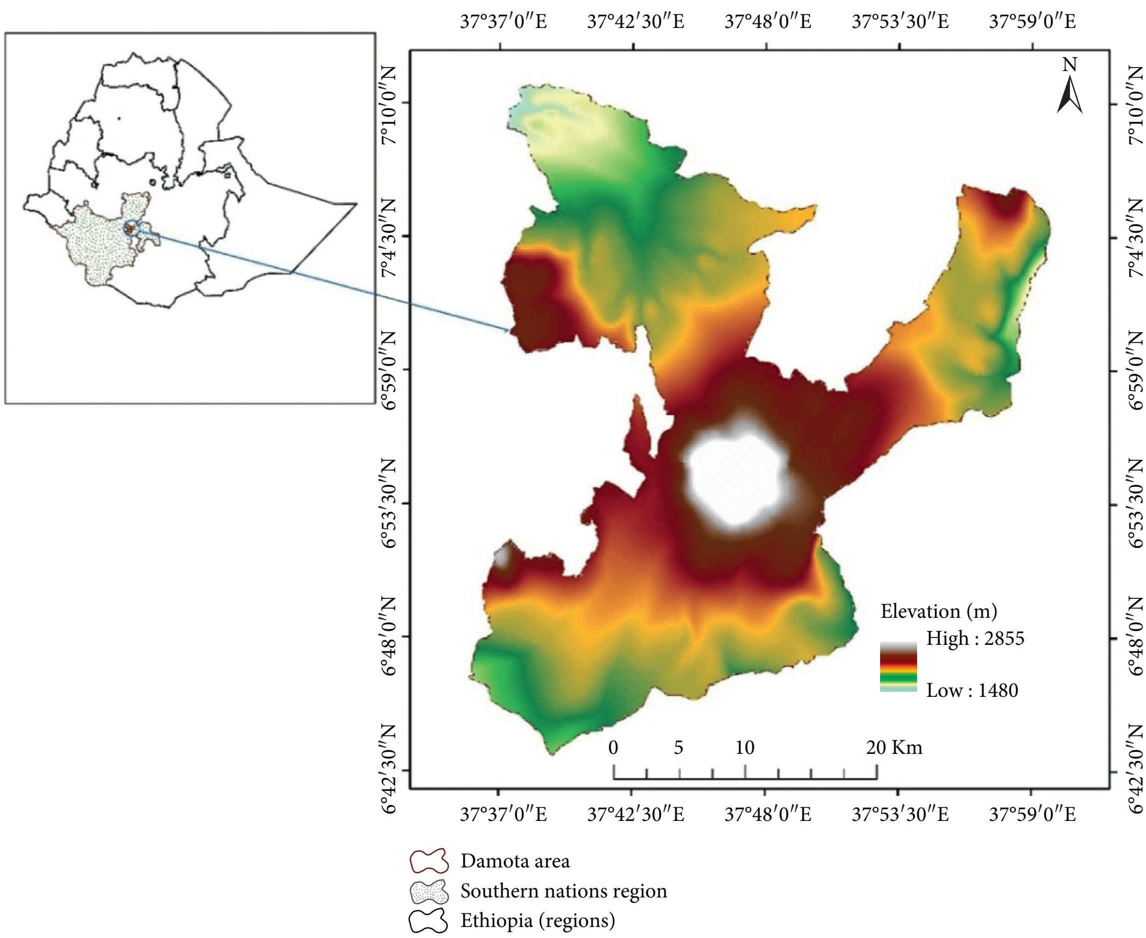


Figure 1: Location of Damota area districts in Ethiopia.

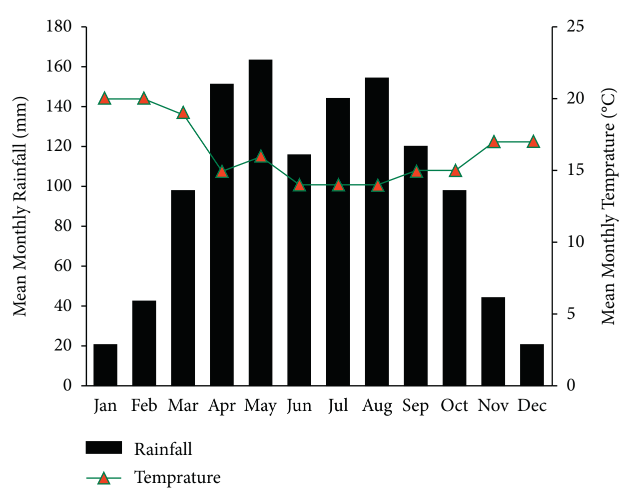


Figure 2: Monthly average rainfall (mm) and temperature (°C) in the study area (computed from 22 years of monthly rainfall and temperature data).

needed. Therefore, Hurni [29] adopted some input data computations in the Ethiopian highland conditions. He made important modifications on R-factor (rainfall erosivity index), C-factor (land use/cover), and K-factor (soil erodibility) so as to make the model applicable using the available data.

RUSLE estimates average annual soil loss using the following equation in a pixel-by-pixel-based overlay analysis of the five preprocessed (computed) erosion factors. The model is given by

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

where A is estimated annual soil loss (t ha^{-1} yr^{-1}), R is rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), S is slope steepness, L is slope length factors (dimensionless), K is soil erodability factor (t ha^{-1} MJ^{-1} mm^{-1}), C is land use land cover factor (dimensionless), and P is conservation/management practice factor (dimensionless).

2.3.1. Model Input Data Processing and Computation

Rainfall Erosivity Factor. The rainfall erosivity is the potential capacity of rain to cause erosion in a given circumstance and represents the erosive force of specific rainfall or the energy of rainfall as a driving force behind soil erosion [26]. In the USLE model, rainfall erosivity is estimated through the multiplication of total storm energy by 30 minutes rainfall intensity, expressed as EI30 measurement [32]. However, it is not mostly possible to find 30 minutes of rainfall intensity in different areas like the current study area. Therefore, the following modified regression equation developed and made it possible to use the mean annual rainfall data by Hurni [29] was applied. The regression empirical equation is given as follows:

$$R = (P \times 0.562) - 8.12, \tag{2}$$

where P is the mean annual rainfall in millimeters.

In this regard, 22-year (1998–2020) annual rainfall of four stations within the study area and bordering districts (*Gandaba*, *Dubo*, *Abala Sipa*, and *Bilate Chericho*) were collected from the National Meteorology Agency of Ethiopia (Table 1). Then, the R-factor values of each station were calculated. The inverse distance weighted interpolation method was used to develop a raster surface with an erosivity value, as it gives a more precise value if annual rainfall is used [33].

Soil Erodibility. Soil erodibility implies the resistance of the soil to the erosive powers of rainfall and runoff energy [8]. The properties of the soil strongly determine the erodibility of the soil at the time of storm rainfall events [31]. Soil texture, soil structure, organic matter content, soil depth, and drainage condition are the main factors that affect the vulnerability of the soil to erosion [26]. In different parts of Ethiopia, two methods are most frequently used such as soil color method and soil property-based methods. The soil color method was recommended by Hurni [29] and reasonably and effectively implemented in the highlands [8, 18, 19, 34, 35]. Thus, this method was employed in this study.

Therefore, soil types and their color were extracted from the digital soil data [36]. The K-value proposed for each soil color (Table 2) [29] was assigned in the polygon soil map (vector file) and finally converted to a raster map.

Slope Length and Steepness. The effect of topography on soil erosion in the RUSLE modeling can be expressed in the length and steepness of the slope [31]. Increasing slope length creates a high accumulation of runoff, and steeper slopes raise the velocity of runoff, which cumulatively increases soil erosion [31]. As defined by Wischmeier and Smith [31] and Renard et al. [32], both slope length and slope steepness can be computed using following equations. LS factors in this study were generated from a 30×30 m DEM with the help of ArcGIS 10.3. Besides, other processing activities were made such as filling silks, generating the flow direction, and flow accumulation.

$$L = \left(\frac{X_h}{22.13}\right)^m, \tag{3}$$

where X_h is the horizontal slope length and m is the exponent of the variable slope as it is defined to the ratio. ε of rill erosion to interrill erosion ε is computed for the soil erosion, which is moderately susceptible to rill and interrill erosion.

The values of m and ε can be calculated by using the following equations both from the DEM of the study area:

$$m = \frac{\varepsilon}{(1+\varepsilon)}, \tag{4}$$

$$\varepsilon = \left(\frac{\sin\theta/0.0896}{\left[3.0(\sin\theta)^{0.8} + 0.56\right]}\right), \tag{5}$$

where θ is the slope angle.

On the other hand, it is described that soil erosion increases fast with the rise in slope steepness than that of the increase with slope length [32]. Therefore, slope steepness can be calculated using the following equation using a raster calculator [32]:

$$\begin{aligned} S &= 10.8 \times \sin\theta + 0.03, \quad \text{if } \delta \leq 9\%, \\ S &= 16.8 \times \sin\theta - 0.5, \quad \text{if } \delta \geq 9\%, \end{aligned} \tag{6}$$

where S is slope steepness factor, $\sin\theta$ is slope angle, and δ is slope gradient in percent.

After the L and S maps are generated from the DEM, a cell-by-cell overlay analysis was conducted using the raster calculator of the ArcGIS environment.

Land Cover Factor. The cover factor implies the effect of the ground cover and vegetation canopy in reducing soil erosion [32]. It can also be explained that the effect of the cover of the land, crops, and crop management practices on soil loss is compared with that of the loss from bare fallow areas [7]. The C-factor can be computed by different methods but C-factor from literature values (traditional system), and normalized difference vegetation index (NDVI) methods are most commonly implemented [37]. The NDVI based C-cover estimation is the best method for tropical areas than the literature value-based method [37]. The NDVI can give a possible unique value for each pixel than that of the traditional method. Besides, land use/land cover classification may not reasonably detect the change of land use and cover as a result of soil and water conservation. But, NDVI can better detect the changes. This is because initially SWC measures can increase water infiltration and accumulates soil, which led to the better and healthy growth of vegetation. This can improve the greenness and density of the existing

Table 1: Mean annual rainfall and R-factor value of rainfall stations.

Stations	Latitude	Longitude	Mean annual rainfall (mm)	Rainfall erosivity value (MJ mm ha^{-1} h^{-1} yr^{-1})
Gandaba	6.835649	37.75583	1306.83	726.32
Dubbo	7.069134	37.69752	1200	666.28
Abala Sipa	6.695725	37.78539	1287	715.17
Bilate Chericho	6.958551	38.03670	708.101	389.83

Table 2: Soil types and recommended K-values.

Soil type	Color	K-value	Source
Chromic Luvisols	Brown	0.2	Gashaw et al. [2]; Moges and Bhat [25]
Eutric Fluvisols	Brown	0.2	Moges and Bhat [25]
Dystric Fluvisols	Brown	0.2	Moges and Bhat [25]
Chromic Vertisols	Black	0.15	Bewket and Teferi [18]; Gelagay and Minale [19]
Eutric Cambisols	Brown	0.2	Bewket and Teferi [18]; Gelagay and Minale [19]
Pellic Vertisols	Black	0.15	Bewket and Teferi [18]; Moges and Bhat [25]

vegetation in the short- and medium-term time scale, but one land-use type may not be converted to other types. For instance, within 5–10 years, shrub woodlands may not be converted to forestland, but degraded shrub woodlands can be changed to healthy shrub woodlands. Therefore, NDVI values can better display the effect of SWC on the landscape.

Prior to the computation of the rescaled-based C-factor, image preprocessing and NDVI calculations were made. The NDVI was computed by using the visible red and near-infrared bands of the satellite imageries as follows:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}. \quad (7)$$

The rescaled NDVI value calculation method developed by Durigon et al. [39] is proved to be the best method of C-factor determination for the tropical areas [38, 39]. Therefore, the rescaled method was employed in this study, and the equation is given as follows:

$$C_{rA} = 0.1\left(\frac{-\mathrm{NDVI} + 1}{2}\right). \quad (8)$$

2.3.2. Management (Support) Practice. The support practice factor (P) in RUSLE is the ratio of soil loss with a specific support practice to the corresponding loss with upslope and downslope tillage [38]. It considers the three methods, such as contours, cropping, and terraces that were important elements to control erosion [39]. However, in our on-site observation, we identified that majority of conservation measures have been constructed on farming lands, and there are limited conservation measures on nonagricultural lands. Besides, conservation practices lack continuity in their implementation. Therefore, the P-factor in this study was determined using the combination of slope class and land use/land cover map [31] and also used in other previous studies [7, 8].

2.3.3. Satellite Image Processing, Classification, and Accuracy Assessment. Two Landsat satellite imageries (2000 and 2020) were captured in the dry season that is cloud-free, and crop harvest was used. Image preprocessing such as rectification, topographic correction, and other image enhancement were done to make the map suitable and easy for the intended classification best fits the then ground data. In this regard, a 1:50 000 toposheet map and DEM were used for image preprocessing.

Six land use/land covers (forestland, shrub woodland, grassland, cultivated land, bare land, and settlement area) were identified through reconnaissance survey and toposheet map. Supervised image classification in maximum likelihoods classifier was performed using training points collected through handheld GPS. Thus, 60 sample points were collected for each land use/cover type in 2020.

The accuracy assessments of the classified maps were performed using the error (confusion) matrix and Kappa coefficient. For this purpose, 240 points (40 in each land use/cover) were collected and used as reference data for accuracy assessment. Samples were selected through stratified random sampling. In this regard, the classified image has an overall accuracy of 87.9 and 88.9% and a Kappa coefficient of 0.863 and 0.867, which shows the classified maps are acceptable [40, 41].

Following the image classification, the land use/land cover and slope class map (in %) were overlaid in a union function of ArcGIS, to find a map that has the attributes of the two maps. Then, literature values were assigned (Table 3). The satellite image analysis was performed using ArcGIS 10.3 and ERDAS 2014 software.

Finally, all raster maps were resampled to 30×30 m spatial resolution to make them compatible for cell-by-cell multiplication. RUSLE factor maps were multiplied to calculate the annual average soil loss.

2.4. The Impact of Land Cover and Greenness Changes on Soil Loss and Erosion Risk. The impact of land cover and greenness changes on soil erosion can be estimated using the RUSLE model. This was done by computing soil loss before (2000) and after (2020) the implementation of SWC. While computing the soil loss and erosion risk, the land covers (C-factor) and conservation practice factor (P-factor) values

Table 3: P-factor values.

Land use/land cover	Slope (%)	P-factor	Sources
Cultivated land	0–5	0.1	Wischmeier and Smith [31]
	5–10	0.12	
	10–20	0.14	
	20–30	0.19	
	30–50	0.25	
	50–100	0.33	
Others	All	1	

were computed from the respective year's satellite imageries, but the R, K, and LS factor maps were similar. Because the changes in these parameters may not be significant in the short time period and difficult to find historical data. Therefore, the variations in the estimated soil loss can be explained by the variations in land cover and greenness change in the past two decades. The overall methodological procedure followed study has been presented in Figure 3.

3. Results and Discussion

3.1. RUSLE Factors. The mean minimum and maximum rainfall data of the area were 708 and 1396 mm, respectively (Figure 4(a)). Rainfall erosivity of the area increases from 432 MJ mm ha^{-1} h^{-1} yr^{-1} in *Bilate Chericho* to 726 MJ mm ha^{-1} h^{-1} yr^{-1} in *Gandaba*, the elevated part of the Damota area (Figure 4(b)). This implies that the erosive power of the rainfall was stronger in the mountainous and highlands and reduced to the level and lower slopes. But, even though the erosivity was lower in the level low lands, the flow accumulation that can move a high amount of sediments is higher.

Erodibility of the soil in the Damota area districts ranges from 0.15 to 0.2 t ha^{-1} MJ^{-1} mm^{-1} (Figures 4(b) and 4(c)). Soils in the area are dominated by brown (Chromic Luvisols, Eutric Fluvisols, Dystric Fluvisols, and Eutric Cambisols) and black (Chromic Vertisols and Pellic Vertisols) colors. Black-colored soils are less erodible than brown color [31]. The more erodible brown-colored soils are concentrated in the mountainous highland areas. This nature of the area together with high erosivity coupled with high LS factor makes it more vulnerable for soil loss (Figures 5 and 6).

The effect of topography (LS factor) was considered higher particularly at the center of Damota area in the Damota Mountain and other steep-slope escarpments in the western and eastern sections. The lowest and the highest L- and S-factor values were 1 and 0.03, and 14.5 and 81.65, respectively. The overlay analysis of these two factors resulted in the LS-value ranging from 0.03 in level slope with minimal flow accumulation area to 359 in steep slopes and high flow accumulation areas (Figure 5).

The land cover factor of the area is computed from NDVI values in a rescaled method so as to better represent the vegetation cover/greenness changes that occurred in the short- and medium-term time scale between the two years (before and after conservation). C-value ranged from 0.066 to 0.175 in 2000 and from 0.051 to 0.099 in 2020 (Figure 7). This implies that the size of bare lands was higher in 2000 and reduced in 2020 (Figure 7). The analysis result indicated that the land covered by vegetation such as forests and shrub woodlands receive low C-factor values, but bare lands and settlement areas experience high C-values. On the other hand, the P-factor values estimated for the area were found between the lowest 0.1 and 1 in both reference years (Figure 8; 2000 and 2020). However, the area covered by each value between 0.1 and 1 is different in the two study periods.

3.2. Impacts of Land Cover and Greenness Changes on Soil Loss. It is frequently reported that the cover of the land is an important factor that determines the vulnerability of the soil and consequent soil loss [8, 31]. In this study, the effects of land use/cover change due to SWC for the past two decades have been evaluated (Table 4 and Figure 8). The soil loss due to rills and interrills in the area in 2000 ranged from 0.028 to 418 t ha^{-1} yr^{-1}, with a mean annual soil loss rate of 29.62 t ha^{-1} yr^{-1}. The total estimated annual soil loss generated from the Damota area in 2000 was 21.3 million tons. On the other hand, in 2020, the annual average soil loss ranged from nearly zero (0.016) in the flat portion to 458.86 t ha^{-1} yr^{-1} in the steeper and undulating mountainous highlands. The mean annual soil loss was estimated to be 29.62 t ha^{-1} yr^{-1}. A total of ~13.5 million tons of soil has been lost each year as a result of water-induced soil erosion.

As a result of land cover and greenness changes, the annual rate of soil loss was reduced by 36.43% (from 29.62 to 22.47 t ha^{-1} yr^{-1}) over the period 2000–2020. Similarly, the total soil loss from the Damota area districts before SWC in 2000 was 21.3 million tons, but the value changed to 13.5 million tons after conservation implementation. This shows a reduction of 36.5%.

Upon the increasing population pressure and demand for natural resources and food, such reduction in soil loss can be explained by the effects of land use/cover change resulted from community-based SWC measures implemented in the area for the past two decades. Different SWC measures have been implemented in the area including physical structures with grass strips (e.g., soil bund, fayna juu, and microbasin), vegetative measures (plantations and area exclosure), and agronomic measures. As the SWC measures are implemented, water infiltration increases and consequently increases groundwater recharge [42]. These situations consequently increase plant growth and regeneration, which consequently improve the land use/cover and landscape greenness.

It was also indicated that soil loss by the sheet and rill erosion showed a reduction nearly by 100% as a result of

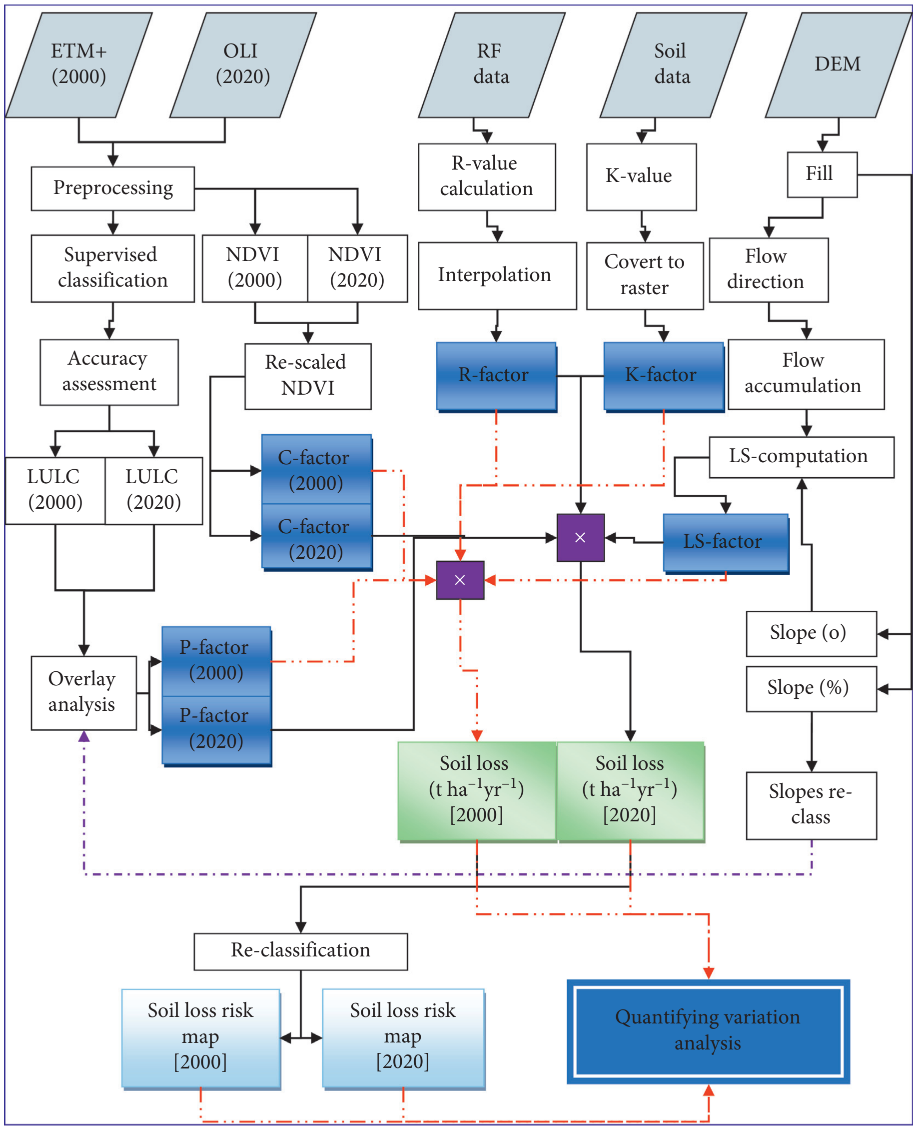


Figure 3: A methodological flow of estimating the effect of land cover and greenness change on soil loss and erosion risk.

watershed management-led improved vegetation cover in grasslands and exclosures [43]. Vegetated areas particularly forest and shrub woodlands generate the lowest average soil loss even though they are concentrated in the steepest slope [8].

However, the mean annual soil loss was found to exceed the range of soil loss tolerance (1–6 t ha^{-1} yr^{-1}) estimated for the Ethiopian highlands in both before (2000) and after (2020) SWC implementation. Besides, 22.4% of the Damota area districts have generated a soil loss amount much higher than the maximum tolerable soil loss value of 6 t ha^{-1} yr^{-1} in 2020 [29].

Our study estimate (on average, 27.21 t ha^{-1} yr^{-1}) is in agreement with the findings of Haregeweyn et al. [7] in the Upper Blue Nile basin, which reported an average soil loss rate of 27.5 t ha^{-1} year^{-1}. It was also consistent with the research results reported for Gelada watershed (23.7 t ha-^{1} yr^{-1} [2]) and Gelana subwatershed (24.3 t ha^{-1} yr^{-1} [27]), in the northwestern, northeastern, and eastern Ethiopian highlands.

Some research findings reported an exceptionally high amount of soil loss particularly centering in the north-western highlands of Ethiopia and of course in the central rift. For instance, Bewket and Teferi [18] reported a soil loss rate of 93 t ha^{-1} yr^{-1} in the Chemoga watershed, northwestern Ethiopia. Similarly, an annual erosion rate of 49 t ha^{-1} yr^{-1} [35], 42.67 t ha^{-1}yr^{-1} [9], and 47.4 t ha^{-1} yr^{-1} [19] was estimated in the Dembecha district, Gumara watershed, and Koga watershed of the Blue Nile basin, northwestern Ethiopia, respectively. Wolka et al. [34] in their study in the central rift valley watershed found a soil loss rate of 45 t ha^{-1} yr^{-1}. The exceptionally high soil erosion rate reported in the northwestern highlands of Ethiopia might be mainly related to the existing high rainfall (long-term average 2,000 mm) and the undulating and steep slope nature of the land than that of the Damota area districts. Belayneh et al. [8] also explained that soil loss is high in the high rainfall and steep-slope gradient-dominated areas. Indeed, a high soil loss rate in the central

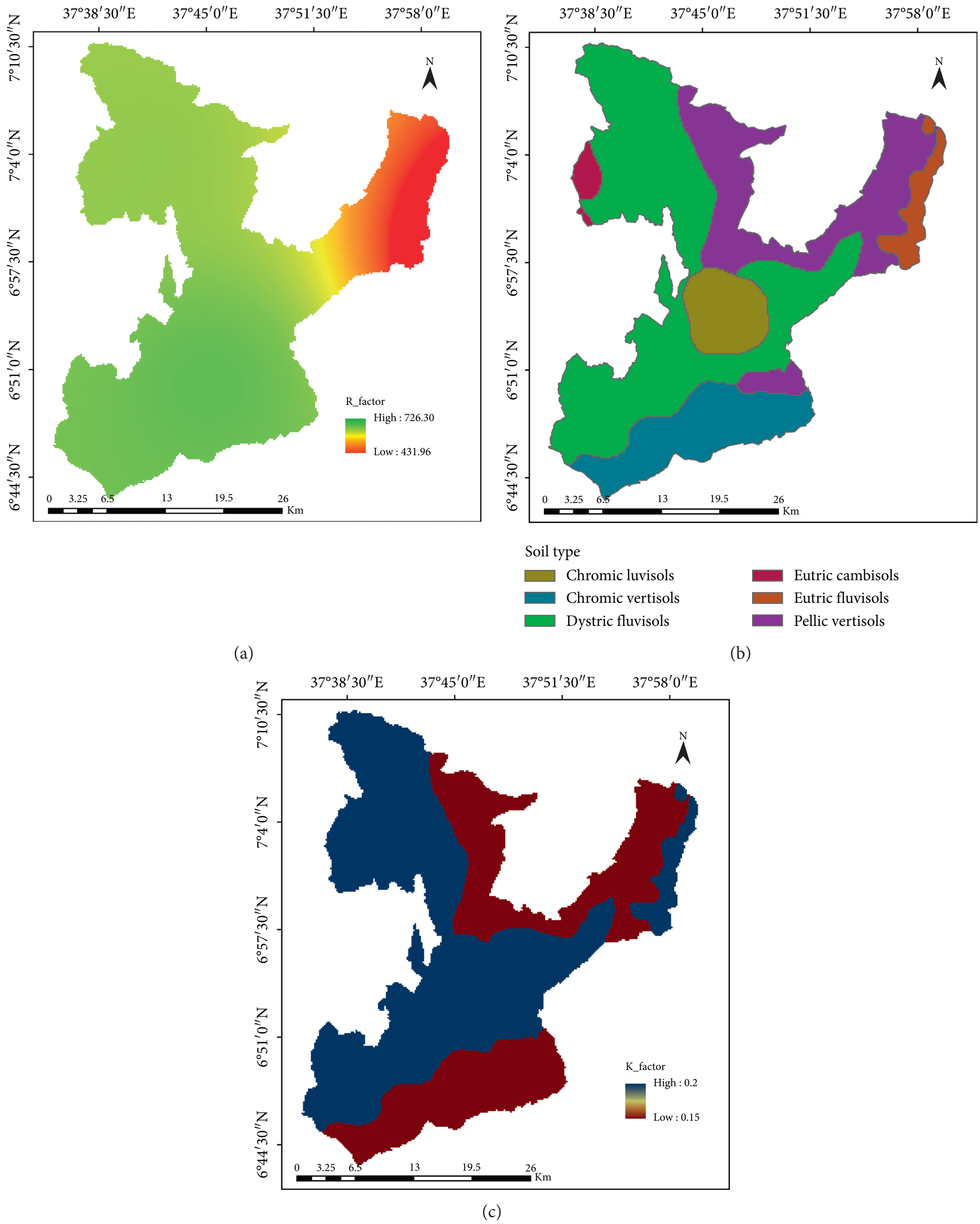


Figure 4: Rainfall erosivity (a), soil map (b), and soil erodibility (c).

rift that has comparatively smaller rainfall could be related to the topography. This is observed in our study that areas dominated by level and gentle slopes experience less erosion and progressively increases with the slope in the Damota area.

In this study, steep (30–45%) and very steep-slope (> 45%) areas generate an average soil loss of 43.23 and 84.82 $t\,ha^{-1}\,yr^{-1}$ (Figure 6). These areas constitute 4.5 and 2% of the area but contribute 17 and 12.5% of the total soil loss. This result is very high as compared to the mean soil loss and the soil loss generated from level and sloping areas that generate from 3.5 to 6.5 $t\,ha^{-1}$ annually. Therefore, slope steepness is the main factor that makes the area more vulnerable to rainfall-induced soil erosion. Belayneh et al. [8] also found a strong relation between slope and soil loss in the Gumara watershed, northwestern Ethiopia. Slope gradient and length are found to be the main factors of soil erosion in the Koga watershed [19].

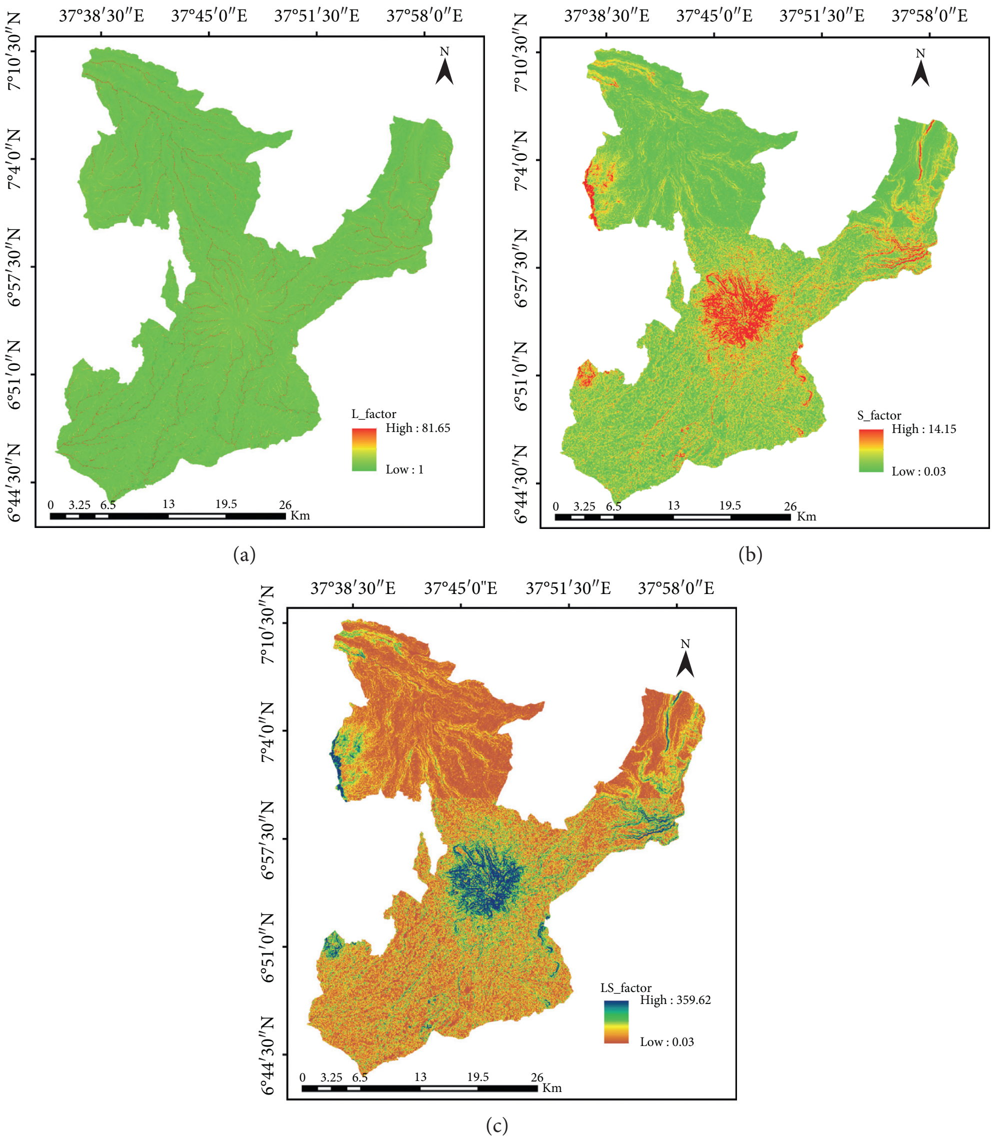


Figure 5: Map showing: m-value (a), L-value (b), S-value (c), and LS-factor (d).

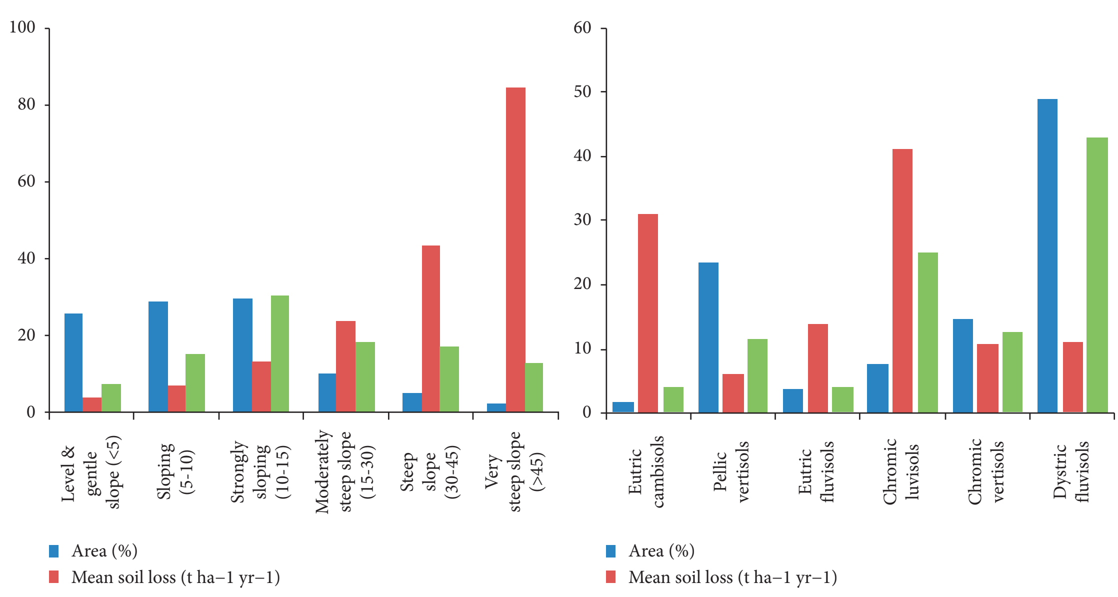


Figure 6: Soil loss in the Damota area in 2020 expressed by slope category and soil types.

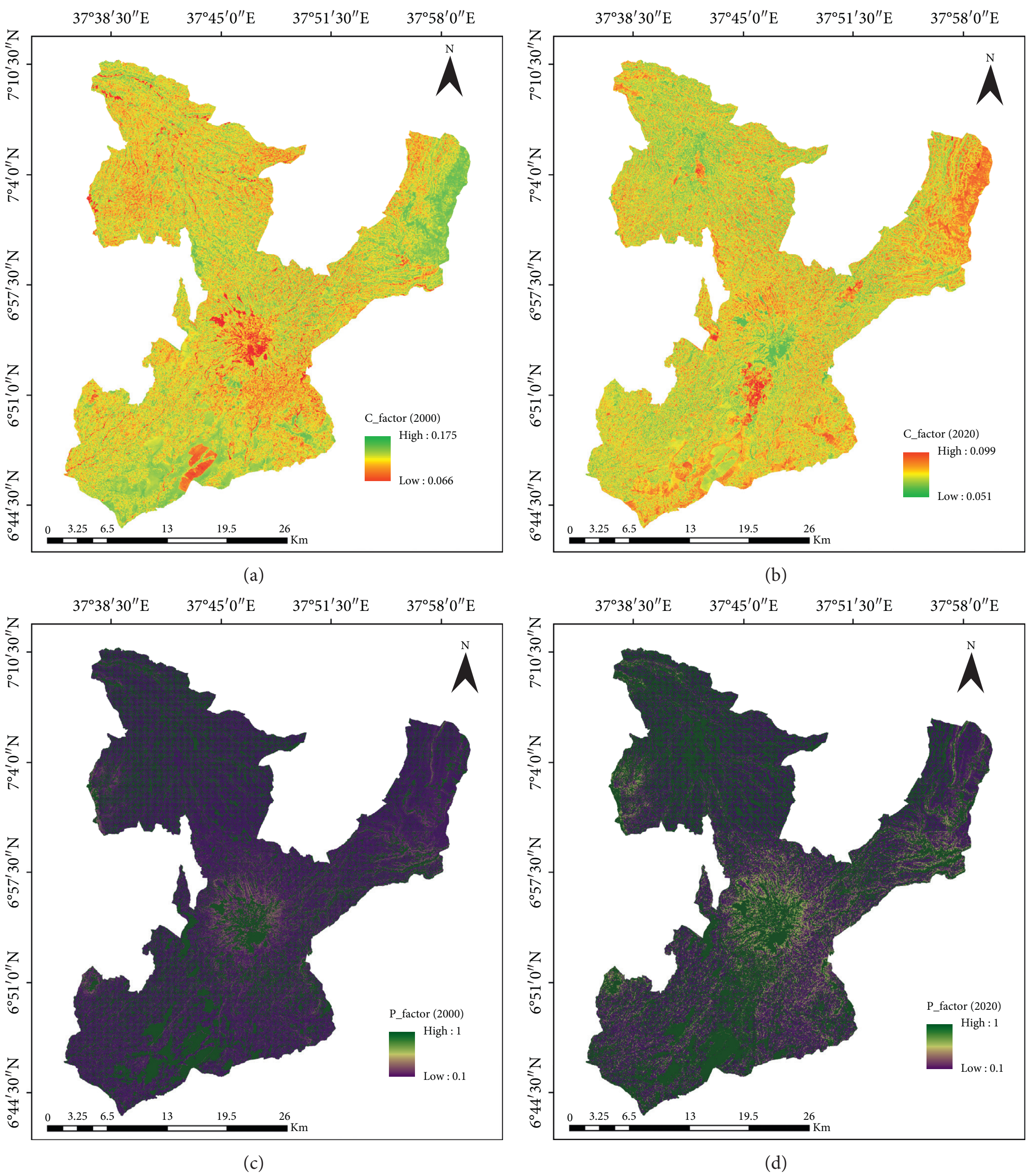
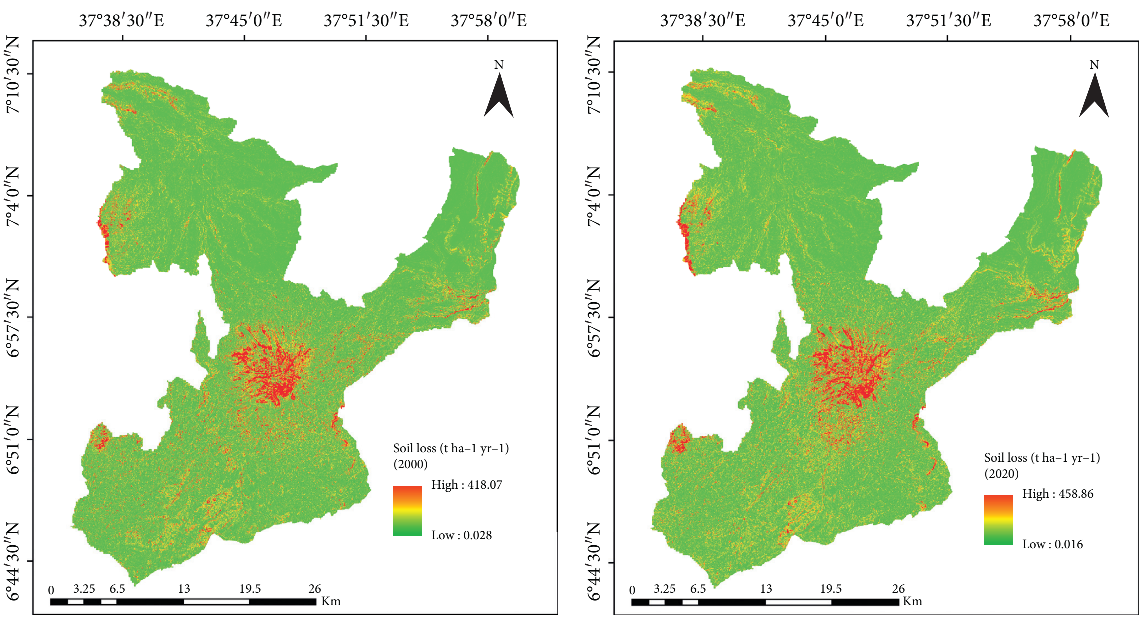


Figure 7: (a, b) *C*-factor of 2000 and (c, d) *P*-factor map of 2020.

The characteristics of the soil have a strong influence on soil erosion. For instance, black-colored soils (Chromic Vertisols and Pellic Vertisols) that have relatively better organic carbon content experienced a very low mean rate of soil loss (11 and 8 $t\,\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$, respectively; Figure 6). On the other hand, soils such as Chromic Luvisols and Eutric Cambisols characterized by brownish color are more susceptible and found to generate the highest amount of soil loss (32 $t\,\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ for Eutric Cambisols and 46 $t\,\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ for Chromic Luvisols) in the Damota area. Besides their characteristics, these soils are concentrated on the steep-slope undulating topographical condition.

3.3. Impacts of Land Cover and Greenness Changes on Erosion Risk. According to the erosion risk classification recommended by Haregeweyn et al. [7], the soil loss map of the study area has been classified into five severity/vulnerability classes. The severity classes/levels are very slight risk, slight risk, moderate risk, high risk, and very high risk representing a mean soil loss rate of <5, 5–15, 15–30, 30–50, and > 50 $t\,\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$, respectively. In this regard, in 2020, 5.2, 7.11, and 12.5% of the Damota area districts have been experiencing very high risk (first level of priority), high risk (second level of priority), and moderate risk (third level of priority) of soil erosion, respectively (Figure 9; Table 5). These areas



(a) (b)

Figure 8: Estimated potential soil loss (a) and risk map (b) of Damota area districts in 2020.

Table 4: Descriptive statistics of quantified soil loss in the years 2000 and 2020.

Study years		Area (ha)	Soil loss (t ha^{-1} yr^{-1})				
			Min.	Max.	Mean	SD	Total
2000		97,600.41	0.028	418.07	29.62	36.71	21277207
2020		97,600.41	0.016	458.86	22.47	22.07	13521754
Change over 2000–2020	unit	—	−0.01	40.79	−7.15	−14.64	−7755453
	%	—	−43.73	9.76	−36.43	−39.88	−36.45

constitute 24.8% of the area but contributed 78.04% of the total annual soil loss of the districts.

This is an important implication that where we need to invest our maximum efforts in SWC instead of trying to stretch our efforts in all portions of the area. Quantitative expression of soil erosion is a fundamental phase for any watershed management [26]. It can guide the SWC planning and implementation. Because centering conservation efforts on these highly vulnerable areas by pressing more efforts in terms of labor, capital, and technology and its effective implementation can bring the desired result [7, 8]. However, conservation implementation in the Damota area and even in different parts of Ethiopia at large has been led without scientifically quantified data and priority levels. Conservation efforts have been invested in the disintegrated form in a large area including less vulnerable landscapes. These might be the main reason that SWC efforts in Ethiopia are not effective and planned.

However, high temporal variability of soil loss severity was observed over the period 2000–2020 (Table 5). The area experiencing very slight soil erosion risk (<5 t ha^{-1} yr^{-1}) was increased from 42.66 to 53.72% with nearly similar average annual soil loss. On the other hand, the area that generates a very high amount of soil loss (>50 t ha^{-1} yr^{-1}) was 11.71% in 2000, and the value decreased to 5.2%. Indeed, the average soil loss was also decreased from 96.44 to 81.82 t ha^{-1} yr^{-1}. The area covered by first, second, and third priority levels (very high risk, high risk, and moderate risk, respectively) in 2000 was 29% but reduced to 24% in 2020. This implies that soil erosion has been strongly influenced by the community mass mobilization and private-level SWC-led land cover and greenness changes in the Damota area.

This is an important implication that SWC measures being implemented in the area have played a role in regenerating vegetation cover and rehabilitation of the degraded landscapes. For instance, the exclosure in the degraded landscapes and plantations in steep slopes together with physical structures on cultivated and barren areas can increase infiltration, decrease runoff, and decrease soil loss. These consequently improve the density and greenness or health of vegetation.

However, on the other hand, the highest value of soil loss in the Damota area districts has shown an increase. This is evident by the increase of the highest value from 418.07 to 458.86 t ha^{-1} yr^{-1}. This might be occurred due to the fact that SWC practices may not cover all areas and most often in the Ethiopian case; some already severely degraded landscape

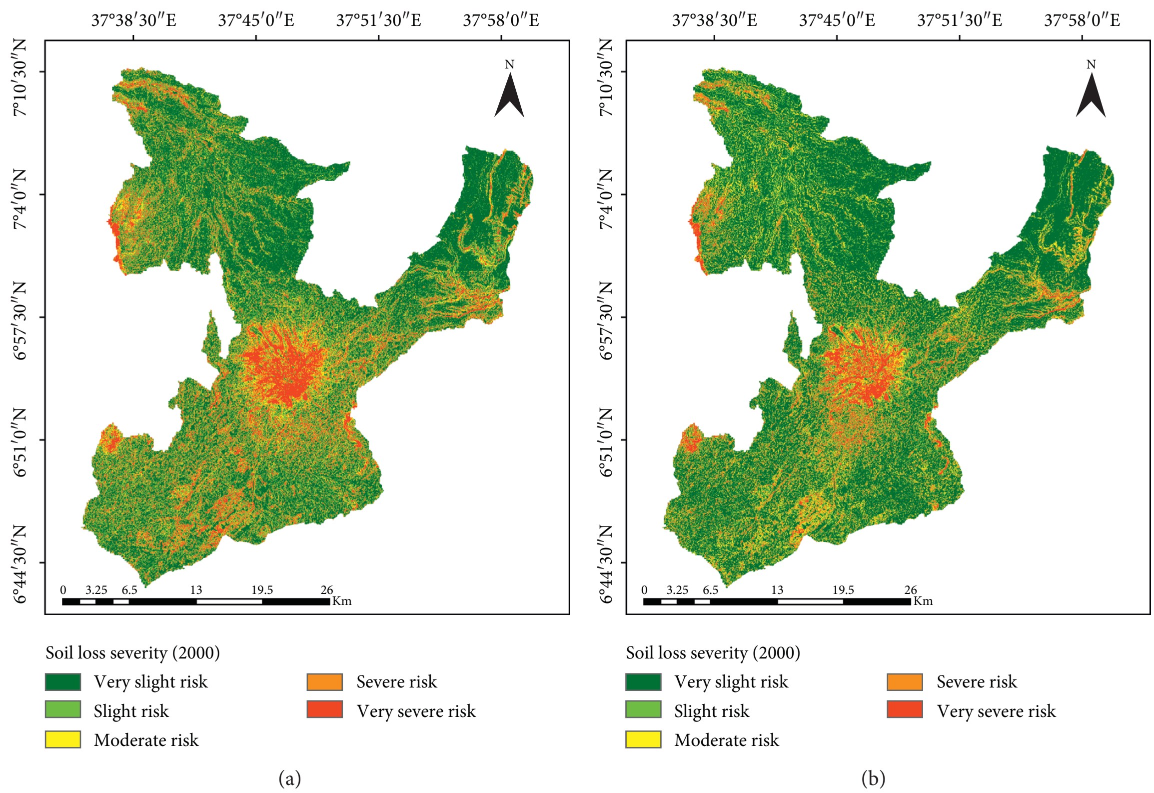


Figure 9: Estimated potential soil erosion risk map of Damota area districts in 2000 and 2020.

Table 5: Soil erosion severity classes and area prioritization in the Damota area districts.

Erosion risk class	2000				2020				Priority
	Area	Soil loss ($t\ ha^{-1}\ yr^{-1}$)			Area	Soil loss ($t\ ha^{-1}\ yr^{-1}$)			
	%	Mean	Total	%	%	Mean	Total	%	
VSR	42.7	1.8	832,064	3.91	53.6	1.8	1,076,464	8.0	V
SR	28.1	8.9	2,705,895	12.6	21.5	8.1	1,894,463	14.0	VI
MR	9.9	20.3	2,177,165	10.1	12.5	22.0	2,983,690	22.1	III
HR	7.7	39.8	3,314,681	15.6	7.1	38.3	2,951,827	21.7	II
VHR	11.6	96.3	12,247,400	57.7	5.2	81.7	4,618,428	34.1	I

Very slight risk (VSR: <5), slight risk (SR: 5–15), moderate risk (MR: 15–30), high risk (HR: 30–50), and very high risk (VHR: >50) [7].

has received very little attention [15]. These areas mostly constitute the highest values of soil loss such as degraded and bare steep-slope areas, degraded gullies, and so on, in which soil erosion in these areas has a high probability to increase alarmingly unless treated with suitable conservation measures. This might be the reason for the observed rise in soil loss even after the implementation of conservation measures.

4. Conclusions and Implications

The RUSLE model had reasonably estimated the effects of community-based SWC-led improvements in vegetation cover and landscape greenness on annual soil loss. The total annual soil loss from the Damota area districts decreased from 21 to 13 million tons from 2000 to 2020. Within this period, the average annual soil loss decreased by 36% from 30 to 22 $t\,ha^{-1}\,yr^{-1}$. There was high spatial variability of soil loss in the area, ranging from 0.016 to 0.028 $t\,ha^{-1}\,yr^{-1}$ in the forest areas to 418 and 459 $t\,ha^{-1}\,yr^{-1}$ in the steep-slope landscapes without vegetation. The area experienced very slight soil loss risk ($< 5\,t\,ha^{-1}\,yr^{-1}$) category was increased from 42.66 to 53.72%, and on the other hand, very high-risk areas ($> 50\,t\,ha^{-1}\,yr^{-1}$) decreased from 11.71 to 5.20% over the period 2000–2020. This is an important implication that the improvements in vegetation cover and landscape greenness as a result of SWC can reduce a considerable amount of soil loss by water. The cumulative effect of the various soil and water protection measures can explain the observed change in soil loss.

Land cover strongly affects the occurrence of soil erosion over an area particularly the sheet and rill forms of erosion. In this regard, rehabilitating the bare and degraded landscapes and conserve/protect high potential areas from further degradation is among the main objectives of soil and water conservation. This leads to improved and healthy land cover and consequently reduces the vulnerability of the soil to erosion.

Soil and water conservation measures reduced the risk of soil erosion through improved vegetation cover. However, still, the rate of soil erosion is very high compared to estimated soil loss tolerance (1–6 t ha^{-1} yr^{-1}) in Ethiopian highlands, and the highest soil loss estimate was higher than that of the estimates in 2000 (rise from 418.07 to 458.86 t ha^{-1} yr^{-1}). Thus, severely degraded and high-risk areas need better attention. Site-specific priority-based implementation of conservation measures is recommended.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethical Approval

Not applicable.

Consent

All authors agreed and approved the manuscript for publication in the ecological process.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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