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Research article

Evaluating potential impacts of land management practices on soil erosion in the Gilgel Abay watershed, upper Blue Nile basin

Temesgen Gashaw [a,*], Abeyou W. Worqlul [b], Yihun T. Dile [c], Solomon Addisu [a], Amare Bantider [d,e], Gete Zeleke [d]

[a] Department of Natural Resource Management, College of Agriculture and Environmental Science, Bahir Dar University, Ethiopia
[b] Blackland Research and Extension Center, Texas A & M University, Temple, TX, USA
[c] College of Agriculture and Life Sciences, Texas A&M University, TX, USA
[d] Water and Land Resources Center, Addis Ababa University, Ethiopia
[e] College of Development Studies, Addis Ababa University, Ethiopia

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ABSTRACT

Assessing the potential impacts of different land management practices helps to identify and implement sustainable watershed management measures. This study aims to assess a change in soil erosion rate under different land management practices in the Gilgel Abay watershed of the upper Blue Nile basin, Ethiopia. The Revised Universal Soil Loss Equation (RUSLE) model that was adapted to the Ethiopian highlands context was employed to estimate the rate of soil erosion. The impact of land management practices on soil erosion was estimated for three scenarios, which were baseline, intensive cultivation, and extensive cultivation scenarios. At the baseline scenario, the mean annual soil erosion was estimated at ~32.8 t $ha^{-1}yr^{-1}$, which is equivalent to a loss of ~13.66 Mt yr^{-1} from the entire watershed. While the rate of soil erosion reduced to ~11.3 t $ha^{-1}yr^{-1}$ during the implementation of intensive cultivation management practice, which reduced the total soil loss in the watershed by 65%. On the other hand, under the extensive cultivation scenario, the mean annual soil erosion rate increased to ~34.4 t $ha^{-1}yr^{-1}$. The findings suggest that implementing agricultural intensification management practices can significantly reduce soil erosion in the watershed.

1. Introduction

The Ethiopian highlands are prone to severe soil erosion (Bewket and Teferi, 2009; Gelagay and Minale, 2016; Haregeweyn et al., 2017; Tamene et al., 2017) due to extreme deforestation, rugged topography, historic settlement, burning of crop residue, exploitative kinds of agriculture and improper/inappropriate land management practices (Bewket and Teferi, 2009; Reusing et al., 2000; Hurni et al., 2015). Several studies reported that majority of cultivated lands in the highlands of Ethiopia have beyond the tolerable soil loss (TSL) rate, which is between 5 to11 t $ha^{-1}yr^{-1}$ (Moges and Bhat, 2017; Gashaw, 2018; Renard et al., 1997). Unless the current soil loss rate is averted, it will hamper agricultural production and economic development (Wischmeier and Smith, 1978; Blanco and Lal, 2008). For example, Taddese (2001) reported that a significant portion of cultivated lands in the Ethiopian highlands has been out of production every year due to soil erosion and degradation. Water-induced soil erosion has also caused sedimentations of water and power supply reservoirs (Wolancho, 2012). Moreover, soil erosion was also affecting the quality of drinking water, which required significant investment for water treatment services.

The severe soil erosion and its environmental and socioeconomic impacts warrants investigating different land and water management practices that may reduce soil erosion. Such practices include intensive cultivation, extensive cultivation, filter strip, tracing, stone or soil bund, agro-forestation and area enclosure (Betrie et al., 2011; Tamene et al., 2017). Although several models exist to estimate erosion, the Revised Universal Soil Loss Equation (RUSLE) model (Renard et al., 1997) is helpful in identifying erosion hot spot areas and suggesting appropriate conservation measures in data scare areas such as the Ethiopian highlands. Since conserving all areas of the watershed at once may be difficult, identifying erosion hotspot areas is helpful to prioritize implementation of soil and water conservation measures in the watershed (Bewket and Teferi, 2009; Welde, 2016; Gashaw et al., 2017).

* Corresponding author.
E-mail address: gtemesgen114@gmail.com (T. Gashaw).

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The Gilgel Abay watershed is one of the agriculturally productive watersheds in Ethiopia. Since the watershed is extensively cultivated for centuries and that it is inhabited by dense population, it has been prone to soil erosion and land degradation which is endangering to the health of the downstream Lake Tana with sediment and nutrient influx. Soil erosion and land degradation is also becoming a serious challenge for food production in the study watershed in particular and in Ethiopia in general. Although evaluating the impact of land management practices for the current and plausible future scenarios is imperative to identify sustainable interventions that may decrease soil erosion and sedimentation of Lake Tana, previous studies provided little attention to such endeavors. For example, several of the studies focused on studying the impacts of climate change on hydrological response (Abdo et al., 2009; Dile et al., 2013; Adem et al., 2016b) and sediment yield (Adem et al., 2016a). Therefore, this study aimed to analyze the impacts of land management practices using different scenarios to identify sustainable interventions that reduce soil erosion in the Gilgel Abay watershed of the upper Blue Nile basin.

2. Materials and methods

2.1. Study area

The study is conducted in the Gilgel Abay watershed, which covers a catchment area of 3886 km^2. The watershed is located in the Lake Tana sub-basin, which is the headwater of the upper Blue Nile basin of Ethiopia (Figure 1). The geographical location of the Gilgel Abay watershed extends between 10°55′-11°50′ N and 36°40′-37°30′ E, and the elevation ranges from 3512 m a.s.l to 1695 m a.s.l. A large part of the watershed (~63%) has <15% slope gradient. The dominant soil types in the study area are Luvisols (62.2%), Alisols (18.1%), Vertisols (9.1%) and Leptosols (6.3%). The watershed is predominantly covered by cultivated land, grassland and shrubland with shrinking forest land. The Gilgel Abay River is the major river draining the watershed and the largest tributary to Lake Tana (Wale, 2008). The Lake Tana is the largest freshwater Lake in Ethiopia and the third largest Lake in the Nile basin (Dile et al., 2013).

The climate of the Gilgel Abay watershed is governed by the seasonal movement of the Inter Tropical Convergence Zone (ITCZ) (Conway, 2000), which resulted in two distinct seasons: the dry season which spans October to May and rainy season from June to September (Haile and Rientjes, 2015). A large part of the annual rainfall (70–90%) occur from June to September (Abdo et al., 2009).

2.2. Land management practices scenarios

The study evaluated the impacts of three land management scenarios on soil erosion. The land management practice scenarios were developed using ArcGIS 10.6. The developed scenarios were baseline cultivation, intensive cultivation, and extensive cultivation. The baseline scenario considered the existing farmers' land use and management systems. The second scenario is developed based on the assumption that sufficient food in the future will be produced for a rapidly growing population through proper applications of agricultural inputs. This scenario also aims to avoid land degradation through restricting cultivation in areas higher than 15% slope. The currently used cultivated lands above the 15% slopes will be used for area enclosure. Since the second scenario was intended to rejuvenate the degraded land and intensify the agricultural production through irrigation and fertilizer application in the rest of the agricultural land it was referred as the intensive cultivation scenario. The third scenario assumed additional production for increasing future food demand will be obtained through extensive cultivation. However, this additional demand will be achieved by expanding of the cultivated lands at the expense of all grasslands, shrublands, and wetlands in areas that have a slope <15%. As a result, this scenario was referred as extensive cultivation scenario. The 15% slope threshold for extensive and intensive cultivation management scenarios was chosen due to the fact that slopes lower that this threshold is under flat to sloping gradient and thus, these areas are convenient for agriculture. On the other hand, areas above 15%

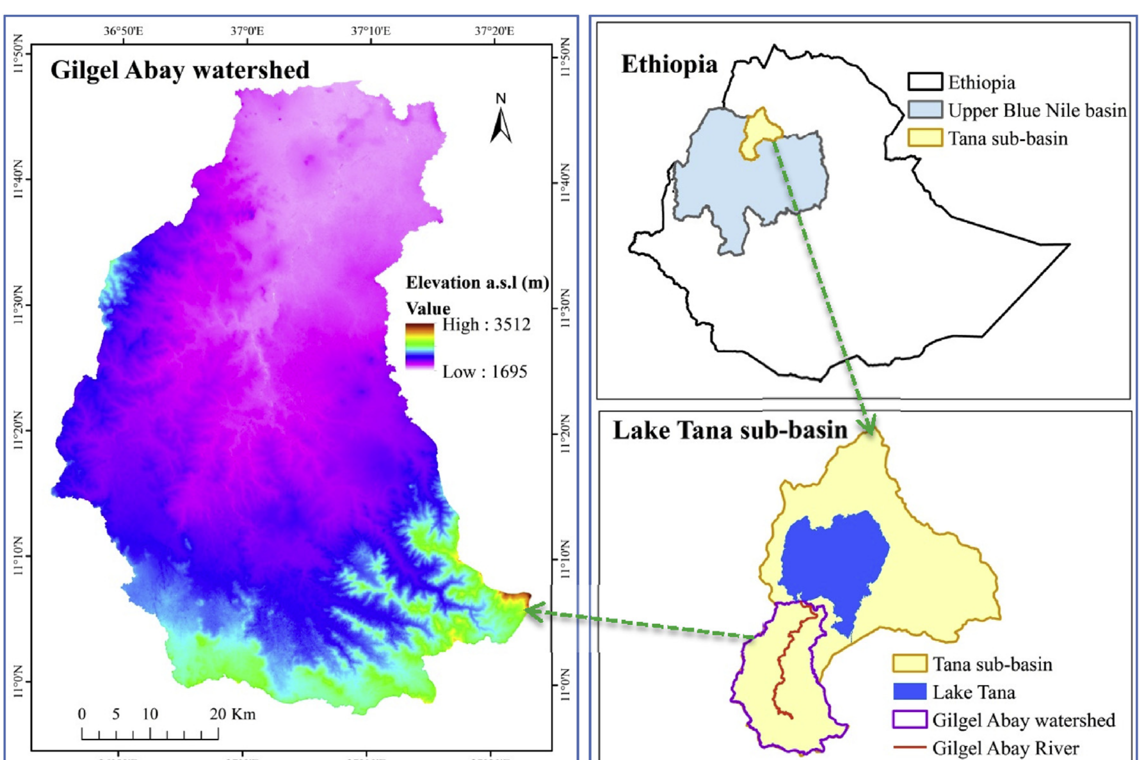

Figure 1. Location of the Gilgel Abay watershed from Ethiopia and Lake Tana sub-basin.

slope are characterized by moderately steep to very steep, and hence, it is assumed that land degradation will aggravate in these areas if it has used for agricultural production (Berhanu et al., 2013; Jembere et al., 2017).

In order to develop the land management scenarios, the 2010 land use land cover (LULC) map of the entire Amhara National Regional State was received from the Abay Basin Authority and then the LULC map of the study area was extracted using the watershed boundary. The obtained

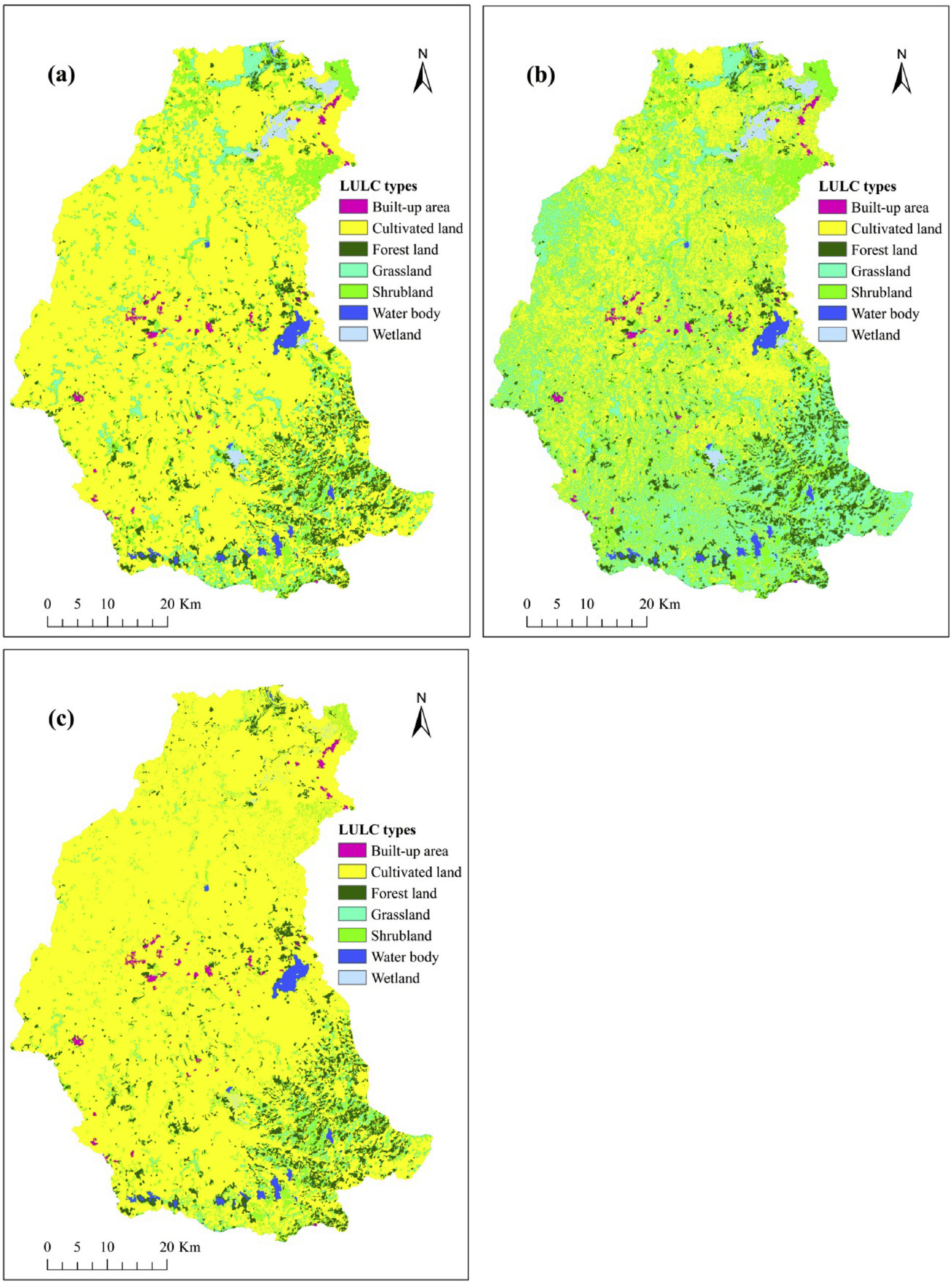

Figure 2. The LULC maps of the study watershed for the (a) baseline, (b) intensive cultivation, and (c) extensive cultivation land management scenarios.

LULC map represents the baseline land management scenario, and as it is described above, the two future probable scenarios are developed within certain management assumptions. Figure 2 presents the LULC maps of the studied scenarios and the areal estimates are presented in Table 1. In the baseline scenario, cultivated land accounted about 76.6% of the study area while grassland, shrubland, wetland and forest land collectively represented about 21.9%. The built-up area and water body covered only 1.5% of the watershed. At the intensive cultivation scenario, cultivated land was reduced to 51.4%. The reduction in cultivated land was due to assumption of area enclosure (976.5 km^2) of cultivated lands which has a slope >15%. Since the area enclosure from cultivated lands will not be converted into forest lands in a short period of time (Tamene et al., 2017), it was assumed that the area enclosed land was added to grasslands, which increased areas covered by natural vegetation in the intensive scenario compared to the baseline scenario. Since the extensive scenario assumed agricultural expansion in the grassland, shrubland, and wetland by converting those lands that has a slope less than 15%, cultivated land for the extensive cultivation scenario covered 86% of the watershed. This happened at the cost of reduction on the coverage of grassland, shrubland, and wetland (Table 1).

2.3. Parameterization of the RUSLE model

The RUSLE model (Renard et al., 1997) was applied to estimate mean annual soil erosion rates and identify erosion hotspot areas. RUSLE was adapted from the Universal Soil Loss Equation (USLE) model by incorporating local watershed information (McCool et al., 1995; Renard et al., 1997). Due to its clarity and simplicity, the method has been widely applied in several studies in Ethiopia and elsewhere in the world (e.g. Angima et al., 2003; de Asis and Omasa, 2007; Kouli et al., 2009; Meshesha et al., 2012; Sharma et al., 2011; Zerihun et al., 2018). USLE (Wischmeier and Smith, 1978) and its extension RUSLE (Renard et al., 1997) provide estimates of mean annual soil erosion rate using six factors (Eq. (1)).

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

Where A is the mean annual soil erosion rate (t ha^{-1} yr^{-1}), R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), L is the slope length factor (dimensionless), S is the slope steepness factor (dimensionless), C is the land use land cover factor (dimensionless) and P is the erosion control practice factor (dimensionless).

2.3.1. Rainfall erosivity (R)-factor

The R-factor represents the erosive force of a specific rainfall (Wischmeier and Smith, 1978), which is determined by the intensity, distribution, and frequency of a rainfall (Amsalu and Mengaw, 2014). The intensity of a specific rainfall is the highest determinant factor of the extent of water-borne erosion (Blanco and Lal, 2008). As a result, the R-factor was derived from rainfall intensity data in the original USLE model. However, rainfall intensity data are not available in the study watershed; for that matter in Ethiopia in general. Hence, the R-factor was developed based on the alternative empirical equation established to the Ethiopian highlands (Hurni (1985), Eq. (2)). The mean annual rainfall of the watershed for the period 1997–2010 (Figure 2a) was used to calculate the R-factor. The study used a gridded monthly rainfall data at a spatial resolution of 4 km, which was collected from the National Meteorological Services Agency (NMSA) of Ethiopia. The gridded dataset was merged from two datasets such as meteorological station records from the NMSA and weather satellite estimates from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) and the United States National Aeronautics and Space Administration (NASA). Finally, the satellite estimates were blended with station gauge records by NMSA together with its international partners. One advantages of using gridded rainfall data is its good capability to represent areal rainfall for the reason that a large number of gridded points are involved in the analysis. To harmonize the spatial resolution of the different inputs used in this study, the R-factor map calculated from the mean annual rainfall data was resampled into a 30 m resolution grid.

$$R = (0.562 \times P) - 8.12 \quad (2)$$

Where R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}) and P is the mean annual rainfall (mm).

2.3.2. Soil erodibility (K)-factor

The K-factor is a measure of the susceptibility of soil particles in the uplands to detach during storm events, which is determined by the soil's physical and chemical properties (Wischmeier and Smith, 1978). Clay soils are generally resistant to detachment while sandy soils, due to their high infiltration rates and thereby less runoff generation, are not easily transported. Conversely, silt soil are detachable, and transportable (Ganasri and Ramesh, 2016). However, if high organic matter exists in the silt soils, it may reduce the susceptibility of the soil surface to erosion and also increases infiltration rate (Zerihun et al., 2018). The K-factor map (Figure 3b) was calculated using Eq. (3) (Wischmeier and Smith, 1978). Soil physical and chemical property data for the upper layer (0–30cm) such as clay, sand, silt and soil organic carbon contents at 250 m spatial resolution were obtained from the International Soil Reference Information Center (ISRIC) database (Hengl et al., 2017). The derived K-factor map from the soil physicochemical properties data was resampled into a 30 m resolution grid.

$$K = \left[2.1 \times M^{1.14} \times 10^{-4} \times (12 - SOM) + 3.25 \times (S-2) + 2.5\,(P-3)\right] / 100 \quad (3)$$

Where K is the soil erodablity factor, M represents a newly defined term, that is $M=$ (%silt + %very fine sand) × (100 - %clay), SOM is the soil organic matter content (%), which was derived from the soil organic carbon; S and P is the soil structure and permeability codes, respectively.

2.3.3. Slope length (L) and slope steepness (S)-factors

The slope length (L) and slope steepness (S)-factors accounts the effects of topography on soil erosion rate (Wischmeier and Smith, 1978; Prasannakumar et al., 2012). Higher slope length and slope steepness

Table 1. The LULC classes of the study watershed and adopted C and P-factors, complied from published sources.

LULC classes	Baseline scenario		Intensive cultivation scenario		Extensive cultivation scenario		C-factor	P-factor
	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)		
Cultivated land	2975.7	76.6	1999.2	51.4	3341	86.0	0.15	0.9
Forest land	238.8	6.1	238.8	6.1	238.8	6.1	0.001	0.7
Shrubland	290.2	7.5	290.2	7.5	117	3.0	0.014	0.8
Grassland	275.6	7.1	1252.1	32.2	118.8	3.1	0.01	0.8
Wetland	46.5	1.2	46.5	1.2	11.2	0.3	0.01	0.8
Built-up area	21.8	0.6	21.8	0.6	21.8	0.6	0.004	0.9
Water body	37.3	0.9	37.3	0.9	37.3	0.9	0.00	0.0

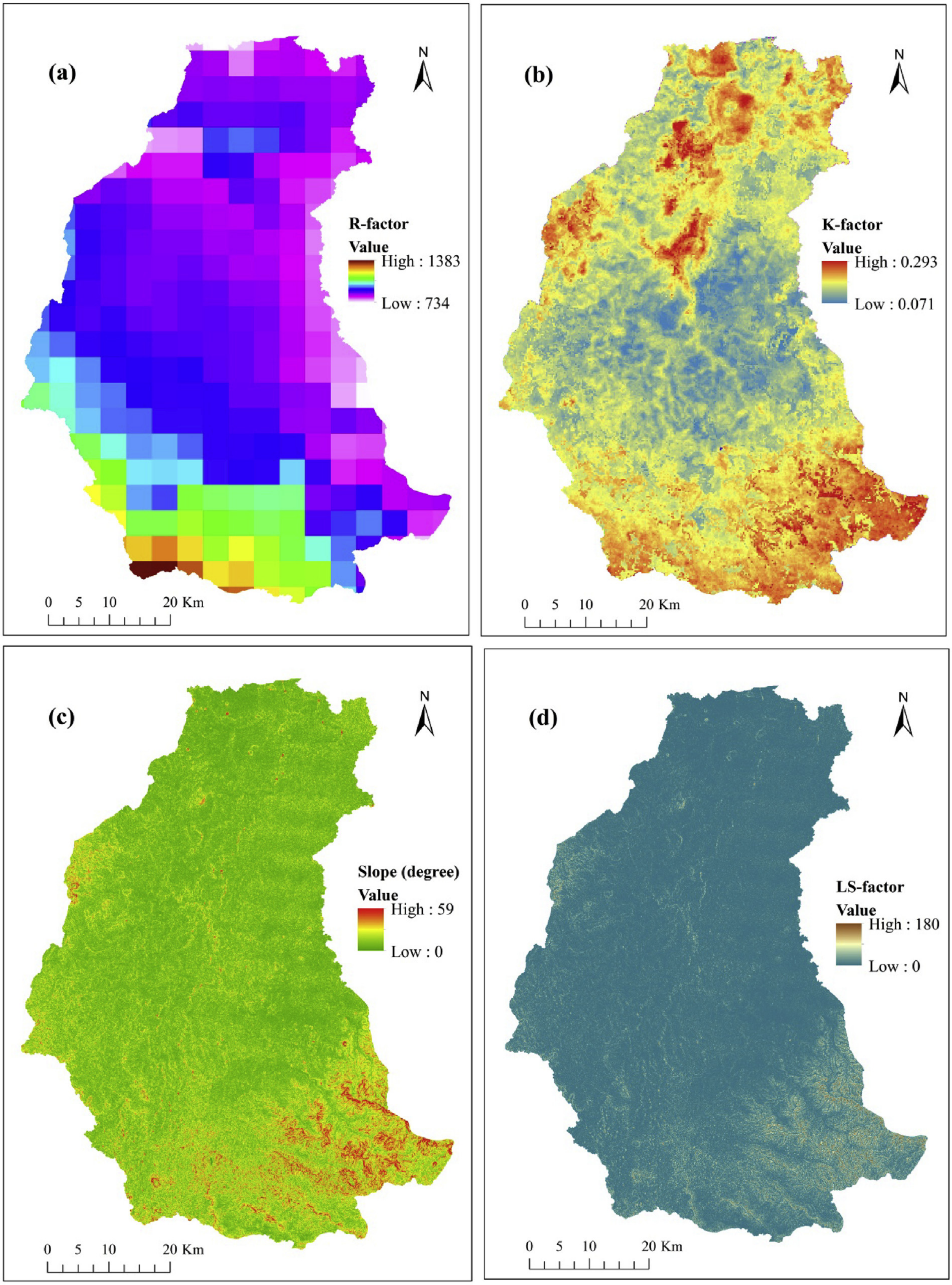

Figure 3. Factors used to calculate the annual soil loss in the Revised Universal Soil Loss Equation (RUSLE) model. The (a) *R*-factor, (b) *K*-factor, (c) Slope and (d) *LS*-factor.

areas are prone to water-born erosion whereas water-born erosion is low in areas where the landscape has shorter slope length and flat slope. In the GIS based application of RUSLE, the *L* and *S*-factors are usually counted together as a product of the two, as *LS*-factor (Moore and Burch, 1986a&b). In this study, the *LS*-factor map (Figure 3d) was developed from a 30 m spatial resolution ASTER Global Digital Elevation Model (ASTER GDEM) using Eq. (4) (Moore and Burch, 1986a&b). ASTER GDEM was obtained from the United State Geological Survey (USGS) website at https://earthexplorer.usgs.gov/.

$$LS = \left(\frac{FA \times RS}{22.13}\right)^{0.4} \times \left(\frac{\sin(S)}{0.0896}\right)^{1.3} \tag{4}$$

Where *LS* is the combined *L* and *S*-factors, *FA* is flow accumulation which is a raster of accumulated flow to each cell, as determined by accumulating the weight for all cells that flow into each downslope cell, *RS* is the spatial resolution of the ASTER GDEM and *S* is the slope gradient (in degree) (Figure 3c).

2.3.4. Land use land cover (C)-factor

The *C*-factor accounts the effects of vegetation cover against erosion (Prasannakumar et al., 2012). Soil erosion by water is very low in very dense vegetated lands due to better protection of the soil surface by vegetation cover. Conversely, in soils where vegetation cover is absent, erosion by water is relatively higher. In order to drive *C*-factor maps for the baseline and the developed two plausible future land management scenarios (Figure 4), *C*-values were assigned for each LULC class from published literature in the upper Blue Nile basin (Gashaw (2018); Bewket and Teferi (2009), Gelagay and Minale (2016) and Moges and Bhat (2017)). The *C*- factor values for cultivated land, forest land, shrubland, grassland and built-up area were compiled from Gashaw (2018) and Moges and Bhat (2017) while *C*-factors of wetland and water bodies were adopted from Bewket and Teferi (2009) and Gelagay and Minale (2016), respectively (Table 1). As described in section 2.2, the 2010 LULC map of the study watershed was extracted from the whole Amhara National Regional State LULC map. This LULC map represents the baseline land management scenario, which coincides with the time frame of the rainfall data (1997–2010). Thereafter, the developed *C*-factor map from each land management practice scenario was changed into 30 m horizontal resolution to correspond with other model factors.

2.3.5. Erosion control practice (P)-factor

The *P*-factor characterizes the role of erosion control interventions in reducing soil erosion rate when rain dropped in the uplands (Wischmeier and Smith, 1978). Using expert-based modeling approaches, Hurni et al. (2015) reported that there are no significant soil and water conservation practices in the Ethiopian highlands. In such cases where there are no significant conservation measures, the literature (e.g. Wischmeier and Smith, 1978) recommend developing a *P*-factor map using land use and slope maps (e.g. Bewket and Teferi, 2009; Gelagay and Minale, 2016; Gashaw et al., 2017; Moges and Bhat, 2017). This method provided lower *P*-value to cultivated lands while higher *P*-value was assigned to other land uses such as natural vegetation covers. Since RUSLE estimates soil loss by multiplying the six factors, a higher *P*-factor would give higher erosion. Thus, the *P*-factor would result in higher erosion in natural vegetation covers than cultivated lands. To avoid this problem, this study derived a *P*-factor map from a LULC map alone. To develop *P*-factor maps for the baseline and two plausible future land management scenarios, *P*-values were given for each LULC class. The *P*-factors of the LULC classes were adopted from studies carried out in the upper Blue Nile basin such as Haregeweyn et al. (2017), Ali and Hagos (2016) and Molla and Sisheber (2017) (Table 1). Consequently, three *P*-factor maps were obtained from the corresponding land management scenarios (Figure 5). To match the developed *P*-factor maps with the rest of the applied erosion model input factors, the *P*-factor maps were converted into 30 m cell size grid.

2.4. Assessing the potential impacts of land management practices

The potential impacts of land management practices on soil erosion were assessed considering the *C*-factor and *P*-factor maps of the RUSLE model independently and keeping the remaining input factors constant. The impacts of the interventions at the sub-watershed scale were estimated by dividing the entire watershed into sub-watershed units using a 30 m resolution ASTER GDEM in the ArcSWAT (Soil and Water Assessment Tool) environment. The topographic analysis provided 27 sub-watersheds.

3. Results

3.1. Soil erosion rate at the watershed scale

The factors of RUSLE were analyzed in ArcGIS 10.6 spatial analyst tool to calculate the spatiotemporal annual soil erosion rate for the three land management practice scenarios. The annual soil erosion rate ranges between <5 t ha^{-1} yr^{-1} to >50 t ha^{-1} yr^{-1} (Figure 6 and Table 2). The estimated soil erosion rate was divided into five severity classes, which were adapted from Haregeweyn et al. (2017) and Zerihun et al. (2018) such as very slight (0–5 t ha^{-1} yr^{-1}), slight (5–11 t ha^{-1} yr^{-1}), moderate (11–30 t ha^{-1} yr^{-1}), severe (30–50 t ha^{-1} yr^{-1}) and very severe (>50 t ha^{-1} yr^{-1}).

The very slight and slight erosion intensity classes together covered nearly 59.1%–73.4% of the watershed at the three management scenarios. The remaining parts of the watershed has affected by the moderate, severe and very severe erosion categories. Compared to the baseline scenario, the intensive cultivation scenario increased the area affected by the very slight, slight and moderate erosion classes while it reduced the severe and very severe erosion intensity affected areas. At the extensive cultivation scenario, areas affected with the very slight and slight erosion classes has reduced while the moderate, severe and very severe erosion intensity classes has increased. The severe and very severe erosion intensity classes were found in the steepest and upland areas. Assuming a Tolerable Soil Loss (TSL) of 11 t ha^{-1} yr^{-1}, 37.4% of the watershed was experiencing annual soil erosion above the TSL limit in the baseline scenario. While under intensive cultivation and extensive cultivation scenarios, ~26.6% and 40.9% of the watershed were having annual soil erosion above the TSL limit, respectively.

Due to the change in land management practices, the mean spatiotemporal annual soil erosion of the watershed was reduced from 32.8 t ha^{-1} yr^{-1} at the baseline scenario to 11.3 t ha^{-1} yr^{-1} at the intensive cultivation scenario, but increased to 34.4 t ha^{-1} yr^{-1} at the extensive cultivation scenario. Consequently, the total soil loss of the watershed at its outlet was ~13.66 Mt yr^{-1}, 4.73 Mt yr^{-1} and 14.32 Mt yr^{-1} at the baseline, intensive cultivation and extensive cultivation land management scenarios, respectively. In terms of assessing the contributions of soil erosion severity classes to the total soil loss, the very severe and severe intensity classes collectively contributed to more than 71% of the total soil loss for the three land management scenarios, though these severity classes covered <32% of the watershed area (Table 2). Although areas affected by the very slight erosion intensity class covered >55% of the watershed area in all the studied land management practice scenarios (Table 2), the soil loss in this severity class was <2.8% of the total soil loss. The slight and moderate erosion affected areas together accounted 5.9–26% of the soil loss at the baseline, intensive cultivation and extensive cultivation land management practice scenarios.

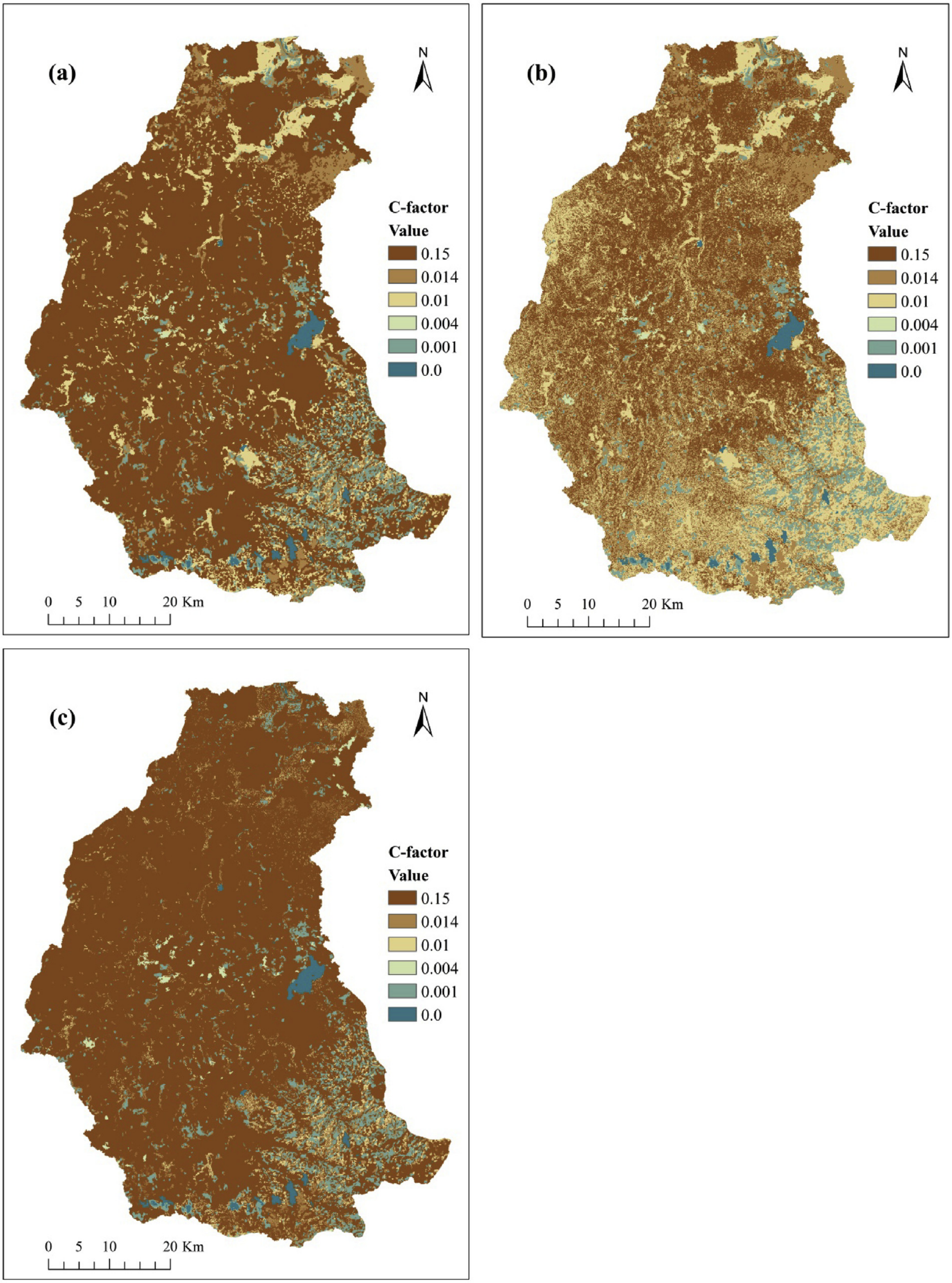

Figure 4. The *C*-factor maps of the study watershed for the three developed land management scenarios (a) baseline, (b) intensive cultivation, and (c) extensive cultivation land management scenarios.

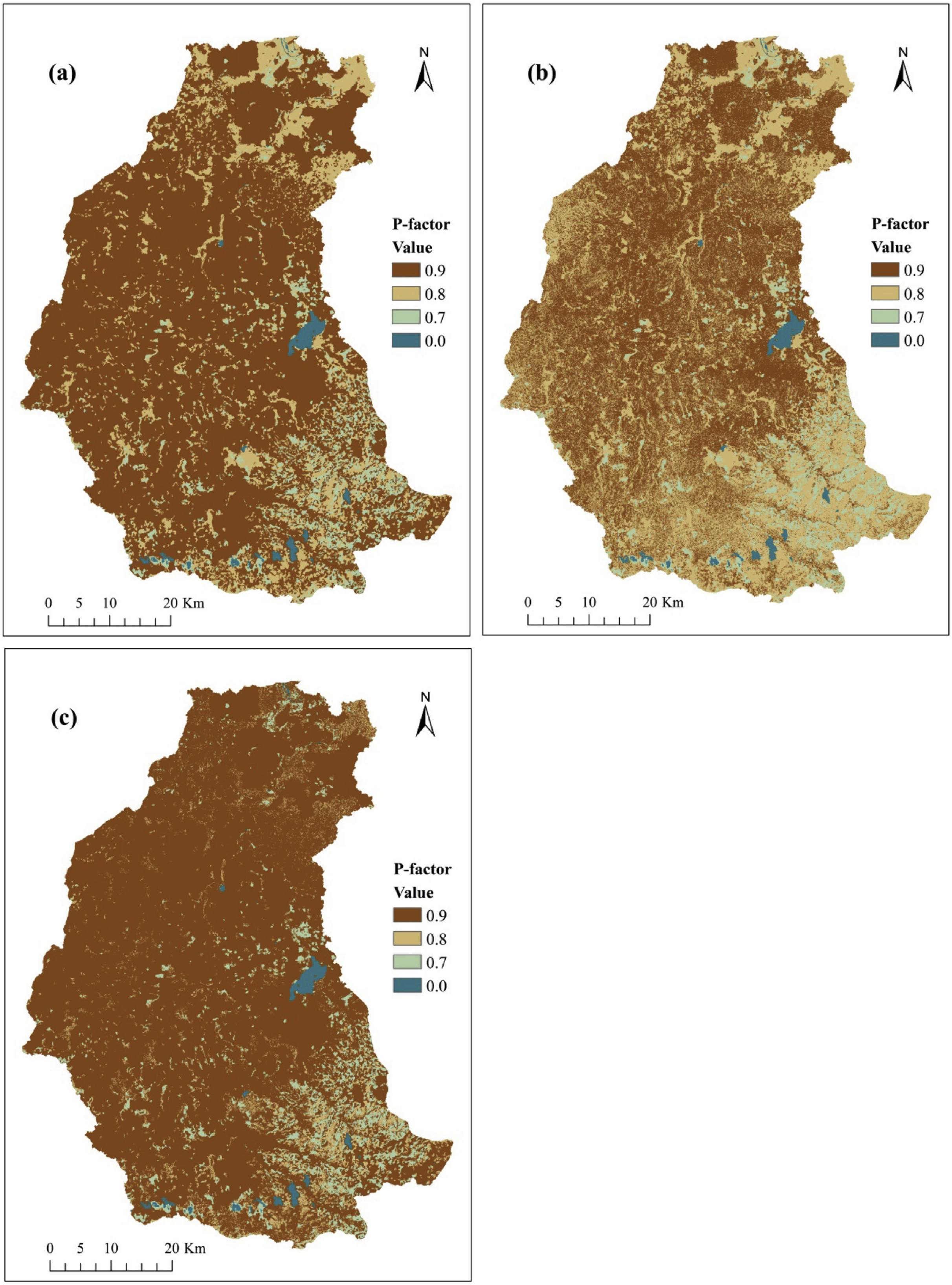

Figure 5. The *P*-factor maps of the study watershed for the (a) baseline, (b) intensive cultivation, and (c) extensive cultivation land management scenarios.

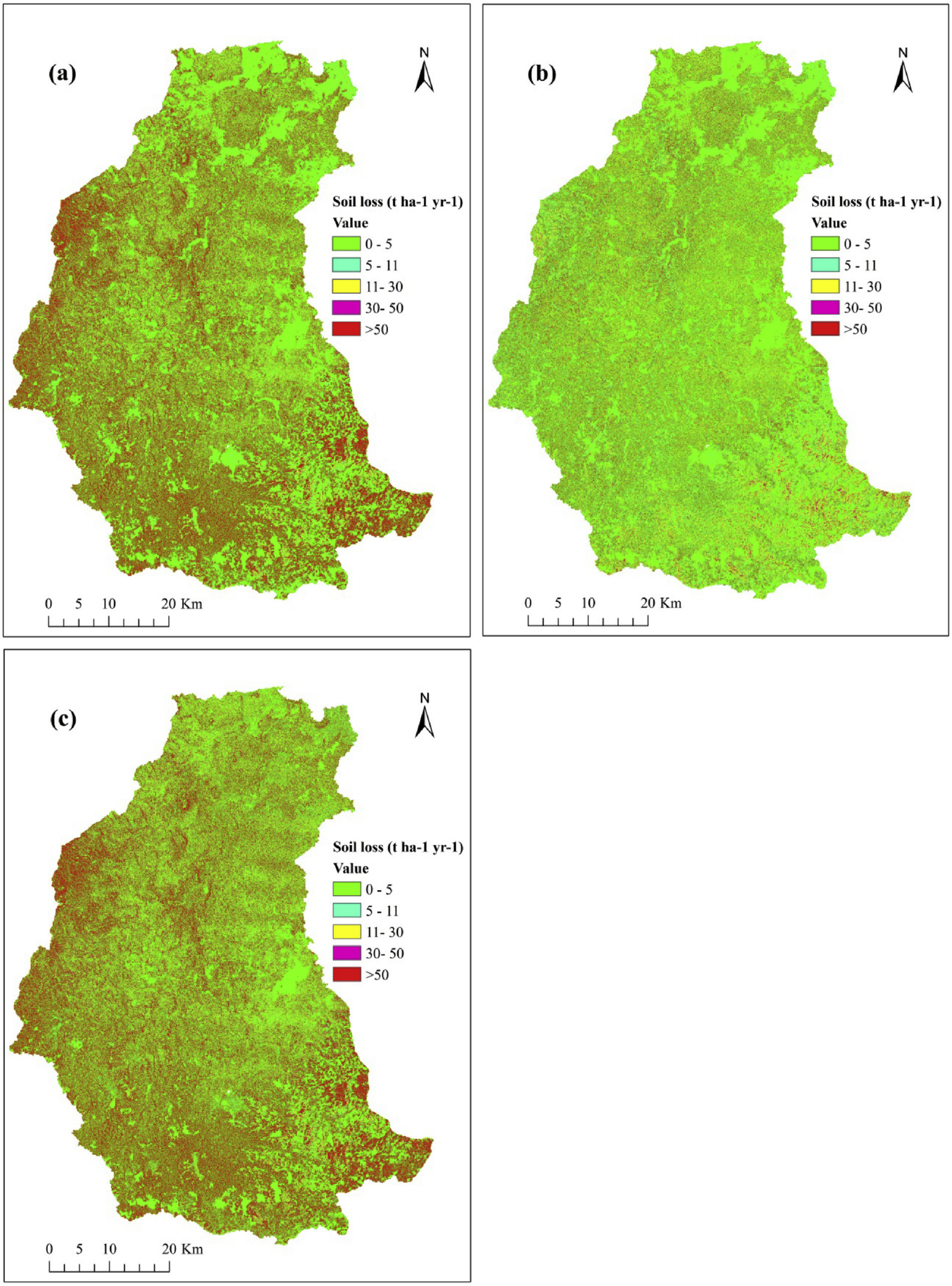

Figure 6. The soil erosion severity map of Gilgel Abay watershed at the (a) baseline, (b) intensive cultivation, and (c) extensive cultivation land management scenarios.

Table 2. Soil erosion rate in Gilgel Abay watershed under different land management scenarios.

Soil erosion rate (t $ha^{-1}yr^{-1}$)	Severity classes	Baseline scenario				Intensive cultivation scenario				Extensive cultivation scenario			
		Area (km^2)	Area (%)	Soil loss (tons in million)	% of soil loss	Area (km^2)	Area (%)	Soil loss (tons in million)	% of soil loss	Area (km^2)	Area (%)	Soil loss (tons in million)	% of soil loss
0–5	Very slight	2294.6	59	0.06	0.4	2483.9	63.9	0.13	2.7	2170.1	55.8	0.03	0.2
5–11	Slight	139.2	3.6	0.11	0.8	368.8	9.5	0.28	5.9	126.5	3.3	0.10	0.7
11–30	Moderate	344.7	8.9	0.70	5.1	493.2	12.7	0.95	20.1	389.0	10.0	0.79	5.5
30–50	Severe	295.8	7.6	1.17	8.6	272.2	7.0	1.05	22.2	338.2	8.7	1.33	9.3
>50	Very severe	811.6	20.9	11.62	85.1	267.9	6.9	2.32	49.0	862.1	22.2	12.07	84.3
Total		3885.9	100	13.66	100	3885.9	100	4.73	99.9	3885.9	100	14.32	100

3.2. Soil erosion rate at the sub-watershed level

The mean annual soil erosion rate of the sub-watersheds at the three land management practice scenarios are shown in Figure 7 and Table 3. At the baseline scenario, the mean annual soil erosion rate varies from 9.8 t ha^{-1} yr^{-1} to 81.2 t ha^{-1} yr^{-1}. At the intensive cultivation scenario, it declined to the range of 6.8 t ha^{-1} yr^{-1} and 14.8 t ha^{-1} yr^{-1}. The mean soil loss increased to the range of 13.7 t ha^{-1} yr^{-1} and 83.1 t ha^{-1} yr^{-1} at the extensive cultivation land management scenario.

The very severe and severe soil erosion rate affected ~49.5% of the watershed area at the baseline scenario while moderate and slight severity soil erosion rate occurred in about 50.2% and 0.3% of the watershed, respectively (Table 3). The intensive cultivation scenario completely changed the soil erosion situation in areas which were affected by the severe and very severe erosion rates in the baseline scenario (Figure 7). Consequently, the moderate and slight erosion affected sub-watersheds account about 54.9% and 45.1% of the watershed. At the extensive cultivation land management scenario, all areas affected by the very slight and slight erosion intensity classes have changed into the higher level of erosion category. Areas affected with moderate erosion have also reduced under the extensive cultivation scenario while the area covered by the severe erosion increased from the baseline to extensive cultivation scenario. On the other hand, the very severe erosion intensity class had the same area coverage under the baseline and extensive cultivation scenarios (i.e. 31.4% of the watershed). Overall, in the extensive cultivation scenario, there are no areas affected by the very slight and slight erosion intensity classes, and the areas classified as severe erosion intensity class increased compared to the baseline scenario (Table 3).

4. Discussions

The obtained mean annual soil erosion rate at the baseline scenario in this study (i.e. ~32.8 t $ha^{-1}yr^{-1}$) is comparable with the reported mean annual soil erosion rate in the Ethiopian highlands. For example, it is related to the soil loss estimated in Jabi Tehinan watershed (i.e. 30.4 t ha^{-1} yr^{-1}) (Amsalu and Mengaw, 2014), upper Blue Nile basin (i.e. 27.5 t ha^{-1} yr^{-1}) (Haregeweyn et al., 2017), Borena Woreda (i.e. 27 t ha^{-1} yr^{-1}) (Shiferaw, 2011) and Wondo Genet watershed (i.e. 26 t ha^{-1} yr^{-1}) (Sisay et al., 2014). The attained soil erosion rate from this study is also in between the rate of erosion estimated in Ribb watershed (i.e. 41.38 t ha^{-1} yr^{-1}) (Moges and Bhat, 2017), Koga watershed (i.e. 47.4 t ha^{-1} yr^{-1}) (Gelagay and Minale, 2016) and Geleda watershed (i.e. 23.7 t ha^{-1} yr^{-1}) (Gashaw et al., 2017). The reduction of soil erosion due to the shift from baseline to intensive cultivation land management scenario indicates that by restricting cultivation above 15% slope gradient and using these areas for area enclosure, the total soil loss from this watershed can be reduced by 65%. On the other, compared to the baseline land management scenario, the rapid increase of soil erosion rate at the extensive cultivation management scenario indicates that this land management practice will amplify soil erosion by water. Thus, permitting cultivation above 15% slope can greatly increase soil loss in the watershed and hence, this kind of cultivation should be restricted by law to condense the ongoing soil loss in the study watershed in particular and reduce the sedimentation rate of Lake Tana in general. In addition, since Lake Tana is the main source of the transnational Nile River, implementing the intensive cultivation management scenario in this watershed would help to maintain a continuous Nile River flow within and beyond the national boundary.

The reductions in areas that had a soil erosion rate of above the TSL limit to the intensive cultivation scenario suggested that it is crucial to avoid cultivation above 15% slope. Area enclosure and improvements in vegetation covers were also reported reducing water-induced soil erosion in northern Jordan (Alkharabsheh et al., 2013), Meleka watershed in Ethiopia (Mekuriaw, 2017) and the Loess Plateau in China (Yan et al., 2018). Conversely, the expansions of cultivated land and reductions of vegetation covers were reported increasing soil erosion in Maithon reservoir catchment in India (Sharma et al., 2011), Central rift valley region of Ethiopia (Meshesha et al., 2012) and Rib watershed in Ethiopia (Moges and Bhat, 2017).

In all of the scenarios, severe to very severe soil erosion rates were observed in the upland areas where watershed is steep. Similar findings were reported in other watersheds in Ethiopia, such as in the Chemoga watershed (Bewket and Teferi, 2009), Koga watershed (Gelagay and Minale, 2016) and Geleda watershed (Gashaw et al., 2017). However, the soil erosion in these areas reduced with the implementation of intensive cultivation; however, it increased with extensive cultivation. Therefore, watershed management practices should target such areas which are prone to soil erosion the most.

5. Limitations and innovation of the study

Due to the absence of measured soil erosion data, validation of the obtained soil loss was made only by comparing the result of this study with previous findings in the Ethiopian highlands. Hence, one of the limitations of this study is the estimated soil loss was not validated with observed soil loss records. Another limitation of this study is though the *R*-factor was computed using rainfall intensity data in the original USLE model (Wischmeier and Smith, 1978), due to the absence of this data in the study watershed, the *R*-factor was developed from the annual rainfall amount based on the relationship established by Hurni (1985) for the Ethiopian highlands.

In spite of the above mentioned limitations, the indispensable innovation of the study is SWAT and RUSLE models were integrated to provide estimates of mean annual soil erosion rate at the watershed and sub-watershed scales in the existing land management practice and two probable future scenarios. SWAT was used to identify sub-watersheds. Henceforth, integrating these models helps to know the rate of soil erosion in each sub-watershed and thus, such kinds of result will help land managers to prioritize erosion hot spot areas for conservation measures (Bewket and Teferi, 2009; Gashaw et al., 2017). The concept can be applied to another area in the Ethiopian highlands and elsewhere for a similar subject.

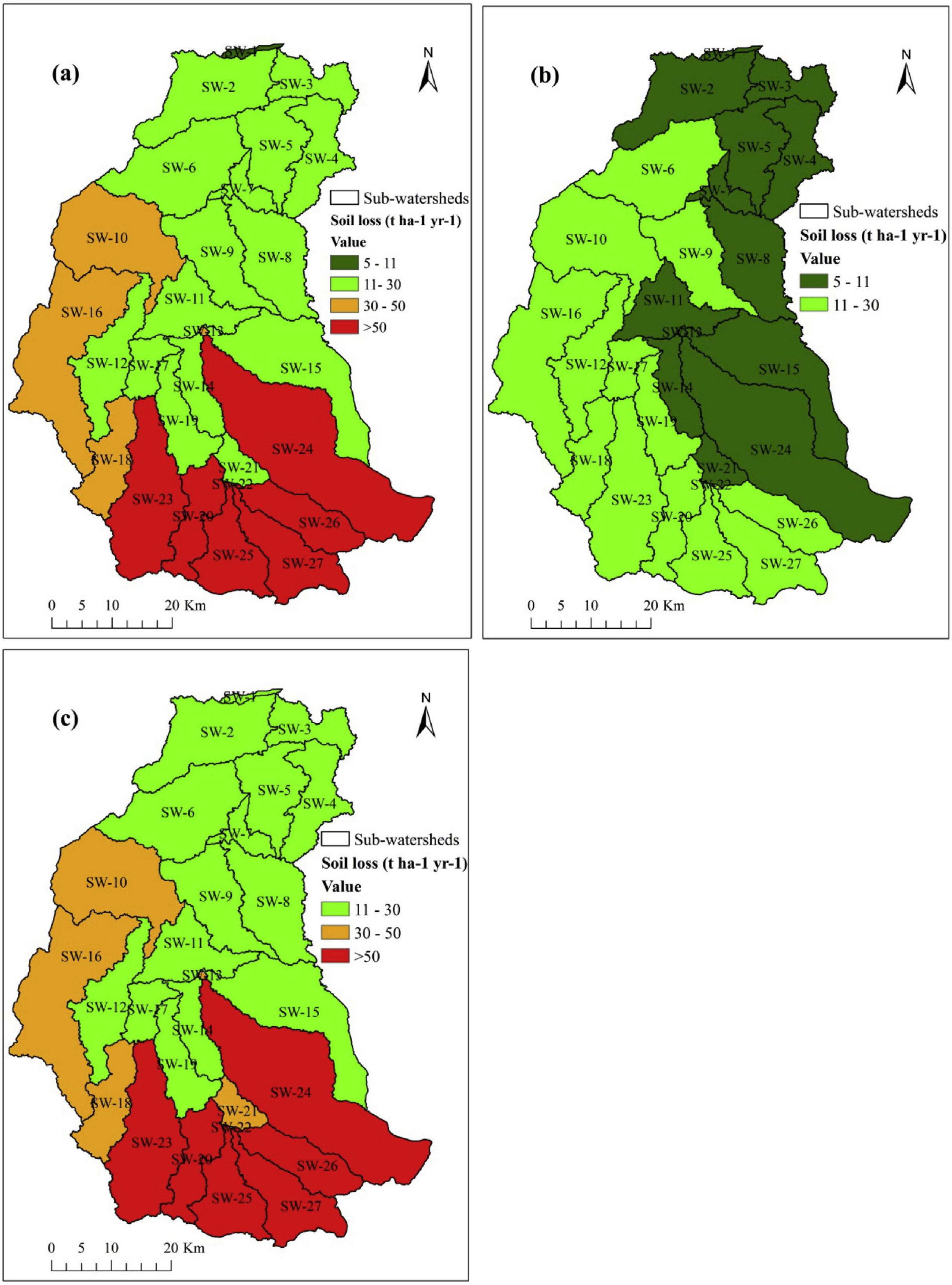

Figure 7. The mean annual soil erosion rate estimates at sub-watershed level for the (a) baseline, (b) intensive cultivation, and (c) extensive cultivation land management scenarios.

Table 3. The estimated mean annual soil erosion rate in each sub-watershed at the three land management practice scenarios.

Mean soil erosion rate (t $ha^{-1}yr^{-1}$)	Severity classes	Baseline scenario		Intensive cultivation scenario		Extensive cultivation scenario	
		Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
0–5	Very slight	-	-	-	-	-	-
5–11	Slight	9.7	0.3	1750.8	45.1	-	-
11–30	Moderate	1951.6	50.2	2135.1	54.9	1919.2	49.4
30–50	Severe	704.5	18.1	-	-	746.6	19.2
>50	Very severe	1220.1	31.4	-	-	1220.1	31.4
Total		3885.9	100	3885.9	100	3885.9	100

6. Conclusions

The study assessed soil erosion in the Gilgel Abay watershed in the existing land management systems and two plausible future scenarios, namely intensive cultivation and extensive cultivation scenarios at the watershed and sub watershed scales through integrating SWAT and RUSLE models. The findings showed the intensive cultivation land management scenario increased very slight, slight and moderate erosion intensity classes and reduced the very severe and severe erosion categories at the watershed scale, which indicate that this land management practice has shifted areas affected by a higher erosion intensity classes into lower erosion categories. The intensive cultivation management scenario has also completely converted areas affected by severe and very severe erosion intensities and increase slight erosion severity category at the sub-watershed scale. Overall, the intensive cultivation land management scenario reduced the total soil loss by 65% compared to the existing land management practice. As it is stated previously, the intensive cultivation scenario assumes that all the currently used cultivated lands that are located above 15% slope were suggested for area enclosure. Hence, the result indicated that conversions of cultivated lands that are found only above 15% slope gradient into erosion-resistant covers are imperative to avert the ongoing soil erosion.

In contrast, the extensive cultivation scenario, which assumes additional production for increasing future food demand will be obtained by expanding the cultivated lands at the expense of the whole grasslands, shrublands and wetlands in areas that are located lower than 15% slope, diminish areas affected by very slight and slight erosion intensity and increase moderate, severe and very severe erosion categories at the watershed scale. Thus, this result discloses that the implementation of the extensive cultivation land management practice scenario will shift areas affected by lower erosion into higher erosion intensity classes. At the sub-watershed level, the extensive cultivation management scenario has totally shifted very slight and slight erosion and reduces moderate erosion intensity class. On the other hand, this land management practice increased severe erosion category, which shows that the extensive land management practice scenario can intensify soil erosion.

In general, the findings of this study attest that intensive cultivation should be implemented in the Gilgel Abay watershed and Ethiopian highlands to abate the alarming soil erosion and also protect the freshwater systems from sedimentations such as the Lake Tana. However, implementations of such interventions require due attention to achieve their fullest potential.

Declarations

Author contribution statement

Temesgen Gashaw: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Abeyou W. Worqlul, Yihun T. Dile, Solomon Addisu, Amare Bantidar: Analyzed and interpreted the data; Wrote the paper.

Gete Zeleke: Conceived and designed the experiments; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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