Chapter 2
Geopedological and Landscape Dynamic Controls on Productivity Potentials and Constraints in Selected Spatial Entities in Sub-Saharan Africa

Yazidhi Bamutaze

Abstract Soil-landscape relations play an important role in the agricultural production systems of Sub-Saharan Africa. As the demands on elevated agricultural productivity grows in the face of increasing demographic pressure and the adverse impacts of global environmental change, we must identify socio-ecological production landscapes that are resilient to environmental changes. This paper analyses a spectrum of spatial and non-spatial datasets covering soil, terrain, land use, and geology in a GIS environment to derive spatial entities that inform the production potentials and constraints of East Africa. Landscape analysis, premised on the geopedological and elevation constructs, culminated in a spatial coverage of lowlands (40 %), plateaux (46 %), highlands (11 %) and mountains (3 %) across the East African region. Regional-level analysis reveals spatially variable soil typologies dominated by Cambisols (24 %) and Ferralsols (13 %). In these geomorphic landscapes and soil types, there are two outstanding anthropogenic threats to productivity: soil erosion and land use/cover conversions and transformations. These must be delicately tackled with site-specific tailored interventions that not only recognize geopedological landscape sensitivity, but also the inherent social systems.

Keywords Geopedological • Geomorphology • Landscape dynamics • Productivity

Y. Bamutaze (✉)
Department of Geography, Geo-informatics and Climatic Sciences,
Makerere University, PO Box 7062, Kampala, Uganda
e-mail: yazidhibamutaze@gmail.com

R. Lal et al. (eds.), *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa*, DOI 10.1007/978-3-319-09360-4_2

2.1 Introduction

Sub-Saharan Africa (SSA) is one of the most dynamic, diverse, and heterogeneous biophysical landscapes in the world. The landscape's complexity manifests in the geomorphological, soil, and geological settings, posing a range of challenges and opportunities that underpin the continental development pathways from household to national levels. The central geomorphological feedback processes associated with its complex and dynamic socio-ecological landscape strongly influence production patterns. Therefore, understanding the inherent ecological fragility of this coupled landscape is fundamental to reduce the effects of geohazards, sustain ecological integrity, and secure people's livelihoods. The need for sustainable landscapes and livelihood systems is critical for SSA because of rapid demographic changes, increasing land degradation, stagnant or declining crop yields, and relatively new threats linked to the increasing variability and changes of the climate.

Sustainable land use practices recognizing a landscape's ecological sensitivities and maintain agricultural productivity are gathering attention. Soil resources are fundamental to fighting the traditional challenges of land degradation, as well as effectively buffering communities from the dangers of climate change. For example, the Comprehensive Africa Agriculture Development Programme (CAADP) has an ambitious annual agricultural growth target of 6 %, a harbinger of development transformation on the continent (Kolavalli et al. 2010). Due to the fundamental importance of quality geopedological resources for agricultural production, only sound landscape stewardship can achieve this goal. Although agricultural production in SSA relies on heavily inherent natural soil fertility, the general understanding of soil geomorphology systems remains dismally low compared to other continents.

It is impossible to underestimate the importance of healthy soil resources for sustainable livelihoods in SSA (Eswaran et al. 1997; Henao and Baanante 2006; Bationo et al. 2006). Because so many livelihoods in the region depend on natural resources, the relationships between soil quality, productivity, and poverty levels are strongly interdependent. However, despite their productive role in agricultural livelihoods, the importance of soils and the multitude of associated environmental services are not widely appreciated in Africa (Dewitte et al. 2013). Consequently, limited efforts have been undertaken to address a range of soil-related issues at a finer scale crucial to improve productivity. In most SSA countries, low crop yields indicate an abundance of poor quality soils (Sanginga and Woomer 2009). Under these conditions, there is need to improve understanding of spatially explicit soil-geomorphic settings crucial for agricultural productivity.

A geopedological perspective embeds geomorphic and pedologic processes throughout the landscape, as well as recognizing biophysical feedback and sociological processes. Thus, this geographically-oriented soil-landscape nexus yields a better understanding of the production systems and ecosystem servicing crucial for the sustainable development of agriculture and biodiversity (Sayre et al. 2013; Griffiths et al. 2011). This paper helps correct the paucity of soil-based landscape studies by using geomorphic and pedologic analysis to present information on productivity potentials and constraints.

2.2 Geographical Settings

This study is confined to the East African region of SSA covering five countries: Uganda, Kenya, Tanzania, Rwanda and Burundi. The region is located approximately between 4°N and 12°S latitude and 29°E to 42°E longitude, as shown in Fig. 2.1.

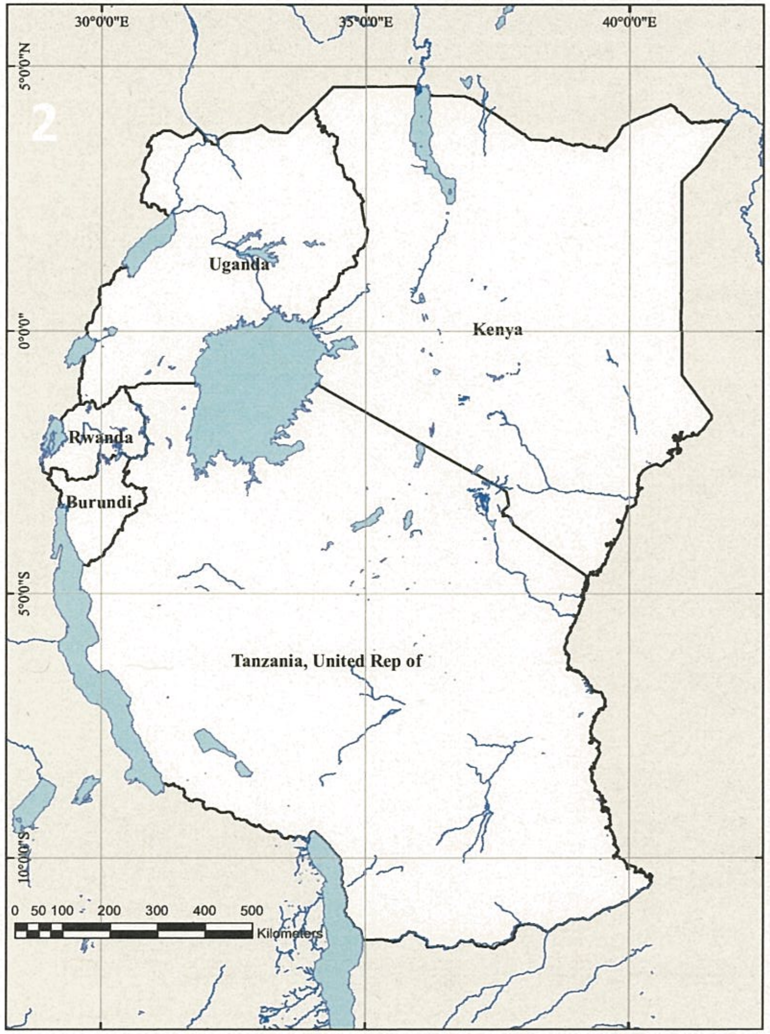

Fig. 2.1 Location map of East Africa

Table 2.1 Key socio-economic characteristics of the East African countries

Parameter	Uganda	Kenya	Tanzania	Rwanda	Burundi
Size (km^2)	241,248	593,116	933,566	24,550	28,062
Population (millions)	35.6	42.7	47.7	11.3	8.7
Population density (persons/km^2)	148	72	51	460	310
Human development index in 2012	0.456	0.519	0.476	0.434	0.355
Annual population growth rate (%)	3.3	2.7	3.0	2.8	3.2
Life expectancy at birth (years)	58	60	60	63	53
GDP per capita by 2012 (US$)	547	943	609	620	251
Agricultural area in 2011 (km^2)	168,874	284,696	392,098	19,149	24,133

The region exhibits a high level of ecological and social diversity in its geology, geomorphology, climate, and vegetation. It displays significant geomorphological features of the East African Rift valley, the Lake Victoria basin and a range of highland and mountainous landscapes. Climatic conditions of the region are diverse and variable. The climatic geography is a function of global, regional, and local factors, notably the Inter-Tropical Convergence Zone (ITCZ) and physiographic features, including topography, latitudinal position, and relative location from major drainage bodies such as Lake Victoria. Major mountain landscapes such as Mt. Kilimanjaro, Mt. Rwenzori, Mt. Elgon, and Mt. Kenya also significantly control the local and regional climatic conditions. Annual rainfall amounts vary from about 250 mm in semi-arid regions to over 2,500 mm in the highlands. The region has a distinctly uneven spatial and temporal rainfall distribution, exhibiting both unimodal and bimodal distribution structures. However, most crop production is confined to areas less than 2,500 m above sea level. The key socio-economic characteristics of the region are found in Table 2.1.

The region's population was estimated to be 142 million people in 2013. The highest and lowest population densities are 460 and 51 persons/km^2 in Rwanda and Tanzania respectively. Agriculture is essential to the East African economy and is dominated by small-scale farming which relies heavily on rainfall. Land degradation is a serious production constraint, principally because of soil erosion and nutrient depletion, a more variable and changing climate, increasing incidences of natural hazards and disasters, biodiversity loss, land use changes and conversions, and rapid population growth.

2.3 Data Sources and Analysis

The data sets used, their characteristics, and sources are given in Table 2.2. The data consist of both geospatial and non-spatial data, gathered from secondary and primary sources. Geospatial data were obtained from an array of sources in formats compatible with digital Geographical Information System (GIS).

The joint FAO and IIASA Global Agro-ecological Zones (GAEZ) portal supplied data on soil and terrain conditions which was used to assess the regional spatial variability of agricultural suitability. A digital soil data set grid from FAO was used to quantitatively analyse the predominant soil types at the national level. A Digital Elevation Model (DEM), based on Shuttle Radar Topography Mission (STRM) 90 m spatial resolution data, was obtained from the Makerere University archives and used for deriving and classifying landscapes. Geomorphic landscapes based on altitude thresholds were delineated as: mountains (>2,000 masl), highlands (1,500–2,000 masl), plateau (900–1,500 masl) and lowlands (<900 masl). The Makerere University archives also supplied a geology shapefile for Uganda to depict geology types spatially. Columbia University's Center for International Earth Science Information Network (CIESIN) provided digital gridded population data, projected for the year 2015. The data was used to map population density hotspots and relate them to landscape typologies. Because the sources of geospatial

Table 2.2 Datasets used, sources and characteristics

No.	Variable	Source	Type	Spatial extent	Usage/ analysis
1	Soil type	FAO & IISA (http://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/)	Spatial	East Africa	Spatial typologies
2	Soil erosion	Field and published data	Spatial	Uganda	Magnitude and variability
3	Geology	Archives	Spatial	Uganda	Types and distribution
4	DEM	Archives	Spatial	East Africa	Landscape delineation
5	Suitability	FAO and IISA (http://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/)	Spatial	East Africa	Quantitative variability
6	Forest cover	World Bank (http://data.worldbank.org/)	Tabular	East Africa	Trend analysis
7	Arable land	World Bank (http://data.worldbank.org/)	Tabular	East Africa	Trend analysis
8	Population	CIESEN (http://sedac.ciesin.columbia.edu/)	Spatial	East Africa	Hotspot sites
9	Erosion Risk	Derived using GLASSOD methodology	Spatial	Uganda	Hotspot landscapes
10	Production data	FAOSTAT (http://faostat.fao.org/)	Tabular	East Africa	Trend analysis

data were so diverse, I employed a range of data quality control measures and standardized all data sets to World Geodetic System (WGS 84) datum in a GIS environment to enable a spatial multiple overlay analysis. After standardizing the data, the East Africa region was clipped out of the continental and global datasets. Relevant tabular and statistical data were then extracted in a GIS and further plotted or statistically analysed in appropriate programmes. Geospatial analyses used ARCGIS 10 software from ESRI. Statistical and tabular data was obtained from the FAOSTAT and World Bank data portals and published data in literature. Data was subjected to an array of statistical analyses, including descriptive and inferential statistics. Descriptive statistical data used mean, standard deviation, coefficient of variation, and percentages. Inferential statistics included linear regression analysis for detecting temporal trends in forest cover change.

2.4 The Geopedological Construct

Geopedology refers to the contribution of geomorphology to pedology, and the resulting feedback (Zinck 2013). It is premised on the fact that geomorphology and pedology constitute intricately inseparable landscape characteristics through geoforms and soils. The geopedological construct thus analyses prime biogeochemical processes to facilitate inferences of landscape constraints and opportunities for agricultural productivity. Thus, coherence and synergies of landscape elements that geomorphology and soils reveal are the most important land quality aspects regarding agricultural productivity. Current agricultural production in SSA is mostly low-input and heavily depends on soil quality. Lucid interfaces between soil-geomorphologic systems and the relevant social systems strongly influence production potentials and constraints. The geopedological construct, therefore, provides a holistic biophysical structure and coupling that represents a socio-ecological production system, as depicted in Fig. 2.2.

2.5 Landscape Dynamics and Agricultural Productivity

2.5.1 Geomorphological Landscape, Productivity Constraints, and Opportunities

A landscape is the highest level in the geopedological hierarchy. The significance of geomorphic landscapes for agricultural productivity is well documented, particularly regarding crop types, production patterns, and yields. The landscapes' influence is largely manifested through moderation of climatic conditions, weathering, soil formation, soil quality, and ultimately soil resilience. From a geomorphological perspective, four landscape typologies based on altitudinal variability and

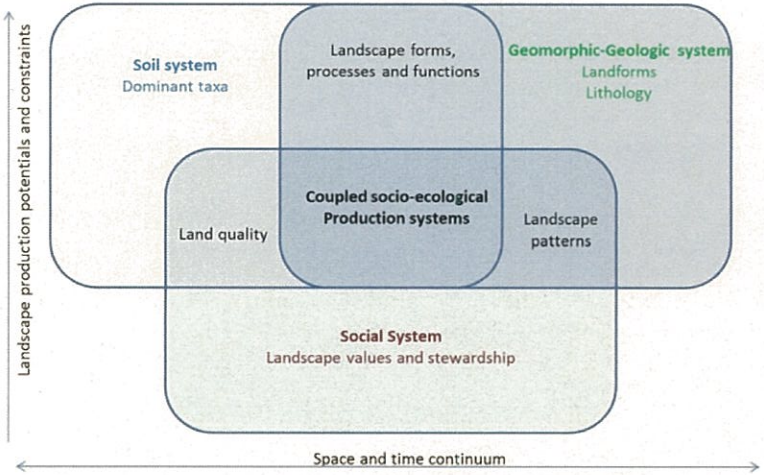

Fig. 2.2 Schematized interfaces of elements influencing productivity dynamics in the geoepedological construct

thresholds were delineated for East Africa: lowlands, plateau, highlands, and mountains. They are associated with diverse challenges and opportunities for agricultural productivity. The spatial distribution and major characteristics of East Africa's landscapes are shown in Fig. 2.3. These landscapes reflect a complex of past and current geomorphological processes, such as volcanicity, faulting, folding, weathering, and erosion. The diverse geographical operations of these processes have resulted in the current terrain configuration of East Africa.

Mountain landscapes are more than 2,000 m above sea level, the highest altitude landscape hierarchy. They cover about 3 % of the area of East Africa. Mountain landscapes are extremely diverse even at short distances. With the exception of urban centers, mountain landscapes have the highest population densities in the region (See Fig. 2.3b). They are attractive for settlement because of good conditions for crop production such as high levels of soil fertility and annual rainfall. The most important perennial crops, such as coffee and bananas, are productively grown in mountain landscapes in what is agro-ecologically classified as montane farming systems. However, mountain landscapes possess high erosive energy because their steep gradients encourage high runoff, which if not managed well greatly damages crops. Consequently, mountain landscapes are prone to a range of geohazards (Table 2.3).

Highland landscapes lie between 1,500 and 2,000 m above sea level, and represent approximately 11 % of the East African region. Over 60 % of Burundi and Rwanda can be categorized as either highland or mountainous. The steep slopes of highland environments and similar geohazards as mountain areas cause severe

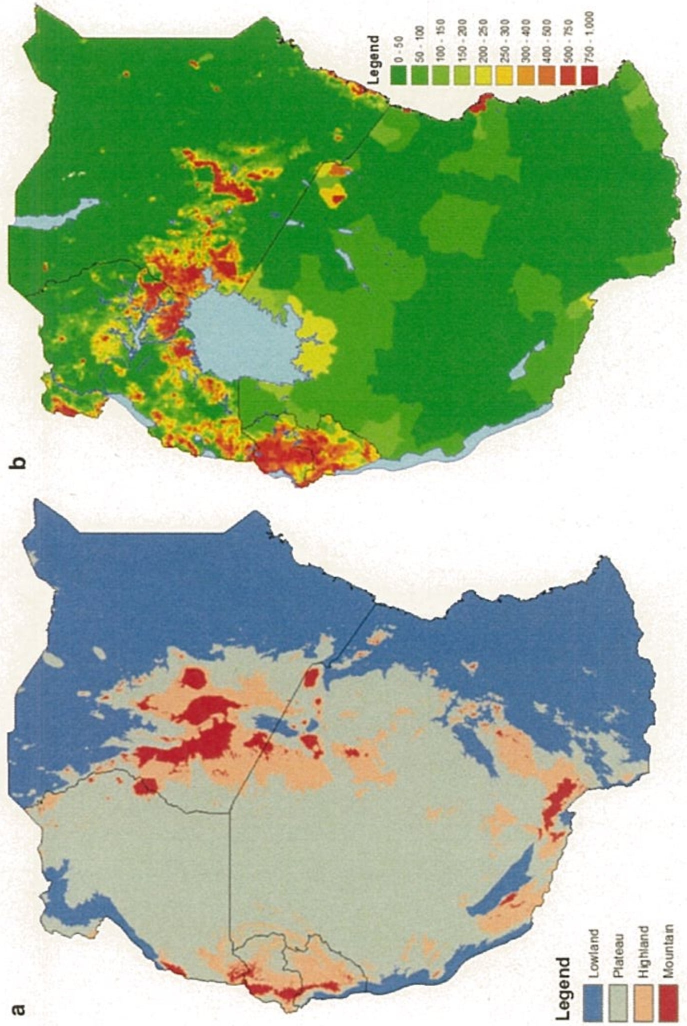

Fig. 2.3 Geomorphological landscape categories (a) and population density hotspots in East Africa (b)

Table 2.3 Selected landscape characteristics in East Africa

Landscape	Altitude (masl)	Coverage	Productivity[a]	Major geohazards
Mountains	>2,000	3 %	High	Erosion, slope failure, land cover transformation
Highlands	1,500–2,000	11	High	Soil erosion, nutrient mining,
Plateau	900–1,500	46	Medium to high	Soil erosion, floods, nutrient mining
Lowlands	<900	40	Low to medium	Flooding, drought

[a]Productivity hinged on low input conditions (natural nutrient conditions)

agricultural production constraints. Geomorphologically, highland and mountain landscapes have high transportation capacities and stream densities that convey both runoff and sediment to the lower landscapes. Plateau landscapes range from 900 to 1,500 m above sea level and represent the largest part of the entire region. Agricultural productivity in the plateau landscape is highly varied and also depends in part on rainfall levels. The Lake Victoria Basin is the most attractive region of the plateau landscape in East Africa. Despite their relatively lower slope gradients, plateau landscapes also experience erosion and nutrient mining. Lowlands, which are below 900 m, constitute a north–south axis in the eastern part of the region parallel to the Indian Ocean. Lowlands occupy about 40 % of the region's landscape, including much of Kenya and a significant part of Tanzania. They are generally characterized by transport-limited slopes, and are prone to flood hazards. For lowland inland regions such as eastern Uganda, flooding is also strongly linked to the climatic and geomorphological conditions in the mountain landscapes that consequently supply runoff to the lower areas.

2.5.2 *Soil and Terrain Influences on Agricultural Suitability*

Agricultural systems in East Africa are typically rain-fed systems. Land suitability under rain-fed conditions depends on the ecological interfaces between climate, soil, and terrain which determine productivity levels and yield dynamics. The spatial extent of rain-fed agricultural suitability in Eastern Africa under low and high input conditions constrained by soil factors alone is found in Fig. 2.4, while that constrained by both soil and terrain conditions is depicted in Fig. 2.5.

Evidently, a change from the low input conditions of traditional subsistence land management and crop varieties, to high input conditions characterized by market-oriented land management practices would change landscape suitability and ultimately improve crop yields by about 24 %. This provides, in part, the rationale for the region's agricultural policy changes which Uganda's Plan for Modernization of

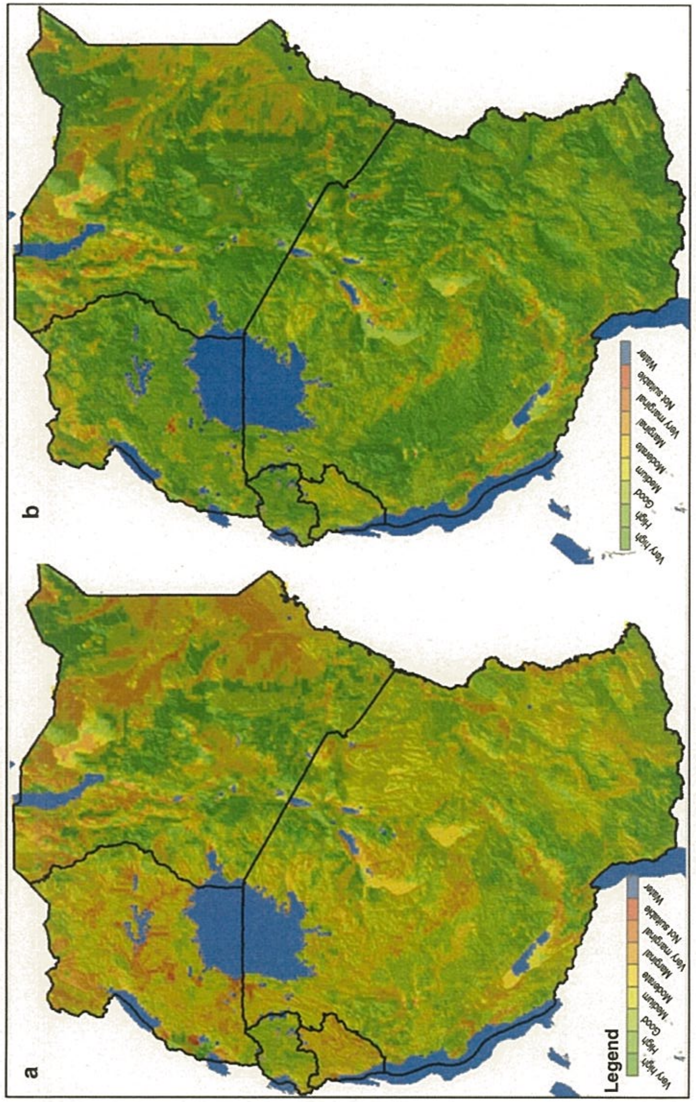

Fig. 2.4 Spatial variability of rain-fed agricultural suitability as constrained by soil under low (**a**) and high input (**b**) conditions

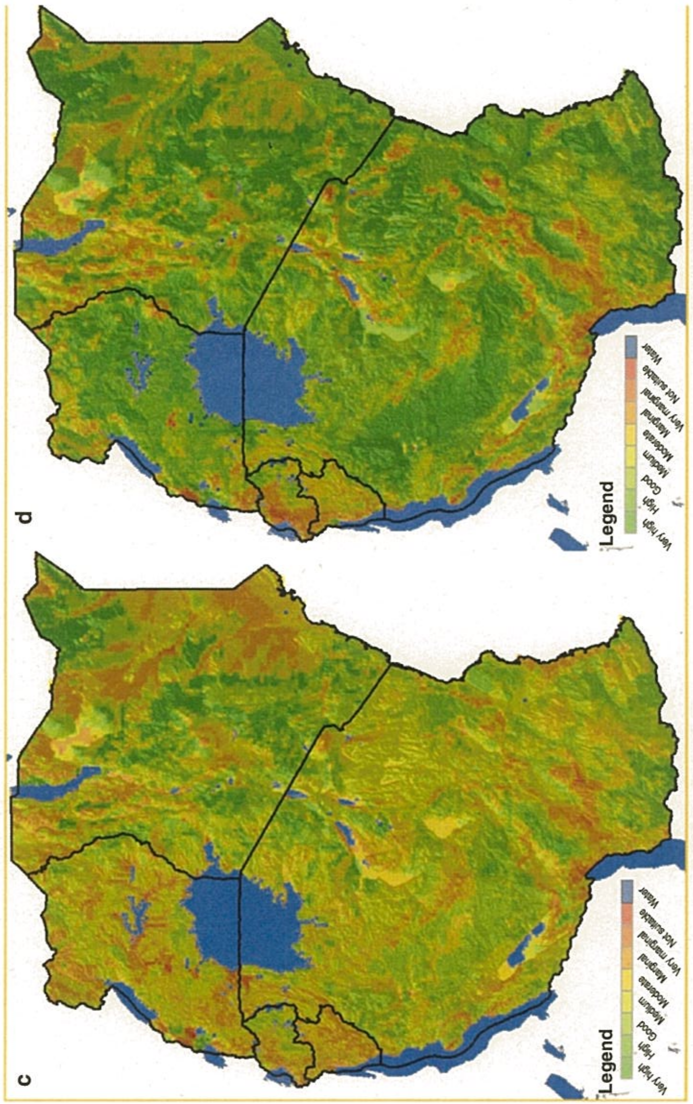

Fig. 2.5 Spatial variability of rain-fed agricultural suitability as constrained by soil and terrain factors under low (**c**) and high input (**d**) conditions

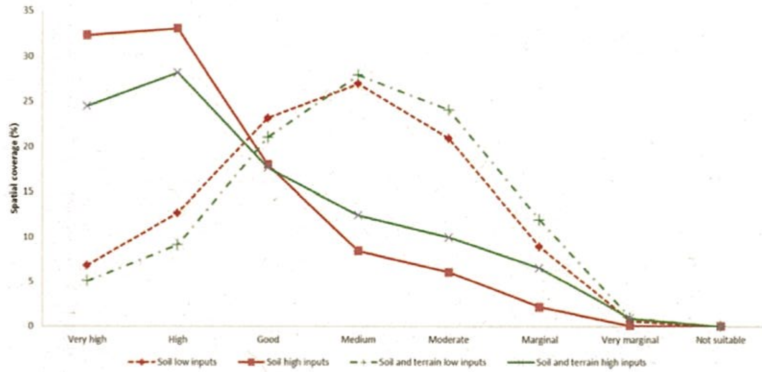

Fig. 2.6 Variation in suitability under low and high input conditions

Agriculture (PMA) exemplifies. This plan focuses on market-oriented agriculture and sustainable management of land resources.

The percentage coverage of agriculturally suiland according to soil conditions alone is compared with that of the coupled soil and terrain conditions in Fig. 2.6. In general, the terrain factor, denoted largely by altitude and slope gradient, imposes more constraints on land's suitability for crop production. Therefore, it is not surprising that areas with proportionally higher highland and mountainous environments, like Rwanda and Burundi pale in suitability when compared to Kenya, Uganda, and Tanzania.

Under low input conditions, a suitability deviation of about 3 % is attributed to the terrain effect, while the deviation is as high as 9 % under high input conditions. In consonance with other studies (Akinci et al. 2013; Xu and Zhang 2013; Igue et al. 2004), high rates of water runoff, soil erosion, higher transportation capacities of water and nutrients, and difficulties with tillage and conservation practices are all evidence of terrain's effect on a landscape's agricultural suitability and productivity. Soil formation and development intimately depends on site topography and geomorphological characteristics, slope gradient having the greatest effect. In East Africa, FAO (2006) categorizes sites with slope gradients of more than 30 % as steeply dissected. For rain-fed agriculture, they are considered severely constrained for crop production. A spatial analysis by van Velthuizen (2007) reveals that areas with slope gradients of more than 30 % represent about 6 % of East Africa's total area and contain 9 % of the rural population.

2.5.3 *Soil Quality and Soil Types*

African soils are among the least fertile in the world, with about 80 % having inherent fertility limitations (Otter et al., 2007). Major soil limitations present huge obstacles to agricultural productivity. Some postulates to explain poor soils

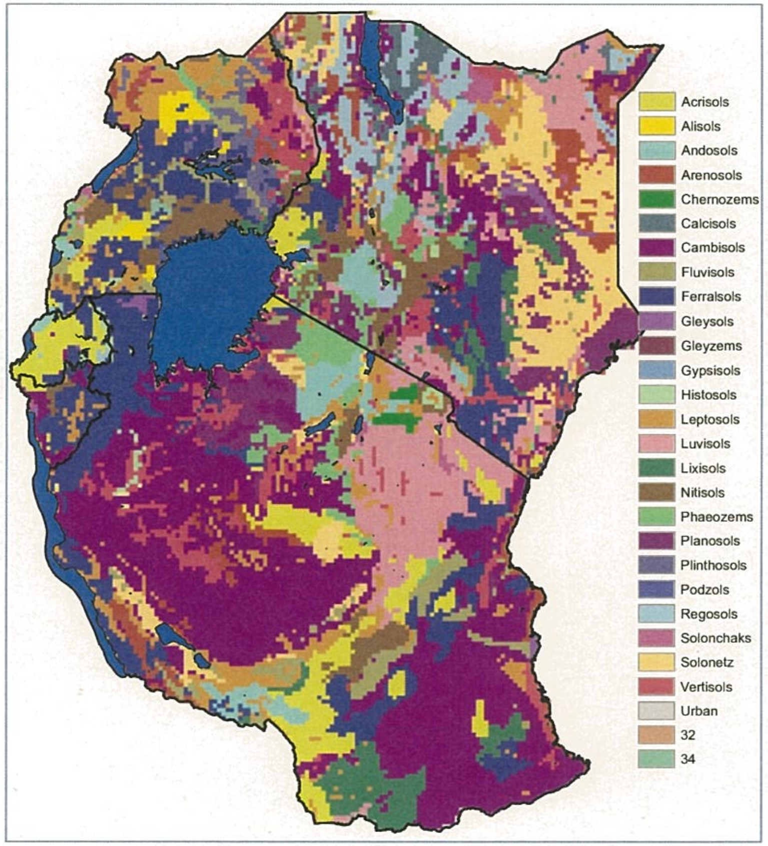

Fig. 2.7 Major soil types of East Africa based on the FAO classification system

implicate their having developed from Precambrian basement rocks as a major causal factor. SSA soils, in particular, are highly diverse and spatially variable (Voortman 2010). Despite providing livelihoods for millions of small scale farmers, the soils of Africa are poorly mapped and badly understood (Sanginga and Woomer 2009). A spatial distribution of East Africa's major soil types based on the FAO soil classification system is found in Fig. 2.7.

Figure 2.8 contains a quantitative analysis of the distribution of the region's respective soil types. The data identifies approximately 25 soil types with diverse production potentials and constraints, signifying a high level of soil diversity and heterogeneity. A recent soil mapping by Dewitte et al. (2013) identified 29 soil types for continental Africa, which is not surprising given the geomorphological, geological, and climatic complexity of the region. The most common soil types in

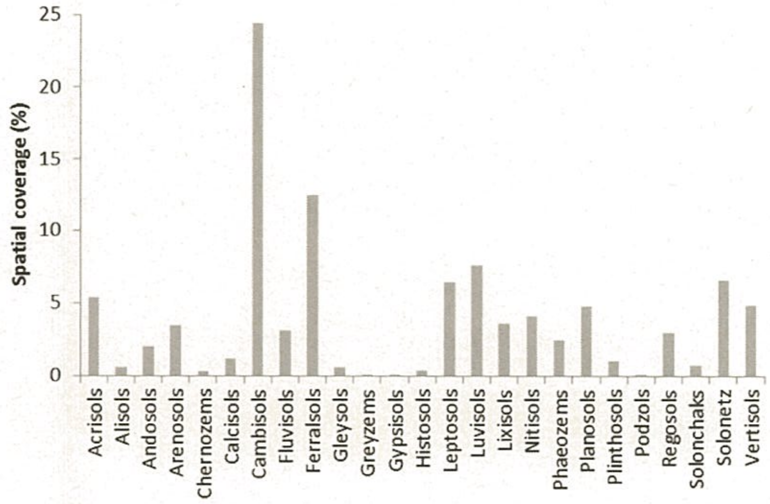

Fig. 2.8 Quantitative distribution of soil types in East Africa

East Africa are the Cambisols and Ferralsols which constitute about 24 % and 13 % respectively of soil. Other soil types with reasonable spatial distribution include Luvisols (8 %), Solonetz (7 %), Leptosols (6 %), Acrisols (5 %), Planosols (5 %), and Vertisols (5 %) as depicted in Fig. 2.8. A spatial analysis reveals that these eight soil types cover approximately 73 % of East Africa's land. The remaining 17 soil types cover only 27 % of the region, with the least common being the Gypsisols (<0.1). This means that many local factors control soil formation and development in the region. Increasing agricultural productivity requires targeted interventions and management strategies adjusted to each soil type.

The variability of soil types and their prevalence at national levels are depicted in Fig. 2.9. There are 22 soil types in Uganda, 23 in Kenya, 19 in Tanzania, 8 in Rwanda and 9 in Burundi. The Ferralsols (25 %) are the most dominant in Uganda, while Calsisols have the lowest coverage (<0.1 %). In Kenya, the Solonetz soils have highest coverage (16 %) and Gypsisols have the lowest. Cambisols dominate Tanzania, occupying 39 % of the land area, while Regosols have the lowest coverage (<0.1 %). Acrisols cover most of the land in Rwanda (62 %), while Nitisols only cover 0.3 %. In Burundi, Ferralsols cover the highest percentage of the land (48 %) while Histols cover the lowest amount (0.3 %).

2.6 Landscape Degrading Processes

Two major factors related to landscape degradation hinder agricultural productivity in SSA and specifically East Africa: soil erosion and land use cover transformations.

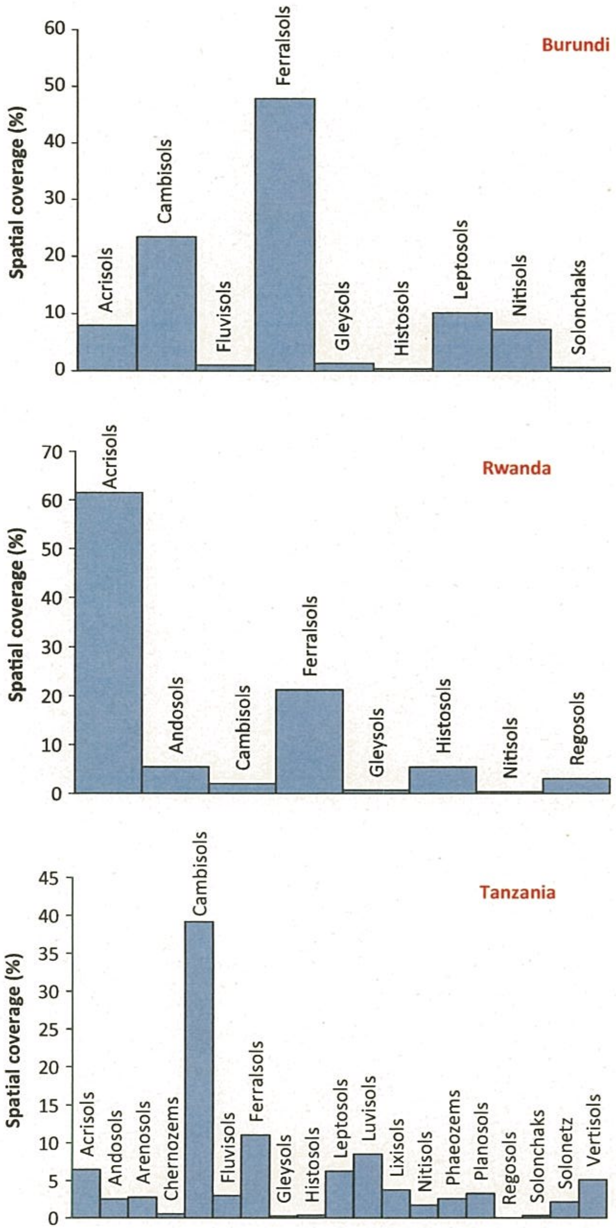

Fig. 2.9 Spatial coverage of soil types in the East African countries

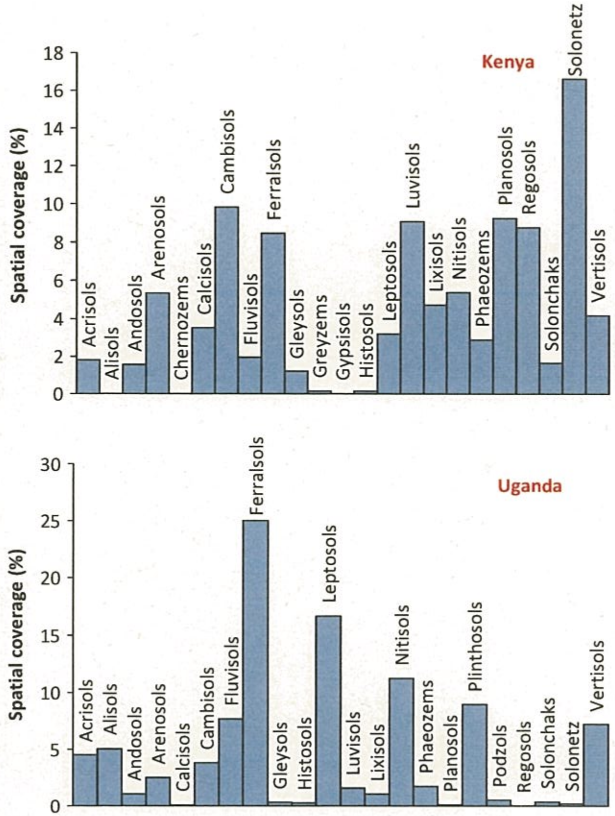

Fig. 2.9 (continued)

2.6.1 *Soil Erosion*

Soil erosion, particularly by water, is one of the most serious threats to agricultural productivity in SSA (Obalum et al. 2012). Soil erosion is omnipresent in the region and reported to be increasing, although comprehensive empirical studies of erosion rates for the entire East African region are scarce. However, scattered reports from both experimental runoff plots and spatial modelling verify its extent and magnitude. Results on annual soil erosion rates from diverse studies based on experimental runoff plots in major Ugandan landscapes are depicted in Table 2.4.

Table 2.4 Measured mean annual soil losses from dominant land use system across landscape categories in Uganda

Author	Soil loss	Landscape category	Land use system
Bagoora (1998)	10–129 t/ha/year	Highland	Maize and beans
Bamutaze (2011)	10 t/ha/year	Mountain	Intercropped annual and perennial
Bamutaze (2005)	25–45 t/ha/year	Mountain	Maize, banana, coffee
De Meyer et al. (2011)	34–207 t/ha/year	Plateau	Footpaths and agricultural fields
Kizza et al. (2013)	10–320 kg/ha/year	Plateau	Forest
Majaliwa (1998)	40–45 t/ha/year	Plateau	Maize, maize-beans intercrop
Majaliwa (2005)	20–85 t/ha/year	Plateau	Coffee, banana, beans
Mulebeke (2004)	25–71 t/ha/year	Plateau	Banana, coffee, beans
Nadhomi et al. (2006)	9–48 t/ha/year	Plateau	Banana, coffee
Nakileza (1994)	3–7 t/ha/year	Mountain	Maize, beans, mixed cropping
Nakileza (2005)	20 t/ha/year	Plateau	Annual cropping
Semalulu et al. (2013)	1–39 t/ha/year	Mountain	Banana, coffee
Tukahirwa (1996)	1–38 t/ha/year	Highland	Sorghum

The spatial variability of Uganda's erosion rate using the GLASSOD methodology is found in Fig. 2.10a. Figure 2.10b is a geopedological map coupling the dominant soils, geology, and geomorphology.

As expected, highland and mountainous landscapes experience more degradation than lower elevations. In Uganda, these landscapes receive substantial annual rainfall. They are dominated by steep slopes of more than 30 % which are especially prone to soil erosion. The ownership of land is extremely fragmented in highland and mountainous landscapes, with land size per household predominantly at less than 1 ha.

In these landscapes, soil erosion is dominated by rill and interill typologies, while gullies are confined to a few areas, particularly in western Uganda. High erosion rates are observed in the heavily populated and intensively cultivated plateau of the Lake Victoria Basin. These dangerous erosion rates are in the range of those observed in the South-western highland and Mt. Elgon in Eastern Uganda. A runoff and soil loss assessment at varied hill slope positions on the Mt. Elgon landscape under annual and perennial cropping (Bamutaze 2005) confirms high erosion across lower, middle, and upper hillslope segments, as Fig. 2.11 shows. Observed annual soil erosion rates from these hillslope segments are higher than the generally accepted tolerable limit of 5 t ha^{-1} $year^{-1}$. This pattern has also been observed at sites in other SSA countries, such as the Ethiopian highlands,

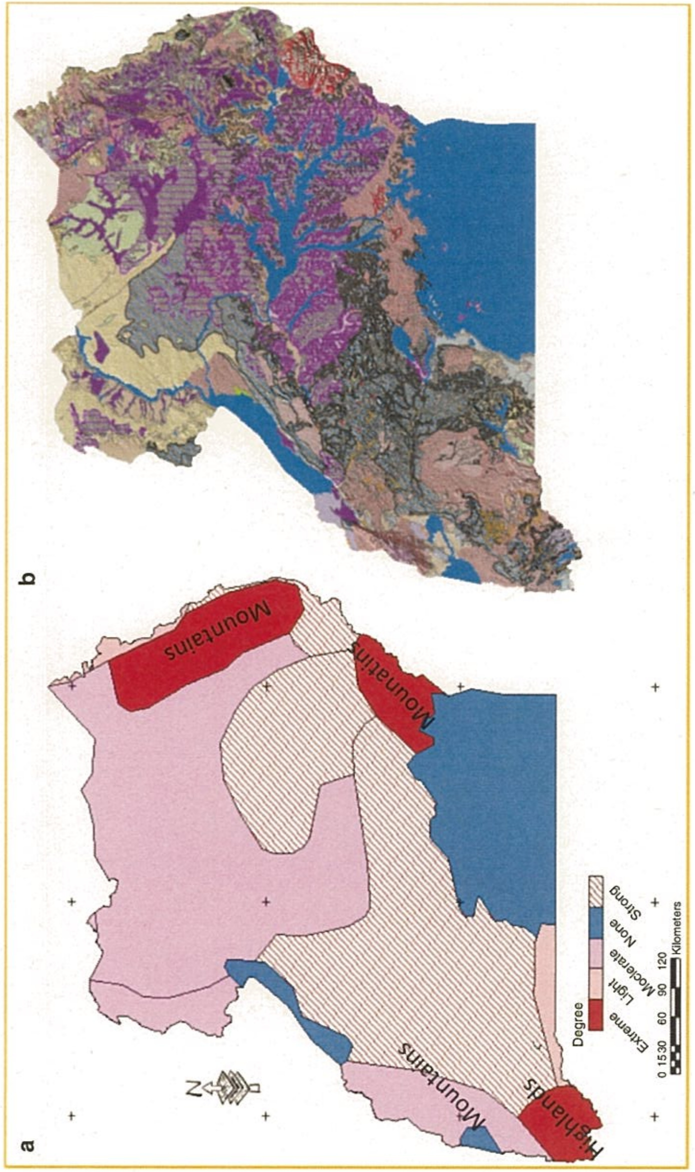

Fig. 2.10 Soil degradation status based on GLASSOD methodology (a) and geopedological entities of Uganda (b)

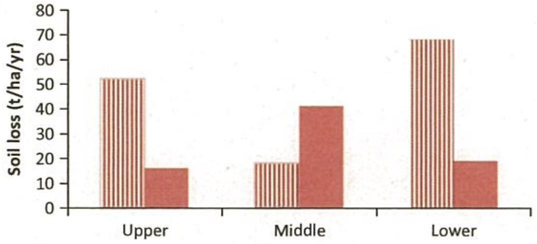

Fig. 2.11 Variability of soil loss rates at diverse slope positions on Mt. Elgon (Source Bamutaze 2005)

(Munro et al. 2008; Nyssen et al. 2009) and Tanzania's Ulugulu mountains (Kimaro et al. 2008). While a mix of natural and anthropogenic factors contribute to these high soil erosion rates (Boardman 2006), poor landscape management is the dominant cause of soil erosion in SSA.

Recent comprehensive quantitative data on yield reductions from erosion in SSA are very limited. According to Lal (1995), erosion-related yield reductions in Africa generally vary from 2 to 40 % with a mean of 8.2 % for the continent and 6.2 % for SSA. These reductions are projected to rise to 16.5 % for the continent and 14.5 % for SSA by the year 2020 if erosion continues unabated (Lal et al. 2004; Obalum et al. 2012). As well, it is estimated that about 1.2 % of soil nutrients in Uganda are depleted annually, which contributes to poor harvest yields (NBI 2012).

2.6.2 *Trends and Implications in Land Use and Coverage Change*

Land use and soil coverage changes are significant terrestrial processes altering biogeochemical processes, ecological dynamics, and the sustainability of agricultural systems (Alkharabsheh et al. 2013). Conversions of forest cover into agricultural fields in East Africa are widespread and increasing. The change in East Africa's forest cover between 1990 and 2011 as a percentage of the total land area is shown in Fig. 2.12. Figure 2.13 displays trends in arable land for the same period.

A regression analysis shows that with the exception of Rwanda, all East African countries experienced a significant reduction in forest cover between 1990 and 2011 ($p < 0.05$). Regional-level analysis shows that forest cover was reduced from about 30 % of the land area to 23 % for the same period. The highest reduction was observed in Burundi (−41 %) and lowest in Kenya (−7 %). Strikingly, all countries except Burundi at least experienced a significant increase in arable land. The observed declining trend in East Africa's forest cover corroborates observations made elsewhere in SSA (Brink and Eva 2009; Were et al. 2013; Gross et al. 2013;

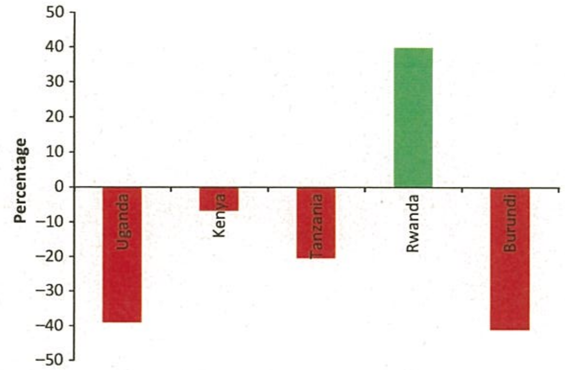

Fig. 2.12 Change in forest cover between 1990 and 2011 in Eastern Africa

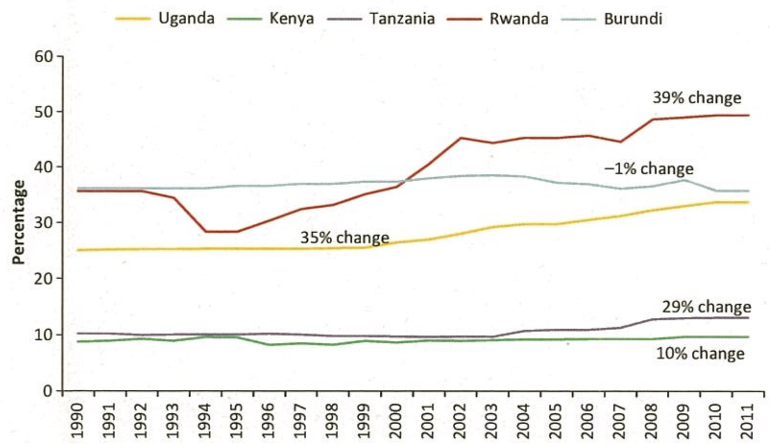

Fig. 2.13 Change in the proportional coverage of arable land in East Africa between 1990 and 2011

Brink et al. 2014). Interestingly, although Rwanda experienced the most rapid increase in arable land (39 %), its forest cover also increased between 1990 and 2011. The most plausible reason for this trend is that Rwanda has implemented environmental laws more firmly than other East African countries and begun a concerted re-forestation programme.

Fig. 2.14 Naked or raped landscape on a ferralsol on Mt. Elgon due to improper land use

Although the relationship between land use change and soil erosion is generally non-linear in the long term (Dotterweich 2013), extensive studies (Defersha and Melesse 2012; Munro et al. 2008; Heckmann 2014; Mohammad and Adam 2010) of the East African region show that land use changes result in high levels of land degradation. In the same region, studies by Mugagga et al. (2011) suggest that these landscape transformations account for the exponential increase in slope failures. Land use and cover change are more pronounced in highland and mountainous landscapes, which is more evident on the Ugandan side of Mt. Elgon than the Kenyan side. Unsustainable conversions from forest cover to annual crops have culminated in a landscape described locally as "naked or raped" (See Fig. 2.14). High soil erosion rates and related sedimentation processes compromise the immediate and long term productivity of these sites.

2.7 Conclusions

The interplay between geomorphology and pedology in tandem with climate plays a significant role in SSA's agricultural production systems. Regional landscape analyses indicate that terrain limitations prevent about 13 % of the region's highland and mountain areas from suifood production. Soil quality in many parts of the region also constrains production. Delineated geopedological landscapes are characterized by a range of geohazards, but the most significant seem to be soil erosion and land use change, particularly conversions from forest cover to cropping activities. For the landscapes to sustain the rapidly increasing human populations occupying them today and in the future, deliberate attention toward socio-ecological sustainability is required.

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Geo-spatial Information Science, 2014
Vol. 17, No. 1, 39–53, http://dx.doi.org/10.1080/10095020.2014.889271

Climate change and land degradation in Africa: a case study in the Mount Elgon region, Uganda

Boyi JIANG[a], Yazidhi BAMUTAZE[b] and Petter PILESJÖ[a]*

[a]*Department of Physical Geography and Ecosystem Science, GIS Centre, Lund University, Lund, Sweden;* [b]*Department of Geography, Geo-Informatics and Climatic Sciences, College of Agricultural and Environmental Sciences (MCAES), Makerere University, Kampala, Uganda*

(Received 5 August 2013; final version received 16 December 2013)

The aim of this study is to estimate and compare soil erosion, in the Mount Elgon region, eastern Uganda, during the last decade. Possible trends and changes in erosion are linked to precipitation/climate change as well as changes in land cover. Two different versions of the Revised Universal Soil loss Equation (RUSLE) are implemented and compared, one using slope length and the other using flow accumulation to estimate the slope length and steepness factor (*LS*). Comparisons of the modeled soil erosion vs. field data indicate that RUSLE based on flow accumulation is preferable. The modeling is carried out for the years 2000, 2006, and 2012, and is based on ASTER remotely sensed data, digital elevation models, precipitation data from the study area, as well as existing soil maps. No significant trends in estimated soil erosion are found to be present during the last decade. Over exploitation of land is probably compensated by improved agricultural management and no significant increase in precipitation. Even if there are reports of more intense and increasing amounts of rainfall in the area, this could not be verified, neither through the analysis of climate data, nor by trends in the estimated soil loss.

Keywords: soil erosion; revised universal soil loss equation (RUSLE); ASTER; Uganda; climate change

1. Introduction

1.1 Background

As one of the most important basic natural resource, land relates to almost all human activities directly or indirectly, and is crucial for sustaining livelihoods in many sub-Saharan African (SSA) countries. Rational utilization of the land resource has been treated as the key factor in the development pathways of many SSA countries. However, land degradation is one of the major and widespread environmental threats both in the past and present years (*1*). Furthermore, soil erosion is regarded as the most serious form of land degradation around the world, especially in developing countries like Uganda, China, and India, as well as some developed countries like Spain (*2–4*). In order to meet their livelihoods, address the economic stress, and accelerate development, some people and development actors in the developing countries utilize land and soil resources in unsustainable and irrational ways as manifested by overgrazing, destruction of forest for urban extension, heavy intensity and unscientific agricultural activities, and land use changes in high frequency (*5*). As a result, soil erosion becomes a serious issue, which negatively impacts the soil quality reducing agricultural efficiency, worsening water quality, causing flooding and debris flow, and habitat destruction (*6*).

Mountain ecosystems are considered as one of the most significant ecosystems, providing huge amount of benefits to humans both in natural and economic aspects via various ecosystem services and products. Nevertheless, unsustainable and unscientific land use practices and improper land management cause serious soil erosion in mountain regions. More and more studies are carried out focusing on mountainous areas in order to get better understanding of why the phenomenon happens and what could be done to solve the problems (*7–10*). In recent years, governments started to pay attention to sustainable agriculture and development. As a result, many environment and land degradation assessment policies were announced and published, which pointed out that soil erosion and land degradation in mountain areas are being increasingly regarded as more serious than in other ecosystems (*11–14*). One of the major reasons for this is land use changes in high frequency, not only modifications but also conversion of the land cover, which has a negative impact on the environment, especially replacement of forest area by agriculture fields due to the pressure of population (*15, 16*). The other major reason is the irregular terrain and topography in the mountain areas, which means that slope diversity and heterogeneity are significant factors for the intensity of soil erosion (*17*). Combined with rapid climate variability and changes, mountain ecosystems are one of the most sensitive ecosystems to climate change. The variation in rainfall pattern significantly impacts the runoff.

In a study by Knapen et al. (*17*), carried out on Mount Elgon in Uganda, it was observed that East Africa has severe land degradation around the highlands.

*Corresponding author. Email: petter.pilesjo@gis.lu.se

They also pointed out that the high vulnerability of the slopes and the high annual precipitation, including steep slopes and high weathering rates, could be important reasons for the serious soil erosion in this area. In the end of their report, human activities due to high population density and associated pressures were considered as the most important factor for land degradation. Another study that focused on land use changes around Mount Elgon done by Mugagga et al. (*8*) indicates that population pressure in the Mount Elgon region has resulted in large areas of forest being replaced by agriculture fields without sustainable management. These unsustainable and unscientific land use practices have caused a lot of environmental problems exemplified by landslides, high erosion rates, and stream pollution loading on Mount Elgon. It is however, predicted that activities supporting forest replacement by cropland and grazing land will continue until 2032 (*18*).

East Arica has been emphasized as the focal point of soil erosion. Better management and sustainable development measures have to be worked out and implemented.

There are two main approaches to study soil erosion, depending on spatial and temporal scales (*1*). One entails on-site measurements, which involves performing irrigation experiments on small-scale plots. The other is off-site quantification through modeling, which can be applied to reveal potential patterns of soil erosion, or evaluate the soil erosion on a large scale. According to the study by Rafaelli et al. (*19*), if data from field measurements are lacking and/or sparse due to costs of manpower and time constraints, off-site modeling techniques are preferable. Lack of data is apparent in the Mount Elgon region, partly due to climatic conditions, with a high cloud cover, and partly due to the location, with steep slopes and a sparse road network making it difficult and expensive to carry out field measurements.

In order to build the quantification model, as many as possible of the criteria that influence soil erosion should be taken into consideration. The Revised Universal Soil Loss Equation (RUSLE) is a widely used soil erosion intensity evaluation model, modified and improved from the Universal Soil Loss Equation (USLE), developed by Wischmeier (*20*). There are several factors included in this model, such as rainfall erosivity, soil erodability, slope length and steepness factor, cover management factor, and conservation practice factor. RUSLE can be treated as a kind of multi-criteria analysis, since the results are calculated according to the influencing factors. GIS technology is thus appropriate due to its powerful multi-criteria processing and calculation capability (*21, 22*). Moreover, in many conclusions of previous studies, highly significant spatio-temporal phenomena or changing patterns were revealed by applying GIS and remote sensing-based soil erosion/land degradation modeling (*23, 24*). Long-term studies can be performed, and the changes in soil erosion intensity patterns can be shown and analyzed using these methods. Hence, evaluation and prediction are possible to carry out much easier and faster than before to address the hazards caused by soil erosion.

1.2. Aims and objectives

The overall aim of this study is to explore possible trends in climate conditions as well as soil erosion in the Mount Elgon region in Uganda during the last decade.

The original RUSLE model structure is compared with an updated RUSLE model, where the slope length factor is replaced by drainage area. If the results of the updated RUSLE gives better results, then the modified parameters would be more appropriate for the study area conditions.

The first specific aim is thus to produce high-accuracy soil erosion estimates for the study area. Second, possible climate and soil erosion intensity trends from 2000 to 2012 are discussed. These aims are addressed through the following objectives:

- To understand the influencing factors in the RUSLE model and the basic usage of the model by reviewing literature and previous studies.
- To perform the two different model calculations for the years 2000, 2006, and 2012 in order to estimate soil erosion and create soil erosion intensity maps.
- To compare the accuracy of the two methods by using field measured data.
- To analyze the soil erosion intensity between 2000 and 2012 as impacted by climate and land use change.

1.3. Research questions

- The major questions which this study addresses are:
- Are there indicative signs of climate change in the study area?
- Is the updated version of RUSLE, using flow accumulation instead of slope length, more preferable?
- How much soil was lost each year during the last decade in the selected micro-catchment on Mount Elgon?
- What is the soil erosion pattern from the year 2000 to 2012?
- Why do possible trends and patterns occur, and what can be done to avoid or mitigate soil erosion in the future?

1.4. General methodology

In order to answer the research questions, several steps are undertaken. Firstly, relevant literature is reviewed, including basic information about Uganda and the certain study area, the factors in the RUSLE model, and

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knowledge about previous use of the model. Secondly, referring to the factors in the model, the data-sets of the study area are collected from various sources. Digital elevation models (DEM), satellite images, climate data for rainfall, and soil classification maps are used. Afterwards, by applying the RUSLE model and the updated RUSLE model, the result of soil erosion intensity of the target years are estimated and presented in tabular formats as well as maps. Finally, an evaluation is performed to assess the accuracy of the results derived using the original RUSLE structure and the modified structure. A statistical analysis is carried out in order to explain the possible soil erosion patterns and trends, as well as the climatic influence.

2. Study area

2.1. Location

The study area is located on the Ugandan territory of Mount Elgon. Mount Elgon is a transboundary mountain which lies on the border of western Kenya and eastern Ugandan. The mountain is the largest and oldest extinct volcano from Pliocene age in East Africa. The elevation is about 4322 m (*25*). The actual study area constitutes a part of Manafwa catchment, lying on the western side, as illustrated in Figure 1. The map shows the position of the study area. It is located between latitude 0.893° and 1.084°, and longitude 34.056° and 34.384° in the WGS84 coordinates system. The total coverage of the study area is 365 km^2.

2.2. Topography

Several studies point out that the geomorphology of the Mount Elgon region is dominated by volcanism (*17, 26*). The elevation in the study area varies between 1084 and 2455 m above sea level. Due to mountainous characteristics, the variation of the slope is large. The largest slope is 50 degree, 48% of the area have slopes less than 5 degrees, 18% of the area have slopes from 5 to 10 degrees, 23% of the area have slopes between 10 and 20 degrees, and 11% of the study area have slopes exceeding 20 degrees.

2.3. Climate

The climate of the Mount Elgon region can be defined as humid subtropical. It is dominated by seasonally alternating moist southwesterly and dry northeasterly air streams. The mean annual air temperature is about 23 °C. Moreover, the average minimum and maximum temperature is 15 °C and 28 °C, respectively. The warmest months in the year are from January to March and the coolest months are from July to August. The onset and cessation of rainfall months are March and December, respectively. The mean annual precipitation is generally around 1500 mm (*7*). The precipitation in the Mount Elgon region shows a weak bi-modal pattern. The rainfall differences are mostly influenced by orographic conditions, altitude, and location.

2.4. Soil

Generally, the soil structure of Mount Elgon is deep and derived from volcanic ash as the product of a single weathering cycle (*11*). A significant characteristic pointed out by Isabirye (*27*) is that the soils of this area are highly variable because of the structure of the carbonatite dome. In a study by Bamutaze (*28*), three main sources of the soil types in Mount Elgon are stated. First, volcanic ash and agglomerates found under volcanic mountains and hills and their pediments have contributed to the formation of the soils. Second, some of the soils are derived from metamorphic rocks, which are the degraded Gondwana surface. Thirdly, another part of soils is derived from mixed volcanic-metamorphic rocks.

2.5. Vegetation and land cover

The distribution of vegetation in Mount Elgon region is influenced by many physical and anthropogenic factors, such as elevation, aspect, soil, climate, and land use practices (*29*). Generally, four different broad vegetation communities can be observed. Mixed montane forest can be found up to elevation of 2500 m, bamboo and canopy montane forest can be found from 2400 to 3000 m, and moorland can be found above 3500 m (*30*). However, the natural vegetation is heavily influenced by human activities. Because of the pressure from the rapidly increasing population, natural vegetation is damaged by intense agriculture and grazing activities, especially in the area below 2200 m. Agriculture lands occupy 47% of the landscape, and grassland areas cover 22% (*31*). This potential damage of the ground cover vegetation, of course, can lead to an increased risk of soil erosion.

2.6. Population and land use

The estimated population density of Manafwa catchment region varies between 250 and 700 persons per square kilometer (*7*). The land use types in the Mount Elgon region are classified as crop lands, secondary forest, natural forest, bare land, and built-up areas. Agriculture lands are the most common land use type across this area and agriculture activities are extremely frequent (*31*). The agriculture activities are mostly carried out below the elevation of 2000 m. Montane farming system and smallholdings are the most common forms of agriculture in this region (*32*). Due to low efficiency in the agriculture and the huge pressure caused by the population, the crop lands are encroaching upon higher mountain areas, which are impacting the natural forest area. Mugagga et al.(*8*) note that the most significant land use changes are the conversion from natural forest to other land use types, especially crop lands and grazing lands. This kind of land management can easily lead to increased land degradation and soil erosion.

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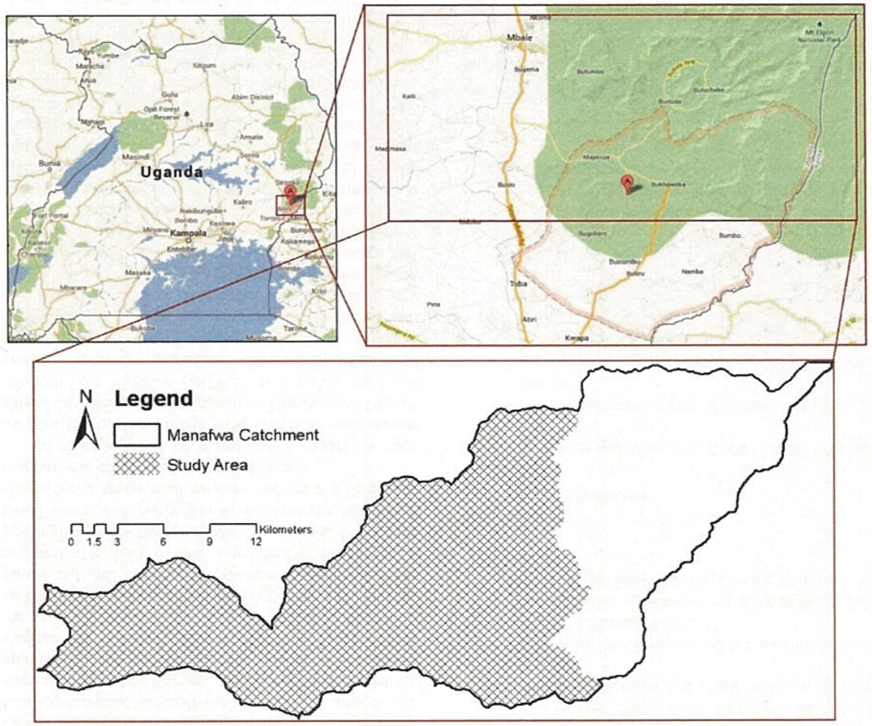

Figure 1. Location of the study area.

3. Materials

3.1. Digital elevation model

The terrain data required for the modeling (flow length, flow accumulation, slope gradient, etc.) were all extracted from a DEM. This original DEM was interpolated by using a 10-m resolution contour map, provided by the Department of Mapping and Surveys for Uganda. The extracted raster DEM was generated in ArcGIS 10 by using the inherent protocols. It is under WGS 1984 spatial reference coordinate system and projected to UTM Zone 36 N. The spatial resolution is 25 m. The elevation range of the Mount Elgon region is from 1041 to 4301 m. The DEM data were used to estimate the slope gradient, flow direction, catchment area, slope length, and flow accumulation for the study.

3.2. Climate data

The climate data are from Bamutaze (*28*), collected from four different climate stations: Bududa, Bulucheke, Buwabwale, and Nabumali. The rainfall data are obtained from the Department of Meteorology of Uganda. The climate data include precipitation, relative humidity, solar intensity, wind speed, and temperature. All the data are provided in DBF format, which can be read as tables by ArcGIS 10 or Excel. The position of the climate stations and the location of the study area are shown in Figure 2.

Only precipitation is significant for this study. The data are distributed in daily form. The rainfall data in millimeter for the target years 2000, 2006, and 2012 were extracted from a larger data-set. The precision of this data-set is 0.01 mm. The rainfall erosivity factor was estimated by interpolating the values from the climate stations.

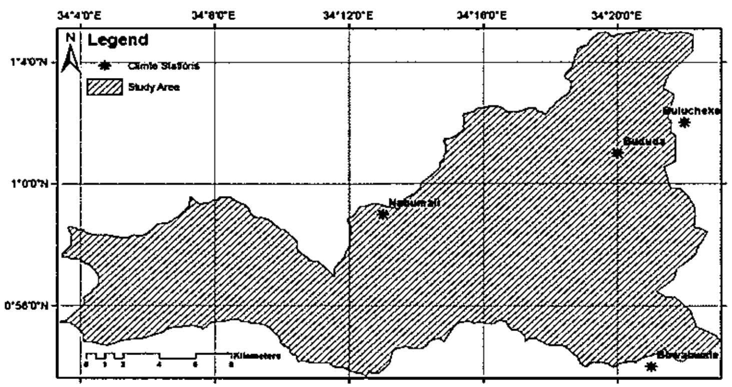

Figure 2. Location of the climate stations and the study area.

3.3. *Soil data*

Due to limitations in the available soil data, a combination of two different types of soil data is used in this study. Two soil maps which contain different soil types as attributes are used (*28*). The soil types are in the Food and Agriculture Organization classification system. One soil map contains more detailed soil information of the area located in the southwestern part of the Mount Elgon region. Unfortunately, there are some gaps in this dataset. In order to fill these gaps, another Uganda national-level soil map with lower resolution is used. As a result, a full soil map of southwestern Mount Elgon was generated to aid the estimation of the soil erodability factor.

3.4. *Satellite remote sensing data*

The used ASTER satellite images are from the summer period of the years 2000, 2006, and 2012. The spatial resolution of the satellite images used is 15 m. All images were geo-referenced under the WGS84 coordinate system. Detailed information about the used ASTER images is shown in Table 1. The three satellite images used are expected to be from the same date. However, due to heavy cloud cover in the Mount Elgon region during summer time this requirement is difficult to fulfill. The data used in this study are the best combination that can be found.

There are three bands in the downloaded data, BAND1, BAND2, and BAND3 N. The corresponding wave lengths of the three bands are shown in Table 2.

In the downloaded data, the digital values for Green, Red, and Near-infrared band were interpreted following the spectral reflectance characteristics. That means the satellite images can be used for Normalized Difference Vegetation Index (NDVI) calculation directly in the further processing stage. The NDVI data indicate the land cover environment. NDVI was thus used to estimate the cover management factor which is one of the components in RUSLE model

3.4.1. *Field data*

Field measurements of soil erosion collected and presented by Bamutaze (*28*) are used in this study. Soil loss was measured in field at 11 different locations in the study area. All measurements were carried out by the use of sediment traps in open streams.

4. Methodology

4.1. *The RUSLE model*

The RUSLE soil erosion model is used to estimate soil erosion intensity in a catchment. The RUSLE model is based on the USLE erosion model structure which was

Table 1. Data about the ASTER images used in the study.

Product ID	Time	Central coordinates	Cloud coverage (%)	Bands
Prodat011	2012/6/27	Lat: 1.107, Long: 34.261	20	Band1, Band2, Band3 *N*
Prodat012	2006/8/30	Lat: 1.111, Long: 34.236	13	Band1, Band2, Band3 *N*
Prodat013	2000/9/30	Lat: 1.124, Long: 34.144	4	Band1, Band2, Band3 *N*

Table 2. The wave length for each of the bands in the VNIR subsystem of ASTER.

Band no.	Wave length (μm)	Color
1	0.52–0.60	Green
2	0.63–0.69	Red
3 N	0.78–0.86	Near-infrared

developed by Wischmeier and Smith (*33*), and improved and modified by Renard et al. (*34*). Five parameters are used in the RUSLE model to estimate soil loss. They are rainfall erosivity (*R*), soil erodability (*K*), slope length and steepness factor (*LS*), cover management factor (*C*), and conservation practice factor (*P*). Referring to the RUSLE model, the relationship is expressed as:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where A (t ha^{-1} y^{-1}) is the estimated spatial average of total soil loss per year; R (MJ mm ha^{-1} h^{-1} y^{-1}) is the rainfall erosivity factor; K (t ha h ha^{-1} MJ^{-1} mm^{-1}) is the soil erodability factor; LS is the slope length and steepness factor (dimensionless); C is the land surface cover management factor (dimensionless); and P is the erosion control conservation practice factor (dimensionless).

The methods and formulas for estimating each of the parameters in the RUSLE model are mainly based on three previous studies: Bamutaze (*28*), Pilesjö (*35*), and Prasannakumar et al.(*10*). The work flow is shown in the flow chart in Figure 3.

4.2. *Rainfall erosivity factor (R)*

The rainfall erosivity factor indicates the erosive force of a specific rainfall (*10*). The relationship between rainfall erosivity and rainfall developed by Wischmeier and Smith (*33*) and modified by Arnoldus (*36*) was used to convert the monthly rainfall values to rainfall erosivity. The calculation was as follows:

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left(1.5 \times \log_{10}\left(\frac{P_i^2}{P}\right) - 0.08188\right)} \tag{2}$$

where R is the rainfall erosivity value in MJ mm ha^{-1} h^{-1} y^{-1} , P_i is the monthly rainfall of the i-th month ($i = 1, 2, \ldots, 12$) in mm, and P is the annual rainfall in mm.

Erosivity values between the rainfall stations were estimated by the use of inverse distance weighting (IDW) interpolation. The rainfall erosivity of the study area for the years 2000, 2006, and 2012 varies between 897 and 2813 MJ mm ha^{-1} h^{-1} y^{-1}. The highest and lowest values both appear in the year 2000. The southwestern part of the study area always has the highest rainfall erosivity values.

4.3. *Soil erodability factor (K)*

Soil erodability values were estimated based on the soil map. There are in total five types of soil classified in the study area, Nitisols, Gleysols, Petric Plinthols (Acric), Lixic Ferralsols, and Acric Ferralsols.

Different soil types normally have different structures, which influence the intensity of the soil erosion. The soil erodability *K*-value indicates the vulnerability and susceptibility of the certain type of soil to detachment by erosion (*24*). The higher the erodibility value the soil has, the more the erosion will be suffered when the soils are exposed to the same intensity of rainfall, splash, or surface flow (*37*). The unit for soil erodibility is t ha h ha^{-1} MJ^{-1} mm^{-1}.

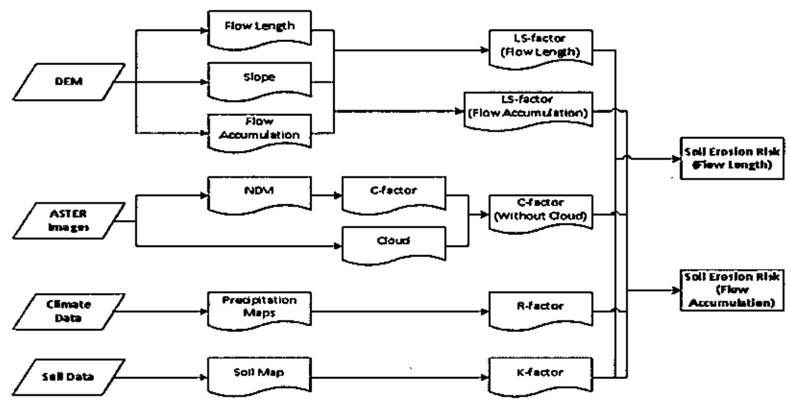

Figure 3. Flow chart of the RUSLE modeling.

Pilesjö (35) estimates soil erodibility values using the color of the soils according to Bono and Seiler (38), Bono and Seiler (39), and Weigel (40). Table 3 shows the *K*-value for different soil colors.

The five different soil types were assigned *K*-values according to the colors of the soils. The colors for the five different types of soil were obtained from ISRIC (41). For the Ferralsols soil there is no detailed subclass classification in the ISRIC document. The color is set to either red or yellow. The *K*-values for the two Ferrosols were thus set using the mean *K*-value of red and yellow color. The *K*-values of the five types of soil are listed in Table 4.

4.4. *Slope length and steepness factor (LS)*

The slope and steepness factor (*LS*) is a combination of slope steepness and slope length, to a high degree affecting the total sediment yield from site. It is considered to be one of the most challenging factors to derive (42). Prasannakumar et al. (10) claim that generating the *LS*-factor also captures factors like compaction, consolidation, and disturbance of the soil.

In this study, two different parameters are used to estimate the *LS*-factor, flow length and flow accumulation. Both flow length and flow accumulation can be used to estimate the contribution of upstream cells in a DEM to downstream cells. Flow length, also called slope length, helps in estimating the water flow along lines

Table 3. The *K*-value for different soil colors.

Color	*K*-value
Black	0.15
Brown	0.2
Red	0.25
Yellow	0.3

Table 4. The colors and corresponding *K*-values for the soils in the study area.

Soil type	Color	*K*-value
Nitisols	Red	0.250
Gleysols	Black	0.150
Petric plinthols (Acric)	Red	0.250
Lixic ferralsols	Red or Yellow	0.275
Acric ferralsols	Red or Yellow	0.275

while flow accumulation is based on drainage area. For a specific cell, the flow accumulation is estimated based on the upslope area and not just along flow lines.

The *LS* factors were estimated by applying the equation proposed by Moore and Burch (43, 44). The relationship is as follows:

$$LS = \left(\text{Flow length (or Flow accumulation)} \times \frac{\text{Cellsize}}{22.13}\right)^{0.4} \times \left((\text{sinslope})/0.0896\right)^{1.3}$$

where *LS* is the combination of slope length and steepness, Flow accumulation or Flow length is the accumulated upslope contribution to a cell, Cell size is the resolution of the raster image, and Sin slope is the sinus value of the slope in degrees.

The estimated *LS* values based on slope length, varying between 0 and 184, are presented in Figure 4.

The estimated *LS* values based on flow accumulation, varying between 0 and 95, are presented in Figure 5.

4.5. *Cover management factor (C)*

The cover management factor represents the effect of plants, crop sequence, and other soil cover surface on soil erosion. The value of *C*-factor is defined as the ratio of soil loss from a certain kind of land surface cover condition (33).

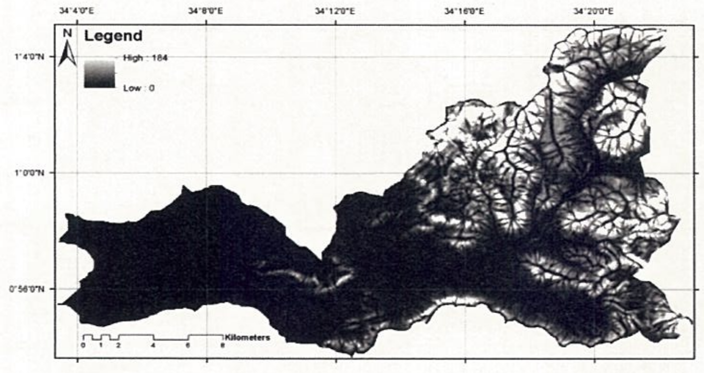

Figure 4. *LS*-factor estimated using flow length.

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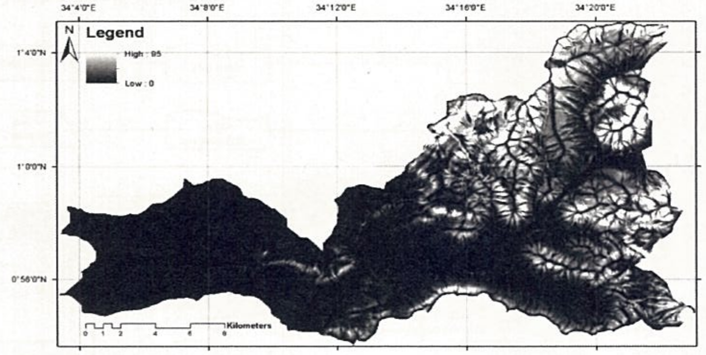

Figure 5. *LS*-factor estimated using flow accumulation.

According to Prasannakumar et al. (10), the NDVI can be used as an indicator of the land vegetation vigor and health. In addition, Karydas et al. (45) and Tian et al. (46) state that due to the variety inland cover patterns, satellite remote sensing data can act as an extremely important role to estimate the *C*-factor.

In this study the original satellite images from the year 2000, 2006, and 2012, with reflectance values in the green, red, and near-infrared bands, were converted to NDVI for the corresponding years.

After calculating the NDVI, the *C*-factor can be estimated by applying the relationship used in Zhou et al. (47) and Kouli et al. (48):

$$C = \exp\left(-\alpha \times \frac{\text{NDVI}}{\beta - \text{NDVI}}\right) \quad (3)$$

where *C* is the calculated cover management factor, NDVI is the vegetation index, and α and β are two scaling factors. van der Knijff et al. (49) suggest that by applying this relationship better results than using a linear relationship can be obtained. They suggest the values for the two scaling factors α and β to be 2 and 1, respectively.

Because of the cloud cover in the rainy season, the quality of the satellite images is limited, which may cause some uncertainties in the results. In order to remove cloudy areas the clouds and the shadow of clouds were classified using unsupervised classification and the spectral bands green, red, and near infrared. The number of unsupervised classes was set to 15. The classes, automatically clustered by the unsupervised classification tool in ArcGIS, were finally grouped to construct cloud layers. In the *C*-factor maps and the final results the cloud areas are shown as black with no data. The cloud (and cloud shadow) areas for the three different years (2000, 2006, and 2012) were 4.92, 0.59, and 12.38%, respectively. Estimated *C*-factor values varied between 0.00008 and 0.66. The spatial distribution of the *C*-factor for the different years is presented in Figures 6–8.

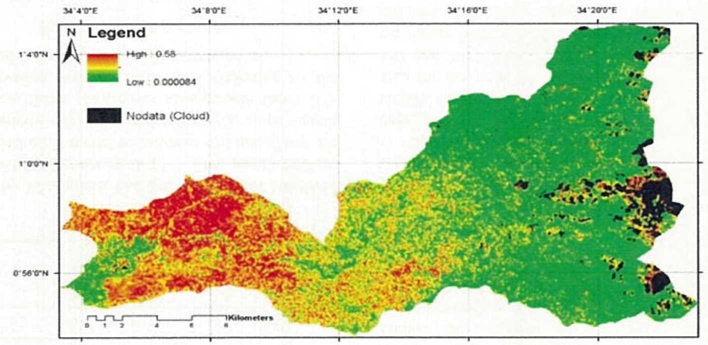

Figure 6. *C*-factor of the study area in the year 2000.

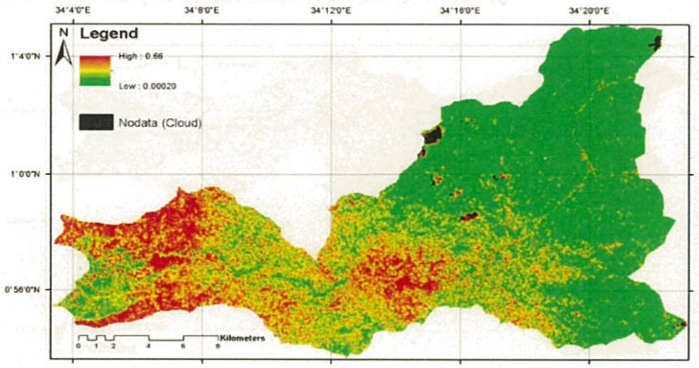

Figure 7. *C*-factor map of the study area in the year 2006.

4.6. *Conservation practice factor (P)*

The conservation practice factor (*P*) is also called as support factor. It represents the soil loss ratio after performing a specific support practice to the corresponding soil loss, which can be treated as the factor representing the effect of soil and water conservation practices (*34, 50*). The range of *P* factor varies from 0 to 1. The lower the value is, the more effective the conservation practices are.

In this study this conservation practice factor was assigned the maximum value of one (1) across the entire study area. The reason for this is that there are no significant conservation practices in the study area. In Manafawa, most of the conservation practices are tree planting, and can thus be considered to influence the cover management factor (*C*) (*28*).

5. Results

In order to estimate annual soil loss, the five factors were multiplied according to the relationship in RUSLE model. In total six layers with annual soil loss were computed, two for each year, one using flow length, and one using flow accumulation. The soil loss was classified into soil erosion risk maps with five different soil erosion risk levels according to Bamutaze (*28*). The thresholds for each of the risk levels are presented in Table 5.

5.1. *Soil erosion risk based on flow length method*

In general, the soil erosion risk maps obtained by flow length method have relatively high annual soil loss values. Exploring the maps (Figure 9) it can be concluded that more than 50% of the area is exposed for very high erosion risk.

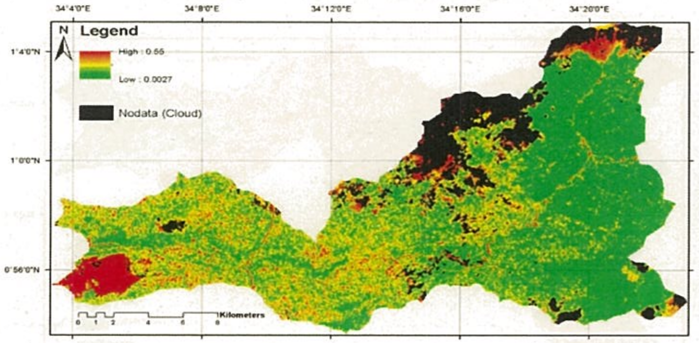

Figure 8. *C*-factor map of the study area in the year 2012.

Table 5. Categorization of soil erosion risk.

Erosion risk	Threshold (t ha^{-1} y^{-1})
Very low	Soil Loss ≤ 2
Low	2 ≤ Soil Loss ≤ 10
Moderate	10 ≤ Soil Loss ≤ 50
High	50 ≤ Soil Loss ≤ 100
Very high	Soil Loss ≥ 100

For the year 2000, Figure 9 illustrates the estimated erosion risk. The soil loss estimated by the flow length method in this year varies between 0 and 4995 t ha^{-1} y^{-1}, with an average value of 364t ha^{-1} y^{-1}; 62% of the area has a very high erosion risk, 13% has high risk, 17% has moderate risk, 6% has low risk, and only 2% has very low risk of soil erosion.

For the year 2006, the estimated annual soil loss varies between 0 and 4698 t ha^{-1} y^{-1}, which is similar to the result of year 2000. However, the mean value is 231 t ha^{-1} y^{-1}, which is much lower than that of 2000. About 55% of the area has very high erosion risk, 16% has high risk, 20% has moderate risk, 7% has low risk, and only 2% has very low risk of soil erosion.

The result for 2012 is estimated and soil loss values of between 0 and 6053 t ha^{-1} y^{-1} were obtained. This is the highest maximum value of all the results. The mean soil loss value is 362 t ha^{-1} y^{-1}, which is close to the one for the year 2000. About 56% of the area has very high erosion risk, 14% high risk, 20% moderate risk, 7% low risk, and only 3% ery low risk of soil erosion.

5.2. *Soil erosion risk based on flow accumulation method*

Generally, the absolute values of annual soil loss using the flow accumulation are much smaller than the results estimated by using flow length method. The results also coincide better with field data, and are thus more reliable.

In the year 2000 the highest estimated soil loss is 1198 t ha^{-1} y^{-1} (Figure 10). The mean value for the whole study area is 103 t ha^{-1} y^{-1}; 31% of the study area is classified to have a moderate soil erosion risk. Higher and much higher risks are allocated to 19 and 30%, respectively, while 14% of the area has low risk of erosion and 6% very low risk.

The estimated soil erosion risk map for the year 2006 is shown in Figure 11. In this year, the estimated annual soil loss varies between 0 and 1129 t ha^{-1} y^{-1} which is almost the same as for the year 2000. However, the mean value decreases to 67 t ha^{-1} y^{-1}, which is the lowest estimated mean soil loss value of all the results. About 39% of the area has moderate risk of soil erosion, high and very high risks are allocated 19% each, 16% of the area has low risk, and 7% has very low risk of soil erosion.

For 2012 the estimated soil loss varies between 0 and 1454 t ha^{-1} y^{-1}. The value 1454 t ha^{-1} y-1 is higher than the maximum values for 2000 as well as 2006. Referring to Figure 12, the area covered by moderate erosion risk is the highest (32%), followed by very high risk (28%), low and high risks (16%), and very low risk (8%).

5.3. *Comparison of the two modeling methods*

Based on the results obtained by the flow length and flow accumulation methods, a comparison of accuracy was carried out in order to judge which of the two methods gave better and more accurate result. The comparison was made from two aspects.

First, from the cartographic point of view, the estimated result maps obtained by using the flow length method have large areas assigned high or very high soil

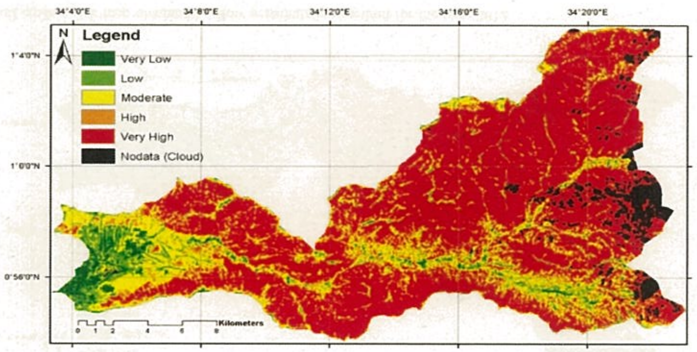

Figure 9. Soil erosion risk map obtained by the flow length method for the year 2000.

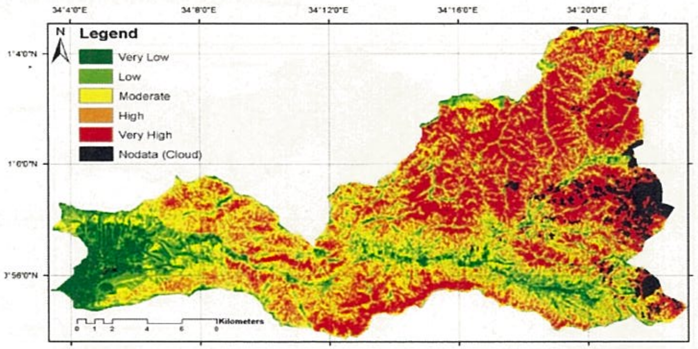

Figure 10. Soil erosion risk map obtained by flow accumulation method for the year 2000.

erosion risk levels. The areas with very high erosion risk level are 62%, 55%, and 56% for the year 2000, 2006, and 2012, respectively. When comparing with field visits and interviews with farmers this is unrealistic. Additionally, the classification method used to generate the soil erosion risk maps is referring to a published study by Bamutaze(*28*), reporting lower soil erosion risks in the region Altogether, this indicates that the results obtained by using the flow accumulation method is better.

Second, according to the results reported by Bamutaze (*28*), from a nearby area in the 1990s, the average annual soil loss value was 43t ha^{-1} y^{-1}, with maximum value of 585 t ha^{-1} y^{-1} on a cell level, and the highest potential erosion value reached up to 778 t ha^{-1} y^{-1}. In the study presented in this paper, the results obtained by using the flow accumulation method gave average annual soil loss values of 103 t ha^{-1} y^{-1}, 67 t ha^{-1} y^{-1}, and 101 t ha^{-1} y^{-1}, with highest values of 1198 t ha^{-1} y^{-1}, 1129 t ha^{-1} y^{-1}, and 1454 t ha^{-1} y^{-1} for the three years 2000, 2006, and 2012, respectively. These estimates are much closer to the previous study than the results obtained by using the flow length method.

To conclude, the results obtained by using the flow accumulation method seem more accurate and reliable than those obtained by using flow length. Thus, further discussion on the soil erosion trends and the relationships between soil erosion and precipitation/climate and land cover is based on the results obtained by the flow accumulation method.

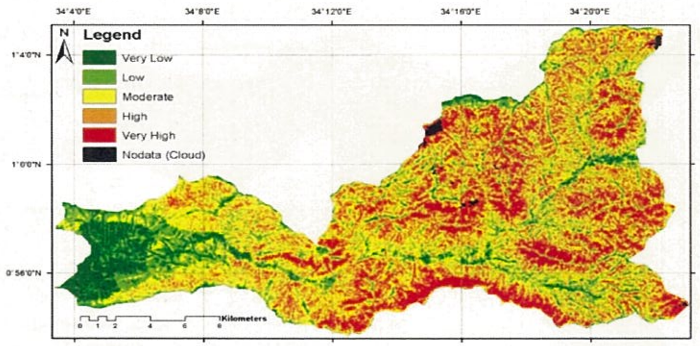

Figure 11. Soil erosion risk map obtained by flow accumulation method for the year 2006.

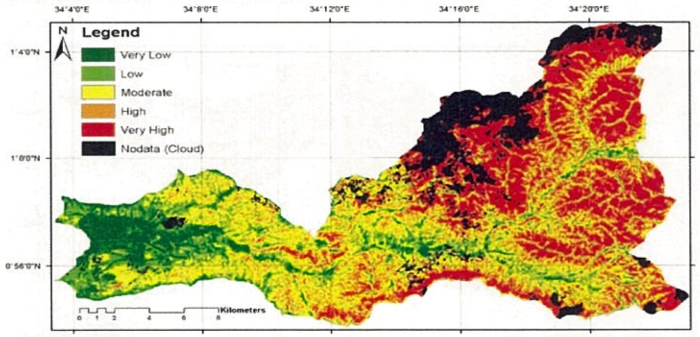

Figure 12. Soil erosion risk map obtained by flow accumulation method for the year 2012.

6. Discussion

6.1. *Uncertainties and limitations*

In general, due to specific characteristics of the study area, a mountainous area located in the Mount Elgon region, finding the data which fulfill the requirements of RUSLE modeling is very difficult. In this study, most of the data are provided by local departments and researchers except for the ASTER remote sensing data. Due to the lack of data, the time series study was only carried out for the three target years 2000, 2006, and 2012.

In the result maps, some of the estimated soil loss values are very high, reaching 1454 t ha^{-1} y^{-1} using flow accumulation, and 6053 t ha^{-1} y^{-1} using flow length. The original DEM data are an interpolated 25-m resolution raster map based on digitized contour lines. Due to the 25-m resolution, some sinks and breaks are removed from the DEM. This results in exaggerated estimations of flow lengths as well as flow accumulation, with corresponding high *LS* values.

Regarding precipitation, only data from four rainfall stations in the region were available for the three years 2000, 2006, and 2012. The precipitation data for the entire study area were generated by running IDW interpolations with data from these four stations, which is not preferable. Moreover, the location for the four climate stations used for interpolation is clustered in the eastern part of the study area. One can thus expect the interpolated precipitation values to be more accurate in the eastern part of the study area.

Five types of soil are detected in the study area, based on a soil map of questionable quality. In Uganda, soil mapping is still at coarse scale, which makes it a challenge to get high-quality data. Additionally, the method used to estimate the *K*-factor is based on the color of a particular type of soil, which can be considered as a rough estimation method. In the study done by Xu et al. (*1*), a more professional *K*-factor estimation method, referring to the study by Sharpley and Williams (*51*), is presented. However, in order to apply this method, more detailed soil parameters not available in this study are required, like the subsoil sand fraction, the silt fraction, the clay fraction, and the topsoil carbon content.

There are also uncertainties in the cover management factor that was estimated by the use of ASTER satellite images. There are mainly two sources generating the uncertainties, one related to the temporal distribution of the satellite data and the other related to cloud cover.

The satellite data are supposed to be from the same month and in summer time. The reason for this is that not only this period has the most vegetation cover, but also that it is the most serious erosion period due to rainfall in the rainy season. However, the rainy season and the mountainous climate conditions result in extremely cloudy weather. It was impossible to find satellite data from the same month for different years. For the target years 2000, 2006, and 2012, the images used in this study are from September 30, August 30, and June 27, respectively. We can thus expect more uncertainty in the image from July 2012. The land cover situation two month earlier than the other two target years may be significantly different.

The uncertainties relating to clouds are always a big problem when using remotely sensed data. In this study, all images are influenced by cloud cover. In the year 2012, the cloud cover is more than 12%. Because the shadow of the cloud has a negative effect on the NDVI and the estimated *C*-factor values, the cloud area was over-classified when carrying out the classification. The classified cloud area also contains cloud shadow. Even though an over-classification was performed, some noise pixels remained. In order to reduce their influence, a low pass 3×3 average filter was used to smooth the *C*-factor data layer.

6.2. *Soil erosion trends related to precipitation and land cover changes*

Mean annual precipitation and mean *R*-factor of the study area for the three years are presented in Figure 13 as blue and red lines, respectively. From 2000 to 2006, the mean annual precipitation decreases from 1290 mm to 1200 mm. Then the precipitation increases from 1200 mm to 1249 mm from 2006 to 2012. The mean annual precipitation for 2012 is approximately the same as for the year 2000. The *R*-factor shows a similar trend. However, the mean *R*-factor value in 2012 is significantly higher than during the year 2000 (1776 and 1448 MJ mm ha^{-1} h^{-1} y^{-1}). This means that the rainfall in 2012 had the biggest effect on soil erosion among the three target years.

Regarding land cover, mean NDVI was used as the detector for land cover changes. As illustrated in Figure 14, mean NDVI values increases from 0.56 to 0.59 during the years 2000 to 2012. The increasing trend is considered as very weak.

From the year 2000 to 2006, 57% of the land area has an increasing NDVI. This area is mainly located in the western part of the study area. The area with decreasing NDVI (47%) appears mainly in the south and east. From 2006 to 2012, an increasing trend is seen with an increasing coverage percentage of 58%. The increasing NDVI is still located in the western part of the study area. The decreasing NDVI is mainly in the northeast. Comparing the year 2000 and 2012, 64% of the land has an increasing NDVI. Even if the analysis is influenced by cloud cover and not significant, one can see clear indications that most of the western part of the study area has got more vegetation cover during the last decade. However, a regular polygon located in the southwest corner has a large decrease in vegetation cover, may be caused by artificial activities such as urban construction, or agriculture land conversion.

Soil erosion changes and trends can be explored in Figure 15. The estimated soil erosion decreases between 2000 and 2006, and increases between 2006 and 2012. This "trend" is similar to the precipitation trend discussed above. There seems to be no significant relationship between land cover changes and soil erosion on the study area scale.

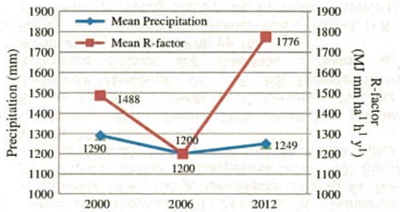

Figure 13. Precipitation and *R*-factor changes from 2000 to 2012.

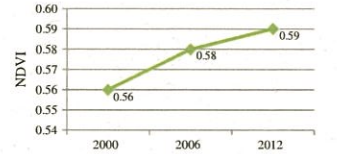

Figure 14. Mean NDVI for entire study area from year 2000 to 2012.

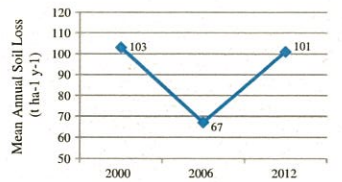

Figure 15. Mean annual soil loss for the entire study area from year 2000 to 2012.

From year 2000 to 2006, 66% of the study area has a decreasing trend in annual soil loss. Most of the area with this decrease is located in the northeastern part of the study area. From 2006 to 2012, there is a general increase in soil erosion risk (52% of the study area). The areas with higher risk for soil erosion are generally located in the southwestern part of the study area. When comparing the two years, 2000 and 2012, one can conclude that 61% of the land has a decreasing trend in soil erosion risk. The 39% of the land with increasing risk is mainly located in the northeastern corner, southeastern corner, and some of the western parts of the study area. The relatively high decrease in soil erosion risk can be seen as contradictory in comparison with the highest maximum soil loss (1454 t ha^{-1} y^{-1} detected in the year 2012. One explanation can, however, be that the erosion area decreases but the intensity of the erosion at some particular places increases.

7. Conclusions

Based on the results of this study we can conclude that, for the study area in the Mount Elgon region, Uganda:

(1) No significant trends in rainfall during the last decade are found.
(2) The modified RUSLE model, using flow accumulation instead of slope length, is preferable when estimating risk of soil erosion.
(3) The risk of soil erosion is not significantly different in 2012 compared to year 2000.
(4) No specific trends or patterns in soil loss, precipitation, and land cover have been found.

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Notes on Contributors

Boyi Jiang is a former MSc student at the Lund University, Sweden, specializing in remote sensing and geospatial modeling. He graduated from the University of Gävle in 2011 with a bachelor degree, and from Lund University in 2013 with a master degree. He is now working as a GIS specialist within environmental modeling and remote sensing.

Yazidhi Bamutaze is a senior lecturer in the Department of Geography, Geo-Informatics, and Climatic Sciences, Makerere University, Uganda. His areas of teaching include Geomorphology, Remote Sensing, GIS, Natural Hazards, and Disaster Risk Management. He has a keen interest in spatial modeling of natural resource- and natural hazard-related aspects.

Petter Pilesjö is a professor in Physical Geography and Ecosystem Science, and the director of Lund University GIS Centre. He has been working with hydrological and soil erosion modeling, including remote sensing and GIS, in Africa for the last 30 years. He also has ongoing research relating to climate change and carbon modeling.

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