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Spatio-temporal assessment of soil erosion risk in different agricultural zones of the Inle Lake region, southern Shan State, Myanmar

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Abstract Myanmar is one of Southeast Asia's climatically most diverse countries, where sheet, rill, and gully erosion affect crop yields and subsequently livelihood strategies of many people. In the unique wetland ecosystem of Inle Lake, soil erosion in surrounding uplands lead to sedimentation and pollution of the water body. The current study uses the Revised Universal Soil Loss Equation (RUSLE) to identify soil erosion risks of the Inle Lake region in space and time and to assess the relationship between soil erosion and degradation for different agricultural zones and cropping systems. Altogether, 85 % of soil losses occurred on barren land along the steep slopes. The hotspot of soil erosion risk is situated in the western uplands characterized by unsustainable land use practices combined with a steep topography. The estimated average soil losses amounted to 19.9, 10.1, and 26.2 t ha^{-1} yr^{-1} in 1989, 2000, and 2009, respectively. These fluctuations were mainly the results of changes in precipitation and land cover (deforestation (−19 %) and expansion of annual cropland (+35 %) from 1989 to 2009). Most farmers in the study area have not yet adopted effective soil protection measures to mitigate the effects of soil erosion such as land degradation and water pollution of the lake reservoir. This urgently needs to be addressed by policy makers and extension services.

Keywords Floating gardens · Land degradation · RUSLE · Soil loss

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Introduction

In many developing countries of Southeast Asia, the overuse of renewable natural resources (forests, soils and fresh water) is an important environmental challenge (Ian, 2002). The economic growth during the last two decades often caused severe environmental degradation such as soil erosion, land degradation, deforestation, water pollution, loss of biodiversity, and degradation of marine and coastal zones (Bahadur 2009).

Soil erosion is a major consequence of human-induced soil degradation that affects 56 % of the world's terrestrial surface (Gabriels and Cornelis 2009). In Southeast Asia, soil erosion risk causes annual average soil losses of 138 t ha^{-1} with major on-site and off-site damages whose severity depends on the resilience of the natural resource base, the institutional and economic conditions, the rate of population growth, and the policy environment (Ananda and Herath 2003; Yang et al. 2003). Myanmar has the highest erosion hazard of

Southeast Asia affecting over 80 % of sloping lands, and combined with soil nutrient depletion, this severely hampers agricultural development (FAO 2000; Amsalu and Graff 2006), particularly in mountainous regions where steep slopes with shifting cultivation prevail (Swe 2003).

In the southern Shan State of Myanmar, erosion occurs as sheet, rill, and gully erosion, causing declines of crop yields and income levels (GAF 1996) and triggering the eutrophication of the Inle Lake water body (Than 2007; Soe 2012). Under these circumstances, quantitative assessments of soil erosion risk at farmers' level are urgently needed to help developing effective mitigation strategies.

For this purpose, models have been developed, such as the Universal Soil Loss Equation (USLE; Wischmeier and Smith 1978; Renard et al. 1997), the Water Erosion Predict Project model (WEPP; Nearing et al. 1989), the Chemical, Runoff, and Erosion for Agricultural Management system (CREAMS; Knisel 1980), the European Soil Erosion Model (EuroSEM; Morgan et al. 1990), the Pan-European Soil Erosion Risk Assessment (PESERA; Kirkby et al. 2000, 2003) and the Soil Erosion Model for Mediterranean regions (SEMMED; De Jong 1994). Among these, the Revised Universal Soil Loss Equation (RUSLE; Renard et al. 1997) has been successfully used in many studies for both agricultural and forest watersheds to identify erosion risks and predict average annual soil losses under different environmental conditions (Angima et al. 2003; Lu et al. 2004; Cohen et al. 2005; Fu et al. 2005; Yue-Qing et al. 2008; Sharma et al. 2011; Prasannakumar et al. 2012; Kumar et al. 2014). The model allows to depict the spatial heterogeneity of soil erosion risks using information about the watershed characteristics and local hydro-climatic conditions (Angima et al. 2003).

The RUSLE approach was used in the current study to identify soil erosion risks of the Inle Lake region in space and time and to analyze the relationship between soil erosion and degradation for different agricultural zones and cropping systems.

Materials and methods

Study area

The Inle Lake watershed is situated in southern Shan State, Myanmar (Fig. 1a). Inle Lake is the second largest inland lake of the country, located at 20° 18′ to 20° 53′ N latitudes and 96° 50′ to 96° 57′ E longitudes and an altitude of 890 m asl (Su and Jassby 2000). It occupies the central part of a trough between two mountain ranges limiting the lake to the East and West. The area is a tourist locations in Myanmar, and because of the rich biodiversity, it was designated as the 190th World's Eco-Region in 1998 (Olson and Dinerstein 2002) and nominated as a fresh water biodiversity hotspot (Lwin and Sharma 2012).

Due to the limited availability of spatial data (soil, land use) for the whole watershed area, the center of the Inle Lake watershed was selected as a study area (Fig. 1b) for the assessment of soil erosion risks. The study area comprises 2115 km^2 and includes the townships of Taunggyi (20°47′ N, 97°02′ E, 1400 m asl), Nyaung Shwe (20° 45′ N, 96° 56′ E, 885 m asl), Kalaw (20°38′ N, 96°34′ E, 1320 m asl), and Pinlaung (20°5′ N, 96°47′ E, 1463 m asl) with a population density of 180, 119, 108, and 49 people km^{-2}, respectively (Ministry of Health 2011). The local climate is characterized by monsoon-dependent annual rainfall of approximately 1370, 931, 1036, and 2113 mm at the four respective locations (observation period from 1988 to 2012; Meteorology and Hydrology Department, Taunggyi and Agriculture Department, Ministry of Agriculture and Irrigation, Nyaung Shwe) with three main seasons: dry summer (mid-February to mid-May), rainy season (mid-May to mid-October), and dry winter (mid-October to mid-February).

The dominant soils in the Inle Lake region are Acrisols, mainly in the uplands (Su and Jassby 2000, Hai et al. 2006) and Histosols including paddy soils (Hydragric Anthrosols) in the bottom valley near the lake.

Given its topography and the prevailing cropping systems, the study area can be divided into three agricultural zones (Htwe et al. 2015b; Fig. 1b): (1) Floating gardens (FG), (2) Lowland (LL), and (3) Upland (UP) cultivation zone. The floating garden zone, where tomato cultivation on floating islands prevails, was identified by a visual identification of gardens in the water body using recent high resolution Google Earth® images (Htwe et al. 2015b). The areas below 1150 m asl adjoined to floating gardens belong to the lowland cultivation zone, which is characterized by paddy fields, sugarcane (Saccharum ssp.), and other crops. We defined the upland cultivation zone as the area on hilly slopes at altitudes above 1150 m asl, where shifting cultivation and agroforestry systems are dominant.
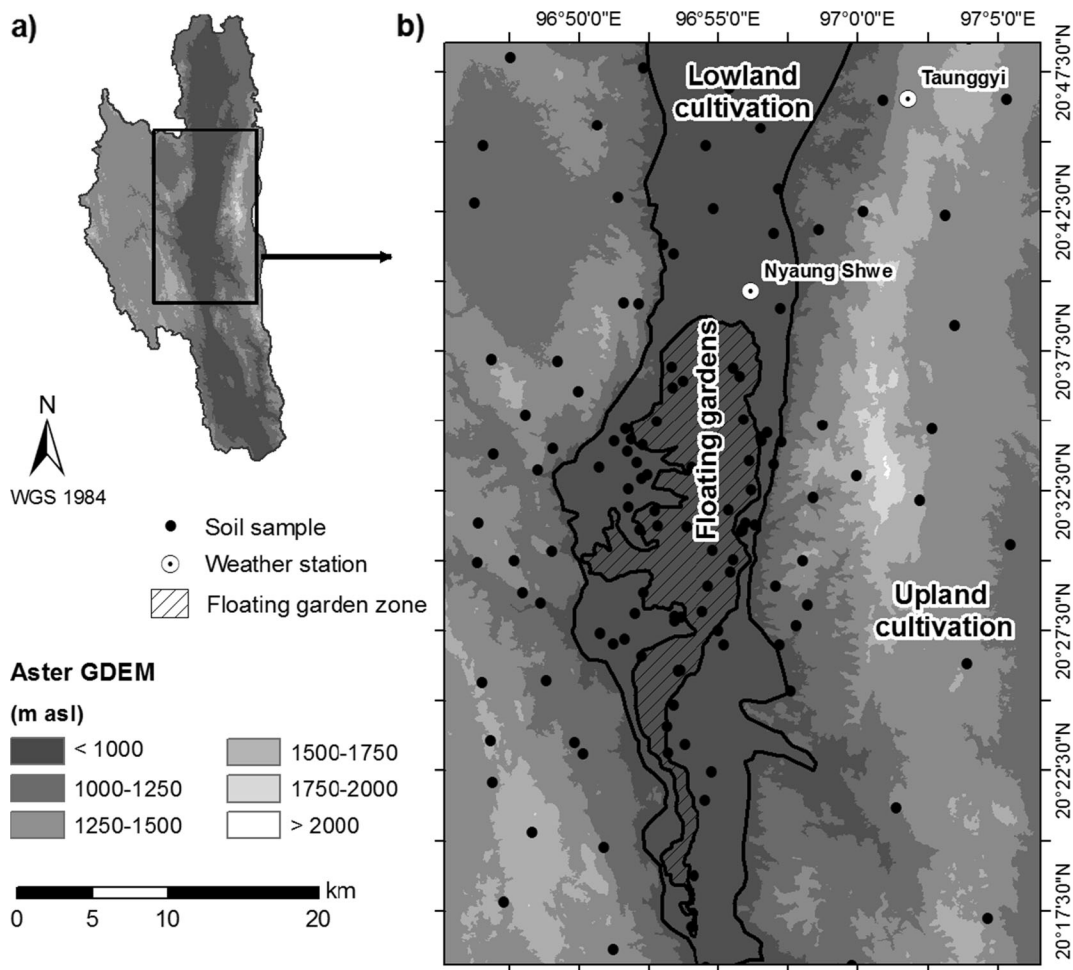
Fig. 1 Location of the study area and weather stations in the Inle Lake watershed in southern Shan State, Myanmar (**a**) and location of the different agricultural zones and soil samples in the study area (**b**)

Farmers' livelihood strategies are divers in the three different agricultural zones and depend on farm size. The diversification strategies range from cash-crop producing large farms to highly diversified small farms (Htwe et al. 2015a).

Household interviews on soil erosion risk

In 2012, semi-structured household interviews were conducted to collect socio-economic data and information on land degradation and soil erosion risk in thirty villages of the three agricultural zones in the Inle Lake region. Village selection was based on a stratified random sampling design for each agricultural zone using a geographic information system (GIS). The interviews were part of a larger survey of 301 households (Htwe et al. 2015a) and included questions about farmers'

perception of land productivity, soil fertility, soil erosion, soil deterioration, depletion of topsoil and nutrients, and effects of soil erosion and degradation over the past 5 years. For each household, the cultivated crops were inventoried, and the limits of the crop fields were determined using a handheld GPS device (Trimble GeoXT, Trimble, Navigation Ltd., Sunnyvale, CA, USA). GPS measurements were subsequently imported into a GIS and used for mapping of crop fields. The resulting land use maps of households were used for the randomized selection of soil samples.

Analysis of soil physical and chemical properties

Soil samples were collected for the different agricultural zones and topographic locations to analyze differences in soil properties between the three agricultural zones

and estimate the soil erodibility factor, an important input variable for the RUSLE model. Altogether, 128 farmers' fields (22 in floating gardens, 51 in the lowland, and 55 in the upland zone) from the household survey were selected for analysis of soil properties. For each field, five soil samples were taken at 0–20 cm depth and pooled together resulting in 128 samples. Samples were air-dried, sieved, and kept for subsequent soil analysis. The soils were analyzed for physical (soil texture) and chemical properties: soil organic matter (SOM), available phosphorus (P), available potassium (K), total nitrogen (N_{tot}), total carbon (C_{tot}), electrical conductivity (EC) and pH using standard laboratory methods. The pipette method was used for soil texture analysis (Gee and Or, 2002) after dispersion with 0.4 N sodium metaphosphate ($NaPO_3$). SOM was estimated by heating the dry soil for 5 h at 550 °C. A CHN analyzer was used to determine N_{tot} and total C_{tot}, and available P was determined according to the method of Olsen et al. (1954) for alkaline soils and Bray and Kurtz (1945) for acid soils. Available K was measured by flame photometry and ammonium acetate as the reagent. EC was measured at a ratio of 1:10 in an aqueous suspension of soil using a portable EC meter. Soil pH was measured in water at a ratio of 1:2.5.

Estimation of soil erosion risk using the RUSLE model

The RUSLE empirical model was used to predict annual average soil loss (A) as follows (Renard et al. 1997; Equation. (1)):.

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

where A (t ha^{-1}yr^{-1}) is the average soil loss of the study area, R (MJ mm ha^{-1}h^{-1}yr^{-1}) is the rainfall-runoff erosivity factor, K (t ha h ha^{-1}MJ^{-1}mm^{-1}) is the soil erodibility factor, LS (dimensionless) is the slope length and slope steepness factor, C (dimensionless) is the cover and management practice factor, and P (dimensionless) is the support practice factor. Each factor in the RUSLE equation was calculated based on existing geospatial data (30 m resolution) such as a digital elevation model, soil/geology map, land cover and land use maps from satellite image classification (Htwe et al. 2015b), climate data (rainfall) and field

measurements (soil samples) and converted into a raster file format. The spatial distribution of soil erosion risk of the selected Inle Lake region (2115 km^2) was calculated for different years (1989, 2000 and 2009) by multiplying the corresponding raster files of each factor within ArcGIS 10.0 (ESRI, Redlands, CA, USA). Estimated soil loss was summarized for land cover classes, agricultural zones, and main cropping systems by using zonal statistics of the Spatial Analysis tool in ArcGIS 10. To calculate the potential soil erosion risk of household's main cropping systems (tomatoes, lowland and upland rice, maize, sugarcane and turmeric), soil losses were summarized for the mapped crop fields.

Calculation of RUSLE factors

Rainfall data (monthly and daily amount of precipitation) of a 21-year observation period (1988 to 2009) was received from four meteorological stations (Taunggyi, Nyaung Shwe, Kalaw and Pinlaung) within the study area (Fig. 1) in order to estimate the rainfall erosivity factor R. Since data on rainfall intensity was lacking for our study area, we derived the R factor for each station using Wischmeier's empirical equation (2) adapted by Wu et al. (2012) and Pan and Wen (2014):

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

where R is rainfall erosivity (MJ mm ha^{-1}h^{-1}yr^{-1}) and P is the average annual precipitation (mm) and P_i is the average monthly rainfall (mm). Due to the limited number of data points, a deterministic interpolation method based on Thiessen polygons was used within ArcGIS to depict the R-factor in space. To improve the resulting R-factor map by considering the altitude, areas of the floating garden, and lowland cultivation zone (<1100 m asl) were extracted and reclassified to the R-factor value of the station at 885 m asl (Nyaung Shwe).

Since field measurements of the K-factor (t ha h ha^{-1}MJ^{-1}mm^{-1}) are often too expensive to conduct, the soil erodibility nomograph (Wischmeier et al. 1971) is commonly used for soil erodibility calculations (Chen et al. 2011; Panagos et al., 2014). An algebraic approximation of the nomograph that includes five soil

parameters (texture, organic matter, coarse fragments, structure, and permeability) was proposed by Wischmeier and Smith (1978) and Renard et al. (1997) and used in the current study (Equation 3, adapted by Panagos et al. 2014):

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

$$*0.1317$$

where:

M is the textural factor with $M = (m_{silt} + m_{vfs}) * (100 - m_c)$;

m_c (%) is the clay fraction content (<0.002 mm);

m_{silt} (%) is the silt fraction content (0.002–0.05 mm);

m_{vfs} (%) is the very fine sand fraction content (0.05–0.1 mm);

OM (%) is the organic matter content; S is the soil structure class (s = 1: very fine granular, s = 2: fine granular, s = 3: medium or coarse granular, s = 4: blocky, platy or massive); p is the permeability class ($p = 1$: very rapid, $p = 2$: moderate rapid, $p = 3$: moderate, $p = 4$: slow to moderate, $p = 5$: slow, $p = 6$: very slow).

This equation is only recommended if the silt content is below 70 % and the organic matter content is known (Panagos et al. 2014). For calculations, we used the results of our soil analysis (soil texture and soil organic matter content). The soil structure class was estimated based on the corresponding FAO soil type and own field observations in 2012 and 2013. The permeability class was estimated using the soil texture classes of collected samples according to the US Department of Agriculture's National Soils (USDA 1983). Since the K-factor was only estimated for the soil-sample point locations, the results were interpolated using ordinary kriging in ArcGIS. Kriging is a geostatistical interpolation method to predict the values of unknown locations using a weighted average of neighboring measured values (Wu et al. 2012; Elbasiouny et al. 2014). The weight depends on the distance of the measured points to the prediction location and the spatial relationships among the measured values around the prediction location (Yaserebi et al. 2009; Phachomphon et al. 2010). Ordinary kriging is the simplest, most commonly used stochastic interpolation technique (Mishra 2009) and the most effective for the production of a soil erosivity map (Alexakis et al. 2013). The resulting map was converted to a raster format.

A Digital Elevation Model (ASTER GDEM, version 2, product of METI and NASA, acquisition date: 17.08.2011) was used in basic terrain analysis and as input variable for the calculation of the topographic LS-factor for each raster cell of the Inle watershed area using the standard method of the hydrology tool in SAGA GIS, which is based on the algorithm of Moore et al. (1991).

Plant crown coverage, ground cover, crop sequence, length of the growing season, and tillage practice are commonly used to determine the C-factor for crop management. Land use and land cover maps were classified for the Inle Lake region based on Landsat images from 1989, 2000, and 2009 in a previous study (Htwe et al. 2015b) and were used to estimate the C values. These land cover maps comprised 11 classes, which were reclassified to C-factor values according to Bhandari et al. (2014) and own field data (Table 1).

P refers to the ratio of soil loss with a support practice such as contouring, strip cropping, or terracing. According to Renard et al. (1997), the P-factor is considered the most difficult factor to determine and the least reliable factor of the RUSLE input factors. By interviewing the farmers during the field visit, it was found that nearly no soil erosion protection measures existed in the studied area. Therefore, the RUSLE model was run with a P-factor of 1.0 to predict erosion potential under current conditions of lacking soil conservation support practices (Renard et al. 1997).

Results

Farmers' perception of soil erosion and land degradation

Altogether, 36 % of the surveyed farmers reported a decline in soil productivity. In the FG zone, only 10 % of farmers noticed a decrease in crop productivity, which reduced the operating life of floating islands, whereas about half of surveyed farmers in LL and UP zones noticed a decline.

About 25 % of farmers reported that their lands had degraded within the last 5 years, and the issue of soil erosion is prominent (Table 2). In the LL and UP zones, 31–33 % of the farmers observed land degradation effects on their farms such as deterioration and depletion of top soil, and 25 % reported a decline in crop yields, whereas only a few farmers had noticed erosion-induced nutrient depletion and water pollution. Further erosion

Table 1 Land cover classes according to Htwe et al. (2015b) and the corresponding C-factor (crop and management practice) in the Inle Lake region, Myanmar

Class	Class description	C value[a]
Agroforest	Trees and crops on cultivated land	0.15
Paddy field	Rice cultivation in the lowlands	0.35
Floating garden	Fields on floating islands in the lake area	0.01
Other cropland	Other field crops (e.g. sugarcane, maize, upland rice, turmeric)	0.45
Fallow land	Fallow fields on cultivated land covered with grass	0.02
Forest	Dense hill forest	0.001
Marshland	Marshy grassland and swamp near lake	0.01
Shrubland	Rangeland or grassland with shrubs and isolated trees	0.01
Barren land	Sparsely vegetated areas and wasteland	1.00
Urban	Settlements, cities, single houses, industrial facilities	0.05
Water body	Open waterbody	0.00

[a] Source: adopted from Bhandari et al. (2014), Roose (1977), Hurni (1987), Morgan (1986), Hashim and Wong (1988) and own field data

effects such as biodiversity losses and changes in livelihood strategies were only mentioned by two farmers.

### Estimated soil losses from 1989 to 2009 using RUSLE models

The R-factor increased with increasing altitude and the lower values were detected for the valley bottom (Fig. 2a). The mean R factor was 1923 MJ mm ha^{-1} h^{-1} yr^{-1}. The maximum value of 3887 MJ mm ha^{-1} h^{-1} yr^{-1} was observed for Pinlaung, and the minimum value (998 MJ mm ha^{-1}h^{-1} yr^{-1}) for Kalaw.

The average K-factor was 0.02 t ha h MJ^{-1} ha^{-1} mm^{-1} (Fig. 2b) with the highest values in the mountain areas of the southeastern and northwestern part of Inle Lake and very low values in the floating garden zone. This difference was mainly due to the high soil organic matter content, which decreased from FG to the UP zone. The soil analysis revealed that EC, N$_{tot}$, C$_{tot}$, and SOM were the lowest in the eroded crop land of the UP zone (Appendix 1). The LS factor (Fig. 2c) varied from 0 in the bottom valley to 89.17 on the steep slopes of the mountains (Fig. 2b).

Land cover changes occurred from 1989 to 2009 with an increase in urban areas, cropland,

Table 2 Soil erosion risk and its effects as observed and perceived (%) by farmers in the Inle Lake region, Myanmar, according to HH interviews

	FG (n = 90)	LL (n = 118)	UP (n = 93)	Total (n = 301)
Observation (%)				
Soil erosion	0.0	6.8	19.4	8.6
Soil deterioration	5.6	11.0	4.3	7.3
Topsoil depletion (of field)	0.0	8.5	9.7	6.3
Other	2.2	5.1	0.0	2.7
Unaware	92.2	68.7	66.7	75.1
Perception (%)				
Yield decline	1.1	25.4	25.8	18.3
Nutrient depletion	1.1	4.2	2.2	2.7
Water pollution	0.0	1.7	2.2	1.3
Decrease of biodiversity	2.2	1.7	0.0	1.3
Livelihood strategies change	1.1	0.0	0.0	0.3
Unaware of changes	94.4	67.0	69.9	76.1
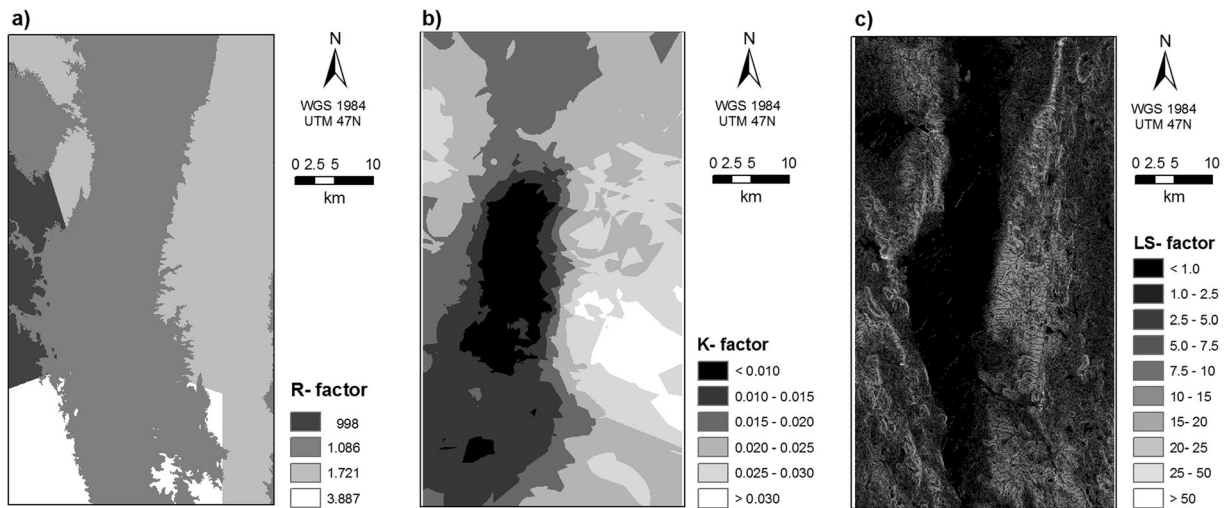
Fig. 2 Maps of the R-factor (MJ mm ha^{-1} h^{-1} yr^{-1}), K-factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), and LS factor and for the Inle Lake region, Myanmar. These factors were constant for the period from 1989 to 2009

and floating gardens. The forest areas increased from 414 to 456 km^2 in 2000 and decreased again to 337 km^2 in the year 2009. These changes were reflected by changing C- factors in the RUSLE model (Fig. 3). The estimated average soil erosion risk was highest for barren land followed by cropland and agroforest areas, whereas nearly no soil loss risk was estimated for urban areas, marshland, and floating gardens (Table 3).

Average annual soil loss rates in the study region varied between 14.0 t ha^{-1} in 1989 (total = 3165 10^4 t yr^{-1}), 13.0 t ha^{-1} in 2000 (total = 2944 10^4 t yr^{-1}), and 16.7 t ha^{-1} in 2009 (total = 3785 10^4 t yr^{-1}). The temporal dynamics indicated a decrease in soil erosion risk from 1989 to 2000 by −7 %. The soil erosion risk was lowest in 2000, when only 21 % of the area was affected by soil losses >5 t ha^{-1} yr^1 (Fig. 4, Table 4).
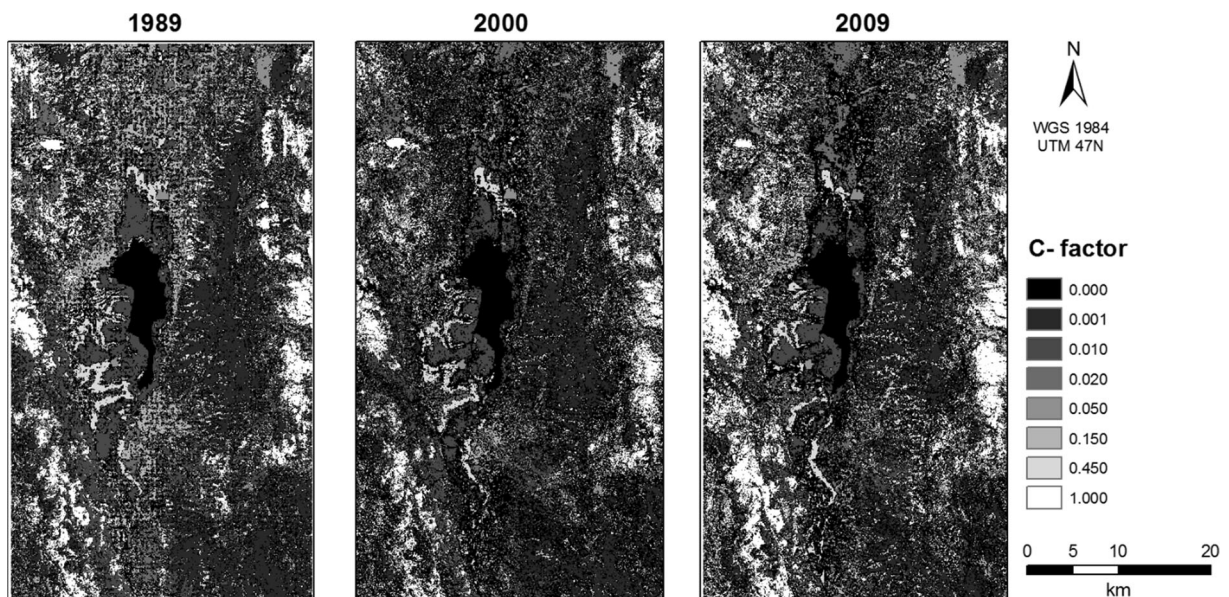
Fig. 3 Maps of C-factor from 1989 to 2009 for the Inle Lake region, Myanmar

Table 3 Distribution of land cover classes in 1989, 2000, and 2009 (Htwe et al., 2015b), changes (%) in comparison to the previous observation year and average soil loss (mean, standard deviation (SD) and percentage of total area) for each land cover class in the Inle Lake region, Myanmar

Land cover class	1989	2000		2009		Average soil loss		
	Area (km^2)	Area (km^2)	Change (%)	Area (km^2)	Change (%)	Mean (t ha^{-1} yr^{-1})	SD	(%)
Agroforest	400.95	369.48	−7.85	375.78	+1.70	9.30	14.22	11.48
Barren land	299.52	288.18	−3.79	323.18	+12.15	79.75	92.09	77.07
Other cropland	53.88	69.26	+28.55	97.28	+40.45	36.04	56.67	8.11
Fallow land	124.42	151.04	+21.39	171.75	+13.71	0.54	1.16	0.26
Floating garden	49.03	59.49	+21.33	68.69	+15.46	0.04	0.23	0.01
Forest	414.22	456.07	+10.10	336.91	−26.13	0.23	0.20	0.30
Marshland	54.73	28.33	−48.23	16.75	−40.88	0.01	0.06	0.00
Paddy fields	61.41	64.88	+5.64	56.59	−12.78	0.69	6.14	0.14
Shrubland	582.67	535.76	−8.05	549.61	+2.59	1.26	1.30	2.26
Urban	29.47	42.69	+44.86	60.11	+40.81	2.48	4.19	0.36
Water body	45.17	50.28	+11.33	58.78	+16.91	0.00	0.00	0.00

Erosion risk was highest for 2009, when soil losses increased again by 29 %. In 2009, 7 % of the area (295 km^2) was exposed to extreme risks (>50 t ha^{-1} yr.$^{-1}$), mostly situated in the upland cultivation zone. The soil loss potential increased from FG with nearly no soil losses to the UP zones (Table 5), where the highest losses were observed especially for the eastern mountain region. From 1989 to 2009, more than 95 % of the observed soil losses occurred in the upland cultivation zone.

Soil losses of different cropping systems in 2009

Among the different cropping systems of the surveyed households, rainfed rice (*Oryza sativa* L.)
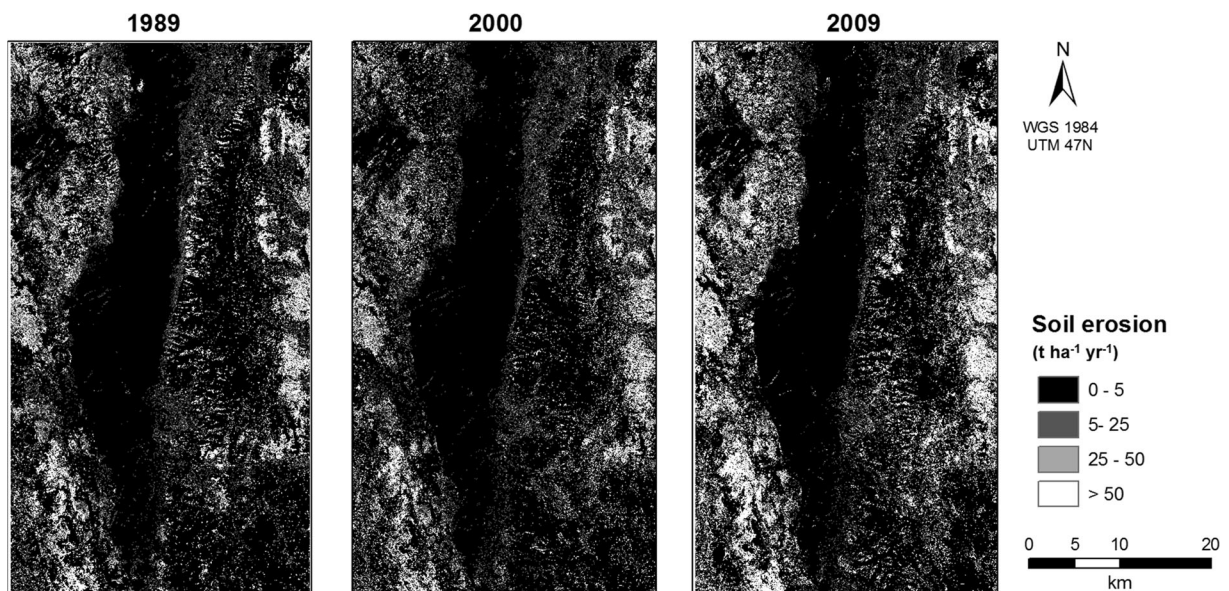
Fig. 4 Predicted soil erosion risk in the Inle Lake region, Myanmar

Table 4 Distribution of soil loss categories and amount of soil loss (10^4 t yr^{-1}) for each category in the Inle Lake region, Myanmar

Soil loss category (t ha^{-1} yr.$^{-1}$)	Area (km^2)			Soil loss (10^4 t yr^{-1})			% Change of soil loss	
	1989	2000	2009	1989	2000	2009	2000	2009
Low (< 5)	1608	1623	1521	120	118	123	−1.4	+4.1
Moderate (5–25)	218	216	258	270	266	331	−1.5	+24.2
High (25–50)	104	102	123	337	327	411	−3.1	+25.6
Extreme (> 50)	185	174	213	2437	2233	2920	−8.4	+30.8
Total	2115	2115	2115	3165	2944	3785	−7.0	+28.6

and maize (*Zea mays* L.) cultivation in the UP zone exhibited the highest soil erosion risk, followed by Sebesten (*Cordia dichotoma* G.Forst.) plantations (Fig. 5). For the floating gardens and lowland cropping systems, nearly no soil erosion risk was determined for the well-leveled and bunded paddy fields, whereas soil losses of 2 to 3 t ha^{-1} were observed for sugarcane (*Saccharum* ssp.).

Discussion

Soil erosion risk from 1989 to 2009

The type of land use, vegetation cover and conservation practices, the nature of terrain, and the climatic conditions play a major role in the extent of actual soil erosion risks (Bahadur et al. 2009; Sharma et al. 2011; Kumar et al. 2014; Ma et al. 2014) and were also in our study important input factors for the RUSLE model. The observed fluctuations in soil loss estimations from 1989 to 2009 were mainly due to differences in land cover. Erosion risks were highest for 2009, when deforestation, cropland expansion, and urbanization occurred especially in the western and southern part of the Inle Lake region (Htwe et al. 2015b). The western part of the upland zone was one of the hotspots of soil erosion risk

because of inappropriate land-use practices combined with a steep topography. Furuichi (2008) observed that gully erosion developed on hilly slopes and at the edge of the flatland in the western part of Inle Lake. The western catchment areas of the Inle Lake region (Thamakan and Heho basins) had numerous very large gullies and several deeply eroded areas (GAF 1996).

Our estimated average annual soil loss rate for the Inle Lake region (16.7 t ha^{-1} yr^{-1} in 2009) was higher than soil losses reported for the Miyun watershed in North China (9.9 t ha^{-1} yr^{-1}; Chen et al. 2011) and the Phewa watershed in Nepal (14.7 t ha^{-1} yr^{-1}; Bhandari et al. 2014), but lower than the reported average soil losses for the Maotiao River watershed in the Guizhou Province of China (28.7 t ha^{-1} yr^{-1}; Yue-Qing et al. 2008).

In our study area, the majority of soil losses (77 %) occurred on barren land, which are mostly situated on marginal sites along steep slopes. The estimated average soil loss on barren land in the Inle Lake region (80 t ha^{-1} yr^{-1}) is comparable to the values reported for the Kangra region of Western Himalaya (60.3 t ha^{-1} yr^{-1}; Kumar et al. 2014) and the Caijiamiao watershed in China (120.8 t ha^{-1} yr^{-1} Pan and Wen (2014), but much lower than findings in the Phewa watershed in Nepal (206. 8 t ha^{-1} yr^{-1}; Bhandari et al. 2014). These case studies

Table 5 Soil losses from 1989 to 2009 in the three agricultural zones of the Inle Lake region, Myanmar

Agricultural zone	Mean ± SD (t ha^{-1} yr^{-1})			Soil loss (%)		
	1989	2000	2009	1989	2000	2009
FG	0.03 ± 0.89	0.05 ± 0.98	0.03 ± 0.76	0.02	0.03	0.02
LL	2.27 ± 9.02	1.83 ± 6.98	1.90 ± 7.59	3.20	2.78	2.24
UP	18.55 ± 51.44	17.32 ± 48.86	22.40 ± 56.87	96.78	97.20	97.75

Fig. 5 Estimated average soil loss for the main cropping systems in the Inle Lake region, Myanmar in 2009. *Error bars* show the 95 % confidence interval
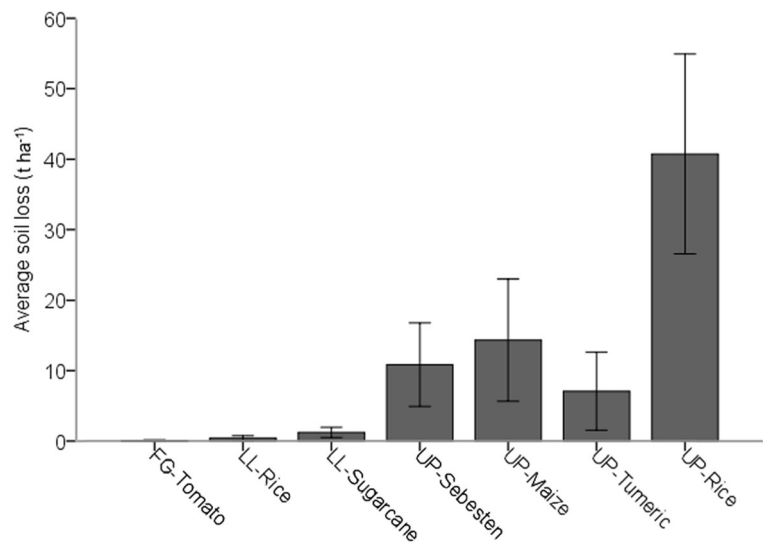
reported similar values for soil losses in croplands ranging between 18.3 to 45.7 t ha^{-1}yr^{-1} (Bhandari et al. 2014, Kumar et al. 2014, Pan and Wen 2014). However, for the Upper Nam Wa Watershed in Thailand, soil losses were even higher (307.3 t ha^{-1} yr^{-1}) for areas affected by shifting cultivation, for shrubland (17.1 t ha^{-1} yr^{-1}) and forest (35 t ha^{-1} yr^{-1}; Bahadur 2009).

The reported differences reflect the prevailing environmental conditions (vegetation composition, climate, soil conditions) in the respective study region but also the different modeling approaches that have been used such as different equations for the calculation of RUSLE factors, in particular for C-factors.

Soil erosion problems and farmers' perception

Similar to other mountain areas in Asia, land degradation is also a major problem (Bahadur 2009) in the Inle Lake region, where deforestation, shifting cultivation, overgrazing, and inappropriate cultivation practices on the steep land cause soil erosion, which leads to sedimentation, eutrophication, and water pollution (Than 2007; Soe 2012). Recent data show average sedimentation concentrations of 0.24 g per liter in the Indein (Balu) stream in the western part of Inle Lake leading to an average monthly sedimentation of 17,009 t (Thuzar 2012). Historical land use changes usually have long-lasting effects on nutrient leaching, acidification, and organic matter depletion of soils (Szilassi et al. 2006). It is well known that on eroded slopes, available

water capacity and organic matter content of soil decrease because of accelerated runoff rates (Duan et al. 2011; Espigares et al. 2011). Our data revealed that N_{tot} and C_{tot} were the lowest on eroded cultivated land in the uplands (Appendix 2).

Altogether, 75 % of the surveyed farmers were not aware of the consequences that inappropriate management of agricultural systems may have on soil erosion and land degradation, likely because of their low level of education and inefficient extension services (Lwin 2006; Lwin and Sharma 2012). Especially in rural mountain areas, attitudes, beliefs, and land-use practices are deeply rooted in people's culture and tradition, possibly limiting adaptation of new management approaches in upland farming. To improve knowledge transfer, a soil conservation committee was established in Shan State as early as 1962 but was only active until 1983 (Than 2006). Since then, the forest department established community forest plantations for the rehabilitation and conservation of forest land and soil and water conservation (Than 2007).

Only 3 % of surveyed farmers established contour-bunds in their cropland on slope areas or practiced traditional soil conservation techniques such as agroforestry with jackfruit (*Artocarpus heterophyllus* Lam.), mango (*Mangifera indica* L.), orange (*Citrus sinensis* L.), avocado (*Persea americana* Mill.), and banana (*Musa x paradisiaca*) hedgerows or terraced fields. To the majority of farmers, technologies for improved soil conservation and soil fertility management are still unknown.

Effects of different cropping systems on soil erosion and land degradation

Among the surveyed cropping systems in the Inle Lake region, average soil loss rates were highest for upland rice cultivation and maize. Even higher erosion rates for upland rice were reported for Thailand with average soil losses between 60 t ha^{-1} yr^{-1} (Turkelboom 1999), 78 t ha^{-1} yr^{-1} (Vien 1997), and 89 t ha^{-1} yr^{-1} (Hurni and Nuntapong 1983).

For sebesten and turmeric plantations, estimated soil loss rates were much lower because of the long cropping period (several years for sebesten and 10–11 months for turmeric). GAF (1996) reported that soil loss of perennial crops such as tea plantation on steep slopes ranged between 7.5 to 32 t ha^{-1} yr^{-1} in the Southern Shan State.

In the LL zone, sugarcane had the highest soil erosion rate probably because of the hilly terrain and land preparation techniques with heavy machines, whereas for paddy, nearly no soil losses were detected, which is comparable to the results of Bahadur (2009) for Thailand. In Southeast Asia, soil loss rates for vegetable crop land on moderate to steep slopes ranged from 38 to 140 t ha^{-1} yr^{-1} (Sidle et al. 2006).

Household interviews revealed that most upland farmers are regularly confronted with food insecurity, and upland rice cultivation yielded the lowest income in our study region but caused the highest soil losses. For the year 2009, the gross margin (Htwe et al. 2015a) was negatively correlated ($r = -0.315$) with total soil loss of the farmers' fields, which can be mainly attributed to the low productivity in upland areas with high erosion risk. Since rural farmers lack the capital to maintain soil resources, which is necessary to avoid erosion-induced nutrient depletion, this will sooner or later result in a poverty trap. Therefore, effective soil and water conservation practices should not only reduce land and soil degradation but also maintain and ensure crop yields and land productivity to enhance the livelihood opportunities of rural people (Daniel and Karin 2013).

Methods used for soil erosion risk modeling

Soil erosion measurement and monitoring approaches are increasingly important for land management planning in developing countries to effectively avoid erosion hazards and soil degradation (Pimentel et al. 1995; Lal 1998), but such monitoring is often limited by the availability of data and budgetary constraints. Therefore, spatial modeling approaches using GIS and remote sensing techniques play an increasing role for rapid risk assessments (Vrieling 2006) but certainly require field verification.

RUSLE can be easily applied as a soil conservation management tool to assess potential soil erosion hazards. Compared to Analytical Hierarchical Process (AHP) or the Pan-European Soil Erosion Risk Assessment (PESERA) models, which are highly data demanding, the necessary input parameters are often available even for remote areas (Morgan 1986; Karydas et al. 2009; Tang et al. 2014). However, RUSLE allows only the estimation of inter-rill or rill erosion from a hill-slope caused by rainfall erosivity; gully or stream-channel erosion are not accounted for (Karydas et al. 2009). Another limitation of the model is its lacking ability to consider the interdependences of soil erosion factors (Alexakis et al. 2013), and fundamental hydrologic and erosion processes cannot be characterized explicitly (Renard et al. 1991).

To better depict the spatial heterogeneity of the Inle Lake watershed area, additional input data would improve the estimation power of our RUSLE-factors, such as a larger network of rain gauges and detailed land use and soil maps. For an accuracy assessment of the erosion maps, independent data for validation are required, such as the collection of runoff and sediments from bounded plots or other field techniques for erosion assessment, which are often complicated, cost and labor intensive (Vrieling 2006). For spatial validation, high-resolution satellite images or aerial photographs are helpful to identify erosion or deposition areas and compare them with modeled soil erosion losses (Vrieling 2006). However, such data were not available for the whole study region and the different observation years.

Conclusions

Soil erosion, sedimentation, and lake eutrophication are serious interacting problems in the Inle watershed area as they are triggered by the demographic pressure and a rapid intensification of land use. Because of data limitations, this study estimated only soil erosion loss at the large watershed scale by using the GIS-based RUSLE model. Although the RUSLE model cannot adequately depict the small-scale spatial heterogeneity of soil erosion risk, the generated erosion maps indicate priority

regions from the soil conservation point of view. Such maps may help decision makers to identify appropriate cropping systems for erosion-prone areas and to more effectively design soil conservation strategies for the watershed surrounding Inle Lake.

During the observation period from 1989 to 2009, soil loss rates fluctuated with changes in land cover; soil losses were the highest for 2009, mainly because of deforestation and cropland extension. The identified hotspots of soil erosion risk are situated in the western upland areas of Inle Lake, where soil protection measures are urgently needed to reduce lake sedimentation and maintain the unique wetland ecosystem. Since in these areas smallholders suffer from low income and food-insecurity, soil conservation practices should focus not only on the reduction of soil loss but also on the improvement of crop yields and alternative livelihood strategies to reduce the poverty trap for rural people.

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