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THEMATIC ISSUE

Impacts of agricultural land-use dynamics on erosion risks and options for land and water management in Northern Mongolia

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Abstract In Mongolia, nomadic herders have successfully been grazing livestock for more than a millennium. However, in recent years, concerns have increased that changes in management and higher livestock stocking rates may negatively affect vegetation and increase soil erosion, overland flow and sediment load of rivers. In addition, ambitious agricultural policies increase the intensity of agricultural land use thus enforcing a conversion of grassland to agricultural land which is far more susceptible to erosion. In this study, we tackle the question how recent land-use dynamics influence erosion risks and which implications these require on water resources management. The study was part of a larger research effort, studying implementation options for Integrated Water Resources Management (IWRM); in this paper, specifically impacts of land use and land-use change on water resources are studied. The study has been carried out in the Kharaa river basin (KRB) in Northern Mongolia, in which grazing and agriculture play key roles. As several erosion and run-off-relevant factors such as slope, soil type or land use and land cover are widely varying in the KRB, sub-regions of the catchment have been analysed to identify susceptible combinations of environmental and land management factors. In our study we identified that erosion risks in the sub-catchments under current land use and management calculated with the Revised Universal Soil Loss Equation sum up to approximately 2–4 Mg ha^{-1} year^{-1} for steppe and 4–9 Mg ha^{-1} year^{-1} for croplands, while erosion rates calculated using ^{137}CS measurements resulted in 2–3 Mg ha^{-1} year^{-1} on steppe and 15 Mg ha^{-1} year^{-1} on cropland. Erosion risk scenarios indicate that land use change as well as management and climate factors can reduce (−30 %) or aggravate erosion risks up to sevenfold and contribute to additional challenges in water and soil management in the KRB. Strategies have to be developed to limit land conversion and implement soil protection in erosion prone sub-regions. IWRM has the potential to bridge sectorial measures, e.g. in agriculture, rural development or nature protection, but erosion and runoff-related impacts currently are addressed in different institutions, legal frameworks and regulations, which may slow down or hamper efficient measures.

Keywords Erosion modelling · Land-use change · Integrated Water Resources Management · Revised Universal Soil Loss Equation · ^{137}CS · Mongolia

Introduction

In Mongolia, the agricultural sector provides income for 40 % of the population, contributing around 15 % to the gross domestic product and is dominated by livestock production, mainly for meat, skin, wool and dairy products (NSO 2010). Due to the favourable climate and soils, the key growing area for crops is located in Northern Mongolia. Particularly the Selenga basin, draining into Lake Baikal, to which also the study region the Kharaa river basin (KRB) belongs, is of key importance for the ambitious national

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goals to increase food security and guarantee food self-sufficiency. To achieve these objectives, not only a National Food Security Plan was established in 2009, but the “3rd Campaign of re-claiming virgin lands” was also announced by the government and different types of financial incentives and assistance were and still are provided to farmers and agricultural companies to facilitate the intended increase of agricultural production (Bayar 2008; Priess et al. 2011; Zoljargal 2013). In the last decades, agricultural land use has rapidly changed. Livestock population has roughly doubled since 2000, but livestock mortality is still affected by the adverse conditions during droughts and especially during extreme winters (called dzud) (Begzsuren et al. 2004; Chuluun and Ojima 2001; Fernandez-Gimenez et al. 2012; NSO 2000–2011). Comparable increases in crop production can be observed since 2006/2007 (NSO 2000–2011). The latter is based on two processes: intensification of production and cropland expansion. As one of the consequences, increased competition for fertile and accessible pieces of land between herders and farmers can be observed in the KRB. Land-use change is resulting not only in strongly increased fencing of fields, but also in agricultural production expanding from the river plains and valleys towards steeper sloping lands with higher erosion risks and potentially less productive higher elevations. In addition, available cropland has been managed more intensively in the last years. In combination with wind and water erosion, agricultural expansion and management are considered the main causes leading to soil degradation in Mongolia (Hickmann 2006). In cultivated landscapes, vegetation cover is changing frequently and the bare soil is exposed to erosive agents more often than under natural vegetation. Methods to model or measure erosion, such as the Universal Soil Loss Equations (USLE) or the isotope cesium-137 (^{137}CS), have been used successfully for decades and adapted to and applied in semi-arid environments (Kato et al. 2010; Onda et al. 2007; Theuring et al. 2013; Walling and Quine 1993). The empirical USLE approach was developed to guide planners in quantifying long-term annual soil loss for feasible combinations of crop systems, land-use and management practices in association with biophysical conditions such as soil, rainfall and topography (Wischmeier and Smith 1978). The ^{137}CS technique was developed to measure net soil redistribution rates based on the distribution of the radioactive isotope of Caesium (Chappell 1999). Other methods use indicators to derive information about expected soil losses. For southern East Siberia, north of the KRB, Korytny et al. (2003) reported indicators for increasing erosion mainly due to land-use change for the first two-thirds of the twentieth century and indicators of slightly decreasing erosion attributed to climate change for the rest of the century, the latter probably also relevant for the KRB. Thus, while some climate factors may contribute to reduce erosion risks and consequences for sediment loads and soil fertility, other factors as the expected increase in summer rains (Nazimova et al. 1999; Korytny et al. 2003) as well as ongoing and expected changes in land use and management may aggravate the problem.

Thus, one of the key questions of the national objective to increase food security is, whether it can be achieved in a sustainable way, i.e. without negative consequences on soil and water resources. With respect to water resources, the expansion and intensification of land use lead to diverse environmental consequences. In the KRB, the contamination of the surface waters with sediments and nutrients is constantly increasing. This is especially problematic because large quantities of water are extracted from surface waters for domestic use without purification (Hartwig et al. 2012; Hofmann et al. 2011). Integrated Water Resources Management (IWRM) and similar measures are considered to be instruments contributing to the objective of avoiding or minimizing environmental impacts. However, to be efficient tools, they need to be addressed explicitly in laws and regulations and implemented at basin or sub-basin level (Horlemann and Dombrowsky 2012).

The study was part of a larger research effort, analysing different factors and implementation options of Integrated Water Resources Management (IWRM) (Karthe et al. 2014; Kalbus et al. 2012). In this paper, we study some of the key environmental aspects of sustainable production, which are the management of land and soils and their impacts on water resources. We focus on different aspects of erosion risks of current land use and the ongoing land-use change processes under the harsh and highly variable weather conditions of Northern Mongolia. Two methods were adapted to regional conditions to calculate current erosion risks, namely the Revised Universal Soil Loss Equation (RUSLE) and the ^{137}Cs method. To assess future erosion risks and their potential consequences for IWRM-related measures, we developed land-use scenarios and simulated them with the RUSLE approach. Based on our results, we analyse IWRM options and limitations to address on-site and off-site effects of erosion and runoff, in the current legal frameworks and regulations addressing IWRM-related institutions and measures.

Study region

This study was carried out within the Mongolian-German project’ Integrated Water Resources Management in Central Asia: Model Region Mongolia’ (MoMo2), aiming at the development of sustainable management strategies adapted to the highly variable continental climate found in the KRB in Northern Mongolia. The KRB covers

Fig. 1 Land cover map from 2010 overlaid by sub-basins borders of the KRB. Upper KRB: Bayan, Kharaa 1, Sugnugr, Tunkhelin; Central KRB: Boroo, Kharaa 2, Mandlin; Lower KRB: Bayangol, Kharaa 3, Zagdelin

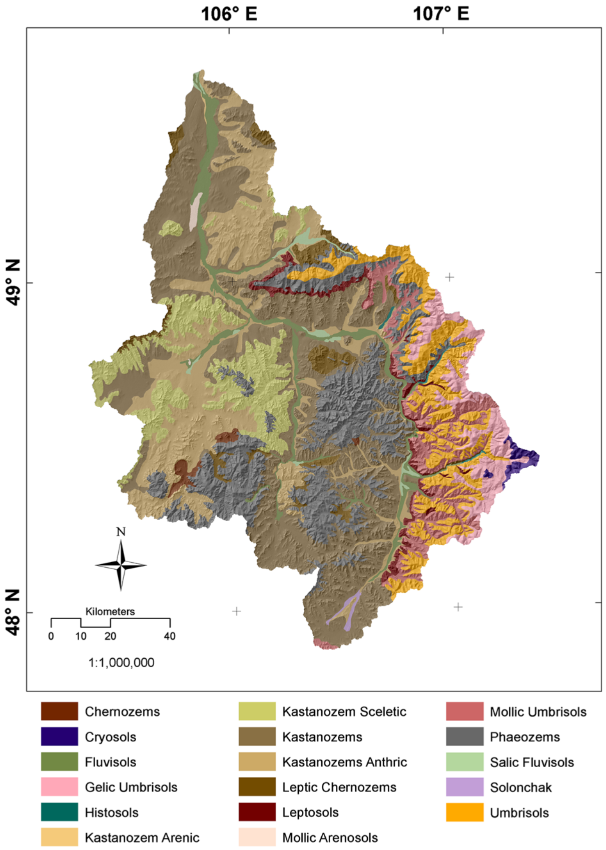

Fig. 2 Digital soil map

14,553 km^2 and is situated north of the capital Ulaanbaatar in the forest-steppe region (Fig. 1). As part of the Selenga basin, the catchment's outlet is located in the North where the Kharaa river discharges into the Orkhon river. The elevation increases from 600 up to ~2,500 m.a.s.l. towards the Khentii mountains in the south-eastern part. Loamy soils (different types of Kastanozems) are dominating, in general terms the lighter sandy soils are located predominantly in the northern part and the heavier loamy soils are exposed towards the southern part (Fig. 2). The climate is semi-arid, but represents one of the most humid regions in Mongolia. Mean annual precipitation ranges from 250 to 430 mm per year (1986–2010), of which approximately 10 % remain in the catchment, while ~90 % are lost via evapotranspiration (Hülsmann et al. 2014; Menzel et al. 2008; Wimmer et al. 2008). Mean annual air temperature is 0.4 °C, with a maximum temperature of 40 °C in the hottest month July and up to −45 °C in the coldest month January. While the southern parts of Mongolia are covered by steppe and desert, more than a quarter of the KRB is covered by forests (28 %), mainly located in mountains in the east and south-east. In the central and lower catchment steppe vegetation dominates (62 %) and is mostly used for grazing. Nine percent of the surface are used for crop production, mainly wheat and potatoes, and increasingly also vegetables, while settlements, industry, infrastructure and water bodies occupy only ~1 % of the surface area. Both agricultural production and natural vegetation are facing environmental conditions strongly limiting biomass production, such as restricted water availability during parts of the growing season, short vegetation periods and the high inter-annual variability of the weather conditions.

For the analysis, the ten sub-basins have been grouped into three categories (upper, central, lower) according to their average slope and landscape characteristics (Table 1). The valleys of the first group of the lower catchment (4°–6°) are characterized by wide flood plains, where 81 % of the KRB's croplands are currently located. The next group is located in the central part of the catchment, where around 18 % of croplands can be found, characterized by smaller valleys and higher elevation (8°). Contrastingly, the steepest and highest sub-catchments are grouped into the upper KRB (11°–13°) providing around 1 % of the croplands, but including a larger fraction of forests (Fig. 1; Table 1).

Table 1 Sub-basins, average slopes and area fractions for cropland, steppe and the total KRB

Location in KRB	Sub-basin	Cropland		Steppe		Total KRB	
		Slope (°)	Area (km^2)	Slope (°)	Area (km^2)	Slope (°)	Area (km^2)
Lower	Kharaa III	2.4	507	4.5	1,874	4.1	2,415
	Zagdelin	1.8	453	5.7	2,035	6.1	2,946
	Bayangol	2.3	73	5.7	582	6.3	780
Central	Boroo	2.2	107	6.8	1,401	7.7	1,973
	Mandlin	2.0	49	7.2	1,619	7.8	2,160
	Kharaa II	2.3	86	7.0	1,343	8.2	2,098
Upper	Bayan	3.8	2	9.0	67	11.1	337
	Kharaa I		0	11.1	307	11.8	825
	Tunkhelin		0	11.4	84	12.9	524
	Sugnugr	2.6	2	10.5	77	12.9	495
	Mean/sum	**2.2**	**1,279**	**6.4**	**9,389**	**7.5**	**14,553**

Means and sums are highlighted in bold

Data and methods

Soil data and soil map

The soil map used for erosion modelling is a refinement of the national soil map of Mongolia (Dorjgotov 2003). In a first step, the map was digitized and the original Mongolian soil classification transferred to the FAO soil classification system (WRB 2006). Enhancement was achieved using further environmental parameters (e.g. topography, land cover) but mainly data from soil profile investigations. For refinement, we included 26 soil profiles, which have been taken during field campaigns in 2008 and 2009. Soil core samples have been analysed for 120 horizons following standard laboratory procedures to determine physical and chemical properties (e.g. texture, bulk density, porosity, C/N). The additional sampling covered all soil units from the original map, with a focus on large units and intensively used soils, which are located mainly in the central and lower catchment. In addition, profile information from 29 soil explorations from Russian-Mongolian campaigns conducted between 1978 and 1981 have been used to generate a detailed soil database for the study area. Finally, the database was linked to the digital map characterizing 17 dominant soil categories (Fig. 2).

Erosion modelling

Soil erosion was estimated by the application of the RUSLE, which is an empirical model to assess erosion which is caused by rainfall, based on information on soil, topography, land use and land management (Renard et al. 1997). The approach is an extension of the USLE developed by Wischmeyer and Smith (1978) and can be expressed as:

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

where A is the estimated average soil loss in Mg ha^{-1} year^{-1}, R is the rainfall erosivity factor in MJ mm ha^{-1} h^{-1} year^{-1}, K is the soil erodibility factor in Mg h^{-1} MJ mm, L is the slope length factor, S the steepness factor, C the crop management and P the support practice factor. While R, K and C are directly related to the area, L and S reflect the catchment area of a certain spot or respective cell on the surveyed surface (Renard et al. 1997). Many studies deal with the problem that resolution of the input data is insufficient in temporal and spatial resolution and therefore not applicable to the approach proposed by Renard et al. (1997). With these limitations the application of the RUSLE requires several adaptations with respect to the derivation of the factors (see Karaburun 2010; Xu et al. 2013; Zhang et al. 2013). In order to generalize the approach to be applicable on basin scale, we generalized for example the R-factor and gridded the soil data and all input factor maps for the calculation of erosion risks to a pixel resolution of 1 km^2 resulting in a total number of 14,553 cells. To derive the R factor, we applied a regression proposed by Renard and Freimund (1994), which uses mean annual rainfall instead of recorded high-resolution rainfall intensities. The relationship is based on data from continental areas in the United States ($n = 132$) and applicable for regions with less than 850 mm of annual rainfall. The regression has the equation:

$$R = 0.0483 \times P^{1.61} \tag{2}$$

with P as the mean annual precipitation derived for each grid cell from spatially interpolated rainfall data measured at 26 metrological stations (for further information on the interpolation procedure see Wimmer et al. 2008). For this study, we derived two R factor maps, one representing an “average year situation” using a 20-year mean (1986–2006) with an average precipitation of 346 mm, the other represents a “wet year situation” using a single year rainfall dataset (1990) with a mean rainfall of 432 mm. Soil erodibility (K) was derived using the approach developed by Römkens et al. (1986) and modified by

Renard et al. (1997). The calculation is based on a worldwide regression analysis of measured K values resulting in the equation:

$$K = 0.0034 + 0.0405 \times \exp\left[-0.5\left(\frac{\log D_g + 1.659}{0.7101}\right)^2\right] \tag{3}$$

where D_g describes the geometric mean weight diameter of the primary soil particles in mm. D_g can be obtained from:

$$D_g = \exp\left(\sum f_i \times \ln\left(\frac{d_i + d_{i-1}}{2}\right)\right) \tag{4}$$

where d_i is the maximum diameter in mm, d_{i-1} is the minimum diameter and f_i the mass fraction for each particle size class (Van der Knijff et al. 2000). We derived K values for the 17 soil types identified in the study area based on the categories represented in the soil map and their underlying soil properties (Fig. 2). Relief factors as inclination (slope), specific catchment area, slope length and the slope length exponent were derived using a digital elevation model which is based on the HydroSheds dataset (Lehner et al. 2008). The modified RUSLE factors L and S have been calculated as follows:

$$L = \frac{\left(\lambda_{i^{m+1}} - \lambda_{i-1^{m+1}}\right)}{\left(\lambda_i - \lambda_{i-1}\right)} \times 22.13 \tag{5}$$

with $m = \frac{\beta}{1+\beta}$ and $\beta = \frac{\left(\frac{\sin(\theta)}{0.0896}\right)}{\left(3\times\sin(\theta)^{0.8}+0.56\right)}$ where λ is the specific catchment area of a cell, multiplied with the cell size and θ is the slope in degree. S was obtained from:

$$S = 10.8 \times \sin(\theta) + 0.03 \text{ (with slope } <9\ \%) \tag{6}$$

$$S = 16.8 \times \sin(\theta) - 0.5 \text{ (with slope } >9\ \%) \tag{7}$$

Contrasting many previous approaches, the modified formula is based on a multiple flow accumulation algorithm (Freeman 1991).

The crop management factor (C) represents the effect of cropping and land management and was derived based on the land cover categories presented in Fig. 1. For the reference period factors for settlement, cropland, fallow and forest are based on literature values from Shi et al. (2004) and Wischmeyer and Smith (1978) with regional adaptations (Table 2). For Settlement we assume a factor of 0.6 due to the situation that most of the roads are unpaved and not covered by vegetation. Most of the cropland in the KRB is managed as wheat/fallow rotation for which Shi et al. (2004) propose a value of 0.58. However, taking into account that in their study a comparably small parcel size of 0.1 ha in average was considered, we slightly increased the factor to 0.6 to take into account the average field size of 70 ha in the KRB which is more erosion prone.

Table 2 Land cover categories and corresponding management factors for the current situation

Land cover	C-factor
Settlement	0.6
Cropland	0.6
Fallow	0.8
Grassland	0.068
Mixed, open forest	0.008
Coniferous, dense forest	0.003

According to Karnieli et al. (2013), on grassland current grazing intensity in the study area results in a biomass cover of approximately 50 %, which corresponds to a C-factor of 0.068 according to the lookup table presented by Wischmeyer and Smith (1978).

Wischmeyer and Smith (1978) propose to link the P-factor according to slope, maximum slope length where protection measures are effective and according to different management measures (e.g. contour, strip-cropping, terracing and so forth). In the KRB agricultural fields are mostly cultivated by strip cropping and contour ploughing. Considering the large size of agricultural fields mentioned above, we assumed that the low end of the range (0.5) suggested for contour ploughing by Wischmeyer and Smith (1978) would not be appropriate, nor the high end of 0.9 suggested for very steep slopes of up to 25 %. Considering the large field plots in the KRB and the mostly moderate to low slopes, we decided to use an intermediate value of 0.75 in all simulations.

Erosion rate calculation with the Cesium-137 method

In addition to the spatially distributed RUSLE approach, we quantified net soil loss at selected erosion prone cropland and steppe sites for comparison and site validation purposes. Compared to the distributed RUSLE approach, which is also suitable for larger scale applications, we have chosen isotope measurements to derive soil loss and sedimentation rates at the hillslope scale (Chappell 1999). The method used relies on the measurement of the isotope cesium-137 (^{137}CS) which is commonly used in erosion studies in semi-arid environments (Chappell 1999; Kato et al. 2010; Onda et al. 2007; Theuring et al. 2013). The artificial isotope ^{137}CS was released to the environment from nuclear weapon tests and nuclear reactors between the 1950s and 1970s (Di Stefano et al. 1999). After fallout, ^{137}CS was strongly absorbed and fixed by the finer soil particles in topsoil and due to the non-exchangeable chemical characteristics leaching in deeper soil layers is limited (Di Stefano et al. 1999). Considering the half-life period, net soil loss and sedimentation rates are estimated

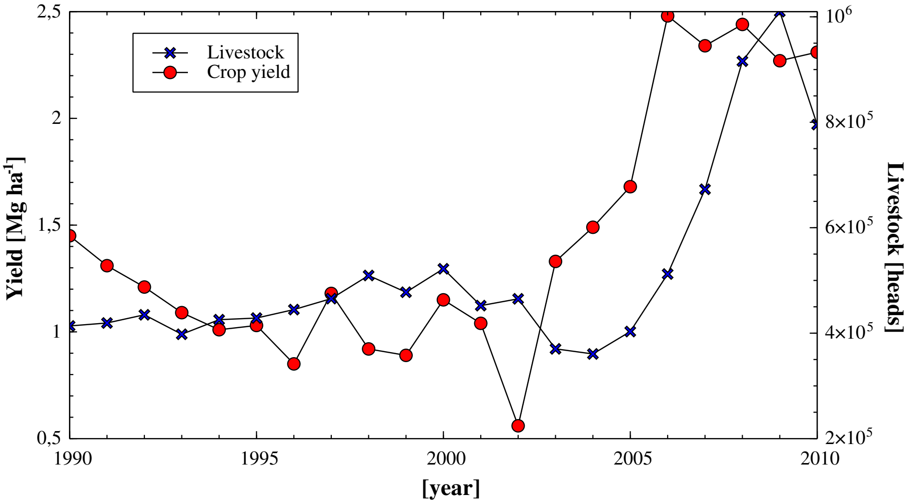

Fig. 3 Agricultural production and livestock development in the KRB. Crop yields indicate the average for cereals, potato and horticulture. Data has been provided by the National Statistical Office of Mongolia (NSO 2000–2011) and converted from district to basin scale using area-based conversion factors

in proportion to the deviance from an undisturbed reference site. Bulk samples for ^{137}CS measurements were taken during field campaigns in 2011 and 2012. In total 110 sites have been sampled, consisting of five topsoil samples for each site. Sampling was conducted using a ferrule with a diameter of 20 cm. Due to the mechanical disturbed top soil layer on agricultural sites, we sampled 0–20 cm on cropland and 0–15 cm on steppe. The radioactivity of ^{137}CS was determined by gamma spectrometry at the Nuclear Centre of the National University of Mongolia. Related soil loss and accumulation rates were calculated using the models developed by Walling and Quine (1993) and Walling and He (1999), applying the "mass balance model 2" for agricultural fields and the "profile distribution model" for steppe. The 110 sampling sites include potential reference sites; however, one could be identified as suitable with a reference value of 1,759 Bq m^{-2}. The analysis of the 110 sites revealed that 67 samples indicate a net soil loss and therefore could be used for comparison with the RUSLE calculations (Table 4).

Erosion risk scenarios

For the development of erosion risk scenarios, we analysed land-use change maps, yields and livestock statistics in the region to derive appropriate erosion risk simulation settings for different near future land use management conditions. Land-cover change was assessed on the basis of classified Thematic Mapper (TM) satellite products provided by the United States Geological Survey. Satellite images for 2006 and 2010 have been classified based on the approach described in Schweitzer et al. (2005) and Erasmi and Priess (2007), using a hierarchical expert classification scheme based on satellite data (e.g. multispectral data and indices), GIS (e.g. cadastral information) and expert knowledge (e.g. location of irrigated areas). The classification procedure was performed using ERDAS IMAGINE Expert Classifier^{TM}. As we applied the same classification methodology for both images, it was important that the images are comparable in their characteristics (Göttlicher et al. 2009). Thus satellite data pre-processing was done for such atmospheric and topographic correction. Accuracy was evaluated using ground control points and regional land-use statistics (NSO 2000–2011). Finally, both maps have been aggregated to a 1 km^2 grid. Between 2006 and 2010 managed cropland including fallow almost doubled from 684 to 1,280 km^2 (+87 %). Cropland expansion was detected mainly on steppe, confirming an increased re-use of set-aside steppe land. In addition, cropland is more intensively managed by increasing use of fertilizes and irrigation, indicated by the increase in yield levels (Fig. 3). Nevertheless, the steppe area also slightly increased (+1.6 %) as a result of forest loss due to wildfires, forest calamities and increasing forest use. In spite of the decreased availability of grasslands suitable for gazing, the number of animals in the KRB has doubled in recent years, compared to the period 1990–2005 (Karnieli et al. 2013; NSO 2000–2011) (Fig. 3).

Motivated by the ongoing fast changes in the agricultural sector, we developed five erosion scenarios, to estimate erosion risks under current and plausible near future conditions. Current conditions in the KRB are characterized by the extent of cropland 1,280 km^2 and steppe 9,390 km^2, intensity of land use corresponding to 50 % vegetation cover on steppe and average climate conditions as described above. For the five erosion scenarios we considered the factors cropland expansion, erosion protection, intensified grazing and increased annual precipitation. For the latter, we used the highest annual rainfalls of 430 mm, as it is in the same range as rainfalls expected for future decades based on IPCC scenarios (data provided by the WATCH project; Weedon et al. 2011; similar rainfall

Table 3 Erosion risk scenarios

	Scenario description	Parameterization of factors
Current status	Current extent of cropland and grassland (Table 1) under present management and climate conditions	*K*, LS factors according to description in 'Erosion modelling'; *C*-factors: Table 2; *R*-factor: average climate (346 mm)
Scenario 1	Cropland expansion + 60 % based on biophysical suitability[a]; corresponding steppe extent −768 ha	Same as current status
Scenario 2	Cropland expansion as in scenario 1, intensified grazing (assuming a loss in steppe vegetation cover from currently 50 to 30 %)	*C*-factor steppe: 0.15 [based on Wischmeyer and Smith (1978)]
Scenario 3	Cropland expansion as in scenario 1, intensified grazing as in scenario 2 and increased precipitation	*C*-factor steppe: 0.15 [based on Wischmeyer and Smith (1978)], *R*-factor: wet climate (430 mm)
Scenario 4	Cropland expansion as in scenario 1, erosion protection via mulching (wheat straw remains) multiplying *C* with a tillage reduction factor of 0.6	*C*-factor cropland: 0.36 (−60 %), *C*-factor fallow: 0.48 (−60 %)
Scenario 5	Erosion protection on cropland and fallow via mulching and increased precipitation	*C*-factor cropland: 0.36 (−60 %), *C*-factor fallow: 0.48 (−60 %), *R*-factor: wet climate (430 mm)

[a] Multi-criteria analysis based on the biophysical factors: elevation, slope, soil type

predictions of +30 to +50 mm by Nazimova et al. 1999; Korytny et al. 2003). Erosion risk scenario details are presented in Table 3.

Results

Erosion risks under current and plausible future conditions

Erosion risks were simulated under current conditions and five scenarios of plausible near future conditions.

Erosion under current conditions

Erosion risks for cropland are generally much higher than for steppe, on average 7.2 vs. 2.0 Mg ha^{-1} year^{-1} (Table 4). Erosion on cropland varies considerably (6.9–8.9 Mg ha^{-1} year^{-1}), but does not necessarily follow the general slope pattern in the lower, central and upper catchment, due to differences in soils, slope length and the locations of fields within the valleys. Due to the much larger extent, erosion pattern in the steppe is more closely related to general slope pattern, although as in croplands, the large standard deviations point to the considerable influences of the other erosion-relevant factors such as soil erodibility and slope length. It is noteworthy that the erosion pattern for the entire area does not follow the strongly increasing slopes from lower via central to the upper parts of the basin, as the latter are covered increasingly by less erosion-prone forests.

^{137}CS erosion measurements conducted in some of the more accessible parts of the Kharaa croplands and steppes in 2010 and late 2012 support the general erosion pattern (cropland $\gg$ steppe), but in some instances indicate erosion rates up to three times higher than the RUSLE calculations. Additionally, ^{137}CS measurements reflect landforms in a much more detailed way, resulting in points of soil accumulation in flat or concave parts of hillslopes or at foot slopes. Nevertheless, consistent patterns were observed in all parts of the KRB and for the two types of land cover to which both methods were applied: Firstly, maximum values of RUSLE estimates covering the entire KRB were consistently higher than ^{137}CS values. Secondly, ^{137}CS means were consistently higher (up to twofold) than RUSLE means. Soil losses in the KRB currently sum up to 0.9 million Mg from croplands and 1.8 million Mg from steppe areas.

Erosion risks under near future conditions

In Fig. 4, future erosion risks calculated with the RUSLE equation are presented as changes in the lower, central and upper basin, relative to the current status.

Figure 4 indicates that the highest increases in erosion risks can be expected on croplands (up to sevenfold), followed by steppe (up to 3.5-fold) and all land-use types (up to threefold). Figure 4a shows that the largest changes on croplands are to be expected in the upper basin, with up to sevenfold increases, when croplands are expanded towards steeper slopes (scenarios 1, 3) under increased rainfall conditions (scenario 3). This shift occurs due to the fact that mainly in the upper, but partly also in the central catchment, the extent of plain area is limited (and they have to be shared with herders), causing additional croplands to be allocated on steeper slopes. On cropland, the simulated erosion protection via mulching considerably reduced erosion risks. However, the positive effect was overcompensated in three out of four scenarios by the factors expansion (to steeper slopes), and higher rainfall. Thus, the only scenarios showing a reduction of erosion

Table 4 Erosion risks under current (2010) land use intensity, extent and average climate estimated using the RUSLE approach and by ^{137}CS sampling (maximum, mean and standard deviation of the 1 km^2 pixels of the sub-basins are presented)

Location in KRB	Erosion risk RUSLE/^{137}CS			Slope	Area 2010	^{137}CS
	Maximum (Mg ha^{-1} year^{-1})	Mean (Mg ha^{-1} year^{-1})	SD (Mg ha^{-1} year^{-1})	(°)	(km^2)	(*n*)
Cropland						
KRB	46.9/31.2	7.2/14.5	5.6/8	2.2	1,279	30
Lower	46.9/31.2	6.9/14.5	5.3/8.6	2.2	1,033	23
Central	42.4/23.3	8.9/14.5	7.0/6.3	2.2	242	7
Upper	6.1	4.2	1.3	3.2	4	
Steppe						
KRB	31.6/6.8	2.0/2.5	1.9/2.1	6.4	9,389	37
Lower	15.8/6.8	1.6/2.3	1.5/2.0	5.2	4,491	19
Central	31.6/6.4	2.1/2.5	2.0/2.0	7.0	4,363	17
Upper	29.0	4.4	4.3	10.8	535	
Total						
KRB	46.9	2.1	3.0	7.5	14,553	
Lower	46.9	2.4	3.3	5.3	6,141	
Central	44.1	1.9	2.9	7.9	6,231	
Upper	29.0	1.4	2.8	12.2	2,181	

No ^{137}CS sampling was conducted in the small steppe and cropland areas of the upper catchment. Wherever one value is presented, it represents the RUSLE result. Values for "Total" include forest areas which have been calculated with the RUSLE approach

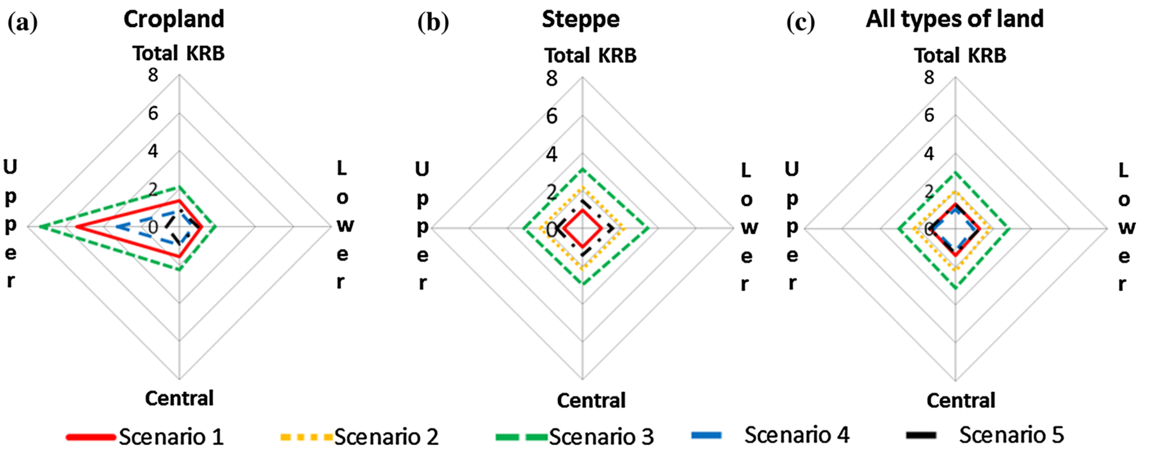

Fig. 4 Scenarios of future erosion risks in the Kharaa basin (erosion scenarios are described above). **a** *Left* cropland, **b** *centre* steppe, **c** *right* all types of land including cropland, forests, settlements and steppe. The spider diagrams show simulated erosion risks relative to the current status for the *lower*, *central* and *upper* parts and for the total KRB; 1 represents the current status, <1 a reduced and >1 an increased erosion risk. Erosion risks in scenario 3 are highest and translate to annual soil losses of 3.1 million Mg from croplands and 5.4 million Mg from steppe

risks were scenarios four and five, assuming no other changes on cropland, but mulching. The patterns are the same for the central and lower sections of the Kharaa, much less pronounced, but also doubling erosion risks under combined expansion and increased rainfall conditions (scenario 3).

Future steppe erosion risks (Fig. 4b) seem to increase more uniformly across the catchment. Contrasting the expected effects on croplands, steppe areas tend to erode stronger in the lower part of the basin, due to the non-uniform increase in rainfall (scenarios 3, 5). The combination of factors increased rainfall and intensified grazing causes a 3.5-fold increase in the lower basin, and a threefold increase in the central and upper parts (scenario 3). Beyond, erosion risks show no pronounced spatial pattern, but can be expected to occur in the entire basin.

Erosion risks across all land use and land cover types (Fig. 4c) are strongly influenced by the largest land cover steppe, and also show no pronounced spatial pattern. An up to threefold increase in all parts of the basin can be expected under conditions of cropland expansion combined with increased grazing intensity and higher rainfalls (scenario 3).

Discussion

The study is motivated by the fast changes recently occurring in Mongolian agriculture, and the questions (1) whether the overarching political objective to increase production and food security can be achieved with little/no negative environmental impacts, especially with respect to vulnerable soils and water resources, and (2) which IWRM measures might contribute to minimize damages.

As prerequisites for the analysis of soil erosion as one of the key-impact indicators, we developed a digital soil map and database, building on available Mongolian and Russian studies, which we complemented by own field surveys, laboratory analyses and GIS work. As explained above, the calculation of erosion risk is based on the ^{137}CS method and the RUSLE equation adapted to semi-arid conditions and the land use and land management in Northern Mongolia, using state of the art multiple flow algorithms and the optional inclusion of erosion barriers to improve the realism of slope length simulation. Due to the limited spatial resolution of input data for this regional-scale assessment, we used a spatial grid of 1 km^2, well aware that the resolution is suitable to calculate average erosion risks (Ranzi et al. 2012; Xu et al. 2013), but of limited use, e.g. to assess erosion peaks caused by small-scale terrain properties and intensive single rainfall events (Hoyos 2005; Prasuhn et al. 2013). Based on the consistent pattern both methods produced, RUSLE erosion risk means could be considered a lower bound or conservative estimate, while ^{137}CS values are based on a considerable lower number of measurements, but can be interpreted as closer to the real risk. This finding confirms other studies (Di Stefano et al. 1999) and needs to be considered when planning IWRM or other measures to mitigate environmental damages and protect limited water resources.

As a contribution to the practical application of erosion risk assessments in Mongolia, we developed a simple to use computer tool based on the methods described above, capable of producing erosion risk maps based on a digital elevation model using the multiple flow algorithm and on user specified land use, land management and climate conditions. The tool can be used for any basin and is freely available for scientific partners and Mongolian authorities and has already been presented and demonstrated during workshops and meetings in Mongolia.

Building on the methods presented above, we were assessing key-drivers of change for the most erosion-prone land use and land-cover classes cropland and steppe, covering ~75 % of the KRB, developing five erosion risk scenarios including the factors 'expansion of cropland', 'intensification of grazing', 'protective measures on croplands' (mulching), and 'climate change' in terms of increasing rainfalls.

Current erosion levels in the sub-catchments at approximately 2–4 Mg ha^{-1} year^{-1} for steppe and 4–9 Mg ha^{-1} year^{-1} for croplands can be considered conservative estimates, using long-term means of annual rainfalls. Erosion rates calculated using the ^{137}CS method are 2–3 Mg ha^{-1} year^{-1} on steppe and 15 Mg ha^{-1} year^{-1}on cropland. As both methods RUSLE and ^{137}CS are based on modelling, an inter-comparison is not considered appropriate for validation. ^{137}CS samples and corresponding erosion (or accumulation) rates better reflect small scale differences in topography as well as site specific conditions (e.g. vegetation, slope length) which may further amplify or reduce erosion. Contrastingly, Onda et al. (2007) reported much lower erosion rates for grazed steppe from the drier western part of Mongolia (approximately 50 % of the annual rainfall of the KRB). Nevertheless their measurements and ^{137}CS calculations confirm the positive correlation between grazing intensity and erosion rates. Results clearly indicate that ongoing and expected near future changes in the agricultural sector mostly will cause considerable increases in soil losses both on croplands and in the steppe used for grazing, confirming soil degradation reported by Hickmann (2006) and losses in steppe biomass due to intensified grazing (Chen et al. 2007; Onda et al. 2007). In general terms, negative effects are higher and almost uniformly distributed in the lower, central and upper KRB in the steppe, increasing 2–3.5-fold, depending on the combination of environmental and land management factors. Contrastingly, erosion risks on cropland are expected 'just' to double in the lower and central KRB where most of the agricultural activities are located, while up to sevenfold increases are predicted in the upper parts of the basin, however, affecting very minor areas of crop production and grazing. The differences in spatial pattern between stronger increases in the lower and central KRB on steppe and the very pronounced increase in the upper KRB on croplands are caused by different combinations of environmental factors determining erosion. The higher erodibility of the sandier grassland soils in the broad valleys of the lower and central KRB under steppe strongly responds to the reduced vegetation cover (from 0.5 to 0.3) and the increased amount of annual rain (from 346 to 430 mm). In the upper KRB it is the combination of higher rainfalls on croplands expanded to steeper slopes (scenario 3) causing a steep increase of up to 30.5 Mg ha year^{-1} corresponding to a sevenfold increase. These findings are consistent with the ^{137}CS measurements. Contrastingly, under the semi-arid conditions of Northern Mongolia, mulching of croplands with wheat straw can contribute to decrease soil losses up to 30 %, and can thus be considered a simple and efficient measure if not to halt, but at least to reduce erosion (Fig. 5b).

Direct on-site effects include annual losses of top-soils between currently 0.9 up to 3.1 million Mg (scenario 3)

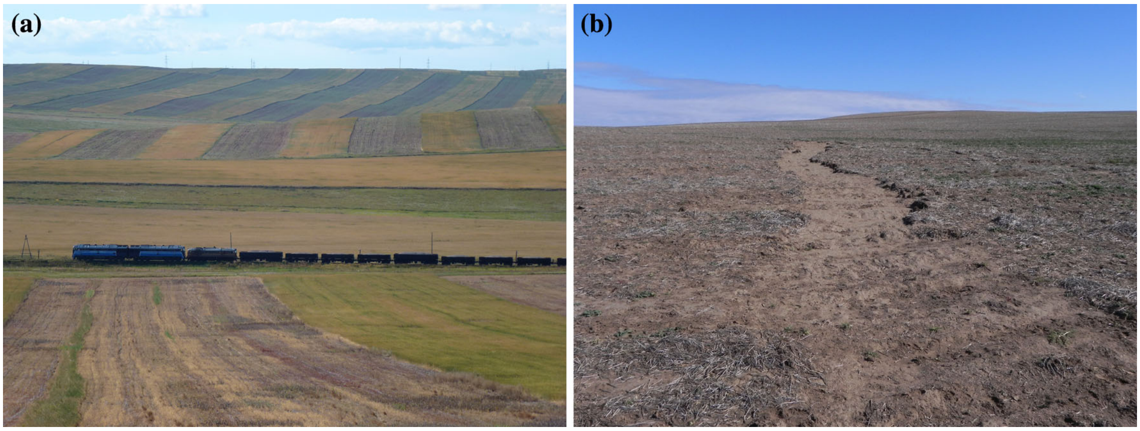

Fig. 5 Land use and erosion in the KRB. **a** Typical strip-pattern of cultivated and fallowed fields; note the erosion marks on the fallows. **b** Erosion and run-off in spite of contour-ploughing and mulching with wheat straw

from croplands and currently 1.8 up to 5.4 million Mg (scenario 3) from steppe areas, reducing water-holding capacities and soil fertility and transporting large amounts of sediments to creeks and rivers. Annual soil losses translate to an average of 220 Mg of nitrogen being lost on cropland and an average of 620 Mg on steppe, causing additional demand for cropland as well as high additional fertilizer costs, counteracting Mongolia's efforts for a more sustainable use of land and water resources and to reduce imports in the food sector and save limited foreign currency reserves. Giese et al. (2013) reported nitrogen losses of 9 kg ha^{-1} from heavily grazed areas in Inner Mongolia, which are 4.5 times higher as the 2.0 kg ha^{-1} estimated for the KRB assuming intensified grazing. The even higher losses in Inner Mongolia occurred probably due to different environmental conditions, especially with respect to wind erosion (Mao et al. 2013).

As our results clearly indicate, challenges to manage soil and water resources considerably differ between the subbasins of the KRB. Consequently, any IWRM measures intended to mitigate environmental damages in the KRB, need to reflect the different combinations of environmental components such as soils and climate, as well as land management and land-use change processes such as expansion of cropland and intensification of grazing.

In the KRB, the commonly very large field sizes correspond with slope lengths of up to 1–2 km without barriers, even in gently sloping and contour-ploughed terrain causing water accumulation, sufficient to break furrows (Fig. 5b). Thus a reduction in slope length, e.g. via strips of grassland or hedgerows, would contribute to reduce the problem. The second process contributing to aggravate soil and water losses is the ongoing cropland expansion to steeper slopes, due to currently attractive economic conditions for agricultural products, but also due to the increasing competition between farmers and herders for accessible and fertile land. As countermeasures such as contour-ploughing and mulching are insufficient to halt erosion, the question arises whether existing legal frameworks and authorities can limit the expansion of croplands on steeper slopes, or require the application additional of soil and water conserving measures as components of IWRM.

Off-site effects of erosion and run-off include the accumulation of sediments and water on foothills and inputs into the Kharaa river and its tributaries. In their study, Theuring et al. (2013) identified that surface erosion contributes approximately 22 % to the suspended sediment load of the KRB, whereas riverbank erosion contributes up to 75 %, mainly caused by livestock trampling.

Addressing erosion problems requires considering both, on-site and off-site effects and corresponding countermeasures, typically involving different legal and regulatory frameworks and institutions at different scales to implement and enforce them. Thus, it is important to analyse the links between natural resources such as soils and water, potential measures to halt or reduce environmental damages and the laws and regulations in which these issues are addressed. Ideally, IWRM bridges sectorial policies and regulations, as it aims at the integration of sectorial and cross-scale approaches (Horlemann and Dombrowsky 2012).

The water law of 2004 (Parliament of Mongolia 2004) first mentioned the aim to introduce IWRM and to create river basin councils (RBC) as participatory bodies in Mongolia. In 2012, a new water law was adopted which opted for the additional creation of river basin agencies (RBA) as governmental authorities. The law also provides the basis for the development and implementation of river basin management plans (RBMP) (Horlemann and Dombrowsky 2012). Both the RBA and the RBC could potentially handle erosion-related problems. However, while many aspects of sustainable use of water resources are addressed in the new water law, erosion and related surface run-off of water are not. Thus, while formally on-site measures to halt or decrease erosion and surface run-off may only indirectly be covered in a water law based IWRM strategy via a RBMP, the problem is addressed in other legal frameworks. The law on land (Parliament of Mongolia 2002), the Law on forest (Parliament of Mongolia 2007), the Law on natural plants (Parliament of Mongolia 1995), as well as the development plan of the Selenge aimag (=district) covering a large fraction of the KRB, all mention erosion, and partly also concrete land-use activities such as agriculture and grazing. Beyond, concrete countermeasures such as protection strips are mentioned. However, the ways of implementing measures, i.e. at which level by which authority and by which types of enforcement, are mostly undefined. The 2012 water law clearly addresses at least two types of options to handle erosion-related off-site effects. First, the construction of reservoirs is considered to take care of overland flows and reduce flood risks. Second, 50 m wide strips around surface waters and riverbanks shall protect rivers, reservoirs and lakes among other aspects from sediment and run-off inputs. Thus, the water law provides a legal basis for including the off-site effects of erosion and surface run-off in IWRM measures, for instance to be defined and implemented by authorities such as the new RBA, which are designed to address land- and water management problems at the scale at which they occur.

Beyond the legal basis, addressing the processes of on- and off-site effects of erosion and surface run-off and potential countermeasures with different degree of detail, successful IWRM-measures require strong institutions and authorities as well as (financial) resources to implement and enforce them, contributing to achieve the political objective to increase production and food security with little/no negative environmental impacts. The authorities such as RBC (implemented since 2009), the RBA (implemented since 2013) and instruments such as the River Basin Management Plan are currently being established. Thus it is timely to discuss IWRM options and try to identify and minimize obstacles and limitations, but too early to assess the performance of IWRM measures in Northern Mongolia.

To conclude, it can be stated that the KRB in Northern Mongolia is undergoing rapid land-use change mainly involving the expansion of cropland, and considerable increases in livestock densities. Current grazing and cultivation practises cause considerable soil and nutrient losses from steppe and agricultural land, and even including contour ploughing and mulching cannot halt, but only reduce erosion risks on cropland. Sediment and nutrient loads of rivers may negatively affect rural water users depending on clean surface water resources. Most combinations of expected near future changes in climate, land use and land management seem to aggravate erosion risks rather than reduce them. Currently, new institutions, regulations and authorities are being implemented in the KRB and other watersheds in Mongolia, based on/guided by IWRM principles, and improved management activities, new regulations as the ones suggested in this paper.

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