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ASSESSMENT OF SOIL REDISTRIBUTION ON TWO CONTRASTING HILLSLOPES IN UGANDA USING CAESIUM-137 MODELLING

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With 5 figures, 4 tables and 2 photos

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Summary: The assessment of soil erosion by Caesium-137 (^{137}Cs) modelling has achieved widespread applications in many regions of the world. Especially for countries in the humid tropics experiencing severe soil degradation, this approach offers the potential to quickly quantify the spatial distribution of soil loss, in order to propose site-specific erosion control measures. This research aims to examine the potential for utilizing the ^{137}Cs approach to assess soil redistribution rates in the humid tropics of Uganda. More specific research objectives are: 1) to investigate the ^{137}Cs modelling approach and its potential for erosion and sedimentation assessments in the humid tropics of Africa; and 2) to identify the spatial distribution of erosion and sedimentation on two contrasting hillslopes in Uganda. Two cultivated hillslopes with contrasting agro-ecological conditions were selected: one highland site with unimodal rainfall distribution with mollic andosols and a relatively steep slope of up to 18% (Kongta), and one lowland site with bimodal rainfall distribution, strongly weathered plinthic ferralsols and a gentle slope of a maximum of 10% (Magada). ^{137}Cs inventories from reference samples were collected in the vicinity of these sites and ^{137}Cs inventories from samples were extracted from the intersections of a regular sampling grid that covered each hillslope. The average ^{137}Cs reference inventories were 392 and 439 Bq m^{-2}, for Kongta and Magada, respectively, which are within the range of the globally interpolated ^{137}Cs inventory estimated for this region. The modeled net soil redistribution indicated for both sites soil erosion with higher soil losses in Kongta (-21 t ha^{-1} year^{-1}) than in Magada (-4.5 t ha^{-1} year^{-1}). Peak hillslope erosion rates were 44.6 t ha^{-1} year^{-1} in Kongta compared to 36.3 t ha^{-1} year^{-1} in Magada. In contrast, sedimentation rates in Magada were as high as 25 t ha^{-1} year^{-1} and significantly higher than in Kongta with 6.4 t ha^{-1} year^{-1}. These ^{137}Cs-based soil redistribution rates were similar to erosion assessments within the same ecological zone based on erosion plot studies and other model applications. Despite the low fallout and some other obstacles, we conclude that the ^{137}Cs method might be a suitable alternative technique to estimate soil redistribution on hillslopes in the humid tropics of Africa, such as in the southern region of Uganda.

Zusammenfassung: Die Abschätzung der Bodenerosion mit Hilfe der Caesium-137 (^{137}Cs)-Modellierung wurde bisher in vielen Regionen auf der Welt erfolgreich eingesetzt. Dieser Ansatz bietet vor allem für Länder mit hoher Bodendegradierung, wie zum Beispiel in den humiden Tropen, eine Möglichkeit zur schnellen Abschätzung der Bodenumverteilungsraten. Die spezifischen Ziele dieser Studie sind: 1) Die Untersuchung des Potentials der ^{137}Cs-Modellierung zur Abschätzung der Erosions- und Sedimentationsraten in den humiden Tropen Afrikas; und 2) die Quantifizierung der räumlichen Verteilung der Erosions- und Sedimentationsraten an zwei unterschiedlichen Hängen in Uganda. Es wurden zwei landwirtschaftlich genutzte Hänge mit unterschiedlichen agro-ökologischen Eigenschaften ausgewählt: Ein Hochlandstandort (Kongta), der durch eine unimodale Niederschlagsverteilung, mollic Andosole und eine relativ steile Neigung von bis zu 18% gekennzeichnet ist, sowie ein Tieflandstandort (Magada), der sich durch eine bimodale Niederschlagsverteilung, stark verwitterte plinthic Ferralsole und einen relativ flach geneigten Hang von maximal 10% auszeichnet. Die ^{137}Cs-Inventare von Referenzproben wurden in der Nähe der beiden Standorte bestimmt während die ^{137}Cs-Inventare von Bodenproben der Hänge an den Kreuzungspunkten regelmässiger Beprobungsgitter ermittelt wurden. Die durchschnittlichen ^{137}Cs-Inventarwerte betrugen für Kongta und Magada jeweils 392 und 439 Bq m^{-2} und waren damit im Rahmen der global interpolierten ^{137}Cs-Inventarwerte für diese Region. Die modellierten Nettobodenumverteilungsraten zeigten für beide Hänge Bodenerosion, mit höheren Erosionsraten in Kongta (-21 t ha^{-1} Jahr^{-1}) als in Magada (-4,5 t ha^{-1} Jahr^{-1}), an. Die maximalen Erosionsraten betrugen 44,6 t ha^{-1} Jahr^{-1} (Kongta) und 36,3 t ha^{-1} Jahr^{-1} (Magada). Im Gegensatz dazu erreichten die Sedimentationsraten in Magada 25 t ha^{-1} Jahr^{-1} und waren damit bedeutend höher als in Kongta mit 6,4 t ha^{-1} Jahr^{-1}. Die ermittelten ^{137}Cs-basierten Bodenumverteilungsraten waren ähnlich hoch wie in der Literatur publizierte Werte, welche in Erosionsmessungen und Modellierungen innerhalb der gleichen ökologischen Zone ermittelt wurden. Trotz des relativ geringen radioaktiven Niederschlags und einiger weiterer Einschränkungen folgern wir, dass die ^{137}Cs-Methode eine geeignete alternative Technik zur Abschätzung der Bodenumverteilung auf Hängen in den humiden Tropen Afrikas, wie zum Beispiel in den südlichen Regionen von Uganda, ist.

Keywords: Soil erosion, soil redistribution, Caesium-137 modelling, humid tropics, Uganda

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1 Introduction

In the humid tropics, heavy and intensive rainfall causes severe soil erosion (Lal 1990). In this climatic zone, most of the soils are old and already heavily weathered due to high temperatures and rainfall, thus soil nutrients reserves are depleted and topsoil nutrients are eroded during the rainy season if there is no soil protection (ter Kuile 1987). As a consequence, soil fertility is one of the key limiting factors in agricultural production in this climatic zone (Kaizzi et al. 2006). Besides direct on-site effects, such as the loss of nutrient rich topsoil from hillslopes, soil erosion may also cause indirect off-site effects, such as soil deposition into water bodies (Tamene et al. 2006).

In Uganda, agriculture in the region within the humid tropics forms the economic backbone of the country. Severe soil erosion is generally reported for nearly all major farming systems (Magunda et al. 1999). Vulnerable regions with high potential soil erosivity are located around Lake Victoria and in the eastern highlands (NEMA 1998). Off-site effects of soil erosion such as eutrophication and water pollution problems have already been identified for Lake Victoria (Chabeda 1984; Isabirye 2005).

In order to counteract these problems, it is important to identify the exact locations from where soil is lost or accumulated within the landscape as a basis for efficient local implementation of soil conservation measures. However, previous soil erosion studies in Uganda focused mainly on erosion plots (Nakileza 1992; Osinde 1994; Tenywa and Majaliwa 1998; Magunda et al. 1999). These plot studies cover only a small area of the landscape and thus interactions between erosion and deposition processes over a hillslope cannot be captured. Over an entire hillslope, soil may be lost from some plots, but may accumulate in other plots (Ritchie 2000; Bacchi et al. 2003). Soil erosion research has therefore turned to process-oriented models that can differentiate between the slope positions (Osinde 1994; Biteete-Tukahirwa 1995; Brunner et al. 2004; Tamene et al. 2006). Yet, these models depend on a large number of input parameters that are often not available for regions of small-scale agriculture in developing countries (Flanagan and Nearing 1995), and on long-term climatic records that are either not available or incomplete (Brunner et al. 2002).

In order to complement those plot and process-oriented studies, we tested whether the Caesium-137 (^{137}Cs) approach can be used as an alternative technique for estimating soil redistribution on hillslopes of a humid tropical region in Uganda, Africa. This approach relies on the assumption that the present redistribution of ^{137}Cs in the soil of agricultural hillslopes is a response to soil erosion, sedimentation and cultivation processes that have occurred since the global ^{137}Cs fallouts in the 1960s (Walling 1998). The major advantage of the ^{137}Cs approach is that it provides a retrospective estimate of spatially distributed erosion and deposition rates, captured in a single site visit for collecting soil profile samples (Walling 1998; Collins et al. 2001; Ritchie and Ritchie 2001; Zapata 2003). Furthermore, due to the relatively small input data set necessary in the random sample distribution as well as the transect-based ^{137}Cs-models, it might be a valuable alternative to the intensively parameterized process models (Evans 1995).

Despite such advances in the development of the ^{137}Cs approach and the great need for soil loss assessments in the humid tropics of Africa, publications on ^{137}Cs applications in this region are rare. There are only a few studies from subhumid regions of Africa, such as Niger (Chappell et al. 1998), Zimbabwe (Quine et al. 1993), Zambia (Collins et al. 2001) and Ghana (Gana 2000; Pennock 2000) and on various scales from Lesotho (Kulander and Stromquist 1989; Walling and Quine 1992). To date, there has been no documented application of this method in the humid tropics of Africa. This may be because ^{137}Cs inventories in the southern hemisphere are almost one order of magnitude lower than in the northern hemisphere (Walling 2001). In addition, it is difficult to find undisturbed sites for collecting ^{137}Cs reference samples, due to the often intensive land use in this climatic zone. Furthermore, the lack of access to institutions with gamma spectrometer detectors in this region hampers the widespread applicability of the ^{137}Cs method. Despite such disadvantages, the ^{137}Cs method might still be considered as an opportunity to quickly estimate the spatial patterns and rates of erosion and sedimentation over hillslopes in the humid tropics of Africa.

The aim of this study is to examine the potential for utilizing the ^{137}Cs approach to assess soil redistribution rates in the humid tropics in Uganda. More specific research objectives are: 1) to investigate the ^{137}Cs modelling approach and its potential for erosion and sedimentation assessments in the humid tropics of Africa; and 2) to identify the spatial distribution of erosion and sedimentation on two contrasting hillslopes in Uganda.

Fig. 1: Overview map of Uganda with locations of the study sites Kongta and Magada

2 Study sites

Two agricultural hillslopes in Uganda with contrasting agro-ecological conditions, Kongta and Magada, were selected for soil redistribution assessment (Fig. 1). Due to high population pressure at both sites (ca. 120 and 270 persons km^{-2} in Kongta and Magada, respectively), most of the land has been cultivated since 1920 (Wortmann and Kaizzi 1998).

The Kongta hillslope is located at 34° 45´ E and 1° 16´ N in the eastern highlands of Uganda at an elevation of 1,907 m above sea level (Photo 1). Geologically, the site belongs to the Mount Elgon volcanic mountain and hills which developed from younger metamorphic rocks that originated by igneous and up-lifting processes of the late Tertiary period. The pyroclastic parent material includes feldspar tuffs, crystal tuffs and agglomerates (Chenery 1960; Harrop 1970). The deep volcanic soils can be classified as mollic andosols (FAO 1998) and consist of mainly dark brown clays and clay loams. The rainfall seasonality is unimodal, stretching from April until November and providing approximately 2000 mm annual rainfall (Kaizzi 2002). The Kongta hillslope is part of the Armanang watershed and has a summit-to-valley distance of about 200 m and a lateral width of about 300 m. The relatively steep landscape has an average slope gradient of 10%, ranging from ca. 3% in some smaller shoulder and footslope positions to 18% in the larger backslope unit (Ruecker, 2005). The farmers cultivate mainly maize both as cash and food crop using ox-ploughs to till the heavy soil. A few relatively low and often interrupted stone lines can be found along contours to reduce soil erosion (Fig. 2).

Photo 1: View on Kongta hillslope

The Magada hillslope is situated at 33° 28` E and 0° 32` N in the lowlands of southern Uganda at an elevation of 1,160 m above sea level, approximately 20 km north of the Lake Victoria shoreline (Photo 2). Geologically, the site belongs to the Buganda surface that covers the southern part of Central Uganda and includes granites, gneisses and schists of the Precambrian age. The Buganda surface is part of the Uganda basement complex and has been exposed to long-term weathering. The Magada hillslope belongs to the Walungogo watershed, has a summit-valley distance of about 480 m and a lateral width of about 300 m. The gently rolling landscape has an average slope gradient of 3%, ranging from ca. 0.5% on interfluvial and footslope positions to 3–5% on shoulders and up to 10% on backslope positions. The shoulder landscape unit represents most of the land that is used for crop cultivation, while the steeper backslope is partly shared between crop cultivation, grazing, natural bush and shrub vegetation. The soils of Magada can be classified as plinthic ferralsols (FAO 1998). They are strongly weathered and leached, and have in general a sandy clay loam to sandy clay texture. On strongly eroded areas, the A horizon has been almost completely removed and the plinthite-rich B horizon is uncovered and hardens when exposed to air, leading to the development of laterite crusts. These crusts cause severe agricultural problems, because the hardened soil can no longer be

Photo 2: View on Magada hillslope

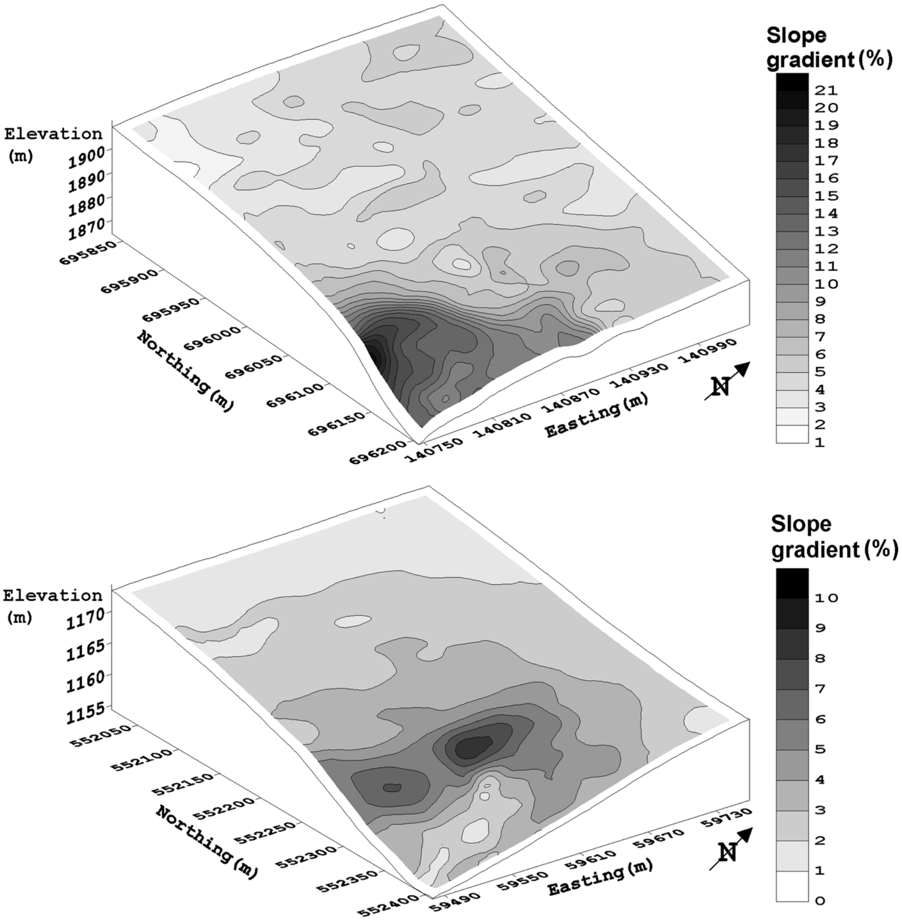

Fig. 2: Slope gradient superimposed on digital elevation model of Kongta (above) and Magada (below) hillslopes, respectively

penetrated for ploughing, thus forcing farmers to stop cultivating this area. The rainfall seasonality is bimodal, stretching from March until May and from September until November and providing approximately 1,319 mm annual rainfall (Brunner et al. 2004). The formerly moist semideciduous forest on the Magada hillslope was completely cleared to reclaim land for crop cultivation. Nowadays only a few mango trees and bushes are maintained in a fragmented pattern between the fields for providing fruits, firewood, and some soil protection.

3 Methods

3.1 ^{137}Cs soil redistribution model

Several different Caesium-137 models have been developed in the past to convert ^{137}Cs measurements to quantitative estimates of erosion and deposition rates. For a better comparison of the model results by standardization of the models and procedures employed, two coordinated research programmes were initiated by the International Atomic Energy Agency (IAEA), "Assessment of Soil Erosion through the Use of Cs-137 and Related Techniques as a Basis for Soil Conservation" and "Sustainable Agricultural Production and Environmental Protection". Six models which appeared to produce meaningful results were selected and put together in a software (Walling and He 2001; IAEA 2008). Walling and Quine (1990) provide a useful review of these approaches which include empirical relationships, theoretical models and accounting procedures.

In this study, one of the latest available and widely used Caesium-137 models, the *mass balance model 2* (Walling and Quine 1990), was chosen to assess the spatially distributed soil redistribution over the two hillslope surfaces. This model assumes that a sampling point with a total ^{137}Cs inventory less than the local reference inventory represents an eroding site, whereas a point with a total ^{137}Cs inventory greater than the local reference inventory represents a depositional site. Besides the ^{137}Cs reference and the ^{137}Cs sample inventories, this model requires information on parameters such as plough depth, relaxation mass depth, and proportional parameters. Compared to previously developed and oversimplified models, this model was selected because it takes the time-variant fallout ^{137}Cs input from the 1950s to the mid-1970s into account. It considers the possible removal of freshly deposited ^{137}Cs fallout before its incorporation into the layer ploughed for cultivation. This model also offers a proper balance between model reliability in assessing spatial soil redistribution based on random points over a hillslope, model complexity and data requirement (Kachanoski and de Jong 1984; Quine 1989; Walling and Quine 1990, 1993; He and Walling 1997; Walling and He 2001). A detailed description of the model may be found in Walling and He (2001).

Table 1: Parameters used to model soil redistribution in Kongta and Magada

Model parameters	Kongta	Magada
^{137}Cs reference inventory (Bq m^{-2}) (A$_{ref}$)	392	439
Input year of sample collection (t)	2001	2001
Input year of start of cultivation (t$_0$)	1954	1954
Proportionality factor (γ)	0.7	0.7
Bulk density (kg m^{-3}) (B)	855	982
Plough depth (m)	0.18	0.12
Particle size correction factor (P)	1	1
Mass depth of the plough layer (kg m^{-2}) (d)	154	118
Relaxation mass depth (kg m^{-2}) (H)	3.8	3.8

3.2 Data collection and sampling framework

A combined soil, terrain, land use and land management survey was carried out from November 2000 to April 2001 to collect data on the spatial variability of ^{137}Cs and the environment in order to parameterize the ^{137}Cs model (Ruecker 2005). Bulk density determination was based on the core method (Blake and Hartge 1986). The respective samples were collected after tillage using a 35 cm long split-tube-sampler that was hammered into the soil. The parameters and corresponding values for the two sites are listed in table 1.

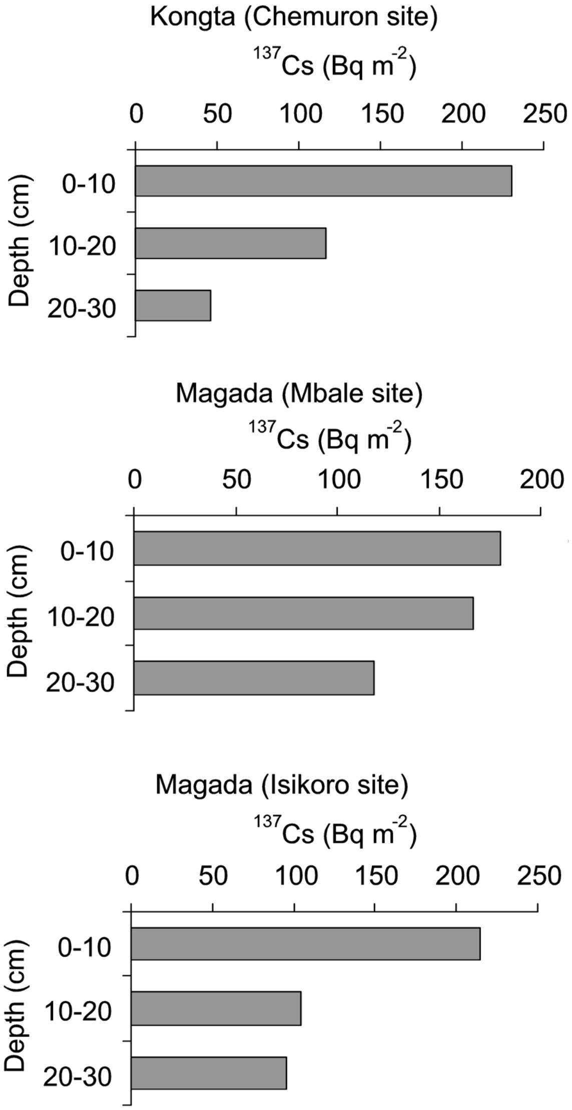

Fig. 3: Reference sample inventories near Kongta and Magada

3.2.1 ^{137}Cs reference sample inventories

The ^{137}Cs reference inventory (A_{ref}) represents the local ^{137}Cs fallout input and thus the ^{137}Cs inventory to be expected at a site with neither erosion nor deposition (Walling and He 2001). As reference sites, two schoolyard sites of ca. 150 x 150 m dimension were identified in the villages of Isikiro and Mbale, which are ca. 1 km south-east and 2 km north-west, respectively, from Magada. For Kongta, a schoolyard area of ca. 100 x 100 m within the 2 km distant village of Chemuron in the west was found to be a suitable reference

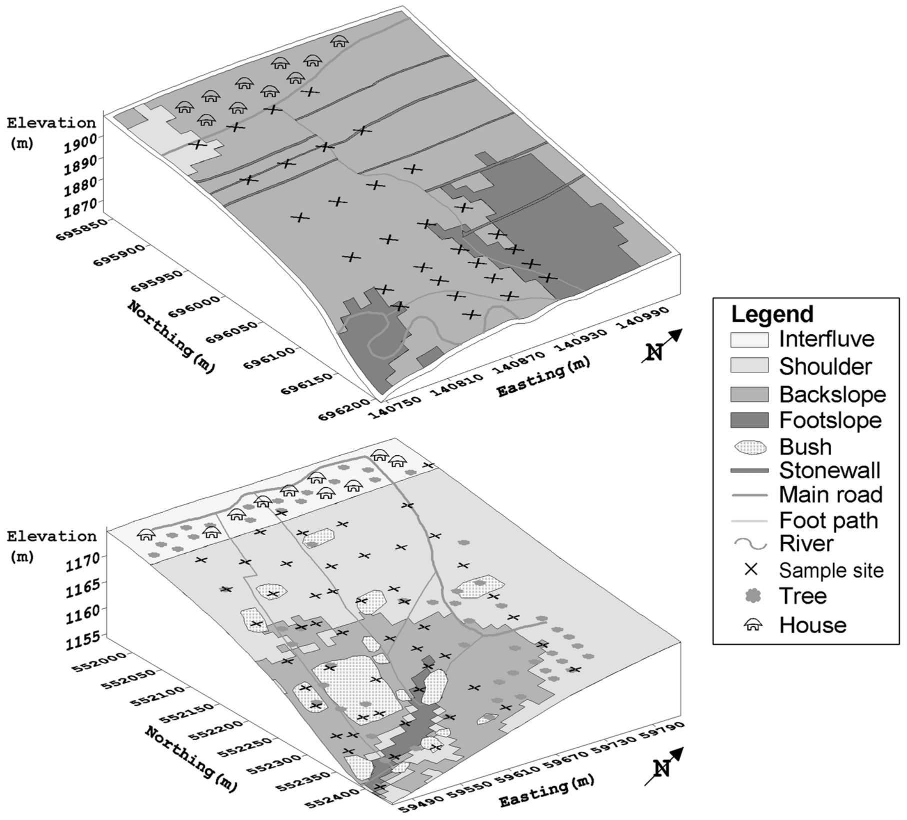

Fig. 4: Sampling frameworks for collecting ^{137}Cs samples from Kongta (above) and Magada (below) (Ruecker 2005)

site. These schoolyards were in a level position and covered by pasparum grass throughout the year. No erosion, sedimentation, cultivation or other disturbance took place after 1954, as several local citizens who have been living in these villages confirmed. Following random sampling within each schoolyard, four soil samples were collected at incremental depth with a split-tube-sampler. The ^{137}Cs inventory distributions measured for 0–10 cm, 10–20 cm and 20–30 cm depth are shown in figure 3.

The depth profile graphs show that ^{137}Cs inventories decrease gradually with depth from topsoil layers. This gradual ^{137}Cs inventory decrease indicates typical ^{137}Cs depth distribution patterns for undisturbed reference sites (Walling and Quine 1993). Based on farmers' accounts and the vertical distribution of ^{137}Cs profiles, these locations were considered to be suitable reference sites. The average ^{137}Cs reference inventory of two samples for Magada amounted to 439 Bq m^{-2}. The one reference site measurement that was available for the Kongta value yielded 392 Bq m^{-2}.

3.2.2 ^{137}Cs samples from hillslopes

Soil samples were collected from the intersections of a regular sampling grid that covered each hillslope. Each grid element comprised ca. 40 m along the elevation contours and 60 m in the downslope direction. In addition, samples were taken at locations in between that grid where erosion or sedimentation patterns were visually identified during field visits or where the slope shape was irregular, as in Magada. In Kongta 30 samples and in Magada 52 soil samples were collected, proportional to the different sizes of the hillslopes (Fig. 4). A split-tube-sampler with a diameter of 50 mm was used to collect the samples down to 30 cm depth. All samples from the hillslopes were used in the ^{137}Cs model.

3.2.3 Model parameterization

The input year of sample collection accounts for the year when the soil samples were taken, while the input year of start of cultivation (t_0) is the year when the first cultivation began on this site (Tab. 1). The proportional factor (*y*) represents the proportion of ^{137}Cs receipts that are removed in runoff before incorporation in the plough layer, with a maximum value of 1.0 if all erosive rainfall occurs immediately prior to tillage. In practice, it can be estimated as a proportion of annual erosive rainfall. This value was set to 0.7 reflecting that high-intensity rainfall occurs at the study sites (Schuller et al. 2003). The particle size correction factor (P) recognizes preferential entrainment and deposition of particles dependent on their size, and is a function of the soil texture. Given the restricted range of soil textures in the study sites, and the empirical observation that in situ soils and colluvium have essentially the same textures, this factor is not considered relevant here, and has been set to unity. The mass depth of the plough layer is estimated as the product of tillage depth and soil density. In Magada, tillage is performed with a hand hoe which penetrates ca. 0.12 m into the soil. The average soil density in the plough layer is 982 kg m^{-3}. In Kongta, ox-ploughs are used for tilling, with tillage depths down to ca. 0.18 m and an average soil density in the plough layer of 855 kg m^{-3}. The mass depth of the plough layer is 118 kg m^{-2} and 154 kg m^{-2} for Magada and Kongta, respectively. Relaxation mass depth (H) is the depth to which ^{137}Cs initially infiltrates when first delivered to the soil surface. It is expressed as mass depth (kg m^{-2}). According to He and Walling (1997) empirical values of H are 3.8 kg m^{-2} for cultivated soil, which has been adopted for this study.

3.3 ^{137}Cs measurements and data processing

Soil samples for ^{137}Cs measurement were slightly disaggregated and then air-dried. The weight of the whole air-dried sample was recorded. The fractions greater and less than 2 mm were separated and weighed. The corrected fine fraction weight was then calculated by subtracting the coarse fraction weight from the total sample weight. A representative subsample of ca. 400 g of the fine fraction was submitted for ^{137}Cs measurement.

^{137}Cs samples were measured using a gamma spectrometer detector from the Isotope Laboratory at the University of Göttingen in Germany. The accuracy of measurement depends on the counting statistics, with the 1σ error in the number of counts defined as $\sqrt{n}$, where *n* is the number of counts (e.g., a count of 1,000 would correspond to an error of ± 31.62 or ca. ± 3%). Average measurement time was ca. 250,000 s or ca. 3 days. The count measurements were calibrated to a reference sample. The ^{137}Cs concentration (Bq kg^{-1}) of a sample was transformed into ^{137}Cs inventory (Bq m^{-2}) according to Sutherland and de Jong (1990). The soil redistribution rates corresponding to these ^{137}Cs inventory patterns were estimated by the mass balance model. The soil redistribution rates in Magada and Kongta were then spatially mapped using ordinary kriging to visualize the spatial patterns of erosion and sedimentation patterns within each hillslope.

Table 2: Descriptive statistics of ^{137}Cs inventories (Bq m^{-2}) in Kongta and Magada

Site	N	Mean	Min.	Max.	STD	CV (%)
Kongta	30	202	87.3	449	87.2	43.1
Magada	52	382	95.4	905	155	40.7

Abbreviations: STD = standard deviation;
CV = coefficient of variation.

4 Results and Discussion

4.1 Total variability and error of ^{137}Cs inventories

Several studies estimated the global distribution of bomb-derived ^{137}Cs based on the global deposition data for ^{90}Sr (Larsen 1985; Cambray et al. 1989; Garcia 1998). The very low ^{137}Cs fallout estimations in the lower latitudes made it uncertain whether the presently available ^{137}Cs amounts in the selected sites of Uganda are adequate for the successful use of the ^{137}Cs method. The average ^{137}Cs reference inventories were 392 and 439 Bq m^{-2} in Kongta and Magada, respectively. The statistical distribution of the ^{137}Cs inventories found is shown in table 2.

The average ^{137}Cs inventories were ca. 200 and 400 Bq m^{-2} in Kongta and Magada, respectively, while the standard deviations of ^{137}Cs inventories were ca. 100 Bq m^{-2} at both sites. These values are close to the global interpolation values of ^{137}Cs inventories, which range between 300 and 450 Bq m^{-2} for the humid tropics zone of Africa based on combining the global deposition data for ^{90}Sr data with the available data on ^{137}Cs fallout in one ^{137}Cs fallout map (Walling 2001). The variation between minimum and maximum values ranges between 450 and 900 Bq m^{-2} in Kongta and Magada, respectively. The standard deviations and coefficients of variations of ^{137}Cs inventories are relatively large for both sites, with Kongta showing smaller standard devia-

Table 3: Statistics of the 2σ error for ^{137}Cs inventories in Kongta and Magada

		Relative	Absolute				
Site	N	**Mean**	**Mean**	**Minimum**	**Maximum**	**STD**	**CV**
		(%)		(Bq m^{-2})			(%)
Kongta	30	17.2	34.8	12.8	68.6	11.9	34.1
Magada	52	20.5	78.5	37.8	113	15.9	20.3

Abbreviations: STD = standard deviation; CV = coefficient of variation.

tion values than Magada. This may reflect the wide range of soil erosion and sedimentation rates within each hillslope.

The total error of the measured ^{137}Cs inventories was based on the 2σ error (Tab. 3) and provides an assessment of suitability of the ^{137}Cs method when applied in areas such as Uganda. As table 3 shows, the relative mean 2σ error of ^{137}Cs inventories is almost equal for the two sites and amounts to ca. 20%. Similar error values of ^{137}Cs inventories were found in other soil redistribution studies using ^{137}Cs (WALLING and QUINE 1993). The absolute variations of 2σ error of ^{137}Cs inventories are relatively large compared to the ^{137}Cs inventories, though less for Kongta. These error statistics point out that the maximum range of ^{137}Cs inventories may be rather high, which should be kept in mind when considering the estimates of the mass balance model.

Overall the found ^{137}Cs inventories and error statistics highlight that the ^{137}Cs method is applicable in the study region and the modeled erosion rates need to be interpreted with the caution suggested by the identified error.

4.2 Soil redistribution rates and spatial patterns

Spatial estimations of the soil redistribution rates were generated over the hillslopes using random sample inputs to the ^{137}Cs model. Table 4 shows the estimated soil redistribution rates.

The soil redistribution rates show that the Kongta and Magada hillslopes have both experienced net soil losses. The average net soil redistributions are -21.3 and -4.5 t ha^{-1} year^{-1}, for Kongta and Magada, respectively. This large difference reflects Kongta's much higher average erosion rate amounting to 22.9 t ha^{-1} year^{-1} compared to 9.3 t ha^{-1} year^{-1} average soil loss in Magada, while the mean soil deposition in both sites is similar (5.8 and 6.3 t ha^{-1} year^{-1} for Kongta and Magada, respectively). The areas within the hillslope with the highest absolute erosion rates of 44.6 t ha^{-1} year^{-1} are also found in Kongta, compared to relative maximum soil loss of 36.3 t ha^{-1} year^{-1} in Magada.

Such high overall and absolute soil erosion rates in Kongta are most likely the result of several interacting land management, soil and landscape factors. We observed, for example, in Kongta at the beginning of the cultivation season that deep tillage by

Table 4: Descriptive statistics of soil redistribution rates in Kongta and Magada assessed by the ^{137}Cs model

Site	**Soil redistribution**	**N**	**Mean**	**Minimum**	**Maximum**	**STD**	**CV**
				(t ha^{-1} year^{-1})			(%)
	Soil loss	28	22.9	5.3	44.6	10.1	44.3
Kongta	Soil deposition	2	5.8	5.2	6.4	0.9	14.7
	Net soil redistribution	30	-21.0	6.4	-44.6	12.2	-58.1
	Soil loss	36	9.3	0.2	36.3	7.6	81.6
Magada	Soil deposition	16	6.3	0.0	25.0	7.3	116.2
	Net soil redistribution	52	-4.5	25.0	-36.3	10.4	-230.1

Note: Negative values for net soil redistribution indicate soil loss, while positive values for his soil redistribution represent soil accumulation.

Abbreviations: STD = standard deviation; CV = coefficient of variation.

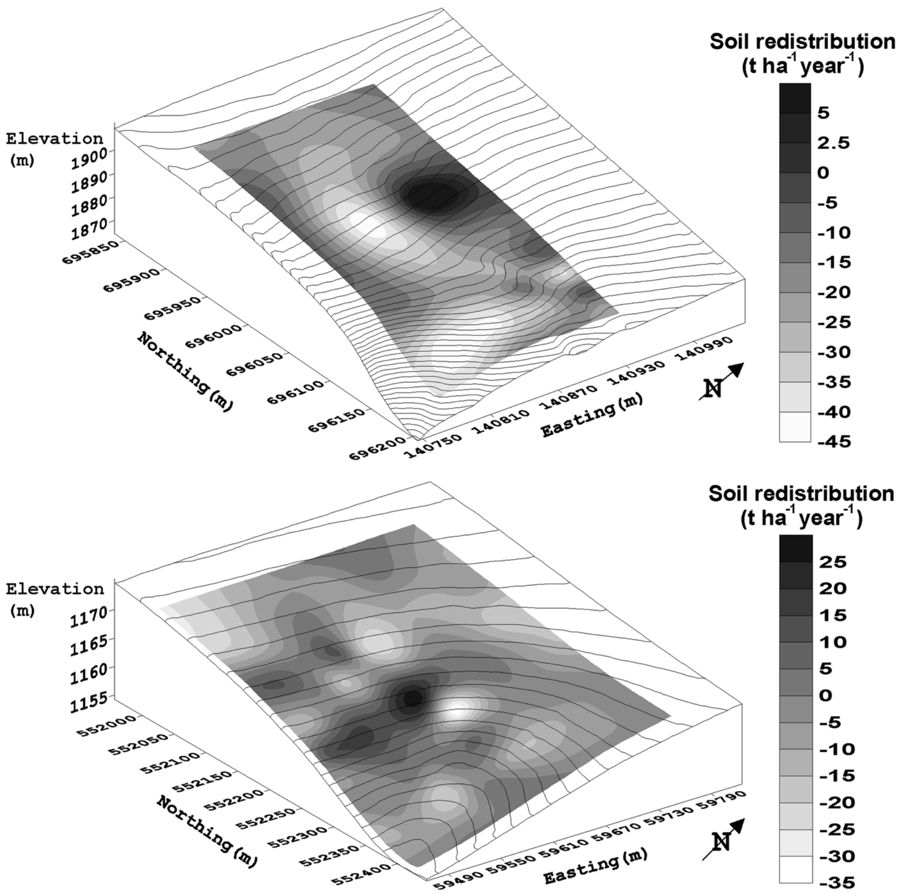

Fig. 5: Spatial pattern of soil redistribution (t ha^{-1} year^{-1}) within ^{137}Cs sampling area of Kongta (above) and Magada (below), respectively overlaid with contour lines (distance 2 m)

ox-plough produces loose soil material that is neither protected by natural vegetation nor cover crops. The strong tropical rainfalls occurring in this region then put considerable amounts of top soil into suspension, causing heavy erosion down the steep hillslope. Since there are only a few small stone lines that are often interrupted, this soil protection measure is ineffective and soil erosion can take place virtually unobstructed (see Fig. 4).

At Magada, the gentle slope gradient and the occurrence of several bushes and trees on the hillslope provide some erosion protection for the soil surface. These environmental factors and shallower tillage by hand hoe may have led to smaller overall and maximum erosion rates at this site (Fig. 4). These localized environmental and land management factors in Magada may also have led to significantly higher maximum sedimentation rates at this site (25 t ha^{-1} year^{-1}) compared to Kongta (6.4 t ha^{-1} year^{-1}). We observed soil accumulations under thick bushes over a larger extent in Magada. The soil redistribution rate at each sample location was interpolated over each site to visualize the pattern of soil redistribution (Fig. 5).

At both sites soil erosion and sedimentation generally occur parallel to the elevation contours and follow major slope gradient pattern, indicating that terrain factors such as slope gradient may have a strong influence on soil erosion (see Fig. 2 and 5). Within these broader zones, smaller islands represent peak values of higher soil loss areas (bright colours) or higher soil sedimentation areas (dark colours). In Kongta, high erosion (ca. 15–20 t ha^{-1} year^{-1}) occurs on the upper part of the backslope that borders on the road. On the middle and lower backslope sections very high soil erosion is found (ca. 25–45 t ha^{-1} year^{-1}). Moderate soil sedimentation (ca. 5 t ha^{-1} year^{-1}) occurs in a smaller area in the middle part of the backslope. Patches with relatively lower and relatively high soil erosion rates appear on the northern and southern part of the footslope, respectively. Differences in slope gradient and availability of stone lines within the hillslope are likely influencing factors determining these erosion and sedimentation patterns (see Fig. 4).

In Magada the zonal pattern of soil redistribution on the west-east facing hillslope occurs according to the following sequence: relatively high soil erosion on parts of the upper shoulder (ca. 12–25 t ha^{-1} year^{-1}), moderate soil erosion on the lower part of this shoulder (ca. 5–12 t ha^{-1} year^{-1}) and moderate soil sedimentation on the middle part (ca. 5–10 t ha^{-1} year^{-1}). The highest soil sedimentation rates over the total hillslope appeared in a broad zone around the upper backslope (ca. 17–27 t ha^{-1} year^{-1}). Little soil erosion occurred on the lower backslope (ca. 1–5 t ha^{-1} year^{-1}) and high soil erosion is seen on the footslope position (ca. 10–20 t ha^{-1} year^{-1}). Magada's north-west to south-east facing hillslope section has relatively high soil erosion rates in the upper and middle part of the shoulder (ca. 12 –25 t ha^{-1} year^{-1}) and shows low to moderate soil sedimentation in the lower part of this shoulder (ca. 3–8 t ha^{-1} year^{-1}). On the backslope to the footslope of this hillslope section low to moderate soil erosion rates (ca. 6–15 t ha^{-1} year^{-1}) are found. In the backslope area one major patch reflecting the relatively highest soil erosion rates (ca. 20–35 t ha^{-1} year^{-1}) is striking. The exact dimension of these soil redistribution patterns is not possible to quantify because of the relatively small number of sampling points available for the hillslopes, which led to inaccuracies in the interpolations. However, the present sampling framework indicated the major landscape-related patterns for the sites.

The alternating spatial patterns of soil erosion and sedimentation suggest that the processes are largely defined by terrain factors, such as the higher and lower slope gradients. However, the relation between hillslope position and soil redistribution rate did not always fit intuitive notions, e.g., in Kongta sedimentation was also found on the steeper backslope position where erosion would be generally expected. This may be due to different land use types and tillage operations that may be prevalent.

4.3 Comparison of soil redistribution rates estimated by the ^{137}Cs model with published results

The results of the ^{137}Cs model were compared with other erosion studies within the same ecological zone. The Ewaso Ngiro basin in Kenya, for example, has an environment similar to Magada with loamy-sandy to loamy soils and a multiple cropping system. The applied Universal Soil Loss Equation estimated an average soil loss of ca. 4.4 t ha^{-1} year^{-1} (Mati 1999), which is very close to the 4.5 t ha^{-1} year^{-1} found in this study. Soil loss measurements in standardized erosion plots in Wanale on Mt. Elgon (Nakileza 1992) for a sandy clay loam with maize crops amounted to ca. 6.4 t ha^{-1} year^{-1} during one season in 1991. Other studies with the same soil and crop, but in the lowlands of the Kabanyolo district in central Uganda, resulted in ca. 26 t ha^{-1} year^{-1} soil loss measured in nonstandardized erosion plots for three seasons (Zake and Nkwiine 1995).

Brunner et al. (2004) estimated soil redistribution at two transects traversing the same Magada hillslope in downslope orientation by a forward simulation of the Water Erosion Prediction Project (WEPP) model. WEPP modelling results showed average soil loss of 2 t ha^{-1} year^{-1} for the entire transect, compared to 4.5 t ha^{-1} year^{-1} calculated by the ^{137}Cs model for the whole hillslope. These WEPP-based modeled values are relatively close to those from the ^{137}Cs model. The different rates may be explained for example by the models' different spatial sampling frameworks. The WEPP model results were based on input data collected from the west-east facing section of the Magada hillslope, only. Further differences between the two model outputs might be caused by the different parameters and time scales considered in the respective studies. The WEPP model combines climatic records of the past decade (1990-1999) with soil profile, crop and land management parameters collected from a single season (2001) to run forward simulations of average annual soil redistribution. In contrast, the ^{137}Cs model takes the time-variant fallout ^{137}Cs input, the infiltration of ^{137}Cs into the soil profile, water erosion and tillage processes from more than four decades into account. Since the WEPP model scenarios are based on present soil, land use and land management conditions and shorter climatic dynamics, the resulting soil losses may be smaller than those from the ^{137}Cs model, which runs on a much longer time-period of ca. four decades, during which both water and tillage processes have been considered.

These comparisons show that the ^{137}Cs estimated soil redistribution rates seem to be within the range of other studies. However, conclusions should be drawn with care, because all studies were based on different spatial and temporal scales, different input data and different processes considered to estimate soil redistribution, hence a direct comparison with the ^{137}Cs approach is not possible.

5 Conclusion

For this study the suitability of the ^{137}Cs approach to estimate spatially distributed soil erosion and sedimentation from random samples of a three-dimensional hillslope surface was tested on the Kongta and Magada hillslopes sites in Uganda. The selected sites were representative for the humid tropics of Africa, where this approach has not yet been applied to date.

Mean ^{137}Cs values on these hillslopes were relatively low, but within the range of globally estimated values for this region, while the mean error of the ^{137}Cs measurements was similar to other ^{137}Cs studies. The average soil loss rates were estimated to be more than two times higher in Kongta than in Magada. The soil redistribution patterns in these sites closely followed the landscape conditions, which broadly changed with higher and lower slope gradients.

Overall, using the detected ^{137}Cs values to estimate the soil redistribution over the hillslopes by a mass balance model provided rates which were within the range of other soil erosion studies on the same hillslope or within the same ecological zone. These findings demonstrate that the ^{137}Cs approach is a reliable method for studying soil redistribution on both hillslopes. An application of this approach to other areas of the humid tropics of Africa may be possible, provided that suitable ^{137}Cs reference inventories can be identified.

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