Assessment of Soil Erosion Using ^{137}Cs on Cultivated Fields Following Natural Forest Conversion in the Kefa Zone of Southwest Ethiopia.

Mekuria Argaw[1*], Paul L.G. Vlek[1], Soojin Park[2], Manfred Denich[1], Demel Teketay[3]

[1] *Center for Development Research, University of Bonn, Walter-Flex Str. 3, D 53113 Bonn, Germany*
[2] *Geography Department, Seoul National University, Shilim-Dong, Kwanat-Gu, 151-742 Seoul, Korea*
[3] *Ethiopian Agricultural Research Organization, P.O. Box. 2003, Addis Ababa, Ethiopia*

Abstract

Soil erosion is a prime cause of loss of productivity of land. Decline in land productivity in most cases triggers the conversion of natural forests into agricultural land. The severe soil erosion in the highlands of Ethiopia is believed to be a result of agricultural conversion. The process of natural forest conversion is a growing phenomenon in the southwest region of Ethiopia. This study was aimed at assessing the magnitude and rate of soil erosion in a 24 km^2 sub-catchment in the Kefa Zone of southwest Ethiopia, using the ^{137}Cs technique. A chronosequence of continuously cultivated fields of 2, 6, 12, 16, 20, 24 and 58 years after conversion were studied. A reference inventory of 2026 ± 176 Bq m^{-2} with a coefficient of variation of 24.6 % was recorded indicating the applicability of the technique in the region. Although weak, the distribution of the ^{137}Cs inventories in the studied fields showed a declining trend (R^2 = 0.2) with increasing years of continuous cultivation after conversion. The values of the younger and older fields were 1994 Bq m^{-2} and 1164 Bq m^{-2} respectively, indicating the greater extent of soil erosion in the older fields than in the younger fields. Estimated rates of soil erosion using the Proportional Model (PM) and Mass Balance Model 1 (MBM1) showed an increasing trend (R^2 = 0.41) with increasing years of cultivation. The rate of soil erosion ranged between 1 t $ha^{-1}yr^{-1}$ in the younger field and 25.7 t $ha^{-1}yr^{-1}$ in the older field. Estimated rates of erosion for the sub-catchment were 11.6 ± 2.6 t $ha^{-1}yr^{-1}$ and 17.3 ± 4 t $ha^{-1}yr^{-1}$ by the PM and MBM1, respectively. An estimate using the Universal Soil Loss Equation (USLE) yielded a rate of 12.3 t $ha^{-1}yr^{-1}$ validating the results from the ^{137}Cs models and the applicability of the technique for soil erosion studies in the Ethiopia. The results of this study showed that soil erosion in the Kefa Zone is on the verge of surpassing the tolerable level and it should be an immediate concern to conservationists and development planners at all levels.

Key words: Caesium-137, Ethiopia, forest conversion, Mass Balance Model 1, Proportional Model, soil erosion

* Corresponding author. Tel. ++49-0228-734948; Fax: ++49-(0)228-731889
E-mail address: margawd@uni-bonn.de; m_argaw@yahoo.com

1 Introduction

Conversion of forests into permanent cultivation or short-fallow systems has been a source of cultivated land in the tropics (Fujisaka *et al*., 1996; Vlek *et al*., 1997). In the tropics, where rainfall is heavy and intense, conversion of forests into agricultural land causes severe soil erosion on cultivated fields unless appropriate preventive measures are taken at the initial stages (Lal, 1995). The short-term effect of forest conversion is a rapid decline of the organic matter in the top soil while the long term effect is a reduced structure and physical instability of the soil (Charman and Murphy, 2000). Structural decline coupled with the absence of amendment interventions results in reduced infiltration, accelerated runoff and accelerated surface soil erosion (Motavalli *et al*., 2000).

Studies indicate that clearing of forests for agriculture and inadequate erosion prevention measures in the past many years have been the main causes of soil degradation in the densely populated highlands of Ethiopia (Feoli *et al*., 2002). Hurni (1988), from plot-measurements, reported a mean annual soil erosion rate of 42 t $ha^{-1}yr^{-1}$ or an equivalent loss of a soil depth of 4 mm yr^{-1} from cultivated fields in the central and northern highlands. Forest conversion in the southwestern highlands had remained insignificant in the past few decades. The opening of inroads and the start of forest logging increased movement of people to the region and triggered the conversion forest land into agricultural land. Forest conversion and cereal crop based farming expanded to new frontiers, especially in the Kefa Zone, following the resettlement of people from the central and northern highlands (Alemneh, 1990). However, reports on the state of soil erosion in the region are scanty.

The ^{137}Cs technique has been used for soil erosion studies in many parts of the world. However, there are not many studies reported from the equatorial region, particularly from Africa using this technique (Collins *et al*., 2001; Chappell *et al*., 1998). This might be due to the low assumed reference fallout, 200-500 Bq m^{-2}, for the region compared to 2000-4000 Bq m^{-2} estimated for the temperate region (Collins *et al*., 2001). This study is a pioneer contribution to the use of the technique in eastern Africa, in the southwestern highlands of Ethiopia. The main objectives are: 1) to assess the rate of soil erosion in continuously cultivated fields that were originally established through conversion of natural forests, and 2) to test the applicability of the ^{137}Cs method under Ethiopian conditions.

2 Materials and Methods

2.1 The ^{137}Cs method

The basic principles of the use of ^{137}Cs as an erosion assessment technique are well covered by other studies (Walling and Quine, 1993; Zapata, 2003). Cesium-137 is an artificial radioactive element with a half-life of 30.12 years in the environment (Richie and McCarty, 2003). Since this half-life is very short on a geological time scale, it is impossible to find any measurable ^{137}Cs remains in cesium bearing rocks. Thus, there are only two sources of ^{137}Cs in the environment: atmospheric testing of thermonuclear weapons in the late 1950s, 1970s, and the 1986 Chernobyl accident (Quine *et al*., 1999). From the atmosphere, ^{137}Cs falls back to the surface of the earth mainly with rainfall. The deposited fallout is rapidly adsorbed by fine soil particles on the ground surface. Once adsorbed, it is not easily detached from the soil and moves physically with soil particles that are carried by other agents. Its mobility and redistribution is associated with the mobility and redistribution of soil particles. This redistribution in agro-ecosystems is a cumulative result of tillage, soil erosion and deposition from the time of fallout to the time of sampling (Zapata, 2003). Loss/gain of ^{137}Cs from a particular point is determined by comparing to a reference site.

Since there is an established empirical and theoretical relationship between the loss and gain of ^{137}Cs and soil, the rates of soil erosion and deposition are readily estimated from ^{137}Cs measurements using conversion models (Walling and He, 2001). Two conversion models, the Proportional Model (PM) and the Simplified Mass Balance Model 1 (MBM1), were used for interpreting the ^{137}Cs measurements into soil erosion/deposition rates (Walling and He, 2001). These models are designed for cultivated soils and are widely used (Wiranatha *et al*., 2001; Bujan *et al*., 2003). Estimations from the ^{137}Cs method are usually validated by comparing results obtained from other methods such as runoff plot-experiments, rainfall simulations and erosion models (Fulajtar, 2003). In this study an attempt was made to estimate the mean annual rate of soil erosion using the adapted Universal Soil Loss Equation (USLE) for Ethiopia (Hurni, 1985). The corresponding factor values of the model parameters were taken from Hellden (1987).

2.2 Description of the study site and sample fields

The study was conducted in the Shomba sub-catchment in the Gimbo District of the Kefa Zone, southwest Ethiopia. The Kefa Zone is situated in the northwestern part of the Southern Nations, Nationalities and Peoples Regional State (SNNPRS) (Fig. 1). The sub-catchment covers an area of 24 km^2. Altitude ranges between 1440 m a.s.l. in the valley bottom and 1725 m a.s.l. at the upper plateaus. The soils of the area belong to the Nitisols (Tafesse, 1996). Interpretation of the 1967 aerial photo and analysis of the 2001 Landsat image has indicated that more than 80 % of the natural forest in the sub-catchment has been converted to agricultural land between 1967 and 2001 (Mekuria, unpublished). The sample cultivated fields, which were studied for erosion, were selected along the chronosequence of forest conversion within the sub-catchment (Fig. 1, Table 1). The age of a field was counted from the first year of conversion up to the time of sampling. Information from aerial photo interpretation and farmers' interviews were used to verify the age of a field.

Table1. Characteristics of the chronosequential sample fields

Age of field	Year of conversion	Area (ha)	Altitude (m)	Mean slope gradient (%)	Mean slope length (m)
2	1999	0.86	1695	20.2	21.8
6	1996	1.6	1648	25.8	17.8
12	1990	1.25	1597	19.5	15.6
16	1986	1.5	1545	16.2	12.7
20	1982	2	1558	10.2	5.8
24	1978	1.8	1564	16.8	21.3
58	1944	1.05	1575	12.8	20

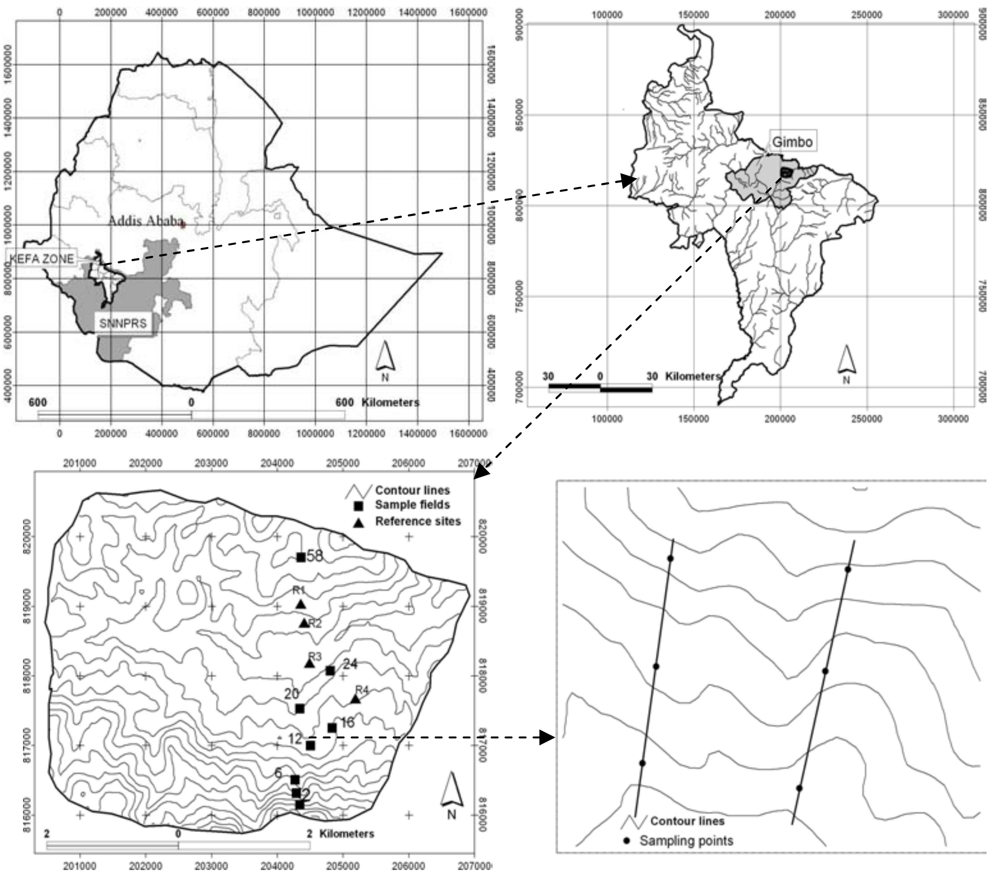

Figure 1. Location of the study area, study sub-catchment, sample fields, reference sites and sketch of the sampling transects and points.

2.3 Soil sampling, analysis of ^{137}Cs activity and data analysis

The general geomorphology of the fields was linear and soil samples were taken from the upper, middle and lower slope positions of each field. Bulk core soil samples were collected along two parallel transects using a 5 cm diameter and 40 cm long *Eijkelkamp* (model 04.17) undisturbed Split-Tube-soil sampler. To determine the local ^{137}Cs reference fallout inventory, four uncultivated reference sites (R_1, R_2, R_3, and R4) were sampled at the middle and lower plateaus of the sub-catchment (Fig. 1). From each reference site, two bulk core soil samples were collected at two corners of a 30 m x 30 m grid area. Six incremental depth samples (10 cm each) from two of the reference sites were collected for depth distribution analysis. Soil samples were air-dried, lightly disaggregated, and ground using a mortar and passed through a 2 mm wire mesh in order to separate coarse and fine fractions (< 2 mm). Total fine fractions of each sample were weighed and recorded for determining the ^{137}Cs inventory.

Activity of ^{137}Cs in the soil samples was analyzed in the isotope laboratory (ISOLAB) of the University of Göttingen, Germany. Activity of ^{137}Cs was measured by gamma spectrometry with an HP detector of 26 % relative efficiency and a PC-based multi-channel analyzer with a total spectrum area of 2000 Kiloelectronvolt (KeV). Caesium-137 was represented by a peak on the electrical signal spectrum centered at 662 Kev. Inventory (Bq m^{-2}) of each sample point was determined by using the total fine weight of the sample, the horizontal surface area (surface area of the sampling device) and the ^{137}Cs concentration (Bq kg^{-1}) measured for the sample (Walling and Quine, 1993).

One-way ANOVA was used to assess variations in ^{137}Cs inventories and rates of soil erosion among the different years of cultivation and among the slope positions. Means were separated by LSD. Regression analysis was used to determine the relationship between the ^{137}Cs inventories, rates of soil erosion with years of cultivation. Data were analyzed using the Statistical Package for Social Sciences (SPSS) (Bryman and Cramer, 2001).

3 Results and Discussion

3.1 Reference ^{137}Cs inventory and its depth distribution

The minimum and maximum reference ^{137}Cs inventories from the bulk core profile samples were 1292 and 2996 Bq m^{-2} in the first and third reference sites, respectively (Table 2). The estimated mean reference inventory, which represents the total fallout inventory at the study area, was 2026 ± 176 Bq m^{-2} with a coefficient of variation (CV) of 24.6 %. This variability is within the range of the moderate category 15-35 %, which is an acceptable range for CV of ^{137}Cs reference sites (Sutherland, 1996; Pennock, 2000).

Table 2. Reference ^{137}Cs inventory from bulk core and incremental depths

Core profiles		Incremental depths			
Sample points	(Bq m^{-2})	Sample points	0-10	10-20	20-30
R_1 1	1292	R_1 3	1878	981	461
R_1 2	2324	-	-	-	-
R_2 3	1957	-	-	-	-
R_2 4	2065	-	-	-	-
R_3 5	1779	-	-	-	-
R_3 6	2996	-	-	-	-
R_4 7	2910	R_4 9	2072	112	211
R_4 8	1588	-	-	-	-
Mean	2026	Mean	1974	546	336
S.D.	499	S.D.	138	614	125
S.E.	176	S.E.	98	434	176

The depth distribution showed that 69 % of the ^{137}Cs inventory was found in the upper 10 cm of the soil surface with 19 % and 12 % in the 20 and 30 cm layers, respectively. The pattern shows an exponential decrease with increasing depth (Fig. 2). Large ^{137}Cs concentration on surface soil and exponential decline with depth are typical characteristics of an undisturbed reference sites in many ^{137}Cs related studies (Walling and Quine, 1993). These characteristics affirm the reliability of the reference inventories for estimating loss or gain of ^{137}Cs in the study fields.

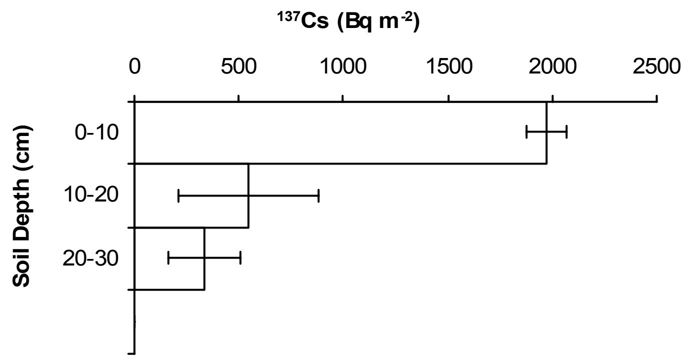

Figure 2. Depth distribution pattern of ^{137}Cs in the reference profiles.

The mean reference value in this study is in good agreement with the work of Chappell *et al*. (1998) in Niger, who found mean reference inventory of 2066 ± 125 Bq m^{-2} from 11 uncultivated sites in a soil depth of 60 cm. In northern Ghana, Pennock (2000) reported a reference value of 925.1 Bq m^{-2} (55 % less than in this study), in an uncultivated site with a CV of 21.3 % from 12 core profiles in a soil depth of 25 cm. However, the available evidence is insufficient to explain the variability of fallouts in the region.

3.2 Distribution of ^{137}Cs inventories in the cultivated fields

The mean inventory for the cultivated fields was 1649 ± 81 Bq m^{-2} with a CV of 22.5 %. This value is lower by 19 % than the local mean reference inventory, indicating a net loss of ^{137}Cs from cultivated fields in the sub-catchment. The negative residuals in Table 3 indicate that each field had experienced a net loss of ^{137}Cs in the course of cultivation after conversion. Since the removal and redistribution of ^{137}Cs is associated with the physical processes of soil erosion, the net losses from the fields are indicators of soil erosion (Guimaraes, 2003). The high mean value that was recorded from the field cultivated for 6 years might be a result of deposition of ^{137}Cs containing soil from the upper slope areas as a result of water erosion. For instance, Zhang *et al*. (2003) in China reported that distribution of ^{137}Cs inventory on cultivated slopes was caused by water erosion and tillage practices.

Table 3. Mean (± S.E) and residuals of ^{137}Cs inventories (Bq m^{-2}) in the different slope positions of the cultivated fields (n = 21).

Age of field	Upper slope	Middle slope	Lower slope	Mean	Residuals
2	1475	2215	1795	1828 ± 214[a]	-198
6	1622	2164	2196	1994 ± 186[a]	-32
12	1396	1777	1141	1437 ± 185[a]	-589
16	1679	1229	2331	1746 ± 320[a]	-280
20	1703	1801	1752	1752 ± 28[a]	-274
24	1041	1015	1447	1167 ± 140[b]	-859
58	1577	1661	1612	1616 ± 24[a]	-410

[a] mean values with similar letters are not significantly different ($LSD_{\alpha = 0.1}$)

The increase in ^{137}Cs inventories in the middle and lower slopes of the younger fields (2, 6 and 16 years) might indicate that redistribution of soil in the early years of cultivation after conversion was more under the influence of soil tillage than water erosion. This is because tillage redistributes ploughed soil within the cultivated field, whereas water erosion takes away soil from the cultivated field (Zhang *et al*., 2003).

The ^{137}Cs inventory was negatively correlated with years of cultivation. A general declining trend in the total amount of ^{137}Cs inventories was observed with increasing years of continuous cultivation after conversion (R^2 = 0.2) (Fig. 3a). This reflects an increasing degree of soil erosion with increasing years of continuous cultivation. Low inventory of ^{137}Cs in the upper slopes of the cultivated fields (Fig. 3b) suggests that soil was removed and either deposited in the middle and lower slopes, or taken away entirely/partially from the fields.

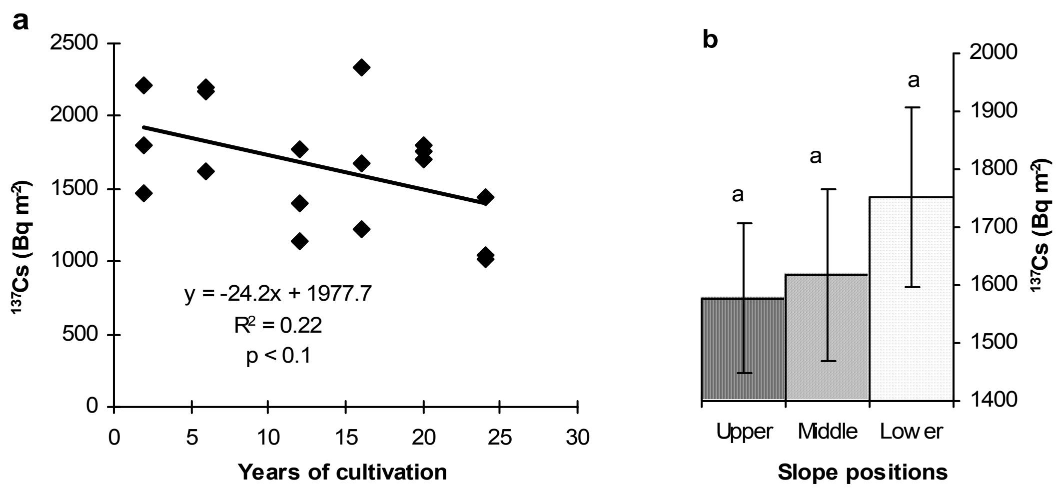

Figure 3. Relationship between ^{137}Cs inventories and years of continuous cultivation (a) and mean inventories in the slope positions (b). Same letters indicate no significant difference.

3.3 Estimated rates of soil erosion/deposition

The mean rate of soil erosion/deposition estimated by both the PM and MBM1 showed a net loss of soil from all the fields (Table 4). The rates of soil erosion were generally higher than the rates of depositions. Soil deposition was observed in the middle and lower slopes of the younger fields (2, 6, and 16 years of cultivation, Table 4). There were no soil depositions in any of the fields cultivated for more than 16 years. This may show that in the early years of cultivation, soil is accumulated within the slopes. These processes continue with increasing years of cultivation and culminate in complete removal of the soil from the fields.

Table 4. Soil erosion (-) and deposition (+) rates (t $ha^{-1}yr^{-1}$) in the slope positions and mean values for each field by the PM and MBM1 (n = 21).

Age	Upper slope		Middle slope		Lower slope		Mean	
(years)	PM	MBM1	PM	MBM1	PM	MBM1	PM	MBM1
2	-18.2	-26.1	+6.28	+9.05	-7.7	-9.9	-6.5	-9
6	-12.5	-17.2	+4.3	+5.9	+5.3	+7.3	-1.0	-1.3
12	-20.7	-30.4	-8.2	-10.7	-29.1	-46.8	-19	-29
16	-10.8	-14.5	-24.8	-38.5	+9.5	+14.3	-8.7	-12.9
20	-9.3	-12.5	-6.5	-8.5	-7.9	-10.4	-7.9	-10.4
24	-29.5	-49.3	-30.3	-51.2	-17.3	-24.9	-25.7	-41.8
58	-13.3	-18.4	-10.8	-14.6	-12.3	-19.9	-12.2	-16.6
Mean	-16.3	-24.1	-10	-15	-8.5	-12.9	-11.6	-17.3

The net loss of soil was positively correlated with years of cultivation (R^2 = 0.41) and showed an increasing trend with increasing years of continuous cultivation after conversion (Fig. 4a). More than 46 % of the net loss of soil was recorded from the upper slopes of the fields. The mean rate of soil erosion in the slopes generally decreases from the upper to the lower slopes (Fig. 4b). This pattern is consistent with the general characteristics of erosion dynamics on linear slopes. On linear slopes, the effect of runoff is considerably higher in the upper slopes, whereas at the middle and lower slopes runoff and magnitude of erosion could be hindered by the accompanying depositions of sediments from the upper slopes (Bewket and Sterk, 2003).

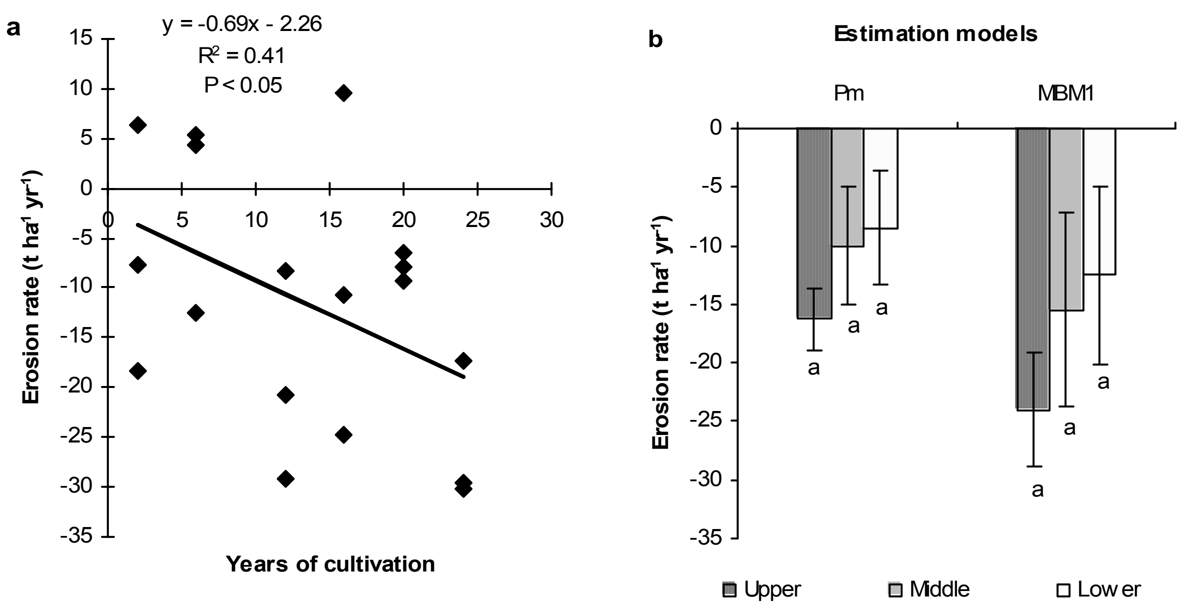

Figure 4. Relationship between the rates of soil erosion and years of continuous cultivation (a) and mean rates of soil erosion in the different slope positions (b). Same letters on error bars indicate no significant difference.

The estimated mean rates of soil erosion for a cultivated field in the sub-catchment were -11.6 ± 2.6 and -17.3 ± 4 t $ha^{-1}yr^{-1}$ by the PM and MBM1, respectively. The adapted USLE yielded a mean annual rate of 12.3 ± 1.5 t $ha^{-1}yr^{-1}$. The result from the USLE and reports from similar studies support the estimated rates from the ^{137}Cs models. The results in this study are in good agreement with the findings of Gunten (1993) and Eyasu (2002) in the Gununo (Wolayita) area of the southern region of Ethiopia. The rainfall, soil and farming systems in the Gununo area are similar to the present study area. Gunten (1993) reported a rate of 13 t $ha^{-1}yr^{-1}$ for cultivated fields from plot-experiments. From the same region, Eyasu (2002) reported a range of 6-13 t $ha^{-1}yr^{-1}$ from cultivated fields using the USLE. The estimated rates from the ^{137}Cs models and the USLE indicate that soil erosion in the Kefa Zone is on the verge of surpassing the tolerable level, which is 2-18 t $ha^{-1}yr^{-1}$ (Hurni, 1988).

4 Conclusions

The estimated reference ^{137}Cs inventory in this study is considerably high compared to values reported from similar studies in Africa and elsewhere. Thus, the results suggest that there is a sizeable amount of ^{137}Cs fallout in the equatorial east Africa region, specifically in southwest Ethiopia so that the ^{137}Cs technique can be applied for long-term and medium-term soil erosion studies. The results also indicate that soil erosion in cultivated fields increases with increasing years of cultivation after conversion. This will impair the productivity of the land in the long run, and may have a spillover effect on the further conversion of the remaining natural forests into agricultural land. Thus, soil erosion needs to be given due policy consideration so that the efforts to conserve the remaining natural forests and plant genetic resources in the Kefa Zone would become effective.

Acknowledgments

We thank the German Academic Exchange Service (DAAD) for supporting the study of the first author. The German Federal Ministry for Education and Research (BMZ) and the German Technical Cooperation (GTZ) are gratefully acknowledged for supporting the field research.

References

Alemneh, D., (1990). Environment, Famine and Politics in Ethiopia: A view from the Village. Lynne Rienner Publishers Inc, Colorado.

Bewket, W. and Sterk, G., (2003). Assessment of soil erosion in cultivated fields using a survey methodology for rills in the Chemoga watershed, Ethiopia. Agriculture, Ecosystems and Environment, 97: 81-93.

Bryman, A. and Cramer, D., (2001). Quantitative Data Analysis with SPSS Release 10 for Windows: A Guide for Social Scientists. Routledge, London.

Bujan, A., Santanatoglia, O.J., Chagas, C., Massobrio, M., Castiglioni, M., Yanez, M., Ciallella, H. and Fernandez, J., (2003). Soil erosion, evaluation in a small basin through the use of ^{137}Cs technique. Soil & Tillage Research, 69: 127-137.

Chappell, A., Warren, A., Oliver, M.A. and Charlton, M., (1998). The Utility of ^{137}Cs for measuring soil redistribution rates in southwest Niger. Geoderma, 81: 313-337.

Charman, P.E.V. and Murphy, B.W., (2000). Soils: Their properties and Management. Oxford University Press, Melbourne.

Collins, A.L., Walling, D.E., Sichngabula, H.M. and Leeks, G.J.L., (2001). Using ^{137}Cs measurements to quantify soil erosion and redistribution rates for areas under different land use in the Upper Keleya River basin, southern Zambia. Geoderma, 104: 299-323.

Eyasu E., (2002). Farmers' Perception of Soil Fertility Change and Management. Institute for Sustainable Development, Addis Ababa.

Feoli, E., Gallizia, V. and Zerihun, W., (2002). Processes of environmental degradation and opportunities for rehabilitation in Adwa, Northern Ethiopia. Landscape Ecology, 17: 315-325.

Fujisaka, S., Bell, W., Thomas, N., Hertado, L. and Crawford, E., (1996). Slash-and-burn agriculture, conversion to pasture, and deforestation in two Brazilian Amazon colonies. Agriculture, Ecosystems and Environment, 59: 115-130.

Fulajtar, E., (2003). Assessment of soil erosion on arable land using ^{137}Cs measurements: a case study from Jaslovske Bohunice, Slovakia. Soil & Tillage Research, 69: 139-152.

Guimaraes, M.F., Filho, V.F.N. and Richie, J., (2003). Application of Cesium-137 in a study of soil erosion and deposition in southeastern Brazil. Soil Science, 168 (1): 45-52.

Gunten, A.B., (1993). Soil Erosion Process in a Twin Catchment Set-up in Gununo Area, Ethiopia. Soil Conservation Research Project Report 23, University of Berne, Switzerland.

Hellden, U. (1987). An Assessment of Woody Biomass, Community Forests, Land Use and Soil Erosion in Ethiopia: A feasibility study on the use of remote sensing and GIS-analysis for planning purposes in developing countries. Lund University Press, Lund, Sweden.

Hurni, H., (1985). Soil Conservation Manual for Ethiopia. Ministry of Agriculture, Addis Ababa.

Hurni, H., (1988). Degradation and conservation of the resources in the Ethiopian highlands. Mountain Research and Development*,* 8 (2/3): 123-130.

Lal, R. (1995). Sustainable Management of Soil Resources in the Humid Tropics. UNU, Tokyo.

Motavalli, P.P., Discekici, H. and Kuhn, J., (2000). The impact of land clearing and agricultural practices on soil organic C fractions and CO_2 efflux in the Northern Guam aquifer. Agriculture, Ecosystems and Environment, 79: 17-27.

Pennock, D.J., (2000). Suitability of ^{137}Cs Redistribution as and Indicator of Soil Quality. ACTA GEOLOGICA HISPANICA, 35: 213-217.

Quine, T.A., Walling, D.E., Chakela, Q.K., Mandiringana, O.T. and Zhang, X., (1999). Rates and patterns of tillage and water erosion on terraces and contour strips: evidence from caesium-137 measurements. Catena, 36: 115-142.

Ritchie, J.C. and McCarty, W.G., (2003). ^{137}Cesium and soil carbon in a small agricultural watershed. Soil & Tillage Research, 69: 45-51.

Sutherland, R.A., (1996). Caesium-137 soil sampling and inventory variability in reference locations. Hydrological Processes,10: 33-50.

Tafesse, A., (1996). Agroecological Zones of South western Ethiopia. Ph.D. Thesis, University of Trier, Germany.

Vlek, P.L.G., Kühne, R.F. and Denich, M., (1997). Nutrient resources for Crop Production in the tropics. *Philosophical Transactions of the Royal Society of London,* B, 352: 975-985.

Walling, D.E. and Quine, T.A., (1993). Use of Caesium-137 as a Tracer of Erosion and Sedimentation: Hand Book for the Application of the Cesium Technique. Overseas Development Administration Research Scheme R4579. Department of Geography, University of Exeter, UK.

Walling, D.E. and He, Q., (2001). Models for Converting ^{137}Cs Measurements to Estimates of Soil Redistribution Rates on Cultivated and Uncultivated Soils, and Estimating Bomb-derived ^{137}Cs Reference Inventories. A Contribution to the IAEA Coordinated Research Programmes on Soil Erosion and Sedimentation. Department of Geography, University of Exeter, UK.

Wiranatha, A.S., Rose, C.W. and Salama, M.S., (2001). A comparison of using the caesium-137 technique of the relative importance of cultivation and overland flow on soil erosion in a steep semi-tropical sub-catchment. Australian Journal of Soil Research, 39: 219-238.

Zapata, F., (2003). The use of environmental radionuclides as tracers in soil erosion and sedimentation investigations: recent advances and future developments. Soil & Tillage Research, 69: 3-13.

Zhang, X., Zhang, Y., Wen, A. and Feng, M., (2003). Assessment of soil losses on cultivated land by using the ^{137}Cs technique in the Upper Yangtze River Basin of China. Soil & Tillage Research, 69: 99-106.