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ESTIMATION OF SOIL EROSION ON CULTIVATED FIELDS ON THE HILLY MEGHALAYA PLATEAU, NORTH-EAST INDIA

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Abstract: The estimation of soil erosion rates in complex subtropical agricultural systems of hilly environment is difficult and most of the traditional methods have serious limitations. The ^{137}Cs technique allows to obtain relatively quickly retrospective medium term soil erosion results. The objective of this study was using ^{137}Cs approach to quantify soil loss under agricultural system which develops under growing human pressure on the hilly terrain of the Meghalaya Plateau. The measured values of caesium inventory for all sampling points are between 2% and 63% of the reference value of caesium inventory. The estimated annual soil loss for sampling points located on the slope are between 29 and 79 Mg·ha^{-1}·yr^{-1} in the case of an improved mass balance model. It means that soil erosion in this manually tilled agricultural area cannot be neglected.

Keywords: Soil erosion, Cs-137, mathematical models, Meghalaya Plateau, India.

1. INTRODUCTION

The Meghalaya Plateau located in North-East India is one of the rainiest environments on Earth (Murata *et al*., 2007; **Fig. 1**), where 65% of the population's livelihood dependens on agriculture (Census of India, 2001). The hilly terrain with narrow valleys inbetween, limits the net availability of land for cultivation. However, widespread agricultural expansion onto marginal land in response to population growth has been observed over the last few decades (Tiwari, 2003). Consequently soil erosion accelerated by shifting cultivation - the predominant form of agriculture (which involves cycles of slashing and burning of natural vegetation on a 2–3 ha plot and leaving it to lie fallow for several years after cropping) – is the main cause of soil degradation (Ramakrishnan, 1992).

Most soil loss estimations in hilly North-East India are based on direct measurements at the field or catchment scale. Studies of soil erosion were initiated by the Indian Council of Agricultural Research south to Shillong in 1975. Three year observations on 21-26º slopes show 40 Mg·ha^{-1}·yr^{-1} soil losses under shifting cultivation (Singh *et al.*, 1981). Exceptionally high erosion rates of 145 and 170 Mg·ha^{-1}·yr^{-1} during the first and second year cropping, respectively, were observed on steeper (31-37º) slopes. Quick vegetation regeneration on abandoned fields reduces the soil erosion to few tonnes annually. Similar, general rules were observed during two years of erosion measurements on 20 m long fields located on 40º inclined slopes under modified shifting cultivation system (locally called *bun*) which was developed under intense human pressure near Shillong. The soil loss was found to range between 50 and 56 Mg·ha^{-1}·yr^{-1} for a 10 and 5 years fallow period respectively (Mishra and Ramakrishnan, 1983). Higher erosion rates under 5 year fallow were related to poor physical characteristics of the soil due to

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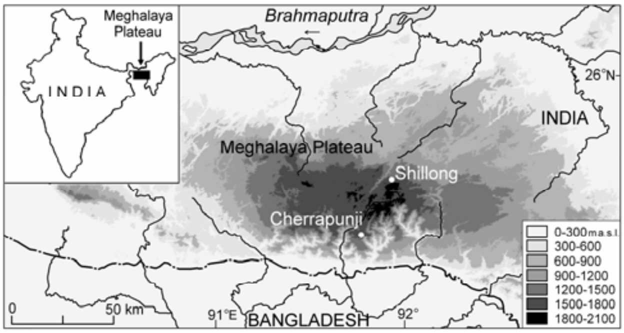

Fig. 1. *Study area (Shillong, India)*

more frequent cultivation and a thinner crop cover. All losses were markedly reduced to 7 Mg·ha^{-1}·yr^{-1} after first year and to 2 Mg·ha^{-1}·yr^{-1} after ten years of fallow vegetation development (Mishra and Ramakrishnan, 1983).

Only one study investigates soil erosion and deposition in the small catchment near Cherrapunji using ^{137}Cs activities. This area is known for it high rainfall ranging from 8000 to 24 000 mm in a given year (Starkel and Singh 2004; Soja and Starkel 2007). The slope soils are largely degraded and overgrown by grasses. The study mentioned above has shown that medium term erosion rates are only 2.1 Mg·ha^{-1}·yr^{-1} (Froehlich, 2004).

The ^{137}Cs technique was widely used in many locations to study soil erosion or sedimentation for both cultivated and undisturbed soil (Zapata, 2003). However only few studies presented application of caesium tracer in areas with steep slopes and manual ploughing in tropical and subtropical climate (Forsyth, 1994; Nagle *et al.*, 2000; Lu and Higgitt, 2000; Collins *et al.*, 2001; Zhang *et al.*, 2004; Neergard *et al.*, 2008, Dupin *et al.*, 2009). Also for India this technique was not used routinely. Simultaneously, for the study area the traditional methods of soil erosion measurements are limited to a few years only and they do not take into account the complexity of land management practices and evolution of agricultural system in time (El-Swaify, 1997). The advantage of the ^{137}Cs technique is that it allows to obtain retrospective medium term soil erosion results and only single field work is needed. The objective of the present study is to use ^{137}Cs approach to quantify soil loss in an agricultural system which develops under growing human pressure on the hilly Meghalaya Plateau located in North-East India. The study area is threatened by soil erosion due to high rainfall, steep slopes and form of agriculture.

2. STUDY AREA

The central part of the Meghalaya Plateau near Shillong, where the study area is located, is composed of weathered Proterozoic quartzites. The relief is hilly with short but steep slopes ranging between 20-40º. The climate is subtropical monsoonal (Köppen climate classification: Cwb), with the warm rainy season spanning from June to September and the dry cool winter from December to February. The mean monthly temperature in Shillong fluctuates between 10ºC in winter (January) and 21ºC in summer (August). Annual rainfall distribution pattern is strongly controlled by the southern escarpment of the Meghalaya Plateau, which is a first barrier to the humid southwest monsoon on its way from the Bay of Bengal. Annual rainfall varies between 11,000-12,000 mm in Cherrapunji (1300 m a.s.l.) and it decreases with the distance from the southern edge of the plateau to only 2400 mm in Shillong (1600 m a.s.l., Prokop and Walanus, 2003). About 70% of the annual rainfall occurs between June and September. The upper part of the plateau is deforested and overgrown by grass intermix with cultivated land and scattered subtropical pines. Forest demise and crop cultivation facilitate soil downwash and deposition of eroded material in the narrow valley floors.

A small catchment (2.58 ha) drained by first order ephemeral stream, located about 5 km south-west of Shillong city at an altitude of approximately 1820-1850 m a.s.l. was selected for soil erosion study (**Fig. 2**). The slopes are convex-concave and they are inclined from 2º on rounded hilltops to 27º on concave parts. The topographic maps and remote sensing images confirm that area was deforested and under cultivation at least 90 years ago. Soils were classified as silty loam Umbric Dystrochrepts (Singh, 2005, **Table 1**). They are deep up to 1.00 m on the hilltops, 0.30-0.40 m on convex part of slope and 1.60-2.00 m in the valley floor

The *bun* cultivation practised at higher elevation of Meghalaya including investigated catchment is a modified form of shifting cultivation adopted for better utilisation of limited land and biomass which are under growing pressure of population and food demand. While at lower elevations the entire forest cover is slashed and burnt in situ (Tiwari, 2003), at higher elevations only the lower branches of pines, which are already sparsely spaced due to previous land-use practice, are slashed. The collected material is then arranged with a spade or hoe in parallel ridges running down the slope and burnt under soil cover. The farmers cultivate crops on ridges in two seasons, namely February to June and July to December. The major crop sown during the first season is potato while cabbage, radish, and legumes are preferred during the second season. The land is cultivated for 2-3 years and then let the land lie fallow for the same period. However few decades ago the length of the fallow period was much longer – between 5 and 10 years (Mishra and Ramakrishnan, 1983; Tiwari, 2003).

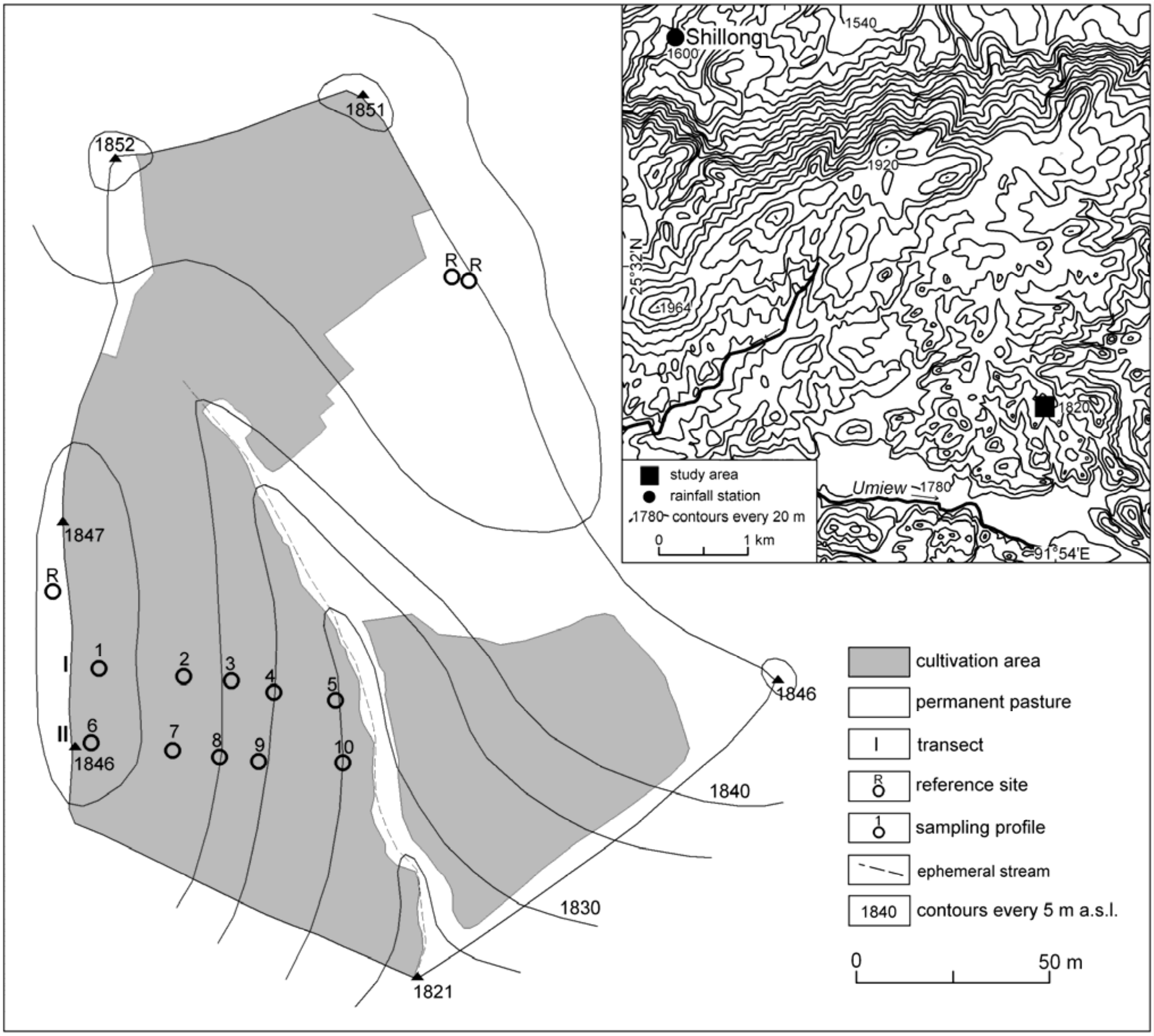

Fig. 2. *Study field and sampling scheme (Shillong, India)*

Table 1. *Soil physical and chemical properties along sampled transects*

Profile number (Fig. 2)	Depth (cm)	Sand 2.0-0.05 mm (%)	Silt 0.05-0.002 mm (%)	Clay<0.002 mm (%)	Texture class	Organic matter (%)
1 –hilltop	0-20	36.2	60.1	3.7	silty loam	1.9
	20-35	21.4	73.8	4.8	silty loam	0.8
	35-50	16.2	78.2	5.6	silty loam	0.6
3 – eroded slope	0-15	26.7	68.9	4.4	silty loam	1.7
	15-30	5.7	82.8	11.5	silt	0.5
5 – footslope	0-20	34.3	61.7	4.0	silty loam	3.3
	20-40	37.7	58.9	3.4	silty loam	3.6
	40-50	35.4	61.1	3.5	silty loam	3.1

3. METHODS

To measure soil erosion and accumulation for a study area the ^{137}Cs technique was used. This method is based on radioactive caesium fallout. ^{137}Cs was introduced into the atmosphere as a result of nuclear weapon tests and also as a results of the accident of the nuclear power plant in Chernobyl. The main period of caesium fallout from nuclear weapons took place in the 1950s and 1960s with the maximum caesium deposition in 1963. ^{137}Cs deposition depends on the latitude and amount of precipitation (Ritchie and McHenry, 1990). After deposition on the ground surface ^{137}Cs is strongly absorbed by the clay minerals (especially by the colloidal fraction) and organic matter in soil. The uptake of caesium by plants is limited. The caesium technique involves measuring of the total inputs of ^{137}Cs on reference areas with neither erosion nor accumulation visible. The comparison between the value of the ^{137}Cs inventory for the reference site and the ^{137}Cs inventory measured for the disturbed location permits to recognize the intensity of soil redistribution processes. To obtain qualitative results of soil erosion from the ^{137}Cs data a model needs to be applied in the calculations. Moreover, the values of annual ^{137}Cs fallout have to be known to be able to use modern mass balance models to calculate soil erosion. In this work, to assess the effects of bun cultivation on medium-term soil erosion, two parallel downslope transects were selected. Soil samples were collected by hammering a 80-mm diameter steel corer on the slope every 15 m. Cores were generally taken to the depth of ca. 50 cm, but at the base of slope sampling up to a depth of 80 cm was performed. Reference sites were sampled on top of grassed hilltops.

The map of the catchment under study was prepared on the basis of a field survey. The elevations, distances and angles were measured by using compass and altimeter. Tape and clinometer measurements became a background for slope cross section survey.

Samples were air dried and sieved to 2 mm prior to the measurement of the ^{137}Cs activity using a high resolution gamma spectrometer. The counting time was at the order of 80 ks and the energy resolution was 1.8 keV for energy of 1.33 MeV. ^{137}Cs activity was determined by counting the 661.7 keV gamma emission. As a reference material soil provided by IAEA (IAEA-375) was used. ^{137}Cs activities were expressed in Bq/kg and corrected with respect to radioactive decay to sampling time. In addition, the absolute grain size composition of the <2 mm fraction of each sample was determined using a Fritsch Laser Particle Sizer Analysette 22 after pretreatment with H_2O_2 and disaggregation. For the estimation of organic matter content loss-on-ignition at 600°C for 3 h was used. Bulk density for samples was calculated from the dry mass of the sample and 100 cm^3 Kopecky cylinder volume. The cultivation depth was estimated to be 10 cm, because that was the depth that spade or hoe was observed to penetrate.

To compare measured values of caesium activity at the study points with reference value of caesium activity the inventories of caesium for each sampling point were calculated. Caesium inventory is defined as a sum of caesium activity of each soil layer in soil profile and expressed in Bq/m^2. To calculate annual values of caesium fallout was used Sarmiento-Gwinn model (Poręba and Bluszcz, 2007). To calculate soil erosion based on caesium three models were used: proportional, simplified mass balance model and mass balance model (Walling and He, 1999).

4. RESULTS AND DISCUSSION

Establishing of the reference value of ^{137}Cs inventory

Reference ^{137}Cs inventory for the study was established by two methods: measurement of ^{137}Cs activity in soil samples from areas where neither soil erosion nor deposition occur and by calculation based on precipitation and nuclear data. For the study area it was a serious problem to find an undisturbed area located near the study valley. An example depth distribution of ^{137}Cs activity for an undisturbed site for the study area is presented in **Fig. 3**. The exponential decline of caesium activity with depth is visible for this sampling point. The mean value of measured values of ^{137}Cs inventory for reference sites for the study area is 1220 Bq·m^{-2} with standard error of 260 Bq·m^{-2}. This value is similar to values obtained for other areas on similar latitude and annual rainfall.

The calculations of ^{137}Cs inventory were done using the precipitation data and the Sarmiento-Gwinn model (Sarmiento and Gwinn, 1986; Poręba and Bluszcz, 2007). This model allows to obtain the value of the ^{137}Cs fallout connected with the nuclear weapon testing. By this method it is possible to obtain both nuclear weapon ^{137}Cs fallout and annual values of ^{137}Cs fallout during nuclear weapon test period. This knowledge is necessary for using mass balance models to calculate soil erosion. Detailed description of this model was well presented by Sarmiento and Gwinn (1986). An example of application of this procedure is described by Poręba and Bluszcz (2007). The calculated based on described above model values of annual caesium fallout will be used to divide the measured value of caesium fallout. The calculated value of ^{137}Cs deposition connected with the nuclear weapon tests based on the precipitation data and Sarmiento-Gwinn model for the study area is 1.1 kBq·m^{-2}. Moreover, the annual values of ^{137}Cs deposition were calculated using this model , which is necessary for mass balance model to calculate soil erosion. The annual values of ^{137}Cs are presented in **Fig. 4**, whereas the cumulated annual values of ^{137}Cs deposition are presented in **Fig. 5**. It is clearly visible, that for the years 1962-1964 more than 52% of the caesium deposition connected with nuclear weapon tests occurred and the highest intensity of the global caesium deposition was in 1963.

Caesium variability on field

The examples of measured values of ^{137}Cs inventory for sampling points located at the middle of the slope (eroded part) and at the foot of the slope(deposition place), respectively, are shown in **Fig. 3**. For middle part of the slope the ^{137}Cs is distributed fairly uniformly through the plough layer. Practically all caesium is contained in the plough layer and bellow the plough depth the ^{137}Cs activity drastically decreases. For the sampling point located at the foot of the slope the ^{137}Cs is still quite well mixed in the plough layer but it is present bellow the plough layer as well. For the sampling point located at the middle part of slope the measured values of ^{137}Cs inventory are between 28 and 230 Bq/m^2 whereas the reference ^{137}Cs inventory was estimated to be 1220±260 Bq·m^{-2}. Thus the ^{137}Cs inventory for those sampling points is substantially lower than the reference local ^{137}Cs inventory. For the sampling points located in the valley bottom the inventories of ^{137}Cs are between 422 and 778 Bq·m^{-2} and those value are still substantially lower than the local reference inventory of ^{137}Cs. On the other hand the depth of presence of caesium suggest that those points are deposition area. It means that for the footslope area si-

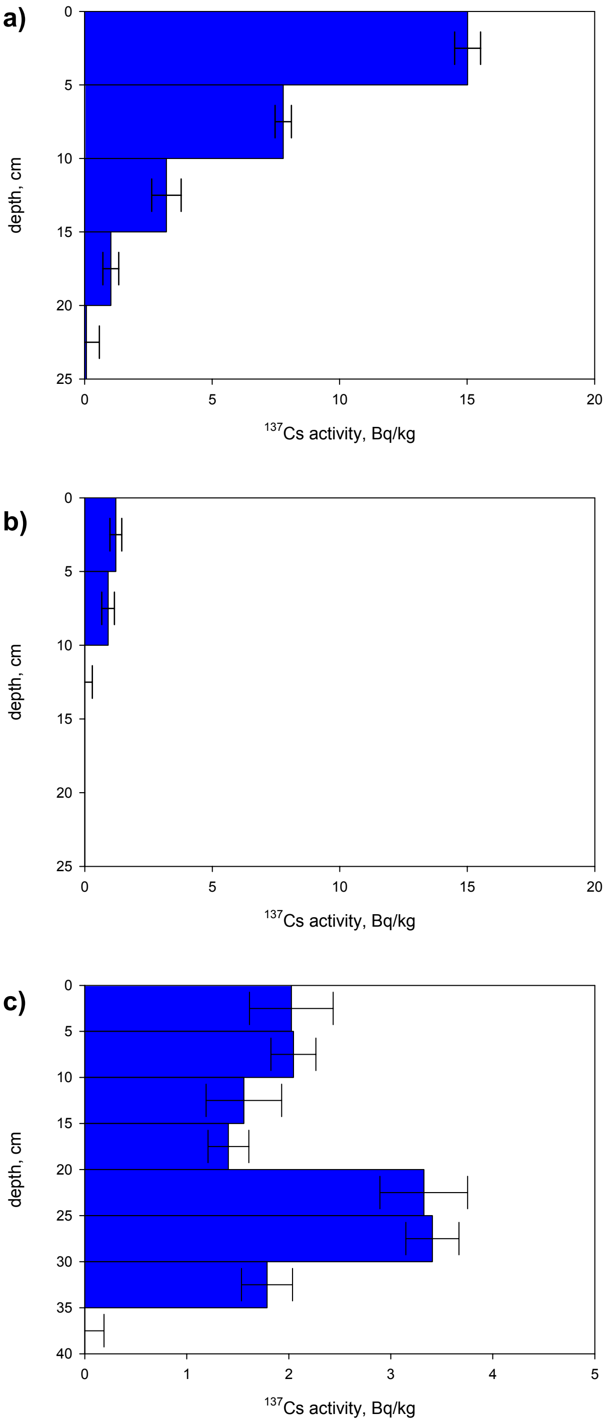

Fig. 3. *Examples of depth distribution of ^{137}Cs in soil profile: reference site near study area (a), eroded part of the slope (b) and deposition area (c).*

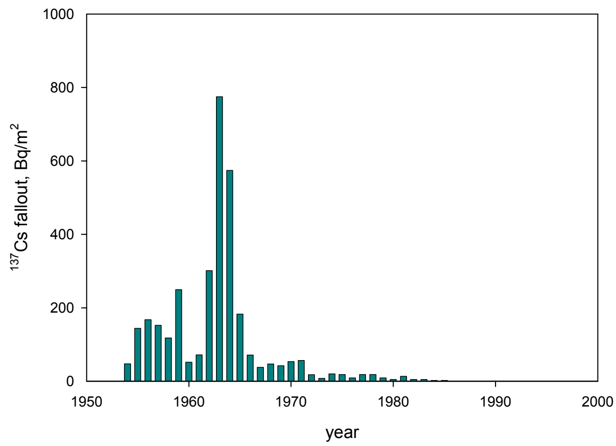

Fig. 4. *The calculated values of annual ^{137}Cs deposition based on the rainfall records according to Sarmiento-Gwinn model for study area.*

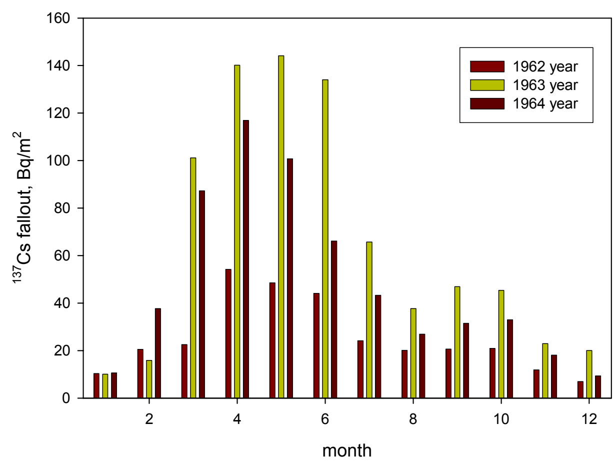

Fig. 5. *Monthly values of ^{137}Cs deposition for study area and for period with highest intensity of ^{137}Cs deposition.*

multaneously occur deposition of eroded material from the slope, and its partial erosion down the valley by ephemeral stream. The eroded material can be replaced later by material transported from the upper part of the valley bottom.

The measured values of the ^{137}Cs inventory clearly show that for all sampling points for both transects ^{137}Cs inventories are smaller than the reference value (**Fig. 6**). It means that all part of the transects are eroded including the footslope area. To study this problem a detailed balance of ^{137}Cs for both transects was done. Those calculations show that about 13077 Bq·m (16% of total caesium fallout) of ^{137}Cs fallout on the transect still remains in the transect and about 84% has been moved to the valley bottom.

Calculation of soil erosion

To calculate soil erosion and deposition based on caesium data three models were applied: proportional, simplified mass balance and improved mass balance. The calculated values of soil erosion in the case sampling point located on the slope for the proportional model are between 14.7 and 18.1 Mg·ha^{-1}·yr^{-1}, for the simplified mass balance model are between 28.7 and 78.9 Mg·ha^{-1}·yr^{-1} and for improved mass balance model are between 34.3 and 72.3 Mg·ha^{-1}·yr^{-1} (**Fig. 7**). In the case of the bottom of the valley the calculated values of soil erosion are equal 5.6-11.5 Mg·ha^{-1}·yr^{-1} for the proportional model, 7.9-17.4 Mg·ha^{-1}·yr^{-1} for the simplified mass balance model and 6.3-21.3 Mg·ha^{-1}·yr^{-1} for the improved mass balance model (**Fig. 7**).

It is visible that the values obtained by the simplified mass balance model and the improved mass balance model are quite similar whereas the value of soil erosion obtained by the proportional model are far away from the mass balance models. The probable explanation of this result is that the main assumption for the proportional model of caesium being well mixed in the plough layer does not hold. This assumption is fulfilled quite well for areas with mechanical and at least annual ploughing. For the study area only manual technique is used and no ploughing is done during the fallow period. Thus the caesium could not be well mixed in the plough layer. Moreover, the proportional model is working well for areas with small or at least medium soil erosion (Poręba and Bluszcz, 2008). For high intensity of soil erosion,

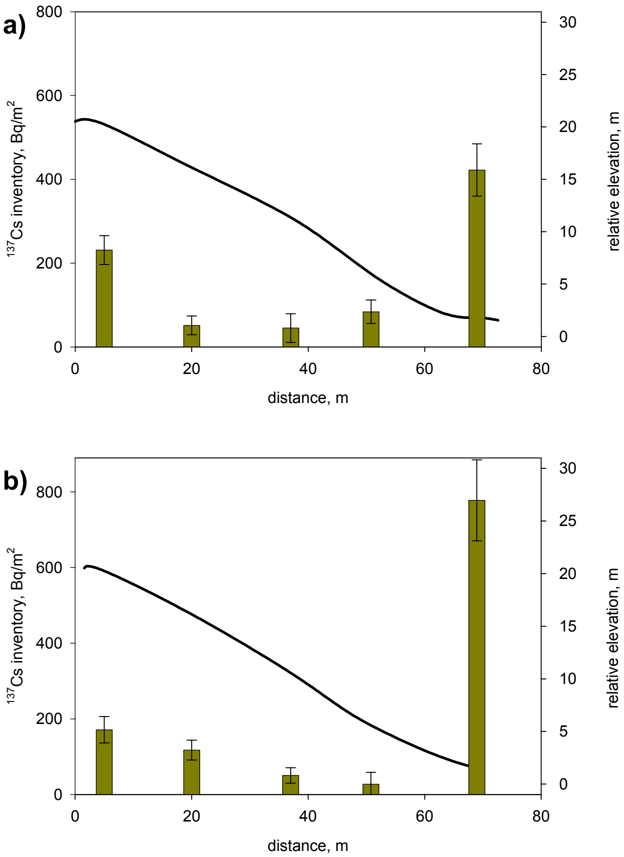

Fig. 6. *The distributions of ^{137}Cs inventory on slopes transects (with marked slope cross section)*

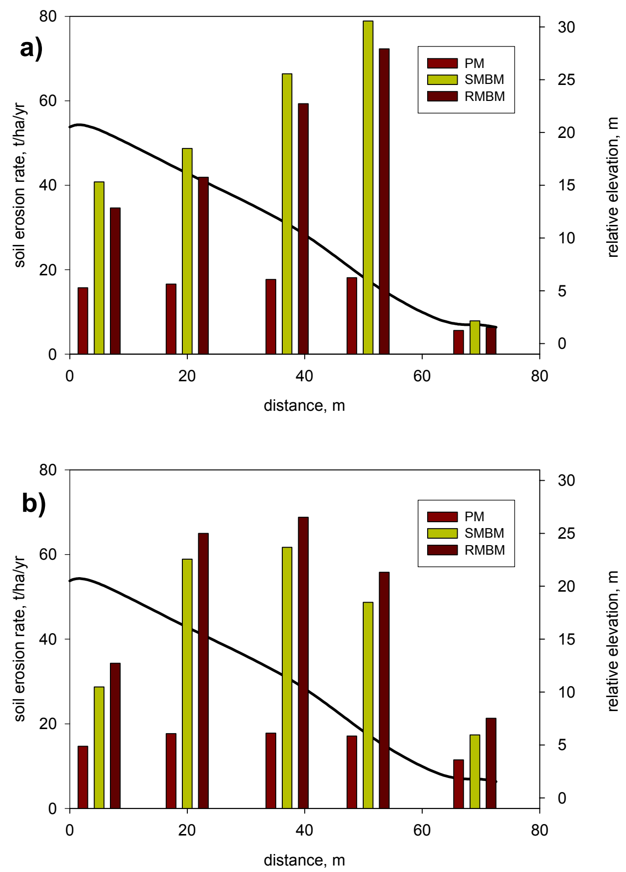

Fig. 7. *Values of soil erosion obtained by caesium method for slopes transects (with marked slope crossection). Soil erosion were calculated by three models: proportional (PM), simplified mass balance (SMBM) and refined mass balance (RMBM).*

results obtained by the proportional model do not agree with mass balance model. It is also visible that soil erosion rates calculated by the simplified mass balance model and improved mass balance model reflect the slope angle and shape along transects. In contrast, there is no visible correlation in case of the proportional model, where soil losses (visible reduction of upper soil horizons in the field) are approximately uniformly distributed along slope transects. It should be mentioned that the simplified mass balance model requires only the total value of caesium fallout, whereas the improved mass balance model requires annual values of caesium fallout. Fortunately, for the study area more than 50% of the caesium fallout occurred between 1962 and 1964 and thus it is justified to use the simplified mass balance model.

There exists a serious problem with sampling points located at the footslope. The measured values of ^{137}Cs inventories for those points are substantially lower than the reference value of ^{137}Cs fallout. At the same time, the maximum depth of caesium presence and depth distribution of caesium in the soil profile suggest that for those points soil accumulation occurs. The detailed calculation needs additional sampling but a rough estimation of this behaviour provides the values of soil accumulation for those points as equal to about 50 $Mg \cdot ha^{-1} \cdot yr^{-1}$, whereas about 250 $Mg \cdot ha^{-1} \cdot yr^{-1}$ were transited through those points.

The measured medium term soil erosion rates (29 to 72 $Mg \cdot ha^{-1} \cdot yr^{-1}$) measured near Shillong are within a wide range of results obtained using ^{137}Cs technique for cultivated fields with steep slopes and manual plough in tropical and subtropical climate (fewer than 150 $Mg \cdot ha^{-1} \cdot yr^{-1}$). In addition, the climate (rainfall), landform (gradient, length and shape of slope), soil type and vegetative cover, the length of fallow, direction of tillage translocation (downslope or lateral) and type of crops also play an important role in influencing soil erosion intensity, particularly in hilly areas. Erosion usually increases with an increasing slope gradient (Kimaro, *et al.* 2005, Dupin *et al.*, 2009), shortening of fallow length (Neergard *et al.*, 2008) and cultivation of vegetable crops downslope (Zhang, 2004). All these conditions are fulfilled in the case of *bun* cultivation near Shillong. The obtained results of soil erosion for both transects clearly show that for the study area intensity of soil erosion is considerable, much higher than that obtained by Mishra and Ramakrishan (1983) using traditional erosion measurements for two years (about 50-56 $Mg \cdot ha^{-1} \cdot yr^{-1}$). It should be mentioned that traditional method was applied only to cultivated fields while the caesium approach takes into consideration also soil loss during fallow periods when the field is overgrown by grasses. High erosion rates can be associated with the progressing decline of fallow period from 10-5 years several decades ago to 2-3 years at present due to population pressure. An important role in the intensification of agriculture plays growing food demand of Shillong city where most of the agricultural products are sold.

The estimated annual soil losses on cultivated fields near Shillong are also much higher than those measured for degraded grasslands (2.1 $Mg \cdot ha^{-1} \cdot yr^{-1}$) near Cherrapunji (Froehlich 2004). This discrepancy can be explained as follows. In the Cherrapunji area, extreme monsoonal rainfall combined with deforestation and progressive erosion in the past facilitated development of resistant stony stony surficial soil layer up to 20 cm thick. Land degradation is so advanced that this area has not been cultivated during the last 90 years (Prokop, 2005). The present-day compact pavement of soil together with dense root grass system, typical for steppe areas, significantly reduces sediment transfer from steep slopes.

5. CONCLUSIONS

Soil erosion in the study area located on Meghalaya Plateau located in North-East India were measured by caesium technique. The obtained values of caesium inventory for sampling points located on the slopes are usually considerably smaller than reference value of caesium inventory (about 2% to about 63% of reference value of the caesium inventory). The calculated values of soil erosion for sampling points located on the slope are between 34 and 72 $Mg \cdot ha^{-1} \cdot yr^{-1}$ (improved mass balance model) and reflects the slope angle and shape along the transects. This value is considerably higher than that obtained using traditional erosion measurements. Higher erosion rates can be associated with progressing decline of the fallow period from 5-10 years several decades ago to 2-3 years now due to growing population pressure. For sampling points located at the footslope the values of caesium inventory are also smaller than the reference value of caesium fallout for the study area although soil deposition for those points is proved due to depth of caesium presence is soil profile.

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