Soil erosion study of Madagascar highland by ^{137}Cs technique

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Abstract
The highlands of Madagascar present various forms of soil erosion due to morphology and vegetation cover. Water-induced erosion is the main destructive factor, aggravated by human activities. Furthermore, the landscapes are generally dominated by rugged and complex terrains, representing two-third of the island area. For soil conservation management, terrace cultivated plots are used by most farmers. In Madagascar, soil erosion phenomena have been studied since 1950s using conventional techniques, but they have a number of important limitations. The INSTN-Madagascar team used alternative techniques such as fallout radionuclide (FRN) techniques, tested successfully for the first time in the country since 2009. Cs-137 is widely used to estimate a retrospective soil erosion rates up to 50 years. The concentration gradient allows more detailed understanding of the spatial soil redistribution associated by fine particles. The study was conducted in terraced plots with different type of plantation, located in Sambaina, Manjakandriana. Using transect approach, samples have been collected along 170 m length, with 18% of slope. Measurements were performed at INSTN-Madagascar laboratory using gamma spectrometry system. By using Mass Balance Model (MBM2), the net erosion rate is estimated at 3.3 $t.ha^{-1}.y^{-1}$, resulting in sediment downstream loss of up to 61%. The obtained results are then compared to other erosion sites in the country.

Keywords: soil erosion, fallout radionuclide techniques, gamma spectrometry, Mass Balance Model

1. Introduction

Soil erosion is a main worldwide environmental threat, especially in most vulnerable ecological systems. The major effects are the redistribution of soil within a field, the loss of soil from a field, the breakdown of soil structure, the decline in organic matter and nutrient resulting to the reduction of cultivable soil surface and a decline in soil fertility [1].
Madagascar is classified among high risk countries of soil degradation. Water-induced erosion is the main destructive factor, accentuated by human activities and agricultural practices. The sensitivity of soil erosion depends on local conditions such as climate, vegetation cover, land topography, particle-size, soil structure, moisture and organic matter. Therefore, soil degradation reduces progressively the land fertility and productivity.
Since 1950s, different conventional models have been developed to predict soil erosion in the country. These models require several local parameters in which they are sometimes very complicated [2]. In addition, some parameters should be reviewed in accordance with climatic conditions in the study area.
The ^{137}Cs fallout radionuclide technique has been tested successfully by the INSTN-Madagascar team since 2009 [3]. The innovative and alternative technique is widely used in several countries of the world [4]. The advantages and the limitations associated to the technique have been recently evaluated [5].

2. Material and methods

2.1. Radiotracer ^{137}Cs

The ^{137}Cs is an artificial radionuclide with half-life of 30 years, produced by the atmospheric testing of nuclear weapons during the 1950s and 1960s. This radionuclide is rapidly and strongly absorbed by fine soil particle-size (< 2 mm) upon his deposition with precipitation. The spatial distribution has a strong correlation with country localisation, rainfall and latitude position. Thus, total fallout in the northern hemisphere was substantially greater than in the southern hemisphere (Fig. 1). Nevertheless, the ^{137}Cs inventory in southern hemisphere is still measurable with adequate detector [6].

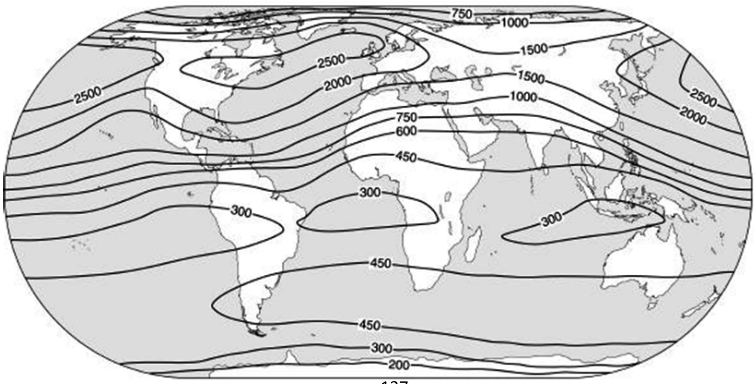

Fig. 1: Global distribution of bomb-derived ^{137}Cs fallout inventories (Based on [7])

With the assumption that ^{137}Cs particle is uniformly deposited at any surface of soil during the same event, the ^{137}Cs associated fine soil redistribution by runoff reflects the movement of the soil. Estimates of soil erosion or deposition rates can be provided by the measurement of loss or gain in the radionuclide inventory relative to the local reference site. An individual sampling point is noted erosion area when ^{137}Cs inventory is lower than the reference value and a depositional point for the ^{137}Cs inventory greater than the reference value. To reflect the original fallout input, the reference site should be a stable area, and requires the following criteria [6]:

- uncultivated or undisturbed site since the first global occurrence of ^{137}Cs fallout (1954),
- site as close as possible to the study area (e.g. around 1 km),
- no erosion/deposition processes, generally a flat area,
- no high bio-disturbing area (e.g. dense forest)

2.2. Conversion model

A conversion model serves to convert the ^{137}Cs inventory (Bq.m^{-2}) into an annual erosion or deposition rate (t.ha^{-1}.y^{-1}). The refined Mass Balance Model 2 (MBM2) was used for estimating mid-term (~50 years) soil redistribution rates of water-induced soil erosion at individual sampling points on the terraced plots [8]. This model is developed, grouped and programmed using the Visual Basic Application (VBA) in Microsoft Excel. Thus, it can be expressed as follows:

$$\frac{dI(t)}{dt} = (1-\Gamma)\Phi(t) - \left(\lambda + P\frac{R}{d}\right)I(t) \qquad 1.1$$

where:

$I(t)$	: ^{137}Cs inventory (Bq.m^{-2}),
Γ	: percentage of the freshly deposited ^{137}Cs fallout removed by erosion before being mixed into the plough layer,
$\Phi(t)$	: annual ^{137}Cs deposition flux (Bq.m^{-2}.y^{-1}),
λ	: decay constant for ^{137}Cs (y^{-1}),
P	: particle size factor,
R	: erosion rate (kg.m^{-2}.y^{-1}),
d	: cumulative mass depth representing the average plough depth (kg.m^{-2})

2.3. Study site and field work

The study site is located at Talatakely village, Sambaina Manjakandriana (47°46’43”E, 18°54’39”S; Fig. 1). The landscapes are characterized by steep and hilly topography. The elevations range from 1367 to 1398 m, and spread on the slope gradient up to 18%. The climate is humid tropical with mean air temperatures ranging from 4 °C in the winter to 32 °C during the summer. The mean annual precipitation is 1245 mm and 73% of rainfalls are between November to March.

The soils are generally ferrallitic [9]. The vegetation covers are dominated by bushes and eucalyptus. In absence of vegetation cover, ferrallitic soils are sensitive to water erosion.

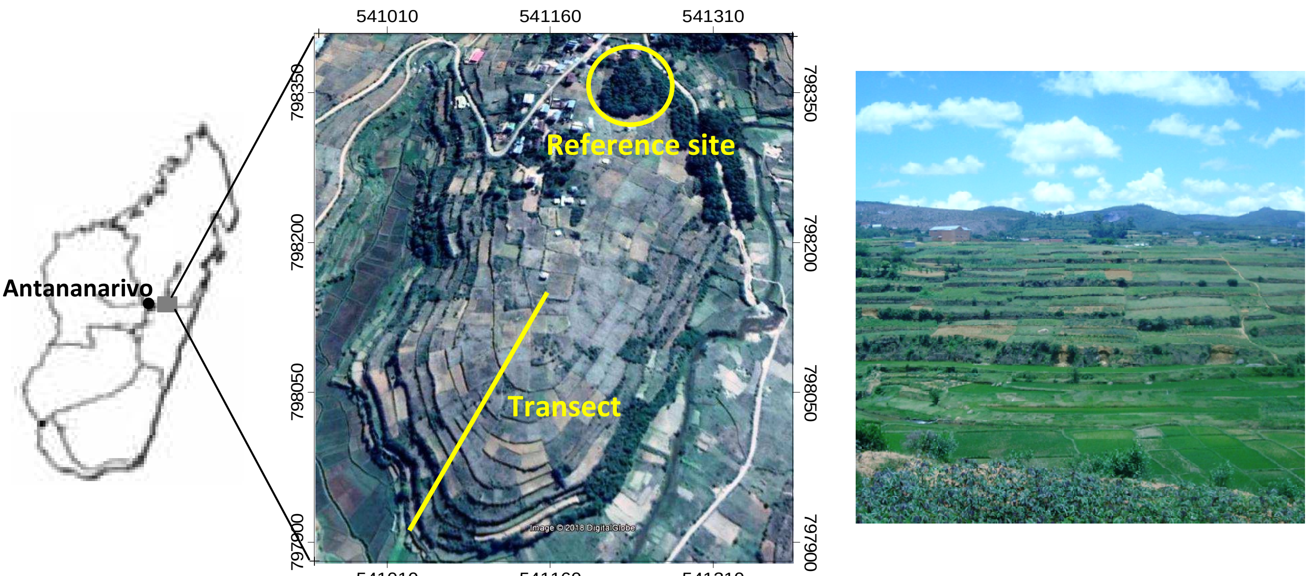

Fig. 1: Study site localisation and overview

To document the key features of the spatial pattern of post-fallout redistribution of ^{137}Cs within the study field, a total of 18 bulk soil cores were collected along 170 m downslope transect, spaced 10 m. To establish the local ^{137}Cs reference inventories, 18 random bulk soil cores were also collected from forest and flat area near the study site (around 100 m). It is noted that the collected samples should be representative of the site. In addition, one sectioned core was collected each from reference and study sites. These sectioned samples were sliced into 2 cm depth increments from the surface to 20 cm, per 5 cm depth increments between 20 and 30 cm, and per 10 cm depth increments up to 40 cm. A motorized percussion corer with a long tube of 1 m and a diameter of 10 cm was used for soil sample collection (Fig. 2). Soil sampling was performed to a depth of 40 cm to ensure that the whole soil profile containing ^{137}Cs is sampled. A Global Positioning System (GPS) device was used to determine the geographical coordinates and elevation of each sample point.

a) b)

Fig. 2: Sampling work (a) and collected samples (b)

2.4. Laboratory work

The samples were oven-dried at 105 °C, disaggregated and passed through 2 mm mesh to separate the gravel from soil. A sub-sample from weighed fine fraction was filled into 100 cm^3 air-tight polyethylene plastic containers whose geometry was similar to that used for system calibration. Activity measurements were undertaken by gamma-ray spectrometry, hyper pure germanium (HPGe) detector with relative efficiency of 30% and 1.8 keV of resolution at 1332.5 keV gamma energy of ^{60}Co. The detector, surrounded by thick lead shield, was coupled to a CANBERRA multichannel analyser. The equipment calibration was performed by certified IAEA-Soil-375 reference material.

For measurement, the samples were placed directly on top of the detector head and counted for more than 24 hours, providing a precision of 10% at the 90% level of confidence. The activity of ^{137}Cs was obtained from the counts at energy 661.7 keV of total absorption peak.

3. Results and discussion

3.1. Specific activity

At the reference site, the profile distribution shows that the maximum activity occurred at 2-4 cm below the surface horizon and decrease exponentially with depth (Fig. 3a). The maximum value (1.1 ± 0.2 Bq. kg^{-1}) can be explained by the timescale radionuclide deposition and the downward diffusion effects. Otherwise, the vertical distribution is similarly obtained value from elsewhere undisturbed sites in the world [10; 11].

At the study site, the profile distribution at the eroding area of the middle plots shows that the maximum activity is mixed within the plough layer of 20 cm. The activities vary between 0.6 ± 0.1 $Bq.kg^{-1}$ and 0.7 ± 0.1 $Bq.kg^{-1}$. No significant activity was detected below this plough layer (Fig. 3b).

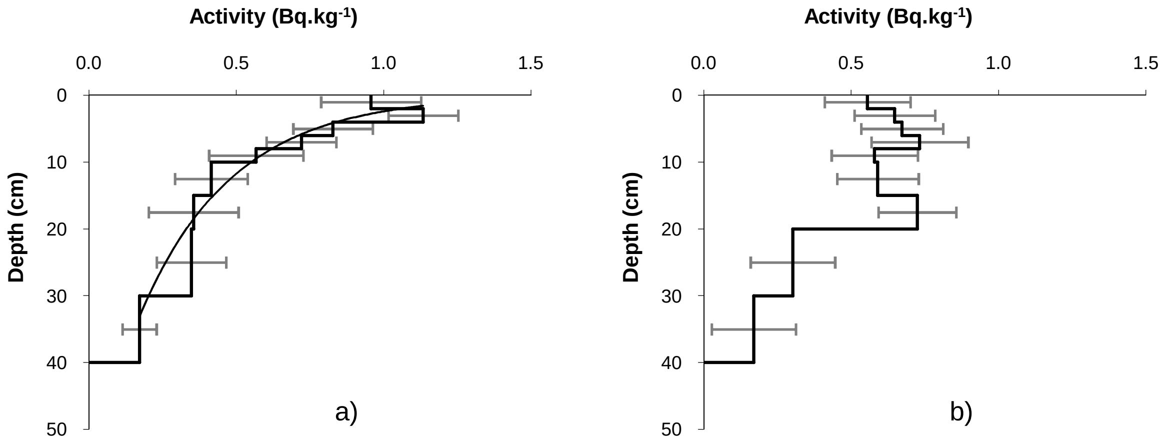

Figure 3: Depth distribution in a) reference site and b) cultivated site

3.2. Local inventory

Analyses of ^{137}Cs in the soil cores collected from reference site indicated an average fallout inventory of 216 Bq.m^{-2}, with coefficient of variation (CV) of 20%. The inventories range between 162 Bq.m^{-2} to 330 Bq.m^{-2}. The total variability may be derived from random spatial, sampling protocols and sample measurements [6]. Anyway, the random spatial variability is relatively similar to the results found in Zimbabwe ranging between 170 Bq.m^{-2} and 334 Bq.m^{-2} [10] and to values reported from other countries [12; 13]. The mean reference value was used to determine the percentage loss or gain of ^{137}Cs at the respective study site.

At the study sites, the ^{137}Cs inventories values ranged from 145 Bq.m^{-2} to 280 Bq.m^{-2}, with an average value of 197 Bq.m^{-2} in which it is below the average reference inventory. The lower value indicates in general the soil loss moving towards outside the study area.

3.3. Erosion and deposition rates

The soil erosion rates were estimated by the appropriate and realistic model (MBM2) to the study plots. The following parameters were used to the model, based on the local conditions:

- Bulk density : 1.2 g.cm^{-3}
- Proportional factor : 0.7
- Relaxation depth : 4.0 kg.m^{-2}
- Tillage depth : 20 cm
- Starting tillage year : 1960

The mean, gross and net soil erosion rates were respectively 7.5 t.ha^{-1}.y^{-1}, 5.4 t.ha^{-1}.y^{-1} and 3.3 t.ha^{-1}.y^{-1} (Table 1). The results show that the depositional zone were observed in the middle and lower slopes of terrace plots. It could be due to reduction of the runoff movement within the stable plot areas (Fig. 4).

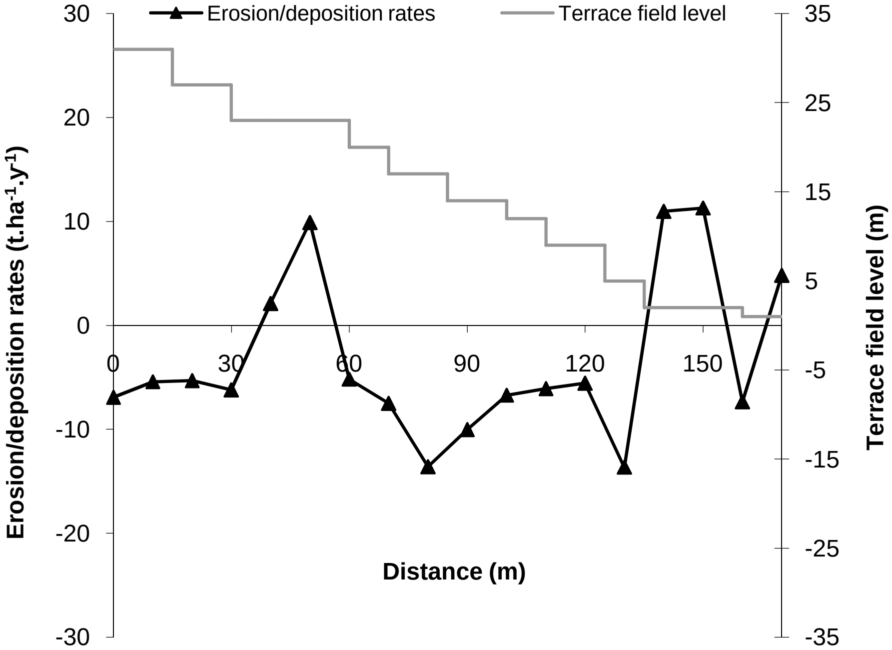

Figure 4: Erosion and deposition rates along the terraced plots

Within whole site, the estimated net erosion rates (3.3 $t.ha^{-1}.y^{-1}$) are lower than the obtained values in slope field (7.4 $t.ha^{-1}.y^{-1}$) in the same region [3]. It means that terraced agriculture plots are significantly efficient methods for soil conservation management.

Table 1 Soil redistribution assessment

Component	Estimate
Number of eroded points	13
Number of deposited points	5
Mean erosion rate ($t.ha^{-1}.y^{-1}$)	7.5
Gross erosion rate ($t.ha^{-1}.y^{-1}$)	5.4
Net erosion rate ($t.ha^{-1}.y^{-1}$)	3.3
Sediment delivery ratio (%)	61
Eroding area (%)	72

4. Conclusion

This study investigated the possibility of using ^{137}Cs measurements to quantify soil erosion in Malagasy traditional agricultural sites. The preliminary results demonstrate the potential use of ^{137}Cs technique for further soil erosion and redistribution studies in Madagascar. In general, this technique is very useful and has many advantages. Firstly, it allows obtaining the average value of soil erosion rate for medium-term (~50 years). Secondly, the ^{137}Cs technique also allows for obtaining the net value of soil erosion. Moreover, compared to the conventional techniques, the ^{137}Cs technique requires only one sampling campaign instead of significantly longer measurements. Finally, it is relatively fast and cheap.

Like all techniques, the ^{137}Cs fallout radionuclide technique has some limitations such as to find an ideal reference site and to choose the appropriate conversion model used. To overcome these limitations, it is recommended to take into consideration other environmental radiotracers (e.g. ^{210}Pb or ^{7}Be) together with ^{137}Cs.

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