

SOIL EROSION FACTOR ASSESSMENT ON CULTIVATED SITE OF MADAGASCAR HIGHLAND BY THE ^7Be TECHNIQUE AND MULTIVARIATE ANALYSIS



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ABSTRACT

Background: Soil erosion is an observable phenomenon of Madagascar Highland. Soil deposition affects upstream cultivated land and downstream waterway silting. **Objectives:** To support and guide mitigation strategies related to agricultural practices, it is necessary to assess the factors involved and influencing the variability of the soil erosion magnitude. **Methods:** Sloped cultivated site at Andranomanelatra Antsirabe, central Madagascar was selected as a study site. Two field work campaigns were carried out: in December 2018 at the beginning of rainy season and in March 2020 at the end of rainy season. Beryllium-7 (^7Be) atmospheric fallout radionuclide technique has been used to determine the impact of short-term rainfall events (< 6 months). ^7Be activities in soil samples were measured through the 477.6 keV gamma ray peak, using a HPGe gamma spectrometry system. To convert inventory ($\text{Bq}\cdot\text{m}^{-2}$) to erosion rate ($\text{t}\cdot\text{ha}^{-1}$), Profile Distribution Model (PDM) was used. Subsequently, statistical multivariate analysis was performed for data treatment to investigate effects of factors involved. **Results:** Considering the site as a whole, net soil erosion is estimated to $2.88 \text{ t}\cdot\text{ha}^{-1}$ and $7.55 \text{ t}\cdot\text{ha}^{-1}$ during 1st and 2nd field work respectively. The value obtained during 2nd fieldwork, which is twice that of the first one, can be explained by the five following factors. High quantity and frequency of rainfall increase soil erosion rate. Longer plot reduces sediment delivery ratio. Soil loss from the upper plot is deposited on the lower plot. Plant with dense cover (maize) reduces soil erosion, whereas plant with low cover (cassava) increases it. Low micro-slope retains soil movement and steep micro-slope increases it. Soil erosion dominates in the upper part of the slope and soil deposition in the lower part. **Conclusions:** The results obtained confirm the ^7Be technique potentiality to determine soil erosion and its causes during a short period of rainfall. In order to minimize erosion factor effects, it is advisable to plant crops with dense cover, otherwise to combine the crops with weak and dense cover. Cultivation in flat site is proposed. In case of sloped terrain, transformation into terrace reduces soil erosion. Finally, cultivated area should be long in order to reduce runoff velocity and to retain sediment.

Keywords: Madagascar, erosion, beryllium-7, spectrometry, model, factor.

1. INTRODUCTION

Highland of Madagascar is largely an agricultural area. The area produces cereals, fruits, vegetables and animal products [1]. However, erosion is seen as a threat in highland of Madagascar. Soil deposition affects upstream cultivated land [2]. To support and guide mitigation strategies related to agricultural practices, it is necessary to assess the factors involved and influencing the variability of the soil erosion magnitude. To achieve the goal, producing soil erosion data at different timescales is needed. Use of conventional monitoring techniques to obtain such information faces many challenges in terms of cost and the result representativeness. The use of fallout radionuclides offers an alternative way to document soil erosion rates [3]. To date, works involving use of fallout radionuclides in Madagascar have focused on the use of caesium-137 (^{137}Cs) and lead-210 ($^{210}\text{Pb}_{\text{ex}}$). These two radionuclides provide respectively information on medium and long-term erosion rates [4, 5, 6]. The possibility to determine impact of short-term rainfall events (< 6 months) and the effectiveness of the agricultural soil conservation has recently directed attention to the use of short-lived fallout radionuclide beryllium-7 (^7Be) [7, 8].

^7Be is a cosmogenic fallout radionuclide having half-life of 53.3 days and gamma energy $E_\gamma=477.6 \text{ keV}$. It is produced in the upper atmosphere by cosmic ray spallation of nitrogen and oxygen [8]. ^7Be is removed from atmosphere by wet and dry fallout. Wet fallout commonly accounts about 90 % of total ^7Be deposition flux to the soil surface and dry fallout is only about 10 % [9, 10, 11]. ^7Be fallout reaching soil surface is rapidly and strongly fixed by soil particles [7]. It is a rapid and irreversible sorption to soil particles upon fallout and transport over the timescale of interest [12]. Because of its short half-life, ^7Be is rarely found deeper than 2 cm [13]. Any ^7Be below 2 cm can be explained by the downward movement of soil particle through fissures formed during dry periods [14].

This paper reports on the use of ^7Be technique to document soil erosion within an agricultural field of Madagascar highland.

2. MATERIALS AND METHODS

2.1. Study site

Study area is located in Tsarazazamandimby village, approximately 20 km north-east of Antsirabe city, Vakinankaratra Region, and 100 km south of the capital Antananarivo (Fig. 1). Two field works were carried out: in December 2018 at the beginning of the rainy season, corresponding to 255 mm total rainfall, and in March 2020 at the end of the rainy season, corresponding to 694 mm total rainfall. Soil samples were collected from reference site and study site. Reference site is an undisturbed stable area nearby the study site, where neither erosion nor deposition has occurred. Study site is a cultivated site with slope up to 16% and composed of two plots: plot 1 (P1) with size of about 660 m² and 12% slope, and plot 2 (P2) with size of about 1780 m² and 10 % slope (Fig. 1). The cropping system consists of a rotation by four plants such as peanut, bean, maize and cassava. Downslope flat and wet areas are dedicated to rice cultivation. The soil is generally ferrallitic, with a bulk density of about 1080 kg.m⁻³.

During each field campaign, 10 soil bulk cores were collected randomly on reference site to determine the ⁷Be inventory, covering the period of investigation. In addition, one core was sectioned into 2 mm depth increments in order to determine the topsoil ⁷Be depth profile. Mabit et al. (2014) suggested that the number of samples collected on reference site should be at least 10 and not more than 15 bulk samples in order to have a good statistical precision of inventory [15]. At the study site, 35 soil bulk cores were collected along 3 transects: 11 samples from the first (T1), 11 samples from the second (T2) and 13 samples from the third transect (T3). Along each transect, sample interval was fixed to 5 m. The bulk core was sampled up to 5 cm depth in order to collect the totality of ⁷Be within the topsoil, using a soil sampler built by INSTN-Madagascar.

At INSTN-Madagascar laboratory, all samples were oven dried at 80°C overnight, manually crushed by pestle mortar, sieved through 2 mm mesh and put into air-tight polyethylene cylindrical containers for the sub-samples and Marinelli beakers for the bulk core samples. ⁷Be activities (Bq.kg⁻¹) were measured using Canberra gamma spectrometry system with 30% relative efficiency HPGe detector. Counting time was fixed to 24 hours.

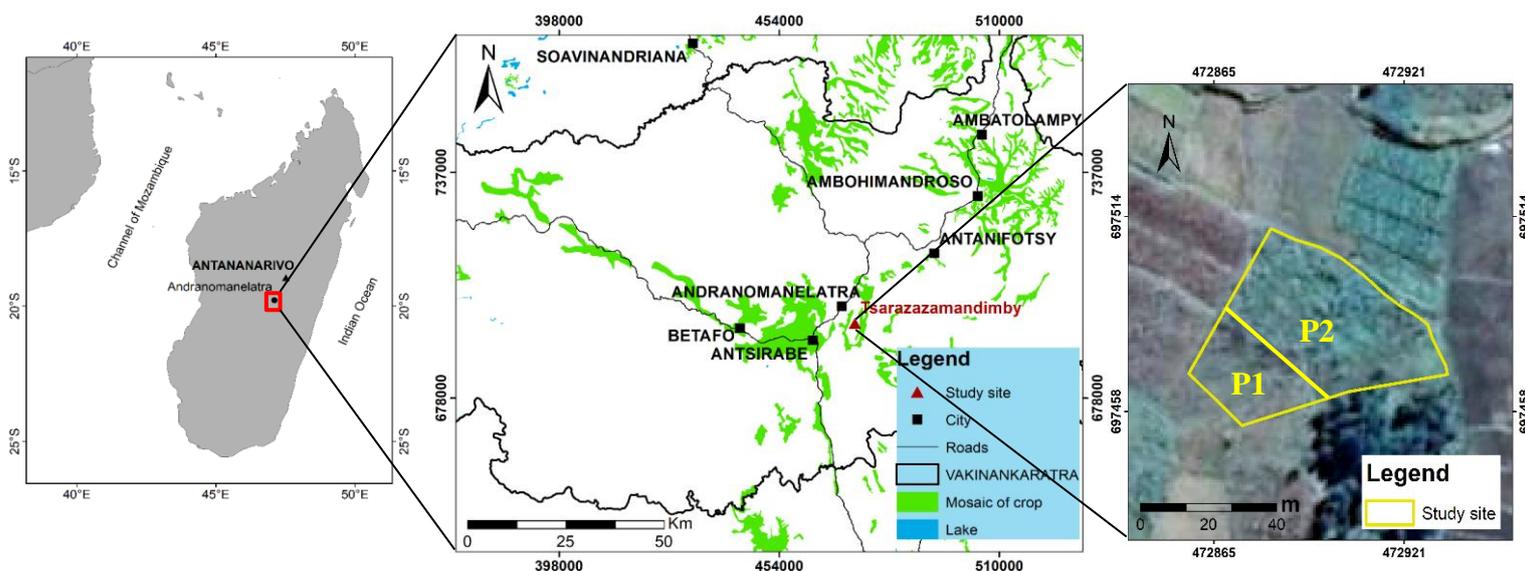


Figure 1: Localization of study site at Andranomanelatra, Antsirabe, Madagascar.

2.2. Equation

Profile Distribution Model has been used to convert the ⁷Be inventory (Bq.m⁻²) to soil redistribution rates (t.ha⁻¹). This model is suitable for cultivated or uncultivated site [16] and is based on the following equation [17]:

$$A_{Be}(x) = A_{Be}(0)e^{(-x/h_0)} \quad (1)$$

avec $A_{Be}(x)$: specific activity of ⁷Be at mass depth x (Bq.kg⁻¹)

$A_{Be}(0)$: specific activity of ⁷Be at soil surface (Bq.kg⁻¹)

x : cumulative mass depth (kg.m⁻²)

h_0 : relaxation mass depth (kg.m⁻²)

Relaxation mass depth describes the downward distribution of ⁷Be into the soil. For an exponential depth profile, 63 % of the total ⁷Be is retained in the depth 0 - h_0 . The higher value of h_0 indicates the deeper penetration of ⁷Be into the soil [18].

The $I_{Be,ref}$ reference inventory is the measured total ${}^7\text{Be}$ inventory at an uneroded stable site:

$$I_{Be,ref} = \int_0^{\infty} A_{Be}(x)dx = h_0 A_{Be}(0) \quad (2)$$

where, the $I_{Be}(x)$ is the ${}^7\text{Be}$ inventory below the depth x , given by the following equation:

$$I_{Be}(x) = \int_x^{\infty} A_{Be}(x)dx = h_0 A_{Be}(0) e^{(-x/h_0)} \quad (3)$$

The inventory below the relaxation mass depth is:

$$I_{Be}(h_0) = 0.368 I_{Be,ref} \quad (4)$$

Assuming that erosion removes a thin layer of mass depth R_{Be} ($\text{kg}\cdot\text{m}^{-2}$) at a sampling point within the study site. The ${}^7\text{Be}$ inventory remaining at this eroded point, $I_{Be}(x)$, will be lower than $A_{Be,ref}$. The soil mass eroded R_{Be} is equal to mass depth removed. By setting $x = R$ in Eq. (3), the remaining inventory at the sampling point can be calculated as:

$$I_{Be}(h) = \int_h^{\infty} A_{Be}(x)dx = h_0 A_{Be}(0) e^{(-h/h_0)} = I_{Be,ref} e^{(-h/h_0)} \quad (5)$$

The erosion rate R_{Be} can there be calculated by the following relation:

$$R_{Be} = h = h_0 \ln \frac{I_{Be,ref}}{I_{Be}} \quad (6)$$

Avec R_{Be} : erosion rate ($\text{kg}\cdot\text{m}^{-2}$)

I_{Be} : inventory at a given point on study site ($\text{Bq}\cdot\text{m}^{-2}$)

$I_{Be,ref}$: reference inventory ($\text{Bq}\cdot\text{m}^{-2}$)

h_0 : relaxation mass depth ($\text{kg}\cdot\text{m}^{-2}$)

h : depth of eroded soil ($\text{kg}\cdot\text{m}^{-2}$)

The value of erosion rate is preceded by a minus (-) sign.

When ${}^7\text{Be}$ inventory for a sampling point within the study site is higher than $I_{Be,ref}$, deposition is assumed to have occurred at this point. The sediment mass deposited per unit area R'_{Be} ($\text{kg}\cdot\text{m}^{-2}$) can be estimated as:

$$R'_{Be} = \frac{I_{Be} - I_{Be,ref}}{A_{Be,d}} \quad (7)$$

avec R'_{Be} : deposition rate ($\text{kg}\cdot\text{m}^{-2}$)

I_{Be} : inventory at a given point on study site ($\text{Bq}\cdot\text{m}^{-2}$)

$I_{Be,ref}$: reference inventory ($\text{Bq}\cdot\text{m}^{-2}$)

$A_{Be,d}$: mean activity concentration of ${}^7\text{Be}$ in the deposited sediment ($\text{Bq}\cdot\text{kg}^{-1}$)

The mean activity concentration of ${}^7\text{Be}$ in the deposited sediment $A_{Be,d}$ is calculated from the following relation:

$$A_{Be,d} = \frac{I_{Be,ref}}{\int_S R_{Be} dS} \int_S (1 - e^{-R_{Be}/h_0}) dS \quad (8)$$

Where S is the area where the sediment is mobilized.

To obtain soil redistribution rate in $\text{t}\cdot\text{ha}^{-1}$, the unit conversion relation is used: $1 \text{ t}\cdot\text{ha}^{-1} = 0.1 \text{ kg}\cdot\text{m}^{-2}$.

h_0 and A_{ref} are the two main parameters involved in the Profile Distribution Model.

2.3. Multivariate statistics

To be able to determine the erosion factor effects in the study site, it is necessary to create a database which, for the current study, contains six variables. Soil erosion is a quantitative and continuous dependent variable. Rainfall (in the context of the current study), land cover and plot are qualitative independent variables. Position and micro-slope are quantitative independent variables. The position is the distance of sampling point along the transect from the upper

slope. The micro-slope is the inclination between two successive sampling points, determined by the finite increment theorem. In the present study, the database contains 70 inputs which are the total number of sampling point during the two field works.

ANOVA (Analysis of Variance) test is used to determine the relation between soil erosion and the qualitative independent variables. It uses Fisher test to verify two hypotheses: the null hypothesis H_0 and the alternative hypothesis H_a in the following way [19]:

H_0 : no difference of the obtained erosion rate between values of a qualitative variable

H_a : existence of difference of the obtained erosion rate between values of a qualitative variable

The multivariate analysis is performed using the XLSTAT package.

Linear regression test is used to determine the relation between soil erosion and the quantitative independent variables. It is carried out by using the R software. Two hypotheses are also checked:

H_0 : the model is not interesting

H_a : the model is interesting

P-value is used to know the significance of H_0 . The following thresholds are generally taken for reference [20]:

$p \leq 0.01$: very strong evidence against H_0

$0.01 < p \leq 0.05$: strong evidence against H_0

$0.05 < p \leq 0.1$: weak evidence against H_0

$p > 0.1$: no evidence against H_0

The presumption against H_0 indicates the importance and significativity of H_a .

3. RESULTS

3.1. Model parameters

Relaxation mass depth h_0 obtained during the first and the second field works are 4.6 kg.m^{-2} and 5.0 kg.m^{-2} respectively, whereas the local reference inventories are $431 \pm 49 \text{ Bq.m}^{-2}$ and $530 \pm 50 \text{ Bq.m}^{-2}$ respectively.

3.2. Soil redistribution rates

During the first field campaign, erosion rates vary from -0.44 to -17.32 t.ha^{-1} , and deposition rates from 6.82 to 17.47 t.ha^{-1} (respectively, from -1.69 to -25.12 t.ha^{-1} , and from 1.76 to 13.30 t.ha^{-1} for the second field work). The net erosion rate is up to -2.88 t.ha^{-1} (during the 1st field work) and -7.55 t.ha^{-1} (during the 2nd field work), as summarized in the Table 1.

Table 1: Soil redistribution assessment on cultivated land of Andranomanelatra Antsirabe.

Soil redistribution parameters	1 st field work	2 nd field work
Mean erosion (t.ha^{-1})	-7.20	-11.99
Mean deposition (t.ha^{-1})	11.68	7.44
Gross erosion (t.ha^{-1})	-5.55	-9.25
Gross deposition (t.ha^{-1})	2.67	1.70
Net erosion (t.ha^{-1})	-2.88	-7.55
Sediment Delivery Ratio (%)	52	82
Eroded area (%)	77	77
Deposition area (%)	23	23

3.3. Effects of erosion factors

a. Effects of qualitative variables

Soil erosion rates are presented in Table 2, in relation to qualitative variables. The obtained results vary from $-0.69 \pm 9.63 \text{ t.ha}^{-1}$ to $-9.04 \pm 9.94 \text{ t.ha}^{-1}$.

Table 2: Effects of qualitative variables on soil erosion.

Variables	Soil erosion (t.ha^{-1})	
	Number of data	Mean \pm SD*
Rainfall 1	35	-2.88 ± 9.30
Rainfall 2	35	-7.55 ± 10.17
Plot 1	30	-9.04 ± 9.94
Plot 2	40	-2.34 ± 9.06
Land cover 1: cassava + peanut	35	-7.54 ± 10.17
Land cover 2: maize + bean	15	-5.80 ± 8.24
Land cover 3: cassava	20	-0.69 ± 9.63

*SD: standard deviation;

The obtained results from ANOVA test are presented in Table 3.

Table 3: ANOVA test between qualitative variables and soil erosion.

Dependent variable	Independent variables	F*	p-value
Soil erosion	Land cover	3.26	0.045
	Plot	8.62	0.01
	Rainfall	4.02	0.049

*F: Fisher

b. Effects of quantitative variables

The linear regression results related to the micro-slope and position effects are illustrated in Table 4.

Table 4: Linear regression model.

Linear regression			p-value
Type	Model		
Simple	$T = -2.1465 * M + 23.4382$	$R^2 = 0.6402$	2.2E-16
	$T = 0.7646 * P - 14.8259$	$R^2 = 0.508$	4.49E-12
Multiple	$T = -1.8008 * M + 0.1664 * P + 16.7309$	$R^2 = 0.6477$	6.66E-16

T : soil erosion (t.ha⁻¹), M : micro-slope (%), P : position (m)

The curves presented in figure 2 show various soil redistribution rates along the transects and in relation to the micro-slopes.

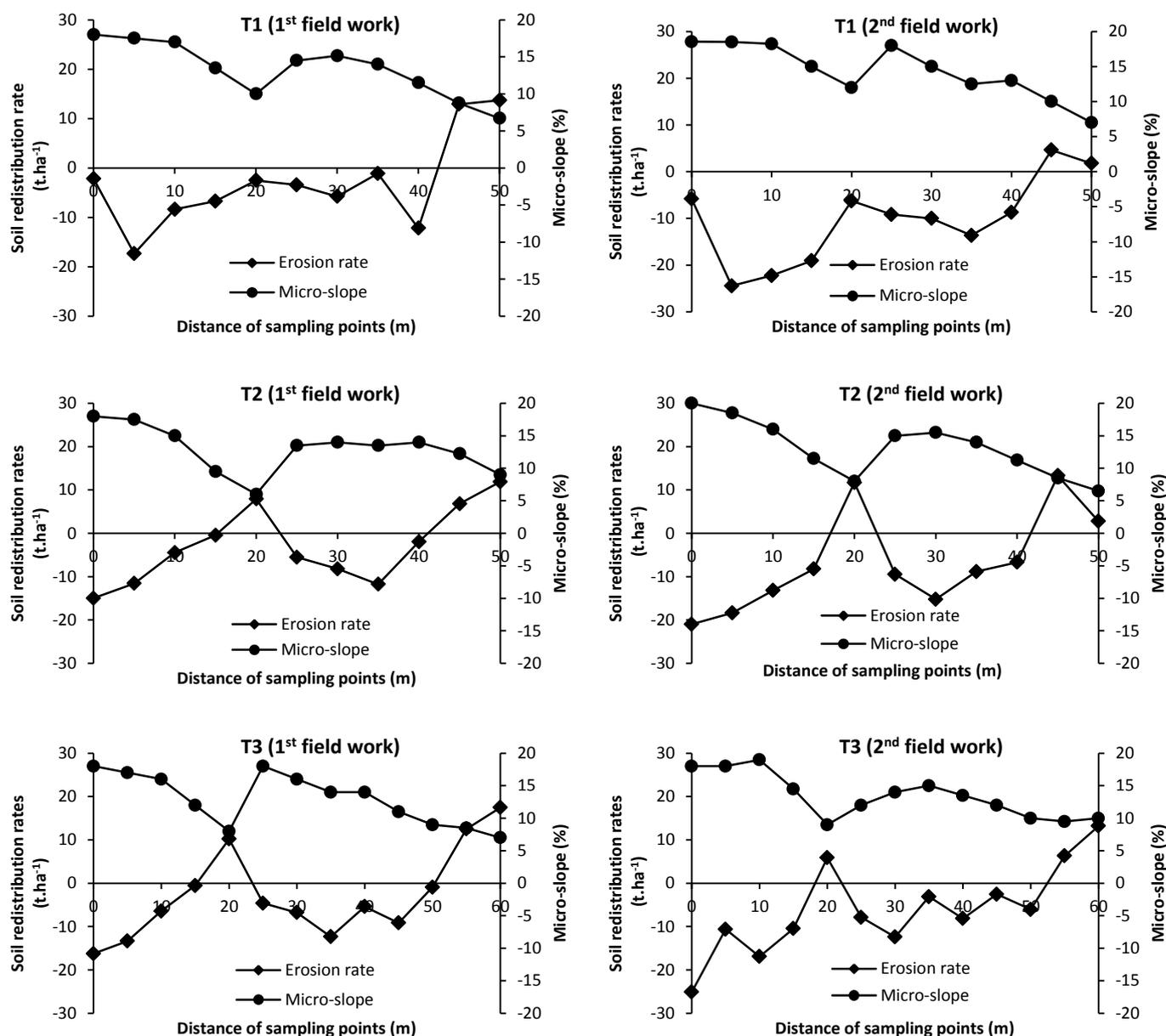


Figure 2: Soil redistribution rates related to the micro-slopes and the distance of sampling points.

4. DISCUSSION

The reference inventory value obtained during the second campaign is higher than during the first one. The difference is due to rainfall magnitude, which is abundant and more frequent during the second field work period. ^{7}Be fallout into soil surface increases with the quantity and the frequency of rainfall [21]. According to p-value in Table 3, rainfall changes cause also high difference on soil erosion value. Indeed, when rainfall and frequency of rain increase, soil became rapidly compact and saturated. Compaction reduces water infiltration capacity and saturation intensify runoff, increasing the surface soil redistribution [22].

Land cover change results in high difference on soil erosion value. This can be explained by the plant cover types and the difference of roots structures. Cultivated areas with cassava and peanut plants are more sensitive to soil erosion compared to other crops. This is due to the low soil cover and the slow growth of cassava plant [23]. Similarly, the peanut plant has also a low cover. Plant roots retain efficiently the soil particles [24]. Root structure of land cover 2 is dense compared to that of the land cover 1 and 3. Thus, the variation of root structure can explain the differences of the erosion values.

Result shows also that plot change results in difference on soil erosion values. In fact, (i) the length of plot 1 (20 m) is smaller than that of the plot 2 (~30m). In the shorter plot, runoff velocity is higher, indicating that the sediment amount leaving plot 1 is higher than that leaving the plot 2, (ii) the two plots are interdependent. As plot 2 is situated downslope of plot 1 and forms a sloped terrace, sediments leaving plot 1 are deposited on plot 2, minimizing soil erosion values on the latter. Indeed, land cover 3, located in plot 2, consists of cassava plants but the resulting soil erosion is lower than that of the other two land covers (Table 2). The low soil erosion value can be explained by the plot interdependence.

The plot p-value is lower than that of the land cover and rainfall (Table 3). It means that length and between plot interdependence have high influence on soil erosion compared to the two other variables.

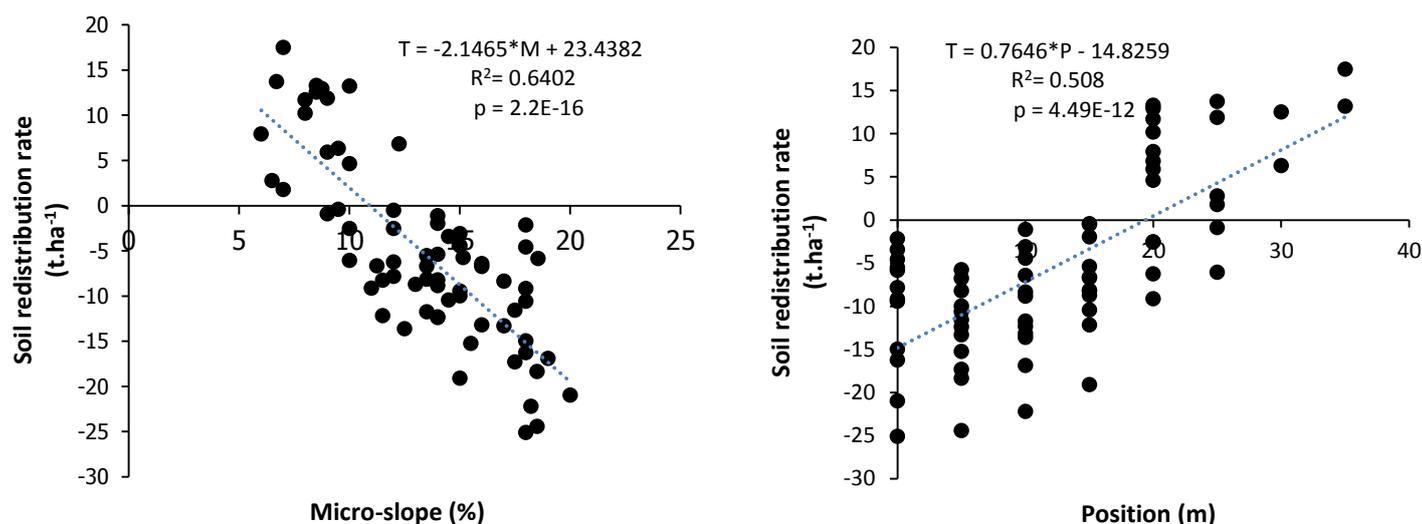


Figure 3: Trends of soil erosion in relation to micro-slope and position.

Concerning simple linear regression, the two very small p-values (2.2E-16 and 4.49E-12) mean that the two models obtained are interesting because they can separately and significantly explain the soil erosion variations. In algebraic term, negative correlation exists between micro-slope and soil erosion. It means that, on the one hand, when micro-slope increases above 10 %, it accentuates downward soil movement. On the other hand, when value is below 10 %, the micro-slope retains soil movement (Fig. 3).

Then, there is a positive correlation between position and soil erosion, meaning that when moving down slope and away from the top, there is more deposited sediment area. Thus, it confirms the downward soil particle movement. The micro-slope p-value is lower than the obtained value from the position parameter, allowing to say that micro-slope effect on soil erosion is higher than position effect. This dominance is due to the fact that micro-slope lower than 10 % retains soil movement.

Regarding the multiple linear regression, the obtained p-value indicates that the model is also interesting and confirms the previous statements. This model shows that 61% of erosion rate variabilities are explained by micro-slope and position together.

In summary, the net erosion value obtained during the 2nd fieldwork, which is twice that of the first one, can be explained primarily by rainfall. However, plot, land cover, micro-slope and position factors influence also the soil erosion variability.

5. CONCLUSION

In conclusion, the present work confirms the potential for using ^7Be technique to document soil erosion in agricultural land, especially in highland of Madagascar, associated with heavy rainfall period (< 6 months). Current results show that the net erosion obtained are -2.88 t.ha^{-1} and -7.55 t.ha^{-1} at the beginning and the end of the rainy season. The value obtained during 2nd fieldwork is twice that of the first one.

Using multivariate statistics, five soil erosion factors in cultivated site were investigated: rainfall, plot length and plot interdependence, land cover, micro-slope and position. These factor effects are:

- high rainfall and frequency increase soil erosion rate;
- Increased plot length reduces sediment delivery ratio;
- Soil loss from the lower plot is compensated by soil delivered from the upper plot;
- Plant with strong cover (i.e. maize) reduces soil erosion and plant with low cover (i.e. cassava and peanut) increases soil erosion;
- low micro-slope retains soil movement and steep micro-slope increases soil erosion;
- Soil erosion dominates in the upper part of the slope, whereas soil deposition dominates in the lower part.

Therefore, the variability of erosion values obtained during the two campaigns can be explained by these previous erosion factors.

In order to minimize erosion factor effects, it is advisable to plant crops with dense cover, otherwise to combine crops with low and dense cover. In addition, cultivation on flat field is proposed. In case of sloped terrain, the transformation into terrace reduces soil erosion phenomenon. Cultivated area should be long and large in order to reduce runoff velocity and to retain sediment. Finally, planting permanent downslope hedge would protect the sediment downward movement caused by the runoff.

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