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# Assessment of soil redistribution rates by $^{137}$Cs and $^{210}$Pb$_{ex}$ in a typical Malagasy agricultural field

N. Rabesiranana [a, *], M. Rasolonirina [a], A.F. Solonjara [a], H.N. Ravoson [a], Raoelina Andriambololona [a], L. Mabit [b]

[a] Institut National des Sciences et Techniques Nucléaires (INSTN - Madagascar), BP 4279, Antananarivo, 101, Madagascar
[b] Soil and Water Management & Crop Nutrition Laboratory, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, International Atomic Energy Agency, Vienna, Austria

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ABSTRACT

Soil degradation processes affect more than one-third of the Malagasy territory and are considered as the major environmental threat impacting the natural resources of the island. This innovative study reports about a pioneer test and use of radio-isotopic techniques (i.e. Cs-137 and Pb-210ex) under Madagascar agroclimatic condition to evaluate soil erosion magnitude. This preliminary investigation has been conducted in a small agricultural field situated in the eastern central highland of Madagascar, 40 km East from Antananarivo. Both anthropogenic Cs-137 and geogenic Pb-210 soil tracers provided similar results highlighting soil erosion rates reaching locally 18 t ha$^{-1}$ yr$^{-1,}$ a level almost two times higher than the sustainable soil loss rate under Madagascar agroclimatic condition. The sediment delivery ratio established with both radiotracers was above 80% indicating that most of the mobilized sediment exits the field.

Assessing soil erosion rate through fallout radionuclides in Madagascar is a first step towards an efficient land and water resource management policy to optimise the effectiveness of future agricultural soil conservation practices.

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## 1. Introduction

Soil degradation induced by human activity is a major concern in Madagascar. Its severity is very high for 21.9 percent of the area (130 081 km$^2$), high for 48.2 percent (286 007 km$^2$), moderate for 24.5 percent (145 153 km$^2$) and low for only 4.6 percent (27 094 km$^2$) (FAO, 2004). To summarise, more than 30% of the island's total soil area, covering 184 338 km$^2$, is degraded.

Soil erosion, the most common form of soil degradation, is present in all its aspects: rill and sheet erosions, landslides, gully erosion and its most emblematic form, the “*lavaka*”.

Soil erosion and sedimentation cause not only on-site degradation of non-renewable natural resources, but also off-site problems such as downstream sediment deposition in agricultural fields, floodplains and water streams. These impacting problems on soil fertility and crop productivity in agricultural land, on water pollution, on sedimentation in lakes, reservoirs, and floodplains are well documented (e.g. Pimentel, 2006; UNEP, 1992; Walling, 2000). Due to their impact on the sustainability of agricultural production, there is a clear need to acquire quantitative data on the extent, magnitude and actual rates of erosion/sedimentation as well as on their economic and environmental consequences.

From the mid-1950s, research activities on soil erosion and soil protection have been conducted intensively in Madagascar, resulting in more than 4200 scientific articles and technical documents (Chabalier, 2006). Studies were performed mainly using Wischmeier erosion plots, for 6 climatic zones in 20 sites, and at the catchment level in 11 sites. Experiments involved quantification of erosion extent, determination of Wischmeier equation parameters for local conditions, investigation on vegetation covering and agricultural practice effects (Chabalier, 2006). Most of the studies lasted 2–7 years. Long term experiments were rare because of logistic difficulties and maintenance cost.

Based on the Universal Soil Loss Equation also termed USLE (Wischmeier and Smith, 1978), four zones were identified in terms of soil erosion sensitivity: the western region with high rainfall erosivity (R > 900 MJ mm ha$^{-1}$ h$^{-1}$ a$^{-1}$) and soil erodibility

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* Corresponding author.
*E-mail address:* instn@moov.mg (N. Rabesiranana).

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($K > 0.2$ t h $MJ^{-1}$ $mm^{-1}$); the central highland with medium rainfall erosivity ($400 < R < 600$) and soil erodibility ($0.005 < K < 0.2$); the eastern central highland with medium rainfall erosivity but low soil erodibility ($K < 0.005$); and the eastern region with high rainfall erosivity ($R > 900$) but low soil erodibility ($K < 0.005$).

The average runoff coefficient was estimated at 25% of the rainfall and was mostly associated with 5–7 major rain and/or cyclone events each year. Depending on the region, the rainfall pattern and the experimental plot characteristics, soil loss measured from erosion plots can reach 500 t $ha^{-1}$ $a^{-1}$ (Andriamampianina, 1997). Even higher soil erosion magnitude has been reported at the catchment scale. For example, a study conducted in Madagascar on the siltation process of a dam reservoir at the lake Alaotra showed a specific erosion of 2000 t $ha^{-1}$ $a^{-1}$ for a density of 8 *lavaka* per $km^2$ within a catchment area of 58 $km^2$ (Mietton et al., 2006). The latest estimates propose figures of 200 up to 400 tons of soil per hectare which are annually removed by soil erosion, whereas the world average is around 11 tons. The majority of the erosive phenomena take place on the plateau and slopes which are used for crop production or as pastures (INSTAT, 2000).

However, despite the intensive research activities conducted during the last 60 years, the lack of direct field measurements makes the calibration and validation of conventional soil loss models difficult (Wischmeier, 1976). Another limitation is the difficulties in spatial and temporal extrapolations such as (1) upscaling of measurements from small bounded runoff plots into soil redistribution rates of fields or landscape units and/or (2) the limited validity of measurements conducted for 2–7 years to integrate climatic variability which require at least 10–15 years data record (Mabit et al., 2002). This is particularly true for investigation of long term impacts on soil erosion of traditionally tended agriculture, in which any parameter is far from being uniform or normalized when compared to runoff plots. Thus, existing classical techniques to document soil erosion are capable of meeting some of the needs, but possess important limitations. The quest for techniques as alternatives or to complement existing methods has directed attention to the use of fallout radionuclides (i.e. FRNs).

FRNs such as caesium-137 ($^{137}Cs$) and excess lead-210 ($^{210}Pb_{ex}$) have been initially uniformly distributed across the landscape via precipitation. The chemistry of both isotopes is well understood (Schultz et al., 1960; Davis, 1963; Robbins, 1978). When reaching the soil surface by wet or dry deposit, they are quickly and strongly adsorbed by fine soil particles and are essentially non-exchangeable in most environments (Tamura, 1964; Cremers et al., 1988; Robbins, 1978). Consequently, physical processes induced by water and/or wind are the dominant factors moving $^{137}Cs$ and $^{210}Pb_{ex}$-labelled soil particles within and between landscape compartments. Therefore, the measurements of $^{137}Cs$ (Ritchie and McHenry, 1990; Walling and He, 1999a) and $^{210}Pb$ (Wallbrink and Murray, 1993, 1996; Walling and He, 1999b) redistribution provide information on medium-term (~50 years) and long-term (~100 years) average soil redistribution rates and patterns, respectively.

$^{137}Cs$ and $^{210}Pb_{ex}$ are being increasingly used and validated worldwide to estimate soil redistribution rates (e.g. Dercon et al., 2012; Gaspar et al., 2013; Guzmán et al., 2013; Mabit et al., 2008, 2013, 2014; Zapata, 2002; Zupanc and Mabit, 2010). Several investigations undertaken in different environments have demonstrated that the use of these isotopes, either independently or in combination, affords a valuable means of assessing rates of soil loss and/or sediment deposition and possesses many advantages over the conventional monitoring or modelling techniques (Loughran, 1989; Mabit et al., 2008, 2013, 2014; Porto and Walling., 2012a,b). Main advantages include the potential for deriving retrospective estimates of erosion and deposition rates based on a single site visit and for assembling distributed information for individual points in the landscape, which can be used to study spatial patterns of soil redistribution as well as to validate erosion models (He and Walling, 2003).

On the African continent, investigations with FRNs for assessing soil erosion in agrosystems have been reported from locations in Northern Africa (e.g. Bouhlassa et al., 2000; Damnati et al., 2013; Nouira et al., 2003), in Western Africa (e.g. Junge et al., 2010) and in Southern Africa (e.g. Collins et al., 2001; Owens and Walling, 1996). But to date, FRNs have never been used in Madagascar to document soil erosion. In fact, the use of radioisotopic soil tracers such as $^{137}Cs$ and $^{210}Pb_{ex}$ in the Madagascar context raises several challenges.

Firstly, the $^{137}Cs$ fallout level is of one magnitude lower in the southern hemisphere than in the northern hemisphere. Moreover, the $^{137}Cs$ world fallout distribution map predicts even very low levels in the south-western Indian Ocean region (see Walling and He, 2000). This assumption was confirmed by several studies conducted at the national level in Madagascar highlighting low $^{137}Cs$ concentration in soil, mass activity of $^{137}Cs$ reaching only a few becquerels per kilogramme (Raoelina Andriambololona et al., 1998).

Secondly, the high rainfall erosivity and soil erodibility, combined with the steep landscape may result in $^{137}Cs$ depletion in soil.

Thirdly, despite several successful investigations performed using $^{210}Pb_{ex}$ as soil tracer in various agroecosystems (Mabit et al., 2014; Matisoff, 2014), $^{210}Pb_{ex}$ as a complementary radioisotopic approach is still questionable in Madagascar due to the limited available studies supporting its use at the regional level (e.g. Benmansour et al., 2013).

This study was therefore undertaken to test for the first time in Madagascar Island the potential of using $^{137}Cs$ and $^{210}Pb_{ex}$ to assess soil redistribution in a typical Malagasy agricultural field.

## 2. Material and methods

### 2.1. Site description

The study area is located in the eastern central highland of Madagascar, 140 km from the Indian Ocean, near Sambaina, Manjakandriana, 40 km East of Antananarivo (18°54′38″ S; 47°46′42″ E) at an altitude of 1400 m a.s.l. (Fig. 1).

This region experiences a highland tropical climate with two main seasons, a dry and cold winter and a warm and rainy summer.

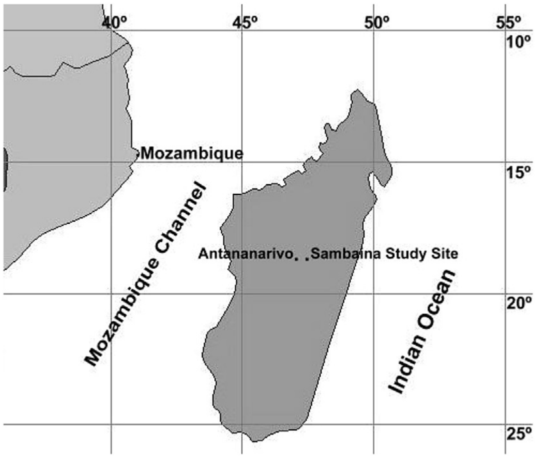

**Fig. 1.** Localisation of the study site.

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