Convert Fallout Cs 137 RadioNuclide Inventories into Soil Erosion Deposition Rates in Senegal Sites

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Abstract

Studies on the fallout of radionuclides using 137Cs as tracers which allows to estimate the rates of erosion and soil deposition was conducted. In this study, the reference inventory used was $414.27 \pm 71.21 Bq\ m^{-2}$ which is the value obtained in the regional African technical projects RAF 5075 funded by the IAEA. The conversion of inventory into erosion and deposition rates we have used MODERN. The new model MODERN (Modelling Deposition and Erosion rates with RadioNuclides) considers the precise depth distribution of any FRN at the reference site and allows adapting it for any specific site conditions. With MODERN the results show the erosion rate is $7.2t\ ha^{-1}\ yr^{-1}$, then with the conversion model: « Mass Balance model II » (MBMII) the erosion rates level varies between 1.3 to $43.0t.\ ha^{-1}.\ Year^{-1}$. The deposition rate assessed at the study site level with MODERN is in the range 7.4 to $8.1t\ ha^{-1}\ year^{-1}$ and varies between 8.54 to $45.68t\ ha^{-1}\ year^{-1}$ with MBMII.

Keywords: Cs137; Inventory; FRN, Erosion rate; Deposition rate; Conversion model; MODERN; ModeRn

Introduction

Soil losses represents one of the most important factors of production reduction worldwide [1] and it has effects on environment with high economic costs [2]. Soil Erosion in Senegal, like countries of the Sahel, is an important factor of land degradation problem. About 62% of Senegal's degraded arable land is due to water erosion, or 1,510,000 hectares and 12% to wind erosion, or 287,000 hectares [3].

Among the types of soil degradation in Senegal, erosion build most of it. The few publications on the study of these phenomena were based on traditional techniques like Universal Soil Loss Equation method, Water Prediction Project model, and Kinematic Runoff and Erosion method etc. For some time now, thanks to technical cooperation with the IAEA, Senegal has initiated studies on the fallout of radionuclides using 137Cs as tracers which allows to estimate the rates of erosion and soil deposition approximately between 50 to 60 years. For soil degradation studies, there are several methods to assess soil erosion/deposition rates [4], like Universal Soil Loss Equation method, Water Prediction Project model, and KINematic Runoff and Erosion method. The universal soil loss equation (USLE) is used for assessing the sheet and rill erosion, but not used for predicting the gully erosion. The gully erosion, caused by concentrated water flow is not counted by this equation, and as such can result greater volume of soil loss [5].

The Water Erosion Prediction Project (WEPP) model is utilized to simulate the sediment and runoff processes. According to previous studies, WEPP model provides impressive results in watersheds of diverse climates and scales but there is a perceived need to similarly validate the model for mine site conditions [6]. The Kinematic runoff and erosion model KINEROS is an event oriented, physically based model describing the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds. The watershed is represented by a cascade of planes and channels [7]. But monitoring the fallout radionuclides activity (FRN method) was recognized as powerful tool for studying the complete erosion and sedimentation cycle across the landscape [8]. For the methods (137) Cs, two theoretically conversion models, the profile distribution (PD) model and diffusion and migration (D&M) model were used to derive estimates of soil erosion and deposition rates from the

(137) Cs measurements. The estimates of soil redistribution rates derived by using the PD and D&M models were found to differ substantially and this difference was ascribed to the assumptions of the simpler PD model that cause it to overestimate rates of soil loss. The results provided by the D&M model were judged to more reliable [9]. By comparing these models, the MBMII model showed more relevant. It takes into consideration a few parameters to refine the results. So, the 137Cs technique can be used in Senegal to study erosion and soil deposition [10] with the MBMII. With the limitations of these models, we have used MODERN for estimate the erosion and deposition rate. MODERN (MOdelling Deposition and Erosion rates with RadioNuclides) is a code which have been developed in the Matlab environment and implemented in the R environment [11]. This model was proposed by Arata et al. (2016a, 2016b) and can be applied under every agro-environmental condition and land use, and it can accurately describe the measured soil profile of any selected FRN profile. This method allows to compare highly detailed inventory depth profiles of fallout radionuclides (FRN, radioactivity per unit area, i.e., Bq/m^2) used as reference site with depth-average- inventories obtained from sample sites [12].

In this paper we briefly introduce the FRN method and describe the concept and the algorithm at the base of the MODERN model. After we describe the modeRn package and the new functions implemented in the R package we have apply MODERN to our results obtained in the regional training course RAF 5075 funded by the IAEA for measured the erosion and deposition rates.

Materials and Methods

Evaluation of erosion and deposition rates with the FRN application

The main threats to soil stability and productivity are soil erosion but its monitoring remains a challenge. It's a long time the artificial radionuclide like the 137 Cs, the natural unsupported 210Pb fallout and cosmogenic 7Be, have been used like soil tracers to provide assess of soil erosion rates under different environmental conditions [8,13-15]). Once deposited on the soil, FRN firmly bind to fine particles at the surface soil and move across the landscape primarily through physical processes [16]. As such these radiotracers provide an effective trail of soil and sediment redistribution. The concept of the FRN method is based on the comparison between the inventory (total radionuclide activity per unit area) at a given sampling site and that of a so-called reference site, located in a flat and undisturbed area. If the FRN inventory at the sampling site is inferior than the reference site, the method indicates that the site experienced soil erosion processes since the main fallout. While, if the site presents a bigger FRN inventory than the reference site, the site experienced deposition processes (Figure 1). From the final comparison it is possible to drift quantitative assess of soil erosion and deposition rates through the usage of conversion models [16].
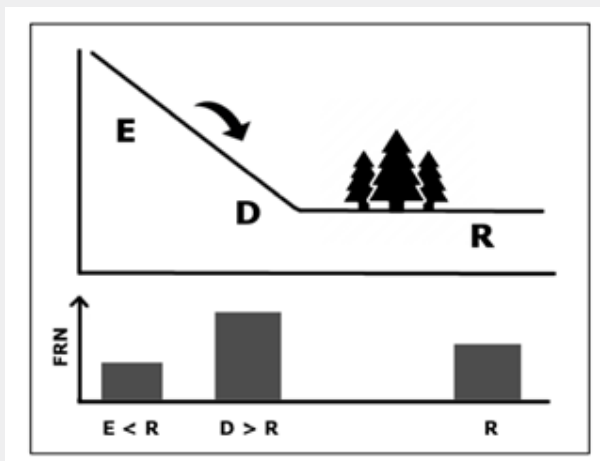

Figure 1: Design of the FRN method, where the content of a reference site (R) is compared to the FRN content of disturbed sites (E and D). If the FRN at the site is inferior than the reference site, the site knowledgeable erosion processes (E), while if the FRN content at the site is bigger than the reference site, the deposition processes (D).

The MODERN conversion model

MODERN is a new model which allows us to convert inventories (radioactivity per unit area) of radionuclide fallout (FRN) into soil erosion and deposition rates. FRN analysis is considered one of the most useful techniques developed over the past 50 years to study soil erosion processes [17]. The modeRn package includes a series of functions developed specifically to analyze FRN soil profiles and works the state-of-the-art method to compare a reference inventory (a soil profile with more than one layer that has at least one FRN value) to a sampling inventory (a soil profile with a single layer) to assess soil loss or gain [18].

This comparison allows us to obtain erosion or deposition rates from FRN inventories. In addition, modeRn helps the user to adapt the reference profile by presenting different physical scenarios of soil redistribution (e.g., ploughing or deposition processes) [19]. MODERN refers soil erosion and deposition rates in terms of thickness of the soil layer affected by soil redistribution processes. To estimate the thickness of soil losses/gains, MODERN aligns the total inventory of the sampling site to the depth profile of the reference site. The point of intersection along the soil profile represents the solution of the model [20,21].

The novelties of MODERN that differentiate it from other commonly used conversion models can be summarised by the following statements. MODERN does not make any assumption on the shape of the FRN depth profile, but accurately describes the measured shape of the FRN soil profile at reference sites. In addition, MODERN is capable to convert the FRN inventories of both erosion and deposition processes to soil redistribution rates, whereas other conversion models for uncultivated soils (e.g., the Profile Distribution Model, the Diffusion and Migration Model [22-26] are specifically developed to quantify rates of only one redistribution process. To increase the evaluation of soil redistribution rates, it allows adapting the depth profile, to simulate the behaviour of the selected FRN under different agro-environmental conditions.

Adaptations of MODERN of the reference FRN depth profile

Three mechanisms for adapting the FRN depth profile to the reference site can be achieved by MODERN. First, MODERN can simulate an arbitrary number of layers below the measured depth profile of the reference site [27]. In these simulated layers, MODERN displays the FRN inventories exponentially down to zero. Very frequently the lower layers of the measured FRN depth profile have a FRN activity, from the detection limit of the detector. At this comes, the resulting depth profile presents a steep step to zero concentrations in the lower layers of the profile. Therefore, MODERN permit simulating the missing FRN layers to create a deeper depth profile [28]. Secondly, MODERN enable an adaptation of the depth profile of the reference site to consider ploughing processes. Regular ploughing affects the FRN vertical distribution in the soil, as all soil layers down to the ploughing depth are mixed more or less homogeneously [29]. Therefore, to simulate similar mechanical mixing processes, MODERN adjusts the reference depth profile, where it assumes an average inventory value at the layers above the ploughing depth. Finally, to estimate deposition rates, MODERN allows defining different deposition scenarios, where the variability of sources with different FRN concentration can be considered. To this end, MODERN allows (i) simulating an arbitrary number of layers above the measured FRN depth profile, and (ii) defining the FRN inventory of each simulated deposited layer, on the basis of the assumptions on the origin of soil layers involved and the thickness of deposited sediment layers [30]. MODERN permits to perform multiple adaptations simultaneously and to adjust the reference depth profile to the specific shape encountered at sampling specific site [31]. The intention is to produce a range of potential solutions, which could be evaluated by expert knowledge (Arata et al. 2016b). Figure 2 show the evolution of the depth distribution of the selected FRN in the reference and sampling sites.
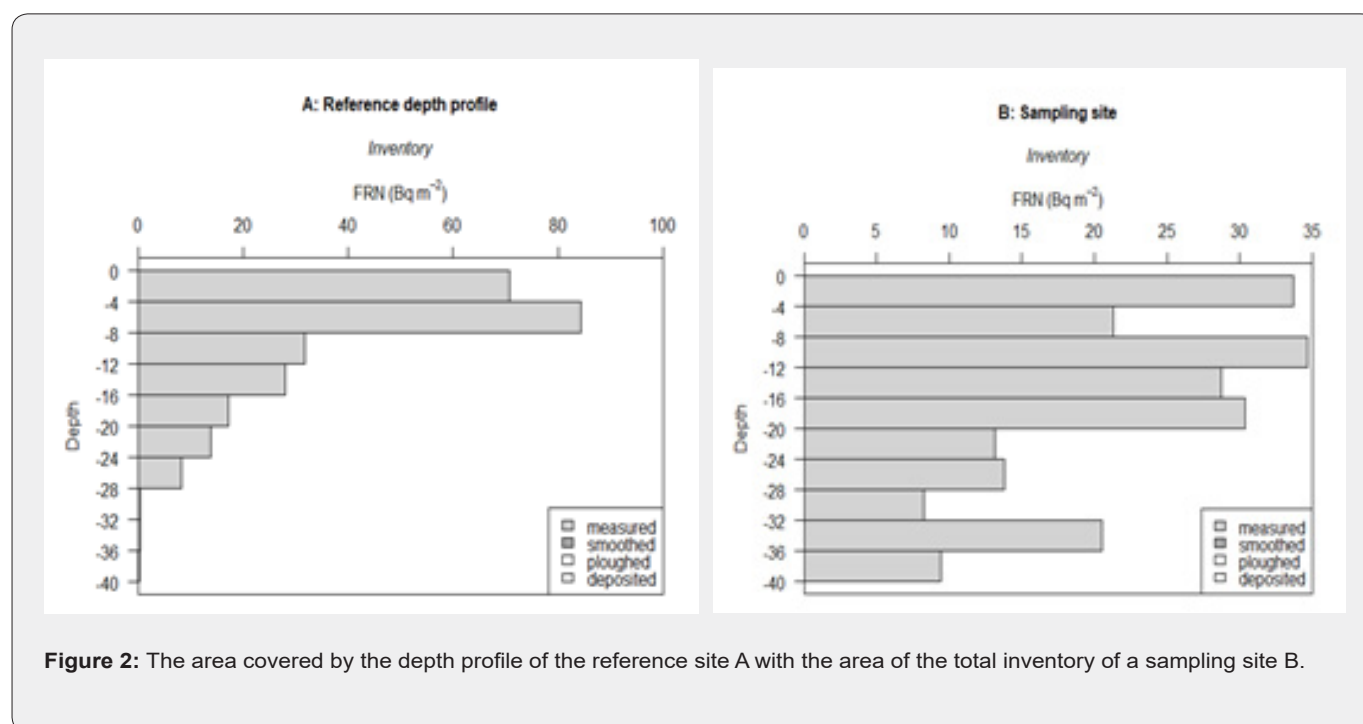

Figure 2: The area covered by the depth profile of the reference site A with the area of the total inventory of a sampling site B.

Method of resolution MODERN

With MODERN, the FRN depth profile of the reference site, possibly amended in order to reproduce different scripts (e.g., erosion or deposition, vertical mixing due to ploughing) is modelled as a step function g(x), which at each increment inc returns a value Invinc. If Inv is the FRN total inventory of a sampling site, measured for the whole depth profile d (cm), the model targets the level x*(cm) from x* to x*+ d (cm) along the soil profile, where the sum of all Invinc of the reference site is equal to Inv. Therefore, x* should fulfil the following equation:

$$\int_{x^*}^{x^*+d} g(x)dx = Inv \qquad (1)$$

Hence, the simulated depth profile, considering the possible adaptations of the profile, is described by the integral function S, where:

$$S(x) = \int_{x}^{x+d} g(x)dx \qquad (2)$$

The function S can be solved through the primitive function G of the distribution function g(x) as follows:

$$S(x) = G(x+d) - G(x) \qquad (3)$$

MODERN give the results in soil losses or gains (x), in length unit. The conversion to yearly soil losses or gains Y in t. ha^{-1}. yr^{-1} can be calculated using the following equation:

$$Y = 10 \times \frac{x^* . xm}{d.(t_1 - t_0)} \qquad (4)$$

Here x_m is the mass depth (kg.m^{-2}) of the sampling site, x^* is erosion or deposition rates in cm, d is the total depth increment considered at the sampling site (cm), t_1 is the sampling year (yr), and t_0 (yr) is the year of the main fallout.

The conversion of MODERN results to erosion/deposition rates

MODERN returns the results only in length unit, which correspond to the thickness of soil losses or gains, if the half-life of the isotope (halfLife), the fallout time (falloutTime), the sampling time (refTime) and the mass depth (massDepth), are not specified by the user when both the reference and the sampling profile are created. However, the function yearlyEDrates allows converting soil losses/gains into yearly soil erosion or deposition rates (t ha^{-1}. yr^{-1}) by the application of equation (4). The funcion accepts 6 arguments (i) the rates of erosion/deposition expressed in unit length or a MODERN object (rates); (i) the mass depth of the sampling site (kg.m^{-2}) (massDepth); (iii) the depth of the sampling profile (which should be expressed in the same unit of rates) (sampleDepth); (iv) the time of the measurement and (v) the time of the comparison (oldTime and newTime, respectively); (vi) the time format used to express the arguments oldTime and newTime (timeFormat).

Results and Discussion

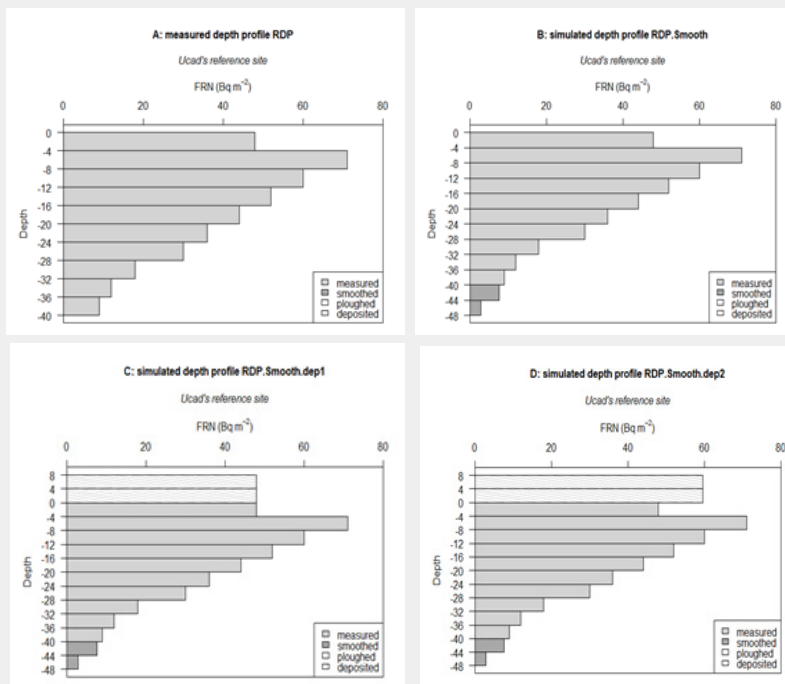### Application of MODERN of the results obtained

Figure 3: The FRN depth profiles at the Ucad reference site, where A: represents the measured one; B includes two additional simulated layers below the profile and C and D present the simulated profiles according to scenario 1 and 2 respectively.

In this results obtained, the reference inventory was 414.27 ± 71.21 Bq.m^{-2}. The list of FRN inventories (Bq.m^{-2}) measured at each depth increment of the profile, name is a new variable which stores the name of the reference site and layer. Thickness is the thickness of each layer of the profile (in this case 4cm). Using the function createReferenceProfile a new "Inventory" object called RDP is created. The name of the isotope used, its half-life expressed in seconds (i.e., 30.17 years = 951441000 seconds), the reference and the mean fallout years are also defined. Finally, the plot function creates the graphical representation of the reference site (Figure 3A). Two different adaptations of the RDP depth profile are performed. As for the first one, 8 cm of soil (equal to 2 layers of the same thickness as those of the reference profile) are simulated below the measured profile, where an exponential smoothing of FRN inventories is simulated. A new "Inventory object is created (RDP.smooth), where the FRN inventories of the simulated layers (Figure 3B), considering the FRN inventories of the three bottom layers of the measured depth profile (NumLay = 4). The second adaptation simulates two layers above the measured reference depth profile, to reproduce the soil deposition dynamics. In this case, [32] assumed two possible scenarios: two layers above the measured reference depth profile were modelled following two possible scenarios. For Scenario 1 (RDP.smooth. dep1) Figure 3C we admitted that sediments derive from an upslope top soil horizon (e.g. the first 4cm).

The FRN inventories of the additional layers were set to be equal to the inventory of the first 4 cm of the reference profile. For Scenario 2 (RDP.smooth. dep2) Figure 3D we hypothesize that the deposited materials originate from an eroded horizon of about 8 cm depth, which was homogenously mixed during detachment and transport processes. Therefore, FRN inventories of the additional layers are equal to the average inventory of the first 8 cm of the reference profile. For this step, the function addDepositionLayers () is used, and the new simulated profiles are plotted (Figure 3C & 3D). Note that each time, a new object of class "Inventory" is generated. The object contains, for each layer, information about the upper and lower depth limits (zup and zdown), the order of inserting (id) the mean, the standard deviation, the minimum and maximum value of the FRN inventory of each layer (mean.FRN, sd.FRN, min.FRN, max.FRN) and the origin of the layer (Origin, i.e., the way the values were obtained). At this point is possible to create an object, of class "Inventory", which represents a profile of a sampling site.

At this point is possible to create an object, of class "Inventory", which represents a profile of a sampling site. In this study we have taken two points in each of the two transects being two sampling sites (i.e., site A and site B) are defined, where site A presents a lower FRN inventory than the reference site (350.0Bq m^{-2}), indicating erosion, while site B has a higher FRN inventory than the reference site (429.0Bq.m^{-2}), highlighting deposition processes. At both sites the FRN inventory is measured until a depth of 40 cm. With the package we have created the profile of

Bargny' site. Finally, is possible to run the comparison between the simulated depth profile of the Ucad reference sites and the profiles of the Bargny site, through the algorithm of the MODERN model. For the example presented in this study three objects of class "MODERN" are been created.

Where MODERN_siteA_1 compares the profile of site A with the simulated depth profile RDP.smooth. As site A is an erosional site, it is not necessary to simulate any deposition dynamics. The objects MODERN_siteB_1 and MODERN_siteB_2 compare the profile of the sampling site B to the simulated reference depth profile according to scenarios 1 and 2, respectively. In particular, the function plot () shows two plots, where the left one presents the overlapping of the two profiles used in the comparison), while the right one presents the line of the function S as in equation (3). The solution, which represents the point of intersection along the soil profile, is visualized in red in both plots (Figure 4).

As an example, we will show a hypothesis in which the inventories of two sampling sites are evaluated against a fictive reference site (i.e., site R), whose total FRN inventory is assumed to be 414.27Bq m^{-2}. The shape of the depth profile is characterized by a FRN peak in the subsurface horizon with an exponential decline below (Figure 4). The first of the two sampling sites (i.e., site A) presents a lower FRN inventory than the reference site (Inv = 350.00Bq m^{-2}), which indicates erosion, while the second (i.e., site B) has a higher FRN inventory than the reference site (Inv = 429.00Bq m^{-2}), highlighting deposition process. At both reference and sampling sites the FRN inventory is measured until a depth (d) of 40cm. At the reference site the depth increments (inc) are 4cm each (Table 1).

As a step, two layers below the measured depth profile are simulated to reach a zero content layers with an asymptotic function (as described above) (Figure 4). In order to simulate deposition processes at Site B, two layers above the measured reference depth profile were modelled following two possible scenarios. For Scenario of the Figure 4A, we hypothesize that sediments derive from an upslope top soil horizon (e.g. the first 4cm). The FRN inventories of the additional layers were set to be equal to the inventory of the first 4cm of the reference profile. For Scenario of the Figure 4B & 4C the authors hypothesize that the deposited materials originate from an eroded horizon of about 8cm depth, which was homogenously mixed during detachment and transport processes. Therefore, FRN inventories of the additional layers are equal to the average inventory of the first 8cm of the reference profile.

Discussion of results obtained

In case of erosion (site A), MODERN estimates a soil loss of 3.8cm, independently of the scenario assumed. If the site is affected by deposition (site B), there are different solutions for the scenarios considered. In our example, MODERN returns a deposition of 3.9cm for Scenario 1 and a deposition of 4.2cm for Scenario 2. To obtain the mass of the eroded soil Y, a mass depth of

386.5 kg m-2 has been assumed for the sites A and B. To calculate yearly erosion or deposition rates, we assumed the peak fallout (t_0) of the FRN to be 1963 and the sampling year (t_1) to be the year 2014. The resulting solution is an erosion rate of 7.2t ha^{-1} yr^{-1} at site A and a deposition magnitude of 7.4 and 8.1t ha^{-1} yr^{-1} depending on the scenario chosen for site B.
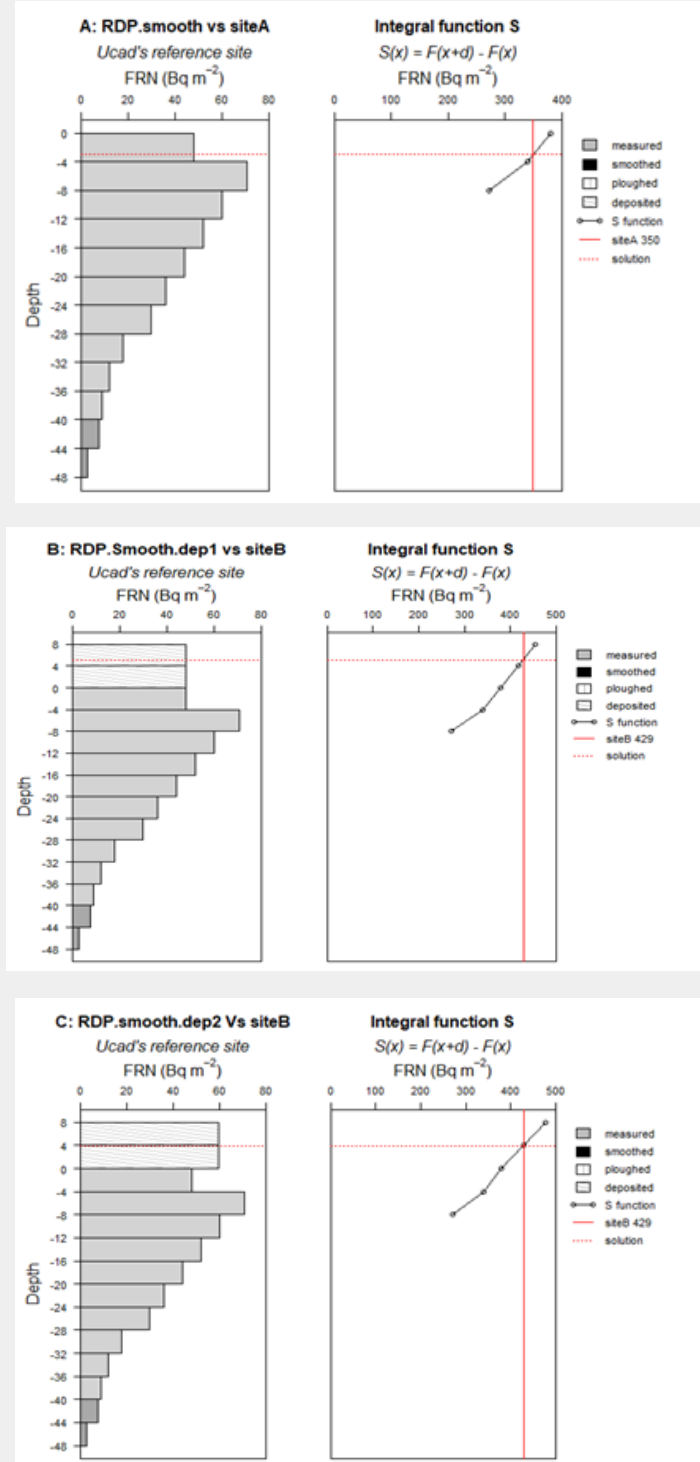

Figure 4: The graphical representation of the MODERN model solution for site A (A) and site B (B and C according to deposition scenarios 1 and 2 respectively.

Table 1: Parameters included in MODERN.

Parameter	Description
Invinc	FRN inventory at the reference site at each increment inc (Bq m^{-2})
Inc	Depth increment of the reference site (cm)
Inv	FRN inventory at the sampling site (Bq m^{-2})
d	Depth increment of the sampling site (cm)
P	Particle size (unitless)
pd	Ploughing depth (cm)
g(x)	Function describing the FRN depth profile of the reference site (Bq m^{-2})
S(x)	Simulated total inventory of reference sites (Bq m^{-2})
x*	Erosion or deposition rates (cm)
xm	Mass depth of the sampling site (kg m^{-2})
t1	Sampling year (yr)
t0	Reference year (yr)
Y	Erosion or deposition rates (t ha^{-1} yr^{-1})

The average erosion rate estimated with MODERN is 7.2t ha^{-1} yr^{-1}, then with the conversion model: « Mass Balance model II » (MBMII) the erosion rates level varies between 1.3 to 43.0t. ha^{-1}. year^{-1}. The deposition rate assessed at the study site level with MODERN is in the range 7.4 to 8.1t ha^{-1} year^{-1} and varies between 8.54 to 45.68t ha^{-1} year^{-1} with MBMII.

The results show that the erosion rate obtained by MODERN is in the range of values of the rates obtained by MBMII and for the deposition rates a difference was noted for the deposition rates obtained by MODERN and that obtained by MBMII. The latter may be due to the fact that MODERN assumes an exponential decline of 137Cs in the measured depth profile. MODERN instead follows the real 137Cs depth distribution.

Conclusion

This article presents the modeRn package for the evaluation of erosion and deposition rates from the FRN Inventories of on reference and sampling sites in Senegal such as the Ucad reference site and the Bargny study site. MODERN, is based on a unique algorithm and a clear and transparent concept. The ability of MODERN to reproduce precisely any FRN depth profile permits a high adaptability to different environmental conditions. The FRN depth profile in the reference site plays a fundamental role in the conversion of FRN inventories into soil redistribution rates, as it is often implemented to describe the shape of FRN depth distribution in the investigated sites before disturbance. The package architecture permits to easily implement and manage FRN inventories in a flexible object class, able to consider the variability of FRN values at each site. Convenient functions are available for simulating different adaptations of the FRN depth profile. Specific plotting and printing functions return the results in a user-friendly way. This package will increase the ability to investigate the impact of the uncertainty in the FRN inventories estimation via the use of statistics tools available in the R platform.

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