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Modelling Deposition and Erosion rates with RadioNuclides (MODERN) – Part 1: A new conversion model to derive soil redistribution rates from inventories of fallout radionuclides

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ABSTRACT

The measurement of fallout radionuclides (FRN) has become one of the most commonly used tools to quantify sediment erosion or depositional processes. The conversion of FRN inventories into soil erosion and deposition rates is done with a variety of models, which suitability is dependent on the selected FRN, soil cultivation (ploughed or unploughed) and movement (erosion or deposition). The authors propose a new conversion model, which can be easily and comprehensively used for different FRN, land uses and soil redistribution processes. 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. MODERN adaptability and performance in converting different FRN inventories is discussed for a theoretical case as well as for two already published case studies i.e. a ^{137}Cs study in an alpine and unploughed area in the Aosta valley (Italy) and a $^{210}Pb_{ex}$ study on a ploughed area located in the Transylvanian Plain (Romania). The tests highlight a highly significant correspondence (i.e. correlation factor of 0.91) between the results of MODERN and the published results of other models currently used by the FRN scientific community (i.e. the Profile Distribution Model and the Mass Balance Model). The development and the cost free accessibility of MODERN (see modern.umweltgeo.unibas.ch) will ensure the promotion of wider application of FRNs for tracing soil erosion and sedimentation.

1. Introduction

Soil erosion is one of the major threats to soil stability and productivity but its monitoring remains a challenge. In the last 50 years, fallout radionuclides (FRN), e.g artificial ^{137}Cs and $^{239+240}Pu$, natural ^{210}Pb fallout and cosmogenic ^{7}Be, have been widely used as soil tracers to provide estimates of induced soil erosion rates under different environmental conditions (e.g. Ritchie and McHenry, 1990; Walling and He, 1997; Ritchie and Ritchie, 2001; Zapata, 2002; Mabit et al., 2008). Once deposited on the ground, FRN strongly bind to fine particles at the surface soil and move across the landscape primarily through physical processes (IAEA, 2014). As such these conservative radiotracers provide an effective track of soil and sediment redistribution.

FRN methods perform efficiently to investigate temporal soil redistribution processes for arable lands, where soil degradation due to agriculture practices affects soil properties and landscape processes (IAEA, 2014). It is also highly effective in assessing erosion and deposition patterns in mountain grasslands where the extreme topographic and climatic conditions hinder the application of more conventional techniques such as sediment traps, erosion pins or experiments under simulated rainfall (Konz et al., 2012; Alewell

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et al., 2014).

The FRN method provides information of erosion processes affecting a specific study area since the time of deposition of the selected FRN and can be performed during a single sampling campaign, thus avoiding time-consuming and costly procedures commonly required to monitor sites over extended time periods (Mabit et al., 2008, 2013). The method is based on a targeted FRN comparison: the inventory (total activity per unit area) at a given sampling site versus the inventory measured in an adjacent and undisturbed reference site, where no soil erosion and deposition have occurred.

One of the major challenges regarding the application of FRN as soil tracers is the conversion of FRN inventories to quantitative estimates of soil redistribution. Different conversion models have been proposed by the scientific community and differ mainly in their underlying assumptions of soil stratification and descriptions of FRN transport processes (IAEA, 2014). Current available models range from relatively simple (e.g the Profile Distribution Model, Walling and Quine, 1990 or the Inventory Method by Lal et al., 2013) to more complex (e.g. Mass Balance Model and the Diffusion and Migration Model (Walling et al., 2002),). As the depth distribution of FRN is strongly dependent on cultivating measures such as ploughing, different models have been developed for ploughed or unploughed soils (please note that previous studies used the terms ploughed, cultivated and disturbed versus unploughed, uncultivated and undisturbed synonymously. The authors think that the pair ploughed and unploughed are the most precise terms, as unploughed grasslands are indeed cultivated and might be seriously disturbed).

The Profile Distribution Model (PDM) (Walling et al., 2002, 2011, 2014) is a very convenient model to estimate erosion rates of unploughed soils. However, as highlighted by Walling et al. (2014), it involves a number of simplifying assumptions on the depth distribution of FRN in the soil (e.g., the exponential depth distribution of FRN in the soil). The Mass Balance Model (MBM) and the Diffusion and Migration Model (DMM) (Walling et al., 2002, 2011, 2014) consider different vertical distribution of the FNR in the soil depending on the land use (ploughed or unploughed) and on the migration processes since the main FRN deposition. In ploughed soils, the Mass Balance Model assumes FRN to be mixed uniformly within the plough layer. In unploughed soils, the Diffusion and Migration model considers the downward diffusion and migration of FRN in the soil profile, and that most of the FRN is located near the surface, usually in the upper 15 cm (Walling et al., 2002).

The MBM and the DMM algorithms include parameters which should accurately describe the physical processes affecting FRN distribution in the soil since the main fallout. The values of these parameters, if not carefully selected, can significantly bias the results of soil erosion calculations (Poręba and Bluszcz, 2008; Iurian et al., 2014). Moreover, their algorithms change when measuring erosion or deposition rates, as different sediment dynamics are considered.

The International Atomic Energy Agency (IAEA) has supported the development of an Excel™ based software which allows the conversion of FRN inventories into soil redistribution rates, through the application of different models (among them the PDM, the DMM and the MBM). The software was initially developed for ^{137}Cs and later extended for the application of ^{7}Be and $^{210}Pb_{ex}$ (Walling et al., 2014). The software is public and freely downloadable, but its code is not editable and thus cannot be adapted to specific environmental conditions (e.g. a particular depth profile of the FRN distribution) or be used for other FRN such as $^{239+240}Pu$.

The aim of this study is to present a new conversion model, called MODERN (Modelling Deposition and Erosion rates with RadioNuclides). The MODERN model is based on a unique algorithm to convert FRN inventories into both erosion and deposition rates. It can be applied under every agro-environmental condition and land use, and accurately describes the soil profile shape of any selected FRN. The MODERN code is transparent and easily adaptable, and can be freely and publicly downloaded. The development of MODERN aims to promote the use of FRN as soil erosion tracers for scientific and applied purposes.

2. MODERN: Modelling Deposition and Erosion rates with RadioNuclides

2.1. Model concept and assumptions

MODERN (Modelling Deposition and Erosion rates with RadioNuclides) is a new model able to convert inventories of FRN into soil redistribution rates. One key advantage of MODERN is its ability to describe accurately specific depth distribution of any FRN in the soil, independent of its depth function's shape. Moreover, MODERN can be applied under various land use conditions (i.e. ploughed and unploughed soils).

The underlying idea behind the model is the comparison of the depth profile of the reference site with the total inventory of a sampling site. MODERN returns 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 (Fig. 1). As with all conversion models, a key assumption of MODERN is that the evolution of the depth distribution of the selected FRN is the same at the reference and the sampling sites. If the soil properties of reference and sampling sites are comparable, the mechanisms influencing the downward diffusion and migration of the radionuclide in the soil should also be similar. MODERN also take into account other assumptions usually undertaken for the application of FRN as soil erosion tracers (e.g. uniform spatially distribution of the local fallout; Rapid, strong and non-exchangeable adsorption of FRN to fine soil particles; Soil associated redistribution of FRN through physical processes). Compared to other models (i.e. the Diffusion Migration Model and the Mass Balance Model) the application of MODERN does not require a transect sampling approach, where the sampling points need to be located along a transect, but performs efficiently also when the sampling points are spatially scattered.

2.1.1. Adaptation of sampling depth

Difference in sampling depths between reference and sampling sites can be also accounted for by MODERN. At the reference site, the soil sample is cut in depth increments, which are measured separately to derive information on the depth distribution of the FRN in the soil. However, deeper layers contain very low FRN activities. As these layers are bulked within a fixed depth, the low activities may result in values below the detection limit of a detector. The resulting depth profile of FRN distribution at the reference site then may have an abrupt step to zero concentrations in the lower layers of the profile (Fig. 2, upper left). Instead, at the sampling site, the soil sample is not cut in depth increments, but all the soil within a certain depth is bulked together, and the FRN inventory is measured as a mean value of the whole soil profile. As a result, the depth to which the FRN inventory is measured at the sampling site may be deeper than the one of the last reference depth increment with activity above the detection limit, and the comparison between the FRN inventories of the two sites may be biased. If this is the case, MODERN can adapt the depth distribution of the reference site and simulate an arbitrary number of layers below the measured depth profile. In those simulated layers

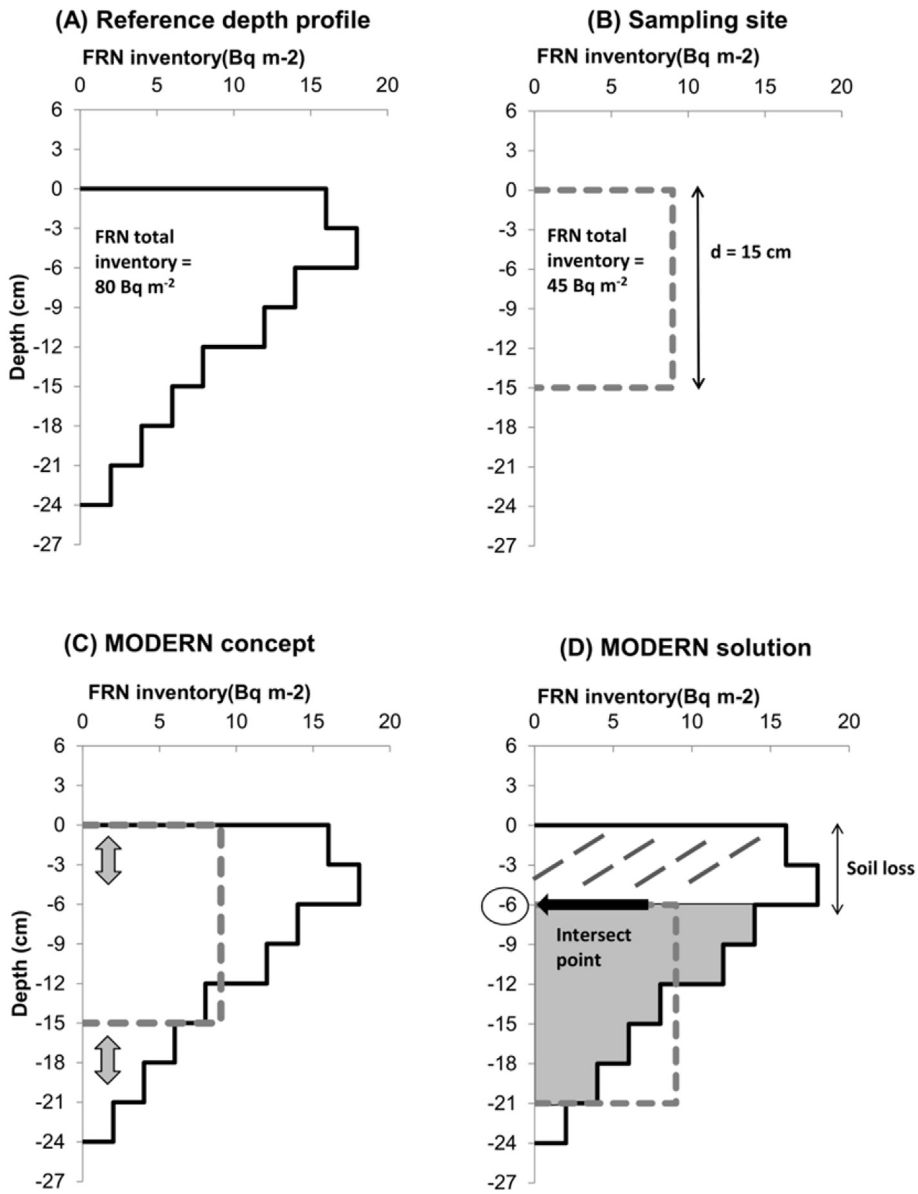

Fig. 1. Concept of MODERN.MODERN compares the area covered by the depth profile of the reference site (A) with the area of the total inventory of a sampling site (B). MODERN overlaps the two area (C) until it finds the intersect point where they match (D).

MODERN smooths the FRN inventories exponentially to zero (Fig. 2, Adaptation 1). It is important to notice that such an adaptation of the depth profile is optional. However, without it, MODERN might not be able to find a solution if the sampling site has a FRN inventory lower than the inventory of the last measured layer of the reference depth profile.

2.1.2. Considering ploughed versus unploughed land management

The determination of soil erosion at ploughed sampling sites very often confronts with the problem of finding an undisturbed reference site. Often these reference sites may be unploughed grasslands with very different FRN depth distribution compared to the ploughed sampling site. When comparing an undisturbed reference site to a ploughed site, MODERN allows an adaptation of the depth profile of the reference site to consider the processes that affect soil redistribution. Regular ploughing affects FRN vertical distribution in the soil, as all soil layers up to the ploughing depth are mixed more or less homogeneously. 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 (Fig. 2, Adaptation 2).

2.1.3. Modelling deposition of eroded material

In case of higher FRN inventory at the sampling site compared to the reference site, net deposition of material is assumed. The assessment of deposition rates with FRN always requires assumptions on the origin of soil layers involved and the thickness of deposited sediment layers. The contributing area of the sediment is variable. Deposition material may origin from a large contribution area including mostly topsoil material or from a small area including also deeper soil layers. A variability of sources with different FRN concentration can be considered in MODERN. An arbitrary number of layers can be simulated above the measured FRN depth profile, and the FRN inventory of each simulated deposited layer can be defined (deposition scenario). Multiple likely deposition scenarios can be evaluated (Fig. 2, Adaptation 3).

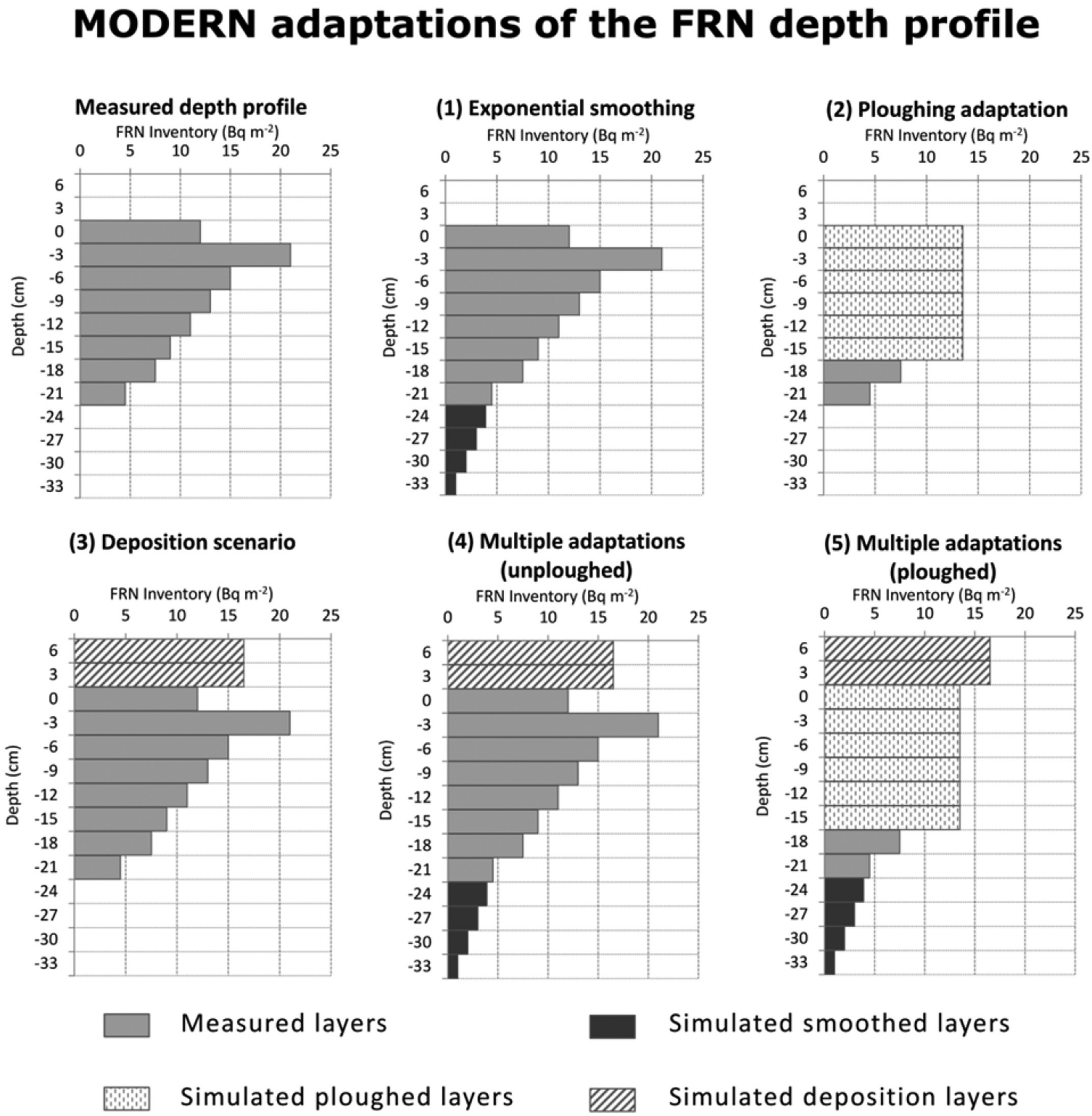

Fig. 2. Possible adaptations of a FRN depth profile performed by MODERN. Upper left: a hypothetical depth profile, measured in depth increments of 3 cm, from 0 to 21 cm; (1): MODERN's adaptive simulation of 4 additional layers below the last measured layer of the depth profile, with an exponential smoothing of the FRN inventories. (2): MODERN's adaptive simulation of mixing processes of FRN distribution due to ploughing activities, with ploughing depth = 15 cm; (3): MODERN simulation of 2 additional layers above the measured depth profile, with sediments originated from an horizon of 6 cm depth, which was homogenously mixed during detachment and transport; (4): MODERN simulation of a depth profile as a result of a combination of multiple adaptations in an unploughed site; (5): MODERN simulation of a depth profile as a result of a combination of multiple adaptations in a ploughed site.

2.1.4. Considering particle size selectivity

The particle size factor is particularly important as water erosion triggers a selective and preferential loss of small grain size fractions. Moreover, the distribution of FRN in soil also demonstrates a significant preferential adsorption of these radionuclides by finer soil particles (He and Walling, 1996). Usually eroded sites are depleted in small-particle fractions while reference sites display the original grain size composition. As fine soil particles are preferentially eroded this will result in an overestimation of FRN based erosion rates if the erosion selectivity is not taken into consideration. However, the authors acknowledge that measuring the particle size factor for a specific site can be very challenging. If a particle size factor is determined, it is possible to consider it in MODERN, by simply dividing the results by it.

MODERN permits to perform multiple adaptations simultaneously and to adjust the reference depth profile to the specific conditions encountered at each sampling site (Fig. 2, Adaptation 5). Then, it is possible to produce a range of potential solutions, which need to be evaluated by expert knowledge and can be considered as uncertainty assessment.

2.2. Model solving method

Using MODERN, the FRN depth profile of the reference site is modelled as a step function *g(x)*, which at each increment *inc* returns a value Inv_{inc}. Please, note that MODERN does not make any assumption or generalization on the shape of the reference site depth profile, but it reproduces accurately the specific measured depth distribution of the FRN. Finally, *Inv* is the FRN total inventory of a sampling site, measured for the whole depth profile *d* (cm) (Table 1).

The model targets the level $x^*(cm)$ from x^* to $x^* + d$ (cm), where the sum of all Inv_{inc} of the reference site is equal to the total FRN inventory of the sampling site, *Inv*. Therefore x^* should fulfil the following equation:

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

In order to find all possible solutions, a number of simulated layers, are added below and above the reference profile (see 2.1. above and Fig. 1), to assess potential soil losses or gains. The new simulated depth profile is described by the integral function *S*, where:

$$S(x) = \int_{x}^{x+d} g(x\prime)\mathrm{d}x\prime \tag{2}$$

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

$$S(x) = G(x+d) - G(x) \tag{3}$$

MODERN returns the results in cm of soil losses or gains. The conversion to yearly soil losses or gains *Y* in t ha^{-1} yr^{-1} can be calculated using the following equation:

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

where *xm* is the mass depth (kg m^{-2}) of the sampling site, *d* is the total depth increment considered at the sampling site as above, t_1 is the sampling year (yr), and t_0 (yr) is the reference year. In case the selected FRN are artificial the latter can be either the year of the main fallout or the year when a particular environmental condition occurred (e.g. a major change in the land use). When using natural radionuclides, as $^{210}Pb_{ex}$ and ^{7}Be, the investigated time window can be adjusted accordingly. In particular, the application of $^{210}Pb_{ex}$ provides a retrospective assessment of long-term soil redistribution rates over a period of up to 100 years (Mabit et al., 2008). Conventionally, the parameter t_0 (yr) is set to 100 years prior to the sampling year t_1. The very short half-life of ^{7}Be (53 days) permits to trace short-term erosion processes, on a time window of maximum 6 months (IAEA, 2014).

3. Application of MODERN

3.1. A theoretical example

As an example, a hypothetical situation is presented where the inventories of two sampling sites are compared to a fictive reference site (i.e. site R), whose total FRN inventory is assumed to be 100 Bqm^{-2}. The shape of the depth profile is characterized by a FRN peak in the subsurface horizon with an exponential decline below (Fig. 3). The first of the two sampling sites (i.e. site A) presents a lower FRN inventory than the reference site ($Inv = 78$ Bq m^{-2}), which indicates erosion, while the second (i.e. site B) has a higher FRN inventory than the reference site ($Inv = 115$ Bq m^{-2}), highlighting deposition process. At both reference and sampling sites the FRN inventory is measured until a depth (*d*) of 30 cm. At the reference site the depth increments (*inc*) are 3 cm each.

As a first step, two layers below the measured depth profile are simulated to reach a zero content layers with an asymptotic function (as described above) (Fig. 3). 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 1, the authors hypothesize that sediments derive from an upslope top soil horizon (e.g. the first 3 cm). The FRN inventories of the additional layers were set to be equal to the inventory of the first 3 cm of the reference profile. For Scenario 2 the authors hypothesize that the deposited materials originate from an eroded horizon of about 6 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 6 cm of the reference profile (Fig. 3, Scenario 1 and Scenario 2).

In case of erosion (site A), MODERN estimates a soil loss of 4.6 cm, 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

Table 1
Parameters included in MODERN.

Parameter	Description
Inv_{inc}	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})
t_1	Sampling year (yr)
t_0	Reference year (yr)
Y	Erosion or deposition rates (t ha^{-1} yr^{-1})

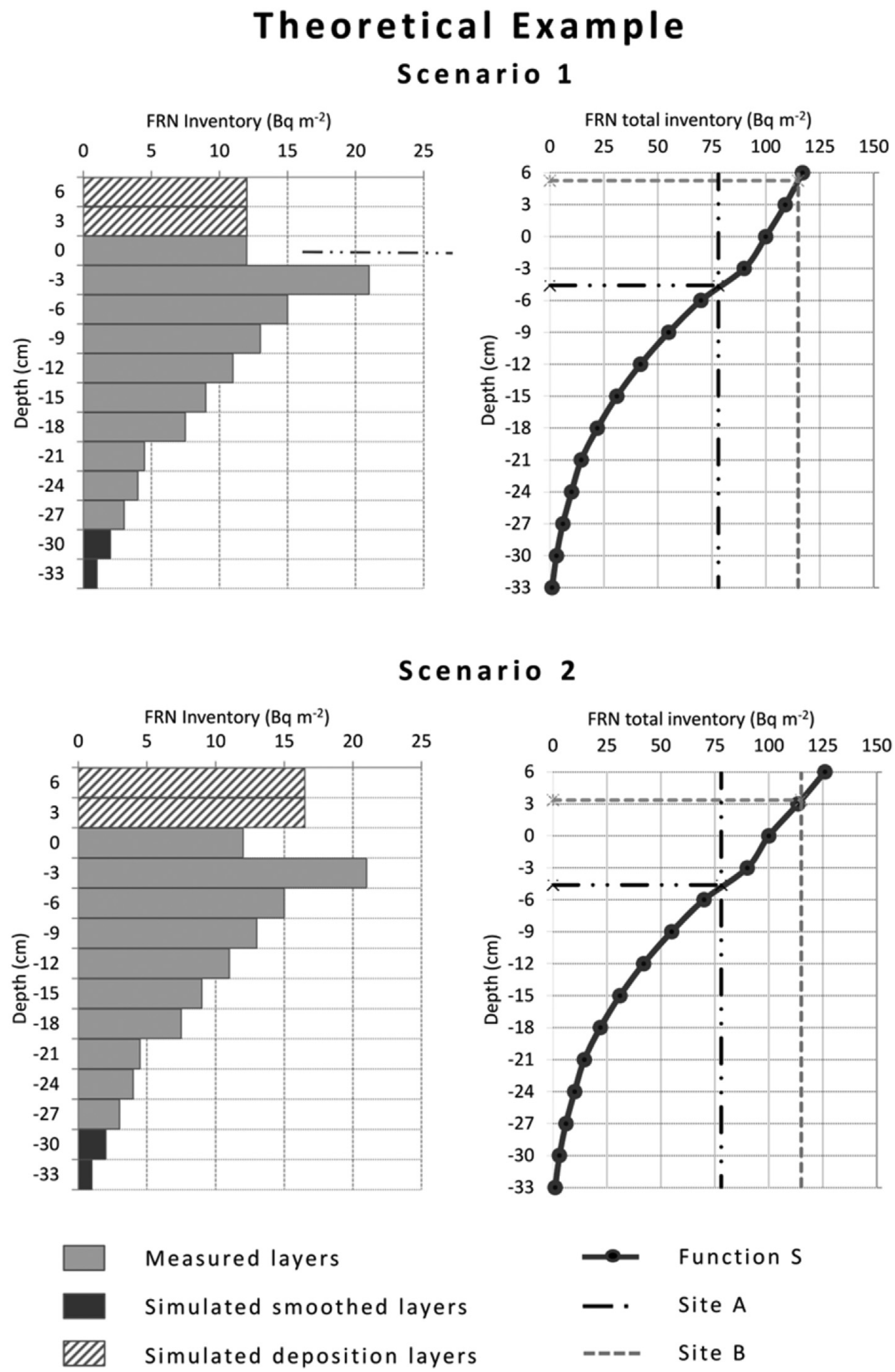

Fig. 3. Example of two hypothetical MODERN scenarios. The Reference FRN depth profile with measured layers is presented with filled light grey bars. The simulated layers for two deposition scenarios are presented with striped bars, while the smoothed layers added below the measured depth profile are presented in dark grey (left). Resulting function S, describing the cumulated FRN inventory of the simulated reference profile, considered for each increment of length $d = 30$. The intersection with total inventories of site A and site B values are also shown (right).

5.3 cm for Scenario 1 and a deposition of 3.4 cm for Scenario 2.

To obtain the mass of the eroded soil *Y*, a mass depth of 100 kg m^{-2} has been assumed for the sites A and B. To calculate yearly erosion or deposition rates, the authors assumed the peak fallout (t_0) of the FRN to be 1963 and the sampling year (t_1) to be the year 2000. The resulting solution is an erosion rate of 3.9 t ha^{-1} yr^{-1} at site A and a deposition magnitude of 3.1–4.8 t ha^{-1} yr^{-1} depending on the scenario chosen for site B.

3.2. MODERN application to a case study in the Aosta valley tracking ^{137}Cs in unploughed soils (test 1)

The artificial radionuclide ^{137}Cs (half-life = 30.2 years) is the most frequently employed FRN to study soil redistribution under different agri-environmental conditions (Mabit et al., 2013; Zapata, 2002). In undisturbed conditions, ^{137}Cs depth distribution in the soil follows an exponential function, with the highest ^{137}Cs concentrations located in the uppermost soil layers (Walling et al., 2002; Mabit et al., 2008).

To test MODERN for soil erosion assessment based on ^{137}Cs inventories at unploughed sites, the authors selected a subset of data from a previous study conducted in an alpine catchment in the province of Aosta (Italy), heavily affected by snow avalanches (Ceaglio et al., 2012; for all data used see Table 2). The detailed description of the investigated site, the specific sampling design and the results obtained in the frame of this study have been reported by Ceaglio et al. (2012).

Soil samples were collected along a main avalanche path in 2010. In the track area, two transects (TA1 and TA2) were sampled, with 5 cores collected within a distance of 15 m to each other. As for the reference sites, 3 reference samples, located in a nearby flat area, were collected, cut in 3 cm depth increments, and used to determine average profile distribution and maximum depth of ^{137}Cs. All samples were oven-dried at 40 °C, lightly ground and sieved and ^{137}Cs activity was measured with a Lithium-drifted Germanium Detector. A least squares exponential fit of the ^{137}Cs depth profile at the reference sites is characterized by R^2 of 0.58.

^{137}Cs inventories of the sampling sites, considered for a depth increment of 9 cm, were converted to soil erosion rates with the Profile Distribution Model (PDM, Walling et al., 2002). The PDM assumes an exponential decline of ^{137}Cs activity in the depth profile, which can be described by the following function:

$$Inv(xm_r) = Inv_{ref}\left(1 - e^{-xm_r/h_0}\right) \tag{5}$$

Where xm_r (kg m^{-2}) is the mass depth from the soil surface of reference sites and h_0 (kg m^{-2}) is a coefficient describing the profile shape. The greater the value of h_0, the deeper is the penetration of the radionuclide into the soil (Walling et al., 2002).

At an eroding point (where the total inventory Inv is less than the reference inventory Inv_{ref}), the erosion rate Y (t ha^{-1} yr^{-1}) can be estimated using the following equation (Walling and Quine, 1990):

$$Y = -\frac{10}{(t^1 - t^0)}\left[\ln\left(1 - \frac{Inv_{change}}{100}\right)\right]h_0 \tag{6}$$

where Inv_{change} is the % reduction of ^{137}Cs total inventory with respect to the local ^{137}Cs reference value (defined as: $(Inv_{ref}–Inv)/Inv_{ref} \times 100$). The parameters t^1 and t^0 (yr) are the sampling and the main deposition years, respectively. Because more than 80% of ^{137}Cs input is connected to the Chernobyl power plant accident (1986) (Facchinelli et al., 2002), the erosion rates were calculated for the time window 1986–2010. The application of PDM resulted in average erosion rates from all sites at the two transect of 8.8 t ha^{-1} yr^{-1} (Ceaglio et al., 2012).

To apply MODERN, the authors represented the reference depth profile according to the ^{137}Cs inventories of the three reference samples which have been sliced in 3 cm increments (Fig. 4). Six additional layers - below the last measured horizon - were simulated with ^{137}Cs inventories declining exponentially. The ^{137}Cs inventories of the sampling sites were smaller than the reference inventory (i.e. 3588 Bq m^{-2}), pointing out net erosion processes affecting all investigated sites. Thus, no deposition layers have been modelled.

The average erosion rate estimated with MODERN is 8.5 t ha^{-1} yr^{-1}, which is consistent with the erosion rates of 8.8 t ha^{-1} yr^{-1} achieved using the Profile Distribution Model (Table 3). In particular, at sites with low inventory change, there is a high correspondence between the results obtained with MODERN and the PDM. For sites with larger deviations from the reference inventory (sites T11 and T25), the results show a significant discrepancy. The latter can be due to the fact that the PDM assumes an exponential decline of ^{137}Cs in the measured depth profile, even if the fit of the depth profile to an exponential function returns a low R^2 of 0.58. MODERN instead follows the real ^{137}Cs depth distribution.

3.3. MODERN application to a case study in a Romanian valley tracking $^{210}Pb_{ex}$ in ploughed soils (test 2)

With a half-life of 22.3 years, geogenic ^{210}Pb is a natural radioactive form of lead which originates as a decay product of ^{238}U. During this decay process, ^{222}Rn partially escapes from the soil surface into the atmosphere, producing ^{210}Pb fallout. The part of ^{210}Pb which remains in the soil is usually termed supported lead and the fallout fraction, reaching the ground via precipitation, is called unsupported lead or lead in excess ($^{210}Pb_{ex}$). $^{210}Pb_{ex}$ is being used as a soil erosion and sediment tracer since many years (Mabit et al., 2008, 2014; Matisoff, 2014).

To perform our next test, the authors used the $^{210}Pb_{ex}$ determination and the resulting soil redistribution rates obtained in the frame of a recent study which was conducted in a cultivated area located in the central part of the Transylvanian Plain, in Romania (Iurian et al., 2013). In this study, where a $^{210}Pb_{ex}$ reference inventory of 9640 Bq m^{-2} was established, two parallel transects having different ploughing practices (up and down the slope and across the slope) were investigated and a total of 14 soil cores (12 bulk and 2 incremental) were collected and the $^{210}Pb_{ex}$ inventories were calculated (Table 2). The conversion of $^{210}Pb_{ex}$ inventories into soil redistribution rates for these ploughed soils (t ha^{-1} yr^{-1}) was done using the Mass Balance Model (MBM, Walling et al., 2002), where the total $^{210}Pb_{ex}$ inventory (Inv, Bq m^{-2}) at year t (yr) can be expressed as:

Table 2
Parameters used for MODERN tests on unploughed soil with ^{137}Cs data from Ceaglio et al., 2012 (1) and on ploughed soil with $^{210}Pb_{ex}$ data from Iurian et al., 2013 (2).

Parameter		Test 1 (^{137}Cs)	Test 2 ($^{210}Pb_{ex}$)
Inv_{inc}	Bq m^{-2}	469–1231	66–2579
inc	Bq m^{-2}	3	2.5
Inv	Bq m^{-2}	126–3192	3660–10970
d	cm	9	35–60
P	unitless	Not determined	0.74–2.39
P'	unitless	Not determined	0.47–0.83
x^*	cm	Target variable	Target variable
xm	Kg m^{-2}	20–50	432–1054
t_1	yr	2010	2011
t_0	yr	1986	1911
Y	t ha^{-1} yr^{-1}	Target variable	Target variable

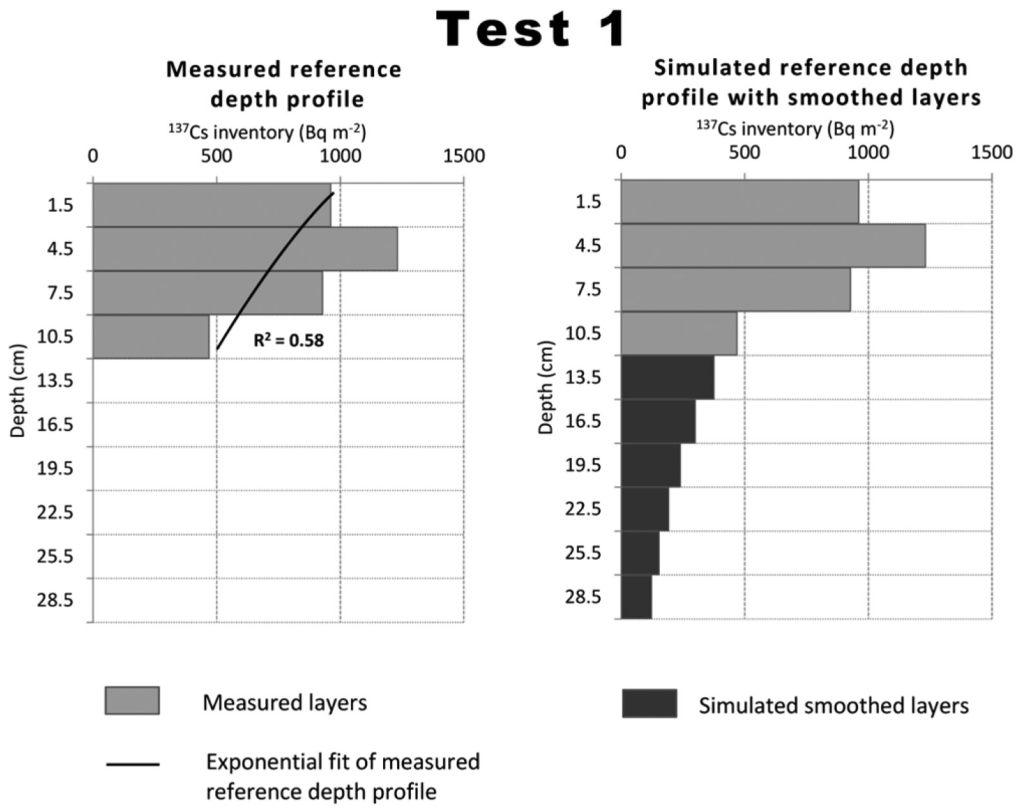

Fig. 4. ^{137}Cs depth profile of the reference site of Test (1), with ^{137}Cs data on an unploughed study area in Aosta valley (Italy) from Ceaglio et al., 2012, with exponential fit (left); Simulated depth profile with simulated smoothed layers (right).

Table 3
Results of the MODERN test (1) compared to published results of the Profile Distribution Model (PDM, Ceaglio et al., 2012).

Test 1: Uncultivated soil (^{137}Cs)		
Site	PDM t ha^{-1} yr^{-1}	MODERN t ha^{-1} yr^{-1}
Transect 1		
T11	−10.1	−16.1
T12	−2.4	−2.5
T13	−6.6	−7.0
T14	−7.4	−5.3
T15	−3.1	−3.8
Transect 2		
T21	−10.7	−7.1
T22	−9.1	−10.5
T23	−5.6	−5.2
T24	−1.1	−1.6
T25	−32.1	−26.3

$$Inv = Inv_{ref}\left(1 - P\frac{\Delta L}{D}\right)^{(t^1-t^0)} \quad (7)$$

where ΔL = annual soil loss (m), D = cultivation depth (m) and P is the particle size factor (unit less) for erosional sites, a parameter which takes the grain size selectivity of erosion and deposition processes into account. Iurian et al. (2013) considered P at eroding sites to range between 1.25 and 2.1 in Transect 1, and 0.74 and 2.39 in Transect 2. In deposition sites, P was estimated to range between 0.37 and 0.85 (Transect 1) and 0.47–0.83 (Transect 2), which highlights preferential transport of finer particles. The parameters t^1 and t^0 (yr) are the sampling and the reference years, respectively. When using $^{210}Pb_{ex}$ as soil erosion tracer, it is commonly assumed that it provides information about erosion magnitude on a time scale of approximately 100 years.

ΔL is calculated as:

$$\Delta L = D\left[1 - \left(1 - \frac{Inv_{change}}{Inv_{ref}}\right)^{\frac{1}{(t^1-t^0)}}\right] \quad (8)$$

The soil erosion rate Y (t ha^{-1} yr^{-1}) is finally calculated as:

$$Y = \frac{10B\Delta L}{P} \quad (9)$$

where B (kg m^{-3}) is the bulk density measured at the site. The

Table 4
Results of the MODERN test (2) compared to published results of the Mass Balance Model (MBM) (Iurian et al., 2013).

Test 2: Cultivated soil ($^{210}Pb_{ex}$)		
Site	MBM t ha^{-1} yr^{-1}	MODERN t ha^{-1} yr^{-1}
Transect 1		
P1	−19.6	−10.8
P3	−18.9	−10.1
P5	−6.7	−5.0
P7	−26.3	−13.8
P9	−23.1	−10.1
P11	−26.2	−15.0
P13	12.2	10.2
Transect 2		
P2	−12.5	−7.1
P4	−16	−9.4
P6	0.7	0.8
P8	−12.2	−7.4
P10	−26.4	−14.5
P12	−19.5	−10.2
P14	5.5	4.3

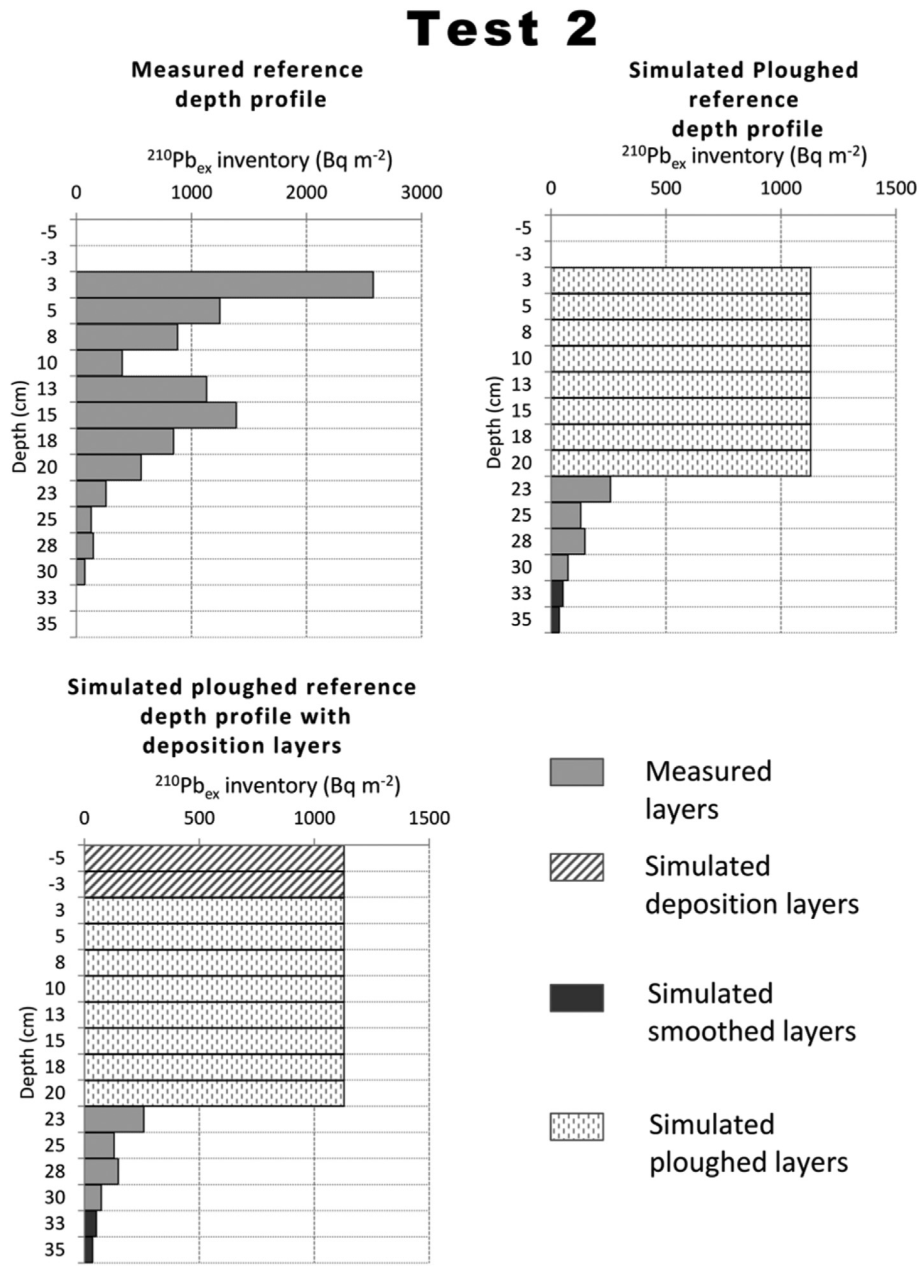

Fig. 5. $^{210}Pb_{ex}$ of the reference site of Test (2), with $^{210}Pb_{ex}$ data on a ploughed study area in Transylvanian Plain (Romania) from Iurian et al., 2013) (upper left); Simulated ploughed depth profile with the inventories of the top 20 cm of the reference profile to have an averaged $^{210}Pb_{ex}$ inventory as a result of soil mixing processes due to tillage (upper right); Simulated ploughed depth profile with additional ploughed layers (bottom left).

model assumes that the original exponential depth distribution is distributed uniformly within the plough layer and that a downward migration beyond the cultivation depth is negligible.

The MBM results in average erosion rates of 20.1 t ha^{-1} yr^{-1} (Transect 1) and 17.3 t ha^{-1} yr^{-1} (Transect 2) (Iurian et al., 2013) (Table 4). In sites P13 (Transect 1), P6 and P14 (Transect 2) the $^{210}Pb_{ex}$ inventories are higher than the reference inventory (10970, 9770 and 10,600 Bq m^{-2}, respectively), highlighting deposition processes. Deposition rates calculated with MBM were 12.2, 0.7 and 5.5 t ha^{-1} yr^{-1} for the sites P13, P6 and P14, respectively (Table 4).

The authors took into account the influence of agricultural practices on the distribution of $^{210}Pb_{ex}$ in the sampling sites for the MODERN application. Thus, the depth profile was first reproduced as it was measured, and then it was adapted as if $^{210}Pb_{ex}$ has been mixed within the ploughed layers. As the ploughing depth of the sites is 20 cm, the simulated horizons of the reference profile from 0 to 20 cm depth were set to have an averaged $^{210}Pb_{ex}$ inventory (Fig. 5).

To investigate deposition processes with MODERN, the authors simulated two deposition layers above the measured depth profile. The $^{210}Pb_{ex}$ inventory of those simulated layers was set as the average value of the $^{210}Pb_{ex}$ inventory measured in the top horizon of the reference site (Fig. 5, Deposition scenario). To convert MODERN results from cm to t ha^{-1} yr^{-1}, selecting a reference year (t^0) as starting point of the investigated time window is required. To be consistent with MBM assumptions, the authors defined a time window of 100 years (with $t^0 = 1911$). The particle size factor provided for each site by Iurian et al. (2013), was also considered.

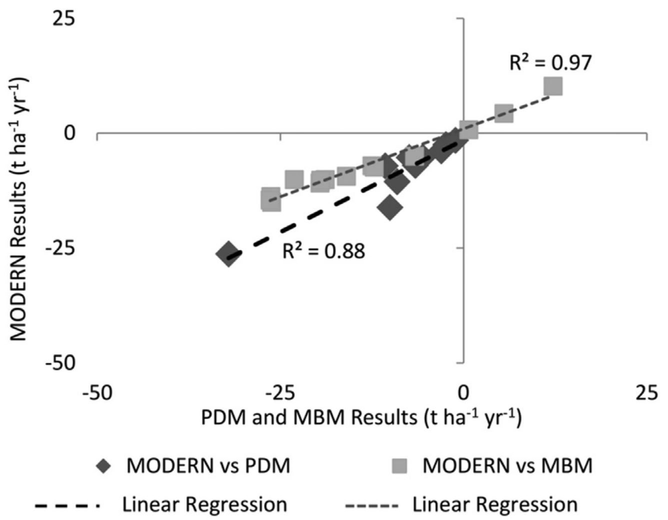

Fig. 6. Relationship between the soil redistribution rates of MODERN and the Profile Distribution Model (PDM) (Test 1) and of Mass Balance Model (MBM) (Test 2).

Average erosion rates estimated with MODERN are lower than the obtained MBM results, with average erosion rates of 10.8 t ha^{-1} yr^{-1} (Transect 1) and 9.7 t ha^{-1} yr^{-1} (Transect 2) (Table 4). However, deposition rates calculated with the two models are similar, with a mean standard deviation of 0.8 t ha^{-1} yr^{-1}. The correlation coefficient between MODERN and MBM results reaches 0.99.

The application of MODERN to the two selected studies highlighted its potential to convert FRN inventories into soil redistribution rates for two different FRN and with different land use of the sites. The results of MODERN correlate closely with the previously published results (R = 0.91) (Fig. 6).

4. Conclusions

A new FRN conversion model to assess soil redistribution has been proposed, described and tested for different FRN and land use conditions. This model, 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 FRN distribution reflects the influence of (i) the behaviour of the selected FRN in the soil and (ii) the characteristic of a study area, in respect to land use, weather conditions, and soil properties. As each study on soil erosion processes presents its own site specific characteristics, any general assumption on the depth distribution of FRN in the soil may prejudice the correct estimation of soil redistribution rates. MODERN allows also to reflect the variability of environmental and agriculture processes responsible for soil redistribution through the establishment of different deposition scenarios. Given the high uncertainty related to deposition dynamics, the authors believe that a presentation of a range of possible solutions and deposition scenarios is the best option in soil erosion studies.

The main limitations of MODERN are the following. So far time-variant fallout input and time-variant migration processes of FRN into soil are not accounted for by MODERN. In both ploughed and unploughed soils some of the fresh fallout that accumulates close to the soil surface is likely to be removed by erosion prior to moving further down into the soil by diffusion or migration or being incorporated into the plough layer by tillage. If this is the case, MODERN might overestimate results. MODERN also does not consider the decay of the selected FRN. Prior the application, the FRN measurements need to be decay corrected to the same year.

Major advantages of the MODERN model can be summarised as follows (i) it is applicable for both erosion and deposition scenarios; (ii) it considers the precise depth distribution of the reference site, independently of its shape; (iii) the parameters required for its application are simple and can be determined with certainty; and (iv) it can easily be adapted to different land use scenarios (e.g. ploughed and unploughed sites). A free and public release of the MODERN model will be associated with this publication. The model codes can be downloaded at modern.umweltgeo.unibas.ch and can be modified for any scientific purpose. This transparent and easily modifiable model will promote a wider application of FRN to assess soil erosion/sedimentation under various agro-climatic and land use conditions.

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