Universität Basel

Departement Umweltwissenschaften

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# M O D E R N

**MO**DELLING **D**EPOSITION AND **E**ROSION RATES WITH **R**ADIO**N**UCLIDES


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## 1. Description

MODERN is a transparent and easily adaptable model, to convert Fallout RadioNuclides (FRN) Inventories into quantitative estimates of both erosion and deposition processes. MODERN describes accurately the specific depth distribution of any FRN in the soil, independent of its depth function's shape. The parameters required for its application are simple and effortless to determine.

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 intersect point along the soil profile represents the solution of the model (Figure 1). As with all conversions 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 takes into account other assumptions usually undertaken for the application of FRN as soil erosion tracers (e.g. the 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 distributed.

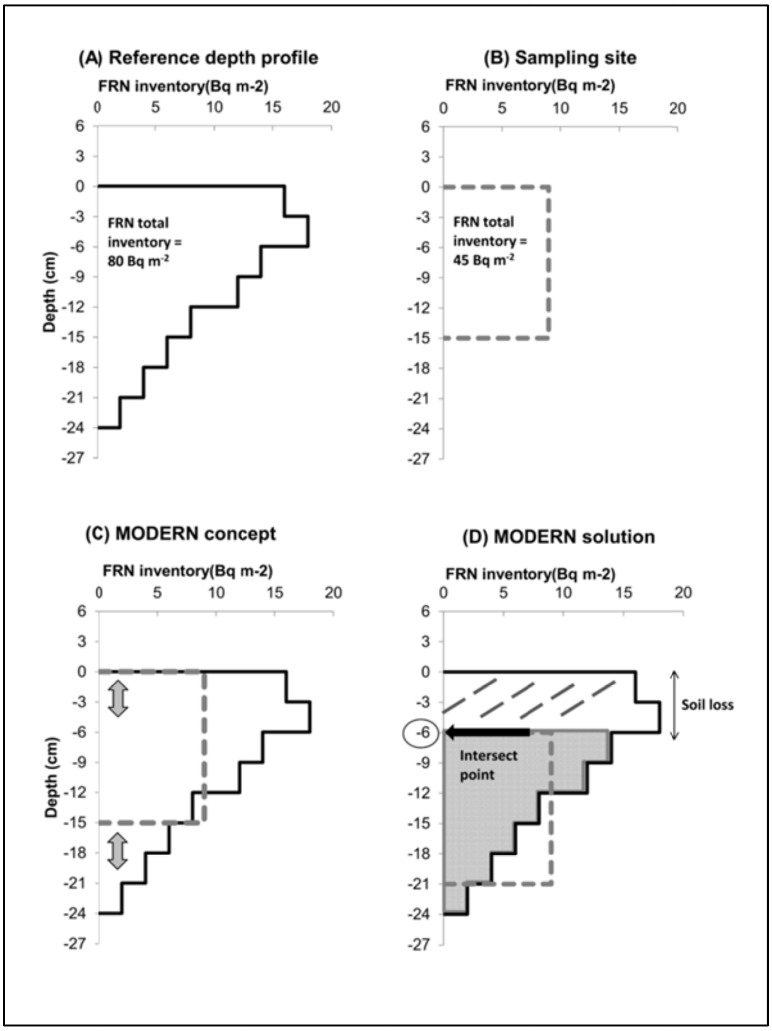


Figure 1: Concept of MODERN.MODERN compares the area covered by the depth profile of the reference site (A) with the area of the total inventory of a sampling site (B). MODERN overlaps the two areas (C) until it finds the intersect point where they match (D).

## *1.1. Adaptation of* **the** *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 (Figure 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 a number of layers below the measured depth profile. In those simulated layers MODERN smooths the FRN inventories exponentially to zero (Figure 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.

### *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, with MODERN is possible to adjust the reference depth profile, where an average inventory value at the layers above the ploughing depth can be assumed (Figure 2, Adaptation 2). <u>Please consider that in the current version of the MODERN model this adaptation has to be performed manually. This means that the user has to calculate the average value of the layers affected by ploughing activities and type them in the code. A new version of the model with an automatic feature for this function will be soon released.</u>

### *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. 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 different deposition scenarios might be assumed (Figure 2, Adaptation 3). The selected scenarios arise from the likelihood that deposition dynamics involve mostly top soil and rarely deeper soil layers.

### *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 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 in not taken into consideration. However, we 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.

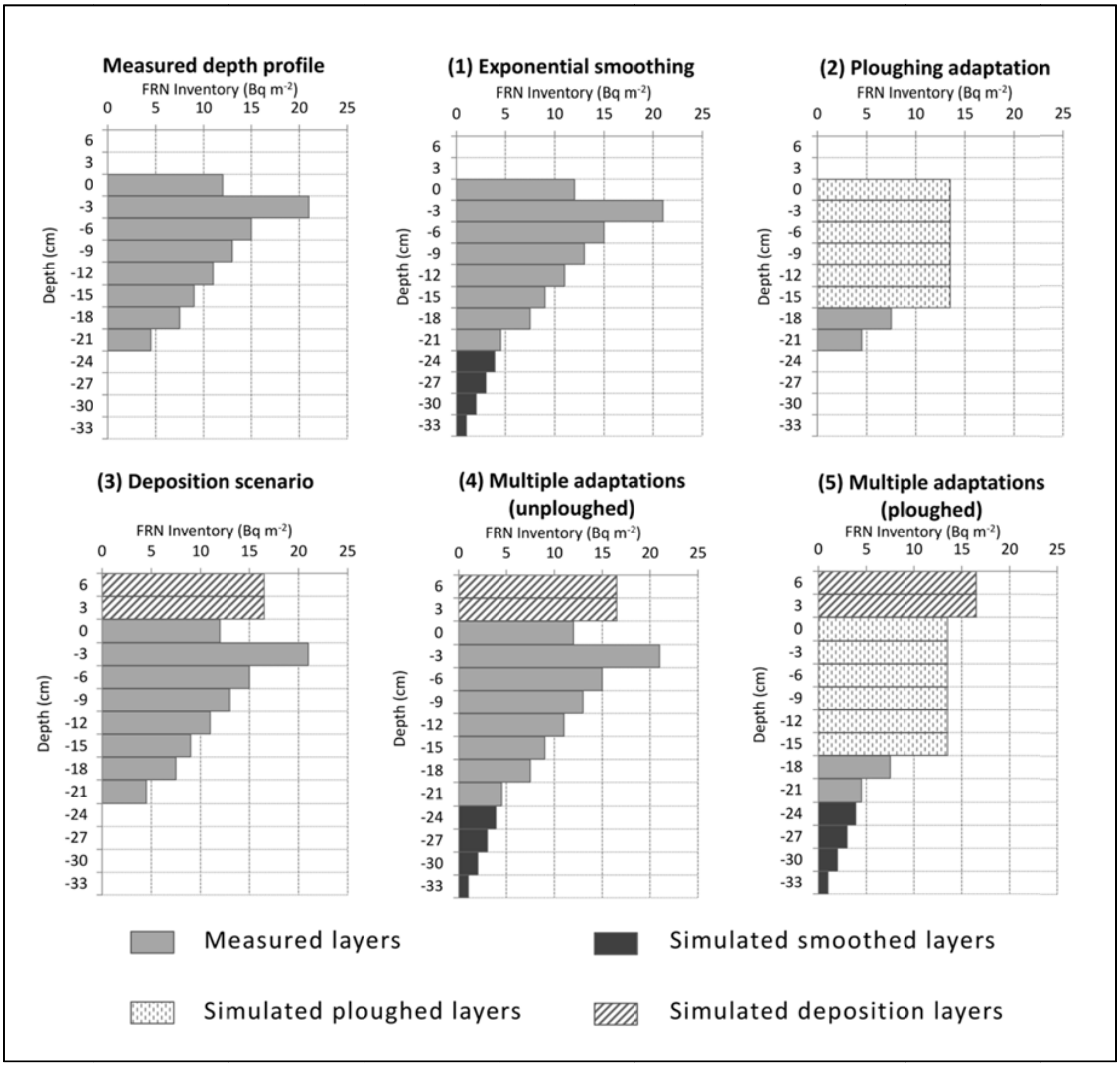


Figure 2: Possible adaptations of a FRN depth profile performed by MODERN. Upper left: a hypothetical depth profile, measured in depth increments of 3 cm, from 0 to 21 cm; (1): MODERN's

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 a unploughed site; (5): MODERN simulation of a depth profile as a result of a combination of multiple adaptations in a ploughed site.

MODERN permits to perform multiple adaptations simultaneously and to adjust the reference depth profile to the specific conditions encountered at each sampling site (Figure 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. 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 $Inv_{inc}$. The parameter *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), 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:

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

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 Figure 1), to assess potential soil losses or gains. The new simulated depth profile is described by the integral function *S,* where:

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

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 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:

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

where *xm* is the mass depth (kg m$^{-2}$) of the sampling site, *d* is the depth increment considered at the sampling site, $t_1$ 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. Requirements

MODERN runs on Matlab™. Therefore to use MODERN it is necessary to install first the Matlab™ Software.

## 4. Folder content

The folder contains different files which can be freely modified by users. Anyway, for the correct working of MODERN, we recommend not altering the files content, apart from the following files:

- MODERN_input
- MODERN_run

### *MODERN_input*

The MODERN_input file contains data about FRN inventories in the reference sites and in the sampling sites, as well the specification of the simulated deposition scenarios.

Study area

MODERN defines a new set of specifications beginning with the word `case` and the name of the current study area between quotation marks. Different study areas can be considered, each of which requires a separate set of specifications.

```
case 'Studyarea1'
```

Specifications:

A. Reference sites

`FRN_ref_inv` = enter here the FRN inventories measured at each depth increment of the reference depth profile (Bq m $^{-2}$). It is possible to enter more than one profile. To simulate the mechanical mixing processes of ploughing activities, it is possible to manually adjust the reference depth profile, where an average inventory value at the layers above the ploughing depth can be assumed.

`FRN_ref_LABEL` = enter here the label of each depth profile considered (it will appear in the outputs).

`FRN_ld`= enter here the depth increment (cm) of the reference site.

B. Sampling sites

`FRN_samp_inv` = enter here the FRN total inventory measured at each sampling point (Bq m$^{-2}$).

`FRN_samp_LABEL` = enter here the name associated to each sampling point (it will appear in the outputs).

`comp_depth =` enter here the depth of the FRN total inventories of the sampling points (one value, cm).

C. Scenarios

In this part MODERN allows modelling one or more potential deposition scenarios. According to the scenario considered, MODERN adds one or more layers on the top of the reference depth profile. It is possible to add as many layers as needed. It is also possible to define the FRN inventory for each simulated layer, as follows. MODERN assigns a number at each layer of the reference depth profile, where 1 is the top layer.

`scenario =` enter each simulated layer, divided by semicolon. Enter 1 for the first simulated layer, followed by the colon. To define the inventory of the added layer there are different options:

- The layer can have as inventory the **same inventory** of a measured layer. The measured layers are also labelled with number with 1 being the top measured layer, 2 the second one, etc.

  **Example**: 3 simulated layers, having as FRN Inventory the same inventory of the first layer of the reference profile:

  `'1:1; 2:1; 3:1'`

- It is possible to enter an **averaged value** of the inventory values of different measured layers. To do so, enter the numbers of all layers of the reference profile to be considered.

  **Example**: 3 simulated layers, having as FRN inventory the average value of the inventories of the first 2 layers of the reference profile:

  `'1:1 2; 2:1 2; 3:1 2'`

- It is possible to define an **exact value** (in Bq $m^{-2}$) for the specific simulated layer, adding a v before the value.

  **Example**: 1 simulated layer, having as FRN inventory the value of 1500 Bq $m^{-2}$:

  `'1:v1500 '`

- It is possible to enter a **percentage** value of inventory values of different measured layers, or also to an average value of different measured layers.

  **Example**: 2 simulated layers, the first being the 20% of the first measured layer, and the second having as inventory the 40% of the average value of measured layers 1, 2 and 3.

  `'1: 20%*1; 2: 40%*1 2 3'`

- All the previous presented options can be performed simultaneously.
  **Example**: 5 simulated layers, where layer 1 has an inventory equal to measured layer 3, layer 2 has 50% inventory of layer 2, layer 3 has an average value of measured layers 2, 3 and 4, layer 4 and layer 5 have inventories of 1000 and 800 Bq $m^{-2}$ respectively.
  `'1: 3; 2: 50%*2; 3: 2 3 4; 4: v1000; 5: v800'`

It's possible to model several scenarios, which will automatically be numbered by MODERN.

### *MODERN_run*

Specify in the MODERN_run file the parameters to run MODERN. It is possible to run different cases at the same time. For each case, compile the file as follows:

`case` number of the case considered.

`site_ID =` enter here the name of the study area, between quotation marks.

`FRN_ref_ID =` number of the reference depth profile to be considered, between square brackets; where 1 is the first one, 2 the second and so on. It is possible to consider at the same time more depth profiles, entering the ID number separated by a space.

`FRN_samp_ID =` number of the sampling point to be considered, between square brackets; where 1 is the first one, 2 the second and so on. It is possible to specify at the same time more sampling points, entering the ID number separated by a space.

`scenario_ID =` number of the simulated deposition scenario to be considered, between square brackets. It's possible to specify more scenarios to be considered. If set to 0, no deposition scenario will be considered.

`plot_ID =` enter 1 for Modern to return a plot, and 0 for no plot.

**Remark 1:** MODERN always compares a single reference profile with a single sampling point, under a single simulated deposition scenario. Therefore, when entering more numbers, remember that MODERN compares the first profile specified with the first sampling point specified, according to the first scenario specified; then the second profile with the second point, and so on. The `plot_id` also follows the same rule.

**Remark 2:** note that the specifications are working if the number of the elements in FRN_ref_ID, FRN_samp_ID, scenario_ID and plot_ID are the same.

### *MODERN Execution and Outputs*

To run the model type `MODERN()` in the command window, specifying in the brackets the case ID to be considered. MODERN will return two types of outputs.

Plot

If in the MODERN_run file, the plot_ID is set to 1, then MODERN will return a plot with the result of the comparison.

In the left part of the plot, a graph is displayed, with the cm of soil in the x axis, and the FRN inventory (in Bq m $^{-2}$) in the y axis. The function *S* is displayed in black, according to the specification set in the MODERN_run. The red line corresponds to the FRN total inventory value of the sampling point considered. The red dashed line indicates where MODERN finds the solution of the model. Under the graph, the output (cm) is displayed, where **positive values indicate soil losses, while negative values indicate soil gains**.

In the right part of the plot, the FRN depth profile is displayed in red. The simulated layers are plotted in blue.

Text file

As the model run, MODERN returns also a text file, which will be named according to the case selected. In the text file, solutions for all pairs “reference profile - sampling site” are displayed. If in the MODERN_input file no specifications are set, MODERN uses as default specifications scenario=0 and plot=0.

### *Special cases*

No solutions

In case of Deposition it can happen that MODERN does not find a solution. In this case a different deposition scenario needs to be considered. We would like to point out, that uncertainty in assessing sedimentation rates is high, since size and location of sediment source areas are often unknown. MODERN enables to simulate and assess different sedimentation scenarios which can then be evaluated with expert knowledge

Range of solutions

In some cases MODERN returns a range of possible solution for deposition cases. All solutions can be considered mathematically valid.

### *Conversion of MODERN outputs*

MODERN returns outputs in cm of soil lost or gained since the main FRN deposition. To convert the results of MODERN from cm to t ha$^{-1}$ yr$^{-1}$, the mass depth of the sample (kg m$^{-2}$), the depth increment of the sample (cm), and the time window between deposition and sampling year (yr) need to be considered, according to the following equation:

$$\frac{MODERN\ output\ (cm) \times mass\ depth\ (kg\ m^{-2})}{depth\ increment\ (cm) \times time\ window\ (yr)} = Soil\ Redistribution\ rate\ (t\ ha^{-1} yr^{-1}) \tag{4}$$

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## *Reference*

Arata, L., Mesuburger, K., Frenkel, E., A'Campo-Neuen, A., Iuran, A.R., Ketterer, M.E., Mabit, L., Alewell, C., 2016. Modelling Deposition and Erosion rates with RadioNuclides (MODERN) - Part 1: a new conversion model to derive soil redistribution rates from inventories of fallout radionuclides. Journal of Environmental Radioactivity, 162, 45-55.