Geophysical Research Abstracts, Vol. 7, 10868, 2005
SRef-ID: 1607-7962/gra/EGU05-A-10868

Estimation of Soil Redistribution Rates with the ^{137}Cs-Tracer Method: Approach to a new conversion Model

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Due to its strong affinity to soil particles of the clay- and the silt-fraction fallout ^{137}Cs has been used as tracer in soil science, especially for estimation of soil redistribution rates, for more than 30 years. The majority of the research was focussed on radiocaesium continuously set free by nuclear weapons tests in the 1950s and 60s. The release of considerable amounts of ^{137}Cs during the Chernobyl disaster in 1986 resulted in a high spatial variability of ^{137}Cs and increased ^{137}Cs inventories in Central- and Eastern European soils by 2 to 3 orders of magnitude.

A wide range of conversion models, allowing to convert changes in ^{137}Cs levels into rates of soil redistribution have been designed in the past decades: empirical, proportional as well as sophisticated mass balance and diffusion/migration models which are state-of-the-art. Empirical and proportional models are rather crude and purely quantitative models, not accounting for different patterns of ^{137}Cs depth distribution and migration mechanisms. Those limitations make them easy to use but also very unreliable. Mass balance and diffusion/ migration models, on the other hand, are capable of simulating the ^{137}Cs depth distribution and its migration, too. Yet, it is, due to the structure of the models, not possible to use the models on both, undisturbed and cultivated (i.e. tilled) soil.

In order to avoid those substantial limitations, a new model based on the proportional approach has been developed. The preliminary requirements for the new model were identified as: simplicity for the user, ability to simulate distribution and migration

processes in the profile, applicability on undisturbed as well as on tilled soils.

^{137}Cs depth distributions in undisturbed soils were simulated using an exponential function extended by an add-on in the form of a Chapman distribution. This allows a flexible, though more exact modelling of the characteristic ^{137}Cs subsurface peak than the usually applied simple exponential or lognormal functions. Homogenous ^{137}Cs depth distributions in cultivated soils were simulated using an inverse Chapman distribution.

Upon contamination of the soil, the initial depth distribution resembles an exponential function. Gradual vertical migration of ^{137}Cs causes the development of a distinct subsurface peak and flattening of the distribution graph in undisturbed soils, whereas continuous ploughing action causes a steady development towards a homogenous depth distribution in cultivated soils.

The functions describing undisturbed and cultivated soil can be combined by superposition and the introduction of a time dependent weighting term. This term is set zero for undisturbed soils and greater zero for cultivated soils, depending on the intensity of ploughing. The more time passes, the more the emphasis in the model shifts towards the term describing the cultivated soil. Thus, at t = 0, the term simulating the undisturbed soil weights 100 % and the term for the cultivated soil does not influence the result at all. At t $>>$ 0, the weight of the term describing the undisturbed soil approaches 0, while the weight of the cultivated soil approaches 100 % (Eq.1).

$$A\left(x,t\right) = A_U\left(t\right)\cdot e^{-\lambda_1(t)\cdot x}\cdot\left(y_{0U}+a_U\cdot\left(1-e^{-b_U\cdot x}\right)^{c_U(t)}\right)\cdot e^{-\lambda_2\cdot t}$$

$$+A_{C0}\cdot e^{-\lambda_3\cdot t}\cdot\left(y_{0C}-a_C\cdot\left(1-e^{-b_C\cdot x}\right)^{c_C}\right)\cdot\left(1-e^{-\lambda_2\cdot t}\right)$$

[Eq.1]

Once the temporal behaviour of ^{137}Cs in the soil profile is modelled, the rate of soil redistribution may be determined (Eq.2), refining the idea of proportional models: the rate of soil loss is directly proportional to the decrease of ^{137}Cs in the profile. Proportional models suggest a linear relation, while the new approach considers a dependence on the ^{137}Cs depth distribution and dilution effects. The assumption is that the difference of integrals between the lower boundary d = 0, which is represented by the soil surface, and the upper boundary d = x, which represents the sampling depth, between t = t_i and t = t_{i+1} equals the integral at t = t_i between the lower boundary d = 0, which again represents the soil surface, and the upper boundary d = E, which represents the depth of erosion within the chosen time increment ($t_i \rightarrow t_{i+1}$).

$$\int_0^{x_s} A(x)_i \cdot dx - \int_0^{x_s} A(x)_j \cdot dx = \int_0^{E} A(x)_i \cdot dx$$

[Eq.2]

The method suggested delivers similar results as mass balance and diffusion/migration models and it succeeds in simulating undisturbed as well as cultivated soils within one model, allowing to describe the transition from exponential to uniform ^{137}Cs depth distribution in tilled soils. Moreover vertical migration and dilution effects of radiocaesium are considered. Compared to the above mentioned models it is rather easy to apply for the user and delivers more reliable results than standard proportional models. Due to the model's sensitivity to parameter changes, the parameters have to be accurately chosen and long-term predictions should be handled with care.