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Mass balance models for use with $^{210}Pb_{ex}$ measurements to estimate soil loss from cultivated land

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Abstract ^{210}Pb (half-life 22.3 years) is a natural product of the ^{238}U decay series that is derived from the decay of gaseous ^{222}Rn (half-life 3.8 days), the daughter of ^{226}Ra (half-life 1622 years). Like fallout ^{137}Cs, $^{210}Pb_{ex}$ reaching the land surface as fallout from the atmosphere will be rapidly adsorbed by the surface soil and its subsequent redistribution within the landscape will reflect the movement of soil and sediment particles associated with soil erosion and sediment transport processes. The radionuclide therefore offers considerable potential for use as a tracer for estimating soil erosion rates. It can be used in regions where ^{137}Cs inventories are low, and therefore difficult to measure, or where they are complicated by additional Chernobyl inputs. Furthermore, due to its essentially constant input over time, it can provide information on erosion rates over a longer period of time. Conversion models utilizing a mass balance approach have been developed for deriving estimates of soil redistribution rates on cultivated land from $^{210}Pb_{ex}$ measurements. There is, however, a need to refine these models to take account of key features of the redistribution of $^{210}Pb_{ex}$ in the soil profile. In most cultivated soils $^{210}Pb_{ex}$ is evenly distributed within the plough layer, but a small proportion of the $^{210}Pb_{ex}$ inventory is commonly found below the plough layer, forming a tail to the depth distribution. This tail reflects the downward movement of $^{210}Pb_{ex}$ into the soil below the plough layer by a range of mechanisms that can be represented as diffusion and migration processes. Existing conversion models ignore this feature of the depth distribution of $^{210}Pb_{ex}$ in cultivated soils and therefore overestimate rates of soil loss. This paper reports the development of a revised mass balance model that takes account of the tail of the depth distribution. Soil losses estimated by using the revised model are greater than those estimated by the existing models and the extent is determined by the soil properties, which are related to transportation of the $^{210}Pb_{ex}$ nuclide from the plough layer to the plough pan layer, such as the plough depth (H), the $^{210}Pb_{ex}$ depth distribution coefficient (h_0) in the plough pan layer and the ratio of soil bulk densities between the plough pan layer and plough layer (γ_{pp}/γ_p).

Key words $^{210}Pb_{ex}$ fallout; cultivated land; soil losses; mass balance model; revision

INTRODUCTION

^{210}Pb with a half-life of 22.3 years, is a natural product of the ^{238}U decay series that is derived from the decay of gaseous ^{222}Rn (half-life 3.8 days), the daughter of ^{226}Ra (half-life 1622 years). ^{226}Ra exists naturally in soil and rock. Upward diffusion of a small part of the ^{222}Rn, which is produced from within soils and rocks, introduces ^{210}Pb into the atmosphere, and its subsequent fallout provides an input of this radionuclide to surface soils (e.g. Turekian *et al.*, 1977; Nozaki *et al.*, 1978; Nevissi, 1985; Graustein & Turekian, 1986; Wallbrink & Murray, 1996). The fallout ^{210}Pb is commonly termed unsupported or excess ^{210}Pb ($^{210}Pb_{ex}$) in the soil, while the ^{210}Pb, that is generated *in situ* by decay of ^{226}Ra and it is equilibrium with ^{226}Ra, is termed supported ^{210}Pb ($^{210}Pb_{su}$) (Robbins, 1978). Upon reaching the land surface as fallout from the atmosphere, $^{210}Pb_{ex}$ will be rapidly adsorbed by clay minerals and organic matter in the surface soil (e.g. Van Hoof & Andren, 1989; He, 1993; He & Walling, 1996). In uncultivated soils, $^{210}Pb_{ex}$ is distributed within the top layer of less than 20 cm in depth and its concentration decreases exponentially as depth increases (He & Walling, 1997; Walling *et al.*, 2003; Zhang *et al.*, 2003). In cultivated soils, $^{210}Pb_{ex}$ is predominantly and evenly distributed within the plough layer (He & Walling, 1997; Walling & He, 1999; Zhang *et al.*, 2003). However, it was recently noticed that a small amount of the nuclide, like a tail, exists within the top horizons of few centimetres in the plough pan layer in cultivated soils and that the nuclide concentration decreases from the interface horizon between the plough layer and plough pan layer, exponentially as depth increases.

Existing conversion models ignore this feature of the depth distribution of $^{210}Pb_{ex}$ in cultivated soils and soil loss rates may be underestimated by those models. This paper proposes a revised mass balance model that takes account of the tail of the depth distribution and discusses effects of some soil properties on assessment of soil losses.

^{210}PB$_{ex}$ transportation from the plough layer into the plough pan layer in cultivated soil

^{210}Pb$_{ex}$ depth distribution in cultivated soils is shown in Fig. 1. The two profiles have similar shapes. ^{210}Pb$_{ex}$ is evenly distributed within the plough layer and a small amount of the nuclide, like a tail, exists within the top few centimetres of the plough pan layer. The ^{210}Pb$_{ex}$ depth distribution shape in the top horizons of the plough pan layer is similar to the uncultivated soil profile in which the maximum ^{210}Pb$_{ex}$ concentration occurs at the surface horizon and it decreases exponentially as depth increases. In the top horizons of the plough pan layer, the maximum ^{210}Pb$_{ex}$ concentration, which is equal to the concentration in plough layer, occurs at the interface horizon and it decreases exponentially as depth increases. For the soil profile of the River Start site, UK, the total ^{210}Pb$_{ex}$ amount is 450 mBq cm^{-2} (He & Walling, 1997), of which the amount in the plough pan layer accounts for about 10%. For the soil profile of the Neijiang site, the total amount is 890 mBq cm^{-2} (Zheng *et al.*, 2007), of which the amount in the plough pan layer accounts for about 17%.

Nuclide movements in soil are a complex set of mechanisms including physical, physico-chemical and biological processes (Pegoyev & Fridman, 1978; Walling & He, 1992, 1993; Zapata, 2002). The little tail of ^{210}Pb$_{ex}$ in the top horizons of plough pan layers should be transported from the above plough layers by either diffusion due to the nuclide concentration differences between the plough layer and the plough pan layer underneath, or migration by downward movements of media, for example, fine particle movements by leaching and insect activities. However, ^{210}Pb$_{ex}$ nuclide generally moves downward from the plough layer with a high concentration, to the plough pan layer with a low concentration.

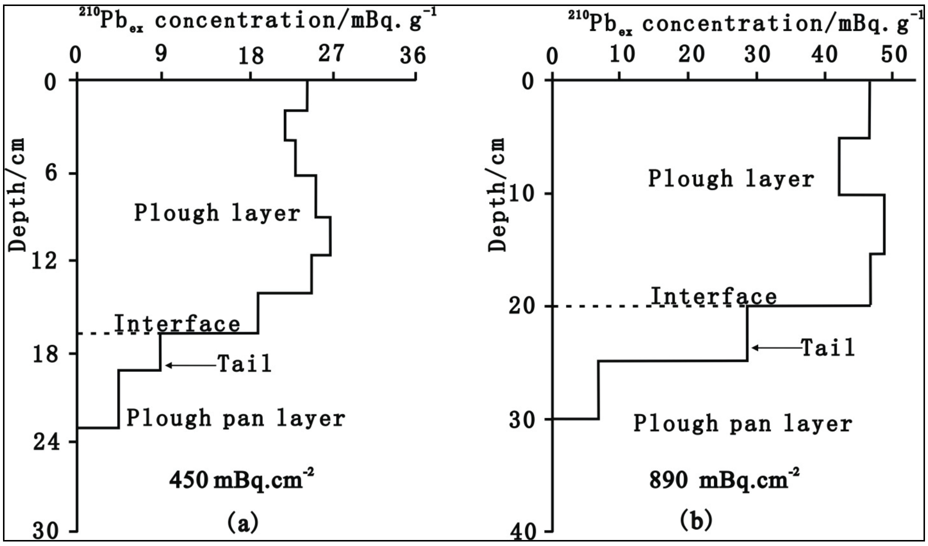

Fig. 1 Depth distribution of ^{210}Pb$_{ex}$ in uncultivated and cultivated soils without erosion: (a) cultivated soil in River Start, UK; (b) cultivated soil in Neijiang, China.

Revised mass balance model

The existing ^{210}Pb$_{ex}$ mass balance model for assessment of soil losses on cultivated land in a steady state, where sheet erosion is predominant, was developed by Walling & He (1997) and it is:

$$(1-\Gamma)\lambda A_0 - (\lambda + PhH^{-1})A = 0 \tag{1}$$

$$I = \lambda A_0 \tag{2}$$

where A = the total $^{210}Pb_{ex}$ inventory in soil (mBq cm^{-2}); λ = ^{210}Pb decay coefficient (0.031 year^{-1}); I = annual ^{210}Pb fallout deposition flux (mBq cm^{-2}.year^{-1}); Γ = proportion of the freshly deposited ^{210}Pb fallout removed by erosion before being mixed into the plough layer; P = particle-size correction factor, defined as the ratio of the $^{210}Pb_{ex}$ concentration of the mobilized sediment to that of the original soil; h = the depth of annual soil losses (cm); H = the plough depth (cm); A_0 = the local $^{210}Pb_{ex}$ reference inventory (mBq cm^{-2}).

If the little tail of $^{210}Pb_{ex}$ in the plough pan layer is taken into account, the total $^{210}Pb_{ex}$ inventory in cultivated soil is the sum of the nuclide inventories in plough layer and in plough pan layer and it is expressed as:

$$A = A_p + A_{pp} \tag{3}$$

where A_p = $^{210}Pb_{ex}$ inventory in the plough layer (mBq cm^{-2}); A_{pp}= the $^{210}Pb_{ex}$ inventory in the plough pan layer, (mBq cm^{-2}).

$^{210}Pb_{ex}$ is evenly distributed in plough layer and A_p can be expressed as:

$$A_p = C_p H \gamma_p \tag{4}$$

where C_p = the $^{210}Pb_{ex}$ concentration in soil of the plough layer (mBq g^{-1}); γ_p = the bulk density of soil of the plough layer (g cm^{-3}).

In the plough pan layer, the maximum $^{210}Pb_{ex}$ concentration, which is equal to the concentration in the above plough layer, occurs at the interface horizon and it decreases exponentially as depth increases. The profile shape of $^{210}Pb_{ex}$ depth distribution in the plough pan layer is similar to those in uncultivated soils and the distribution can be expressed as follows:

$$C_{ppx} = C_p e^{-h_0 \cdot x} \tag{5}$$

where C_{ppx} is the $^{210}Pb_{ex}$ concentration of a horizon in a plough pan layer (mBq g^{-1}); h_0 is a coefficient describing the profile shape of $^{210}Pb_{ex}$ depth distribution in the plough pan layer (cm^{-1}). X is the vertical distance to the interface horizon between the plough pan layer and the plough layer above (cm).

The $^{210}Pb_{ex}$ inventory in the plough pan layer can be calculated by the integral form of equation (5):

$$A_{pp} = \frac{C_p \gamma_{pp}}{h_0} \tag{6}$$

where γ_{pp} = the bulk density of soil in the top horizons of a plough pan layer (g cm^{-3}).

By combination of equations (3), (4) and (6), the total amount of $^{210}Pb_{ex}$ fallout is expressed as:

$$A = C_p H \gamma_p + \frac{C_p \gamma_{pp}}{h_0} \tag{7}$$

The $^{210}Pb_{ex}$ depth distribution shape in soil is unchangeable for a cultivated land in a steady state, where land-use conditions and soil erosion processes are constant for a long period, e.g. >100 years. If the surface enrichment of freshly deposited ^{210}Pb fallout in cultivated soil and the particle selection of soil losses are neglected (Γ= 0, P = 1), annual $^{210}Pb_{ex}$ fallout deposition flux (I) should be equal to the sum of the $^{210}Pb_{ex}$ loss due to decay of the total inventory of $^{210}Pb_{ex}$ fallout in soil and the $^{210}Pb_{ex}$ loss due to soil losses in a year. It can be expressed as:

$$I = A_0 \lambda = A\lambda + C_p \gamma_p h \tag{8}$$

where A_0 = the local $^{210}Pb_{ex}$ reference inventory (mBq cm^{-2}).

By combination of equations (3), (4) and (6):

$$C_p \gamma_p = \frac{A}{(H + \gamma_{pp} \gamma_p^{-1} h_0^{-1})} \tag{9}$$

the depth of annual soil losses can be estimated by using the following equation, which is derived from equations (8) and (9):

$$h_R = \frac{\lambda(A_0 - A)(H + \gamma_{pp}\gamma_p^{-1}h_0^{-1})}{A} \tag{10}$$

where h_R = the depth of annual soil losses by sheet erosion, which is estimated by the revised model (cm).

If no ^{210}Pb$_{ex}$ exists in the plough pan layer, equation (9) becomes:

$$h_E = \frac{\lambda H(A_0 - A)}{A} \tag{11}$$

where h_E = the depth of annual soil losses by sheet erosion, which is estimated by the existing model (cm).

Equation (11) is the existing model developed by He & Walling, if $\Gamma = 0$ and $P = 1$.

Effects of soil properties on assessment of soil losses

Equation (9) shows that the soil properties, related to transportation of the nuclide from the plough layer to the plough pan layer, such as the plough depth (H), the ^{210}Pb$_{ex}$ depth distribution coefficient (h_0) in the plough pan, which reflects the capacity for the nuclide transportation, and the ratio of bulk soil densities of the plough pan layer to the plough layer (γ_{pp}/γ_p), have effects on the soil loss depth, which is estimated by the revised model. The ratio of the estimated annual soil loss depths between the two models is expressed as follows, which is derived from equations (9) and (10):

$$R_h = h_R / h_E = 1 + \gamma_{pp}H^{-1}h_0^{-1}\gamma_p^{-1} \tag{12}$$

Equation (11) indicates that the higher ratio of bulk soil density of the plough pan layer to the plough layer, the thinner plough layer and the higher ^{210}Pb$_{ex}$ transportation capacity with a low coefficient (h_0) will lead to a high ratio of annual soil loss depths estimated by the revised model to the values by the existing model.

For the cultivated soil profile at an eroding site in Neijiang, China (Fig. 1(b)), the total ^{210}Pb$_{ex}$ inventory (A) is 890 mBq cm^{-2}, of which the nuclide amount in the plough pan layer accounts for about 17%, while the local ^{210}Pb$_{ex}$ reference inventory (A_0) is 1286 mBq cm^{-2}. Taking $H = 20$ cm, annual soil loss depth (h_E) is estimated to be 0.28 cm from the ^{210}Pb$_{ex}$ depletion ($A_0 - A$ = 396 mBq cm^{-2}) by using the existing mass balance model (equation (11)). Taking H = 20 cm, $h_0 =$ 0.24 cm^{-1}, which is estimated from the ^{210}Pb$_{ex}$ depth distribution shape in the plough pan layer, and $\gamma_{pp}/\gamma_p = 1.16$ ($\gamma_{pp} = 1.4$ g cm^{-3}, $\gamma_p = 1.2$ g cm^{-3}), annual soil loss depth (h_R) from the same ^{210}Pb$_{ex}$ depletion (396 mBq cm^{-2}) is estimated to be 0.34 cm by using the existing mass balance model (equation (9)). The annual soil loss depth estimated by the revised model is 20% greater than the depth by the existing model.

CONCLUSIONS

The existing mass balance model for converting ^{210}Pb$_{ex}$ depletion to soil losses on cultivated land ignores the little ^{210}Pb$_{ex}$ tail within the few centimetres of the top horizons in the plough pan layer. Based on the transportation processes of the nuclide from the plough layer to the plough pan layer, a revised mass balance model is developed for converting ^{210}Pb$_{ex}$ depletion to soil losses.

Soil losses estimated by using the revised model are greater than those estimated by the existing models and the extent is determined by the soil properties, which are related to transportation of the ^{210}Pb$_{ex}$ nuclide from the plough layer to the plough pan layer, such as the plough depth (H), the ^{210}Pb$_{ex}$ depth distribution coefficient (h_0) in the plough pan layer and the ratio of soil bulk densities of the plough pan layer and plough layer (γ_{pp}/γ_p).

The higher ratio of bulk soil densities of the plough pan layer to the plough layer, the thinner plough layer and the higher $^{210}Pb_{ex}$ transportation capacity with a low coefficient (h_0) will lead to a high ratio of the annual soil loss depth derived by the revised model relative to the value by the existing model.

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