Article Chinese Science Bulletin

Progress of Projects Supported by NSFC
Geography

May 2013 Vol.58 No.15: 1725–1730
doi: 10.1007/s11434-013-5693-6

Response of $^{210}Pb_{ex}$ inventory to changes in soil erosion rates on uncultivated land

SUN Wei[1], YANG Hao[1*], ZHAO QiGuo[1,2], ZHANG MingLi[1] & XU LiangJiang[1]

[1] College of Geography Science, Nanjing Normal University, Nanjing 210023, China;
[2] Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China

Received October 25, 2012; accepted December 24, 2012; published online March 26, 2013

This analysis studies changes in the variation $^{210}Pb_{ex}$ inventory in soil in response to soil erosion on uncultivated land. A model was created to fit the response of $^{210}Pb_{ex}$ inventory to variations in soil erosion rates on uncultivated land using the principle of mass balance. By numerical simulation of the variation in the soil erosion rate in soil of uncultivated land, we prove: (1) past use of what has long been considered the best method of determining $^{210}Pb_{ex}$ levels over the past 100 to 200 years is not scientifically accurate; (2) the model shows that variation in $^{210}Pb_{ex}$ inventory as a function of time varies according to the index law after variation of soil erosion rates in uncultivated land is considered; and (3) the time needed for the variation in $^{210}Pb_{ex}$ inventory to reach a steady-state is affected by changes in the rate of soil erosion and the quality and depth of relaxation in soil of uncultivated land. The results of this research can guide efforts to measure soil erosion rates.

$^{210}Pb_{ex}$ inventory, soil erosion rate, time response, uncultivated

Citation: Sun W, Yang H, Zhao Q G, et al. Response of $^{210}Pb_{ex}$ inventory to changes in soil erosion rates on uncultivated land. Chin Sci Bull, 2013, 58: 1725–1730, doi: 10.1007/s11434-013-5693-6

The radioactive isotope Caesium-137 is not produced naturally. This artificial radionuclide is found in soil worldwide as ^{137}Cs fallout from nuclear tests or nuclear leaks. Most of the fallout occurred from 1950 through 1970. ^{137}Cs has a half-life of about 30.2 years. The ^{137}Cs technique has been used to study average soil erosion rates. Globally, ^{137}Cs fallout has been widely used in erosion studies, especially for measuring medium-long term (about 40 years) soil erosion rates and fruitful results have been achieved [1–13]. Quantifying measurements of ^{137}Cs in the soil is becoming more and more difficult because ^{137}Cs levels continue to decline in soil profiles. Only a few places in the world have had measurable ^{137}Cs deposition since nuclear weapon tests started but the rate of fallout must be known in order to use the ^{137}Cs method to study soil erosion. Also, the application of this radioactive element as a soil erosion tracer is generally difficult for regions in the Southern Hemisphere, where the overall ^{137}Cs inventory is low. Determining the contributions of the Chernobyl nuclear accident to the ^{137}Cs inventory in some countries and regions of Europe has proved difficult. As a result, natural fallout of the radionuclide unsupported lead-210 (called excess–$^{210}Pb_{ex}$) can offer a viable alternative to Caesium-137 as a sediment tracer in many environments.

Recently, some scholars have explored the measurement of soil erosion using $^{210}Pb_{ex}$ [14–16]. $^{210}Pb_{ex}$, a radioactive isotope in the ^{238}U (half-life 3.8 days) decay chain, is continuously produced by the decay of atmospheric ^{222}Rn gas, which has a half-life of about 22.6 years. $^{210}Pb_{ex}$ is derived from the decay of gaseous ^{222}Rn, a daughter of ^{226}Ra (half-life 1622 years). ^{226}Ra occurs naturally in soils and rocks and will generate ^{210}Pb in equilibrium with its parent material. ^{210}Pb is composed of two parts in soil. Some is directly from the decay of soil and rock. Some is from the absorption of decayed ^{210}Pb in the atmosphere by the soil through sedimentation. Upward diffusion of a small portion of the ^{222}Rn produced in the soils and rocks introduces ^{210}Pb into the atmosphere, and its subsequent deposition as fallout

---

*Corresponding author (email: yanghao@njnu.edu.cn) provides an input of this radionuclide to surface soils and sediments that will not be in equilibrium with its parent ^{226}Ra. This fallout-derived ^{210}Pb is commonly termed unsupported or excess ^{210}Pb (^{210}Pb$_{ex}$) when incorporated into soils to distinguish it from the ^{210}Pb produced *in situ* by the decay of ^{226}Ra. The ^{210}Pb then attaches to aerosol particles and settles out of the atmosphere as dry fallout or is washed out during rainfall events [17]. As a fallout radionuclide, which is rapidly and strongly adsorbed by surface soil, unsupported ^{210}Pb will behave in a similar manner to ^{137}Cs. Both are seldom lost by leaching or absorption by plants, although they may move with soil particles [18].

At present, the use of ^{210}Pb$_{ex}$ as a tracer to measure soil erosion has produced gratifying results [19–23]. The total inventory of ^{137}Cs in soil continues to decrease over time through soil erosion and natural decay. The distribution of ^{137}Cs in soil is unstable. ^{210}Pb$_{ex}$ inventory remains stable as long as environmental conditions remain stable. While measuring soil erosion in agricultural lands using ^{210}Pb$_{ex}$, Walling and He [19] provided a ^{210}Pb$_{ex}$ mass balance model for estimating soil erosion rates within stable cultivated land. They assumed ^{210}Pb$_{ex}$ inventory is stable for a cultivated land environment and studied long-term erosion processes, e.g. >100 years. ^{137}Cs has been widely used to establish the measurement of soil erosion rates during the past 40–50 years and ^{210}Pb$_{ex}$ for the past 100–200 years [20,21]. In our recent study of uncultivated land, it takes 100 years for the ^{210}Pb$_{ex}$ inventory to stabilize after soil erosion rates change on cultivated land. 100 years are not a point in time used to measure soil erosion rates using ^{210}Pb$_{ex}$. Our results are consistent with the stable period of ^{210}Pb$_{ex}$ inventory value on cultivated land observed by Zhang et al. [22]. In this paper, we explain the response mechanism of ^{210}Pb$_{ex}$ inventory to changes in erosion rates in soil of uncultivated land. Based on the established mass balance model, the time response of ^{210}Pb$_{ex}$ inventory to changes in erosion rates is quantified. The objective is to correct the error of characterization of time during which the measurement of ^{210}Pb$_{ex}$ accurately reflects soil erosion rates.

1 Response mechanism of ^{210}Pb$_{ex}$ inventory to changes in erosion rates in cultivated and uncultivated lands

1.1 Response mechanism of ^{210}Pb$_{ex}$ inventory to changes in erosion rates in cultivated lands

Previous studies have shown ^{210}Pb$_{ex}$ is almost uniformly cultivated in the deep plough layer in cultivated lands. The ^{210}Pb$_{ex}$ inventory value in the bottom of the plough layer is very low [14,23]. Zhang et al. [22] established the following simplified model to fit the response of ^{210}Pb$_{ex}$ inventory to variation of soil erosion rates in soil of cultivated land in a steady state, based on the principle of mass balance.

$$I = \left(\lambda + h/H\right)A. \tag{1}$$

Zhang et al. [23] suggested the relationship between ^{210}Pb$_{ex}$ disposition deposition fluxes and the reference value can be approximated as

$$I = \lambda A_{\mathrm{ref}}, \tag{2}$$

where A_{ref} (Bq m^{-2}) is the ^{210}Pb$_{ex}$ reference value.

Based on eqs. (1) and (2), the relationship between the area of activity (A) and yearly erosion thickness (h) for cultivated land in a steady state can be represented by the following equation, which can be used to calculate the average rate of soil erosion over many years

$$\lambda\left(A_{\mathrm{ref}}/A - 1\right) = h/H. \tag{3}$$

If rates of soil erosion changed, original mass balances of ^{210}Pb$_{ex}$ in cultivated land would be broken. The following model can be established to fit the response of ^{210}Pb$_{ex}$ inventory to release, decay and deposition, based on the differential equation of area activity changes over time

$$\frac{\mathrm{d}A_t}{\mathrm{d}t} = I - \left(\lambda + \frac{h_{\mathrm{a}}}{H}\right)A_t. \tag{4}$$

If the erosion rate changed from h_0 to h_{a}, eq. (4) is reduced to

$$A_t = \frac{\lambda A_{\mathrm{ref}}}{\lambda + h_{\mathrm{a}}/H} + \left(\frac{\lambda A_{\mathrm{ref}}}{\lambda + h_0/H} - \frac{\lambda A_{\mathrm{ref}}}{\lambda + h_a/H}\right)\mathrm{e}^{-(\lambda + h_{\mathrm{a}}/H)t}. \tag{5}$$

The proportion of ^{210}Pb$_{ex}$ area activity and reference value in cultivated land at the time t is therefore

$$R_t = \frac{\lambda}{\lambda + h_{\mathrm{a}}/H} + \left(\frac{\lambda}{\lambda + h_0/H} - \frac{\lambda}{\lambda + h_{\mathrm{a}}/H}\right)\mathrm{e}^{-(\lambda + h_{\mathrm{a}}/H)t}. \tag{6}$$

Based on the above-mentioned study and with results by Zhang et al. [22], it is possible to establish a model to fit the response of ^{210}Pb$_{ex}$ inventory to the changes of erosion rates in uncultivated land. A detailed analysis follows.

1.2 Relationship between ^{210}Pb$_{ex}$ inventory and soil erosion rate for uncultivated land in a steady state

In uncultivated lands, physicochemical processes and bioturbation such as the rainfall regime, the soil physical and chemical properties and surface enrichment are the primary factors responsible for the distribution of fallout ^{210}Pb$_{ex}$. The distribution of fallout ^{210}Pb$_{ex}$ is in an approximately steady state and its concentration decreases approximately exponentially in the soil profile [14]. Because of soil erosion and radioactive decay, concentrations of ^{210}Pb$_{ex}$ decrease with increasing soil depth. The deposition of atmospheric ^{210}Pb$_{ex}$ causes surface enrichment in the soil. Based on the continued deposition from the atmosphere, natural decay and losses caused by soil erosion, a steady state dynamic mass balance of $^{210}\text{Pb}_{\text{ex}}$ in soil will eventually occur.

The $^{210}\text{Pb}_{\text{ex}}$ concentration in uncultivated lands generally exhibited a broad peak near the soil surface with a downward tail in concentration extending into the lower part of the profile. Its concentration decreases approximately exponentially with cumulative mass depth. The distribution of fallout $^{210}\text{Pb}_{\text{ex}}$ can be approximated as

$$A_x = A\mathrm{e}^{-x/H}, \tag{7}$$

where A_x (Bq m^{-2}) is the area activity density of $^{210}\text{Pb}_{\text{ex}}$ below mass depth x, A (Bq m^{-2}) is the area activity density of $^{210}\text{Pb}_{\text{ex}}$ in the soil, H (kg m^{-2}) is the $^{210}\text{Pb}_{\text{ex}}$ relaxation cumulative mass depth of the initial distribution in the soil and x is the mass depth.

The loss of soil from erosion in uncultivated land estimated by eq. (7) is $(1–\mathrm{e}^{-h/H})A$. Here, the simplified mass balance model of fallout $^{210}\text{Pb}_{\text{ex}}$ from the uncultivated land in a steady state can be expressed as

$$I = \left(\lambda + 1 - \mathrm{e}^{-h/H}\right)A, \tag{8}$$

where λ (0.031 a^{-1}) is the decay constant of ^{210}Pb, I (Bq m^{-2} a^{-1}) is the deposition flux of $^{210}\text{Pb}_{\text{ex}}$, h (kg m^{-2}) is the yearly eroded mass depth, H (kg m^{-2}) is the relaxation mass depth and A (Bq m^{-2}) is the area concentration of $^{210}\text{Pb}_{\text{ex}}$ in uncultivated land.

It is clear from Eqs. (2) and (8) that the yearly eroded mass depth (h) from the uncultivated land in a steady state can be represented by the following equation:

$$h = -H\ln\left(\lambda + 1 - \lambda A_{\text{ref}}/A\right). \tag{9}$$

Eq. (9) can be used to estimate the average erosion rate over many years from the uncultivated land in a steady state.

1.3 Response mechanism of $^{210}\text{Pb}_{\text{ex}}$ inventory to changes in erosion rates in uncultivated lands

The radionuclide $^{210}\text{Pb}_{\text{ex}}$ in rain water will be adsorbed by the surface soil during the infiltration process. When rainfall ceases and water has penetrated completely into the soil, a stable distribution of water in the surface soil will be temporarily established and the fallout $^{210}\text{Pb}_{\text{ex}}$ remaining in the water will be gradually adsorbed by soil particles. The resulting initial distribution of fallout $^{210}\text{Pb}_{\text{ex}}$ in surface soil will therefore depend upon the rainfall intensity and duration, and the physical and chemical properties of the soil [18,19]. $^{210}\text{Pb}_{\text{ex}}$ inventory in the soil can be used as a means of estimating rates of soil erosion [24,25]. In uncultivated land, the area activity of $^{210}\text{Pb}_{\text{ex}}$ decreases with increasing soil erosion rates. The concentration of fallout $^{210}\text{Pb}_{\text{ex}}$ in uncultivated lands decreases more or less exponentially. Figure 1 shows the fallout $^{210}\text{Pb}_{\text{ex}}$ inventory for different erosion rates in uncultivated land. The soil erosion rate has been increasing with increasing losses to erosion of $^{210}\text{Pb}_{\text{ex}}$. $^{210}\text{Pb}_{\text{ex}}$ area activity in the soil profile decreases until a steady state dynamic mass balance of $^{210}\text{Pb}_{\text{ex}}$ in soil is reached through receiving continuous atmospheric fallout inputs. The soil erosion rate has been decreasing with increasing area activity of $^{210}\text{Pb}_{\text{ex}}$ through gradual accumulation in the soil profile until continuous fallout $^{210}\text{Pb}_{\text{ex}}$ inputs and outputs enter a new approximate steady state in the uncultivated land.

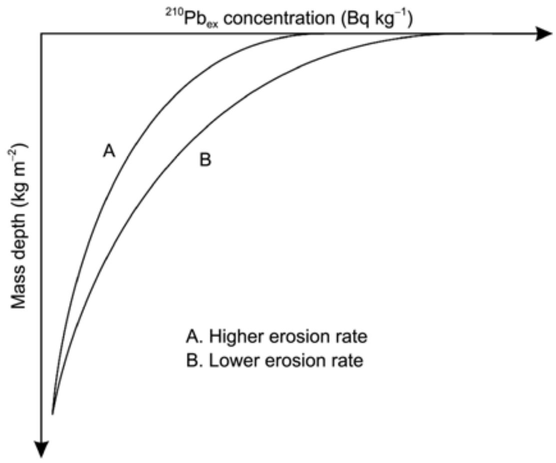

Figure 1 Relationship between erosion rates and fallout $^{210}\text{Pb}_{\text{ex}}$ profiles in uncultivated land.

2 Modeling the response of $^{210}\text{Pb}_{\text{ex}}$ inventory to changes of erosion rates in uncultivated lands

2.1 Model establishment

Taking into account the radionuclide decay effect and the changes of erosion rates in uncultivated land, the variation of the $^{210}\text{Pb}_{\text{ex}}$ area activity in uncultivated land with the time in the soil profile can be represented by the following differential equation:

$$\frac{\mathrm{d}A_t}{\mathrm{d}t} = I - \left(\lambda + 1 - \mathrm{e}^{-h/H}\right)A_t, \tag{10}$$

where t (a) is the time elapsed after the erosion rate changes and h (kg m^{-2} a^{-1}) is yearly eroded mass depth after the erosion rate changes.

When t=0, A_{t0}=A_0. The mass activity of fallout $^{210}\text{Pb}_{\text{ex}}$ before the change of erosion rate can be approximated by eq. (9) as

$$A_0 = \frac{\lambda A_{\text{ref}}}{\lambda + 1 - \mathrm{e}^{-h_0/H}}, \tag{11}$$

where h_0 (kg cm^{-2} a^{-1}) is the yearly eroded mass depth before the change of erosion rate.

When the erosion rate changed from h_0 to h_a, the response of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ area activity over time can be obtained through eq. (4) as

$$A_t=\frac{\lambda A_{\mathrm{ref}}}{\lambda+1-\mathrm{e}^{-h_a/H}}+\left(\frac{\lambda A_{\mathrm{ref}}}{\lambda+1-\mathrm{e}^{-h_0/H}}-\frac{\lambda A_{\mathrm{ref}}}{\lambda+1-\mathrm{e}^{-h_a/H}}\right)\mathrm{e}^{-\left(\lambda+1-e^{-h_a/H}\right)t}. \tag{12}$$

The solution A_t to eq. (12) is the area activity of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ over time after the change of erosion rates in uncultivated land. When the time t >100, $\mathrm{e}^{-\left(\lambda+1-e^{-h_a/H}\right)t}<10^{-3}$, which can be approximated as 0. The area activity reaches a state of equilibrium. The distribution of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ in uncultivated lands is in a new approximate steady state. The same results were obtained by He and Walling [14]. For land which has been under cultivation for >100 years and where the erosion rates were well-distributed, it can be assumed that the distribution of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ in the soils is in an approximate steady state [14]. A minimum duration time (100 years) is needed to obtain a steady state for the fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ in the eroded soils. The view stating fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ could be used to characterize soil erosion rates over the long term (in the last 100 years) is not scientifically reasonable. Eq. (9) given in this paper is suitable to estimate the erosion rates in uncultivated lands under steady state conditions of the fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$.

2.2 Simulating the response process of $^{210}\mathrm{Pb}_{\mathrm{ex}}$ inventory to changes of erosion rates in uncultivated land

The proportion between the fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ area activity and the reference value in the soils at the time t can be represented as

$$R_t=\frac{A_{\mathrm{t}}}{A_{\mathrm{ref}}}, \tag{13}$$

where R_t is the proportion between $^{210}\mathrm{Pb}_{\mathrm{ex}}$ fallout in the area activity and the reference value in the soils at the time t.

When the time $t\to\infty$, the area activity of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ in the uncultivated lands is in an approximate state of equilibrium. A_{a} can be approximated as

$$A_{\mathrm{a}}=\frac{\lambda A_{\mathrm{ref}}}{\lambda+1-\mathrm{e}^{-h_a/H}}, \tag{14}$$

where A_{a} (Bq m^{-2}) is the area activity of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ at the yearly erosion mass depth h_{a} in a steady state. Solution of eqs. (12) and (13) yields

$$R_t=\frac{\lambda}{\lambda+1-\mathrm{e}^{-h_{\mathrm{a}}/H}}+\left(\frac{\lambda}{\lambda+1-\mathrm{e}^{-h_0/H}}-\frac{\lambda}{\lambda+1-\mathrm{e}^{-h_a/H}}\right)\mathrm{e}^{-\left(\lambda+1-e^{-h_a/H}\right)\mathrm{t}}. \tag{15}$$

Eq. (15) has been used to simulate the changes of the proportion between the fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ area activity and the reference value in the soils at the time t. Figure 2 presents the changes of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ concentration in the soils over time. When H=250 kg m^{-2}, curve $A1$ shows the erosion rate decreased from h_0 (10 kg m^{-2} a^{-1}) to h_{a} (1 kg m^{-2} a^{-1}) and the erosion rate increased from h_0 (1 kg m^{-2} a^{-1}) to h_{a} (10 kg m^{-2} a^{-1}) in curve $A2$. As Figure 2 shows, the proportion between fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ area activity and reference value in the soils changes approximately exponentially over the time. Fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ area activity has been decreasing with the increasing erosion rate and *vice versa*. If $t\to+\infty$, the fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ area activity in the soils becomes the steady state corresponding value under the erosion rate (h_{a}). Levels of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ area activity in the soils drop rapidly in the first several years after the erosion rate changes, then apparently changes slowly after 20 years, with very little change after 50 years, and reaches a state near equilibrium after 100 years. At the time 14 years, curves $A1$ and $A2$ intersected. The proportion value in curve $A1$ increased from 0.442 to 0.614. The change in volume is 0.172; for curve $A2$, the proportion value decreased from 0.886 to 0.608, with the change in volume being 0.278. Theoretically, soil erosion rates, estimated by fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ mass balance model, for the uncultivated lands should reach a steady state after 100 years. In reality, it is often difficult to obtain the history of soil erosion changes and land use at the sampling sites. Some sampling plots may not be located in the uncultivated lands in a continuous steady state for more than 100 years. If fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ in the uncultivated lands is not in a steady state, based on the $^{210}\mathrm{Pb}_{\mathrm{ex}}$ area activity in the sampling sites, it can be seen that the erosion rates (corresponding value in the longitudinal axis on the right side of Figure 2) estimated by using fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ mass balance model have some errors compared to actual values. The error decreased with the increasing number of years since the change in the erosion rates. Finally, the estimated change in erosion rate is close to the actual one.

Figure 3 depicts the response of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ inventory to the changes of erosion rate in the different uncultivated

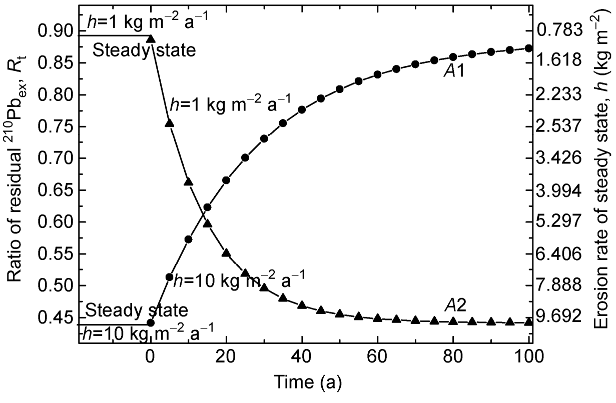

Figure 2 Response of fallout $^{210}\mathrm{Pb}_{\mathrm{ex}}$ concentration to the changes of erosion rates in the uncultivated lands.

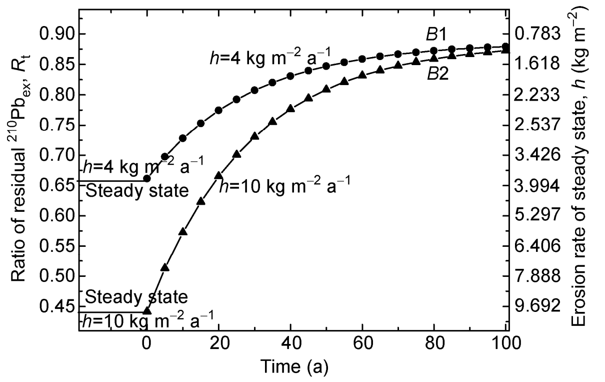

Figure 3 Response of fallout ^{210}Pb$_{ex}$ inventory to the changes of erosion rate in the different uncultivated lands.

lands. *B*1 curve shows the erosion rate decreased from h_0 (4 kg m^{-2} a^{-1}) to h_a (1 kg m^{-2} a^{-1}); for *B*2 curve from h_0 (10 kg m^{-2} a^{-1}) to h_a (1 kg m^{-2} a^{-1}). Figure 3 shows that it requires 26 years for the erosion rate to decrease to 2 kg m^{-2} a^{-1} for *B*1 curve or 46 years for *B*2 curve. Also, it takes 44 years until the erosion rate decreased to 1.5 kg m^{-2} a^{-1} for *B*1 curve or 64 years for *B*2 curve. These data illustrated that with a smaller change of volume of the erosion rate, less time is needed for fallout ^{210}Pb$_{ex}$ reaching a steady state, and *vice versa*.

Figure 4 shows the response of fallout ^{210}Pb$_{ex}$ inventory to the changes of erosion rate in the uncultivated lands at the different relaxation mass depths. *C*1 and *C*2 curves represent the uncultivated lands at the relaxation mass depth *H* (*H*=250 kg m^{-2}); and for *C*3 and *C*4 curves, *H*=150 kg m^{-2}. As Figure 4 shows, the changes of volume for erosion rates are different in the uncultivated lands at the different relaxation mass depths within the same time. Figure 4 shows the same soil erosion rate changes. After 20 years, *C*1 and *C*3 curves demonstrate the increasing of erosion rate, from 1 to 6.40 kg m^{-2} a^{-1} and from 1 to 7.19 kg m^{-2} a^{-1}, respectively; *C*2 and *C*4 curves represent the decreasing of erosion rate, from 10 to 3.93 kg m^{-2} a^{-1} and from 10 to 3.28 kg m^{-2} a^{-1}, respectively. After 40 years, the erosion rate depicted in *C*1 and *C*3 curves increased to 8.95 and 9.50 kg m^{-2} a^{-1} respectively and decreased 2.25 and 1.88 kg m^{-2} a^{-1} depicted in *C*2 and *C*4 curves, respectively. Theoretically, in the uncultivated lands at the different relaxation mass depth, the time needed for a steady state for the distribution of fallout ^{210}Pb$_{ex}$ tends to infinity. Changes in relaxation mass depth can affect erosion rates in the uncultivated lands. The smaller the relaxation mass depth, the greater the soil erosion rate change, and *vice versa*.

Figure 5 shows the response of fallout ^{210}Pb$_{ex}$ inventory to the changes of erosion rate in the uncultivated and cultivated lands. Here, we make a comparison between the response model of fallout ^{210}Pb$_{ex}$ inventory to the changes of erosion rate in the uncultivated lands established in this paper and the response model in cultivated lands obtained by Zhang et al. [22]. At the relaxation mass depth *H* (*H*=250 kg m^{-2}), two curves are obtained under the conditions of the different erosion rate change trend, increasing from h_0 (1 kg m^{-2} a^{-1}) to h_a (10 kg m^{-2} a^{-1}) and decreasing from h_0 (10 kg m^{-2} a^{-1}) to h_a (1 kg m^{-2} a^{-1}), respectively. *D*1 and *D*2 curves represent response models in the uncultivated land, and *D*3 and *D*4 curves in the cultivated land given by Zhang et al. [22]. As Figure 5 shows, *D*1 and *D*3 curves coincide, as do *D*2 and *D*4 curves. The results show that no matter whether the uncultivated or cultivated lands are discussed, the response mechanism of fallout ^{210}Pb$_{ex}$ inventory to the changes of erosion rate is almost uniform. In this paper, we proved the modeling for the response of fallout ^{210}Pb$_{ex}$ inventory to the changes of erosion rate in the cultivated soil is correct. Furthermore, this paper gives some supplementary information and alternative views for the model by Zhang et al. [22]

3 Conclusion

The view that fallout ^{210}Pb$_{ex}$ could be used to characterize average soil erosion rates over the long term (in the last 100 or 200 years) is not scientifically reasonable. One can conclude

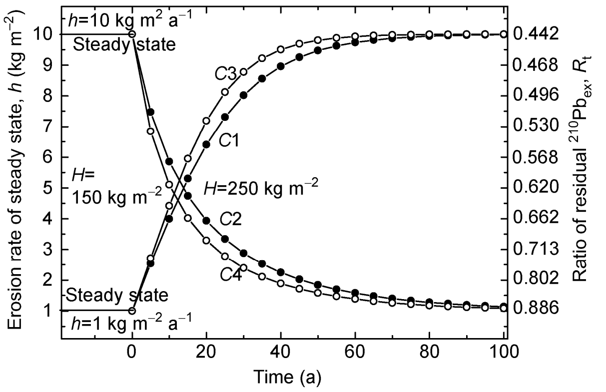

Figure 4 Response of fallout ^{210}Pb$_{ex}$ inventory to the changes of erosion rate in the uncultivated lands at the different relaxation mass depths.

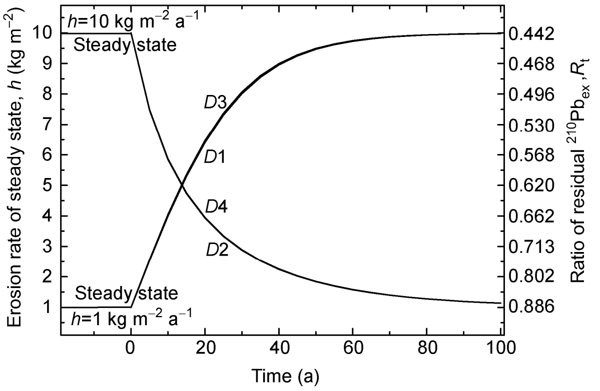

Figure 5 Response of fallout ^{210}Pb$_{ex}$ inventory to the changes of erosion rate in the uncultivated and cultivated lands.

a minimum duration time (100 years) should be needed to obtain a steady state for the fallout $^{210}Pb_{ex}$ concentration in the soil profiles after the changes of the erosion rate in the uncultivated lands. The duration time (100 years) is not the time characterized by soil erosion rates by using $^{210}Pb_{ex}$ measurement.

When the rate of erosion changed in the uncultivated lands, $^{210}Pb_{ex}$ area activity in the soil profile responded rapidly and decreases or increases approximately exponentially with the passage of time. The area activity increases with the decreasing rates of soil erosion, and *vice versa*. The rate of soil erosion is inversely proportional to the $^{210}Pb_{ex}$ concentration. Fallout $^{210}Pb_{ex}$ area activity in the soils drops rapidly in the first several years after the erosion rate changes, then apparently changes slowly after 20 years, with very little change after 50 years, and reaches a state near equilibrium after 100 years.

In the uncultivated lands, the changes in erosion rates are related to the relaxation mass depth and the time needed for a steady state of fallout $^{210}Pb_{ex}$ to develop. The data illustrates the smaller the change of volume of erosion rate, the smaller the time needed for fallout $^{210}Pb_{ex}$ to reach equilibrium, and vice versa. Changes in the relaxation mass depth can affect erosion rates in the uncultivated lands. The smaller the relaxation mass depth, the greater the soil erosion rate change, and *vice versa*.

In this paper, we make a comparison between the response model of fallout $^{210}Pb_{ex}$ inventory to the changes of erosion rate in the uncultivated land and the response model in cultivated lands obtained by Zhang et al. [22]. The results show that no matter whether uncultivated or cultivated lands are being discussed, the tracing mechanism is almost uniform. The similar behavior of fallout $^{210}Pb_{ex}$ in soils makes it a satisfied alternative to ^{137}Cs for measuring soil erosion rates. Fallout $^{210}Pb_{ex}$ can not only be used to quantify the rate of soil erosion for a past 100 years but also investigate the response of soil erosion to the recent land use change.

This work was supported by the National Natural Science Foundation of China (41030751, 41173094 and 41103047) and the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions. The authors thank Prof. Zhang Xinbao of the Key Laboratory of Mountain Environment Evolvement and Regulation, Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, China.

1 Pennock D J, Lemmon D S, de Jong. Cesium-137 measured erosion rates for five parent-material groups in southwestern Saskatchewan. Can J Soil Sci, 1995, 75: 205–210

2 Walling D E, Quine T A. Use of ^{137}Cs measurements to investigate soil erosion on arable fields in the UK: Potential applications and limitations. J Soil Sci, 1991, 42: 147–165

3 Walling D E, Woodward J C. Use of radiometric fingerprints to derive information on suspended sediment sources. In: Erosion and Sediment TransPort Monitoring Programmes in River Basins. IAHS Publ, 1992, 210: 153–164

4 Zhang X B, Li S L, Wang C H, et al. The ^{137}Cs research of the source of soil and sands in small basin of loess plateau. Chin Sci Bull, 1989, 34: 210–213

5 Zhang X B, Li S L, Wang C H, et al. A study of sediment delivery from a small catchment in the loess plateau by the ^{137}Cs method. Chin Sci Bull, 1990, 35: 37–42

6 Wallbrink P J, Murray As. Determining Soil loss using the inventory ratio of excess lead-210 to cesium-137. Soil Sci Soc Am J, 1996, 60: 1201–1208

7 Zhang X, Higgitt D L, Walling D E. A preliminary assessment of the potential for use caesium-137 to estimate rates of soil erosion in the Loess Plateau of China. Hydrolog Sci J, 1990, 35: 243–252

8 Yang H, Chang Q, Du M, et al. Quantative model of soil erosion rate using ^{137}Cs for uncultivated soil. Soil Sci, 1998, 163: 248–257

9 Liu J Y, Qi Y Q, Shi H D, et al. Estimation of wind erosion rates by using ^{137}Cs tracing technique: A case study in Tariat-Xilin Gol transect, Mongolian Plateau. Chin Sci Bull, 2008, 53: 751–758

10 Hu Y F, Liu J Y, Zhuang D F, et al. Distribution characteristics of ^{137}Cs in wind-eroded soil profile and its use in estimating wind erosion modulus. Chin Sci Bull, 2005, 50: 1155–1159

11 Qi Y Q, Liu J Y, Shi H D, et al. Using ^{137}Cs tracing technique to estimate wind erosion rates in the typical steppe region, northern Mongolian Plateau. Chin Sci Bull, 2008, 53: 1423–1430

12 Shao Q Q, Xiao T, Liu J Y, et al. Soil erosion rates and characteristics of typical alpine meadow using ^{137}Cs technique in Qinghai-Tibet Plateau. Chin Sci Bull, 2011, 56: 1708–1713

13 Yang H, Du M, Chang Q，Minarni K, et al. Quantitative model for estimating soil erosion rates using ^{137}Cs. Pedosphere, 1998, 8: 211–220

14 He Q, Walling D E. The distribution of fallout ^{137}Cs and ^{210}Pb in undisturbed and cultivated soil. Appl Radiat Isotopes, 1997, 48: 677–690

15 Mabit L, Benmansour M, Walling D E. Comparative advantages and limitations of the fallout radionuclides ^{137}Cs, $^{210}Pb_{ex}$ and ^{7}Be for assessing soil erosion and sedimentation. J Environ Radioact, 2008, 99: 1799–1807

16 Walling D E, Collins A L, Sichingabula H M. Using unsupported lead-210 measurements to investigate soil erosion and sediment delivery in a small Zambian catchment. Geomorphology, 2003, 52: 193–213

17 Robbins R A. Geochemical and geophysical application of radioactive lead. In: Nriagu J O, ed. The Biogeochemistry of Lead in the Environment. Amsterdam: Elsevier, 1978. 286–383

18 Zapata F. The use of environmental radionuclides as tracers in soil erosion and sedimentation investigations: Recent advances and future developments. Soil Till Res, 2003, 69: 3–13

19 Walling D E, He Q. Using fallout lead-210 measurements to estimate soil erosion on cultivated land. Soil Sci Soc Am J, 1999, 63: 1404–1412

20 Zheng J J, He X B, Walling D, et al. Assessing soil erosion rates on manually-tilled hillslopes in the Sichuan hilly basin using ^{137}Cs and $^{210}Pb_{ex}$ measurements. Pedosphere, 2007, 17: 273–283

21 Li Y, Zhang Q W, Reicosky D C, et al. Using ^{137}Cs and $^{210}Pb_{ex}$ for quantifying soil organic carbon redistribution affected by intensive tillage on steep slopes. Soil Till Res, 2006, 86: 176–184

22 Zhang X B, Zhang Y Q, He X B, et al. Response of $^{210}Pb_{ex}$ inventory to changes in erosion rates in soil of cultivated land (in Chinese). Acta Pedol Sin, 2010, 47: 593–597

23 Zhang X B, Walling D E, Feng M Y, et al. $^{210}Pb_{ex}$ depth distribution in soil and calibration models for assessment of soil erosion rate from $^{210}Pb_{ex}$ measurements. Chin Sci Bull, 2003, 48: 813–818

24 Walling D E, He Q, Quine T A. Use of caesium-137 and lead-210 as tracers in soil erosion investigations. In: Batalla R J, Garcia C, eds. Tracer Technologies for Hydrological System. Proceedings of a Boulder Symposium, July 1995. Wallingford, UK: IAHS Publication, No. 299, 1995. 163–172

25 Wallbrink P J, Murray A S. Determining soil loss using the inventory ratio of excess lead-210 to cesium-137. Soil Sci Soc Am J, 1996, 60: 1201–1212