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Evaluation of soil erosion rates in the hilly-gully region of the Loess Plateau in China in the past 60 years using global fallout plutonium

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ABSTRACT

Soil erosion strongly threatens the sustainability of natural ecosystems over the world, especially in the Loess Plateau in China, where has suffered severe soil erosion along with extensive land reclamation and deforestation from the 1950s to the 1970s. The large-scale vegetation restoration practices are supposed to be effective for reducing soil erosion, but the quantitative evaluation of soil erosion, particularly the response of land utilization types and vegetation coverage changes on the mitigation of soil degradation is still not well understood. Pu isotopes in soil cores collected from the forest, grassland slope, apple orchard, and cornfield in a typical watershed in the hilly-gully region of the Loess Plateau were analyzed to estimate the soil erosion rates in different land-use types. Widespread soil erosion at rates of 5.1–40.5 t/ha/yr. in this region in the past 60 years was estimated. The influences of human activities in the past decades, type of land utilization, level of vegetation coverage, and terrain on the soil erosion in this region were discussed, and the accumulation of the eroded soil in the study sites was explored. Different types of land utilization showed diverse soil erosion rates (forest (slight) < grassland (light) < apple orchard = cornfield (moderate)), indicating that natural vegetation rehabilitation, particularly restoring forest with high vegetation coverage is a practically effective conservation measure for soil erosion control; convex micro-topography on sloping fields is critical in alleviating soil loss by depositing eroded soil.

1. Introduction

Soil erosion is a severe ecological threat, detaching about 75 billion tons of soil per year from the world’s terrestrial ecosystems (Pimentel and Kounang, 1998). The large erosion deprives the fertility of surface soil, and the deposition of the eroded soil on the riverbed and reservoirs further threatens the sustainability of water systems (Telles et al., 2011; Issaka and Ashraf, 2017). Uncontrolled human deforestation and land reclamation are the primary causes of soil erosion across the world, especially in the loess landscape. The Loess Plateau in northwestern China is one of the world’s most susceptible regions to soil erosion, where 60 % of the area is eroded at rates of 50–100 t/ha/yr. (Cai, 2001; Zhao et al., 2013). The loess hilly-gully region located in the middle of the Loess Plateau is an important agricultural area owing to the large scale of loess platform terrain (Fu and Chen, 2000; Huang and Gallic-hand, 2006). Meanwhile, this region has suffered serious soil erosion in the past few decades due to the damage of natural vegetation coverage by deforestation and land reclamation along with the expanding populations in the 1950s–1970s (Wei et al., 2006; Zhao et al., 2013). To prevent the ecological problems induced by soil erosion, various measures have been launched to mitigate soil erosion in some watersheds of the Loess Plateaus since the 1970s, such as afforestation terracing, etc. (Zhao et al., 2013). From the 1990s, extensive measures were implemented in the Loess Plateau, such as the Forest Conservation Project and Grain-to-Green Project by returning the reclaimed sloping farmland to forest or grassland, to recover and improve the vegetation coverage (Li...
et al., 2012). However, the extent of soil erosion in the hilly-gully region of the middle Loess Plateau during the past decades and the effectiveness of the current countermeasures on soil erosion have not been well evaluated.

Field survey, runoff plots, modeling and remote sensing are commonly used techniques to estimate soil erosion rate (Lal, 1994; Yue et al., 2005; Zheng et al., 2007; Mabit et al., 2008; Xu et al., 2015; Sepuru and Dube, 2018; Parsons, 2019; Zhang et al., 2019). Most of these methods are either time/labor/resource-consuming or qualitative evaluations for large areas (e.g., more than 10–30 km), which cannot provide precise estimations on soil erosion rates at the specific sites and insights into the soil erosion history in the past decades.

Radionuclides are effective tracers to monitor environmental processes in oceanography, pedology, atmospherics, etc. (Walling et al., 1999; Alvarado et al., 2014; Qiao et al., 2020). Based on the tight association of some naturally occurring and anthropogenic radionuclides with soil particles, this technique has been applied to trace the movement of soil particles, e.g., the soil erosion and redistribution processes (Zapata and Nguyen, 2009). The naturally occurring \(^{7}\)Be and \(^{210}\)Pb and anthropogenic \(^{137}\)Cs, \(^{239,240}\)Pu are the commonly used radionuclides for different erosion scenarios with the timescale stretching from months to decades (Walling et al., 1999; Zheng et al., 2007; Mabit et al., 2008; Xu et al., 2015; Zhang et al., 2019). The short-lived \(^{7}\)Be (T\(_{1/2}\) = 53.3 d) induced from cosmic radiation is suitable for short-term erosion events, such as individual rainfall events (Mabit et al., 2008). \(^{210}\)Pb (T\(_{1/2}\) = 22.2 yr.), a decay product of \(^{222}\)Rn escaped from soil to air, can be applied for a time-scale of decades, but its application is significantly limited by the difficulties on the accurate determination of low-level \(^{210}\)Pb present in the soil. \(^{137}\)Cs originated from the global fallout of nuclear weapon testing in the 1950s–1980s is the most commonly used radotracer for the assessment of medium-term soil erosion (Zhang et al., 1990, 2003). As a gamma emitting radionuclide, \(^{137}\)Cs can be readily measured by gamma spectrometry without chemical separation. However, due to its relatively short half-life (T\(_{1/2}\) = 30.2 yr.), more than 75 % of the global-fallout-derived \(^{137}\)Cs have decayed away since its maximum fallout in 1963, causing its measurement more and more challenging (Gering et al., 2002).

The long-lived \(^{239}\)Pu (T\(_{1/2}\) = \(2.4 \times 10^4\) yr.) and \(^{240}\)Pu (T\(_{1/2}\) = \(6.5 \times 10^3\) yr.) with the same origination and feature of strong association to soil particles as \(^{137}\)Cs are ideal replacement of \(^{137}\)Cs for this purpose (Alewell et al., 2017). The rapid development of mass spectrometry techniques, especially inductively coupled plasma mass spectrometry (ICP-MS), has enabled the determination of ultra-trace levels of \(^{239}\)Pu and \(^{240}\)Pu in environmental samples (Xing et al., 2018) and made it an alternative of \(^{137}\)Cs to estimate soil erosion. Global-fallout derived \(^{239,240}\)Pu (sum of \(^{239}\)Pu and \(^{240}\)Pu) has been used to evaluate soil erosion in different areas with diverse vegetation types or terrains, such as in the forested catchment of Germany (Calirli et al., 2020), the loess landscape of Poland (Loba et al., 2021), the wet-dry tropics of Australia (Lai et al., 2020), the Central Swiss Alps (Musso et al., 2020), and the bay region of northeastern China (Xu et al., 2013; Zhang et al., 2016). The application of plutonium isotopes in soil erosion estimation in the Loess Plateau is very limited. Zhang et al. (2019) estimated soil erosion rates in two slopes in a catchment (covered by artificial forest and natural grass, respectively) in the Loess Plateau using plutonium isotopes for the first time. The investigated sites in their study were specialized restoration areas with only two land utilization types.

In this study, we investigated soil erosion rates in the hilly-gully region with different land utilization and vegetation types by determining \(^{239}\)Pu and \(^{240}\)Pu in soil profiles collected from the uncultivated sites (forest and grassland) and cultivated sites (apple orchard and cornfield) in the Heimugou (Luochuan County), a typical watershed in the hilly-gully region of the middle Loess Plateau of China, to understand the change of the erosion rate and the major influencing parameters in the past 60 years, as well as to evaluate the effectiveness of the soil erosion mitigation measures.

2. Materials and methods

2.1. Study sites and sampling

The Heimugou Catchment (35°42’35”–35°44’45”N, 109°24’56”–109°28’12”E) is located in Luochuan County, Shaanxi Province, China (Fig. 1). This 7-km long gully spreads from south to north with slopes of 20–60° on both sides and flat land on the top. A stream flows at the bottom of the catchment to the Xiangshe River which joins to the Luohe River and finally flows to the Yellow River. The Heimugou Catchment is a typical watershed in the Beiluo River Basin in the middle Loess Plateau that has contributed about 7.1 \(\times 10^7\) t of soil particles to the Yellow River through the erosion processes during 1958–2012 (Zhu et al., 2004; He et al., 2016). The altitude difference of the catchment is about 250 m from the lowest point at the bottom elevation (elevation = 870 m) to the highest point at the top (elevation = 1120 m).

The mean annual precipitation in this region is 533 mm in the past 60 years, mostly (60–70 %) occurring from July to September (Fig. S1). The mean annual evaporation (1629 mm) is about three times higher than the mean annual precipitation, resulting in a relatively dry condition of the soil for most of the year. The annual mean wind speed is quite constant throughout the whole year, with an annual mean value of 2.2 m/s (Fig. S2). The main soil types in the Heimugou Catchment are Quaternary loess, Neogene red clay, and Triassic sandstone-mud-stone. The soil type of all sampling sites in this study is Lishi loess, a kind of Quaternary loess, developed in the late Middle Pleistocene with a silt-dominated texture that is easily eroded (Wang et al., 2019). The major natural vegetation species in the hilly-gully region of the Loess Plateau are Robinia pseudoacacia for trees and Agropyron cristatum, Imperata cylindrica (L.) Beauv, and Bothriochloa ischaemum for grasses, and the main crop types are maize, wheat, and apples. In the study area, most of the farming land is located on flat loess tableland, and the slopes on both sides of the gully are grassland and forest (part of them also on the flat Loess tableland). Eight soil cores with 40–65 cm depth were collected from four natural grassland sites, two forest sites, and two arable land sites in the Heimugou Catchment in July 2020 (Fig. 1, Table 1). Four grassland sites are successively located on a grassland slope with 80–90 % grass coverage and no visible disturbance (Fig. 2). Among them, one site is located on the top flat area (G1); two sites are from the slope with gradients of 20° (G2) and 40° (G3), respectively; and one site is on a platform with a gradient of 2° (G4) at the bottom of the slope and nearby a vertical scarp of 100–150 m height above the catchment bottom.

Two forest soil cores (F1 and F2) were collected from a top flat area covered with condensed locust trees and grass (vegetation coverage > 90 %) in the north of the Heimugou Catchment without disturbance by human activities since the 1950s. Two soil cores were collected from an apple orchard (A1) and a cornfield (A2) on the flat arable field area of the Heimugou Catchment, respectively. The apple orchard (total 2668 m\(^2\)) was used for cultivating winter wheat in 1950–1995 and has been planting apple trees since 1995. Tree spacing is 4 m between the rows and 3 m between the plants on a row. The cornfield was typical rain-fed farmland with the maize’s growing period from April to October. This field was seeded with winter wheat from 1950 to 1985 and then converted to cultivate maize since 1985.

The soil cores from natural grassland (G1, G2, G3, and G4) and forest (F1 and F2) were manually collected using a stainless-steel spade (10 \(\times\) 10 cm) with 2-cm intervals in the upper 30 cm and 5-cm intervals for the depth of 30–65 cm. Two 60-cm deep soil cores (A1 and A2) were collected with the stainless-steel soil tube auger (4.0 cm in diameter) and divided into 5-cm intervals. The collected soil samples were sealed in plastic bags and transported to the laboratory. After removal of plant roots and stones (>2 mm), the samples were weighed and dried in an oven at 105 °C until constant weight. An aliquot of soil sample was taken for measurement of grain size, and the remaining soil was ground and sieved through an 80-mesh sieve.
2.2. Radiochemical analysis of plutonium isotopes in soil samples

A modified method by Zhang et al. (2019) was applied for the determination of plutonium isotopes in the soil samples. In brief, 5–10 g of the homogenized soil powder was ashed at 450 °C for 12–15 h to remove organic matter. The difference of the sample weights before and after the ashing was measured as the loss-on-ignition (LOI) to estimate the organic matter content in the sample.

$^{242}$Pu tracer (~5 mBq) was spiked to the sample to monitor the chemical yield of plutonium during chemical separation. The sample was then digested with 80–100 mL of Aqua regia at 150 °C for 30 min and at 200 °C for 2 h. The leachate was filtrated through a glass fiber filter, and the residue was rinsed with diluted 0.5 M HNO$_3$. 2.0 M NaOH solution was added to the leachate to adjust pH8–9, and the formed hydroxides co-precipitate was separated by centrifuging to remove the matrix elements. The precipitate was dissolved with 3–5 mL of conc. HCl, 200–300 mg of K$_2$S$_2$O$_7$ was added to the sample solution to reduce plutonium to Pu(III). 20 % ammonia solution was then added to the sample solution to adjust pH8–9 to co-precipitate Pu(OH)$_3$ with Fe(OH)$_3$. After separation of the precipitate by centrifuge, 1–2 mL of conc. HCl was added to dissolve the precipitate, and then conc. HNO$_3$ was added to convert Pu(III) to Pu(IV) and prepare the sample in 3.0 M HNO$_3$ solution. The prepared sample solution was

Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>Site</th>
<th>Land use</th>
<th>Elevation (m a.s.l.)</th>
<th>Terrain</th>
<th>Location</th>
<th>Gradient</th>
<th>Bulk density ($g/cm^3$)</th>
<th>pH §</th>
<th>LOI *%</th>
<th>Soil particle sizes # %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unploughed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20–200 μm</td>
</tr>
<tr>
<td>F1 Forest</td>
<td>1100</td>
<td>Tableland</td>
<td>Flat area</td>
<td>0°</td>
<td></td>
<td></td>
<td>1.27</td>
<td>8.1</td>
<td>5.4 (9.6–2.5)</td>
<td>56.7</td>
</tr>
<tr>
<td>F2 Forest</td>
<td>1100</td>
<td>Tableland</td>
<td>Flat area</td>
<td>0°</td>
<td></td>
<td></td>
<td>1.29</td>
<td>NA</td>
<td>4.9 (7.1–2.8)</td>
<td>50.6</td>
</tr>
<tr>
<td>G1 Grassland</td>
<td>1110</td>
<td>Tableland</td>
<td>Top</td>
<td>0°</td>
<td></td>
<td></td>
<td>1.36</td>
<td>8.2</td>
<td>4.8 (12.6–2.7)</td>
<td>51.0</td>
</tr>
<tr>
<td>G2 Grassland</td>
<td>1085</td>
<td>Slope</td>
<td>Upper</td>
<td>20°</td>
<td></td>
<td></td>
<td>1.44</td>
<td>NA</td>
<td>4.5 (6.2–2.5)</td>
<td>NA</td>
</tr>
<tr>
<td>G3 Grassland</td>
<td>1060</td>
<td>Slope</td>
<td>Middle</td>
<td>40°</td>
<td></td>
<td></td>
<td>1.29</td>
<td>8.3</td>
<td>4.1 (7.1–3.2)</td>
<td>31.5</td>
</tr>
<tr>
<td>G4 Grassland</td>
<td>1050</td>
<td>Slope</td>
<td>Lower</td>
<td>2°</td>
<td></td>
<td></td>
<td>1.36</td>
<td>8.0</td>
<td>4.8 (10.3–2.7)</td>
<td>45.6</td>
</tr>
<tr>
<td>Ploughed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1 Arable land</td>
<td>1120</td>
<td>Apple orchard</td>
<td>Flat area</td>
<td>0°</td>
<td></td>
<td></td>
<td>1.42</td>
<td>NA</td>
<td>2.3 (3.0–2.3)</td>
<td>NA</td>
</tr>
<tr>
<td>A2 Arable land</td>
<td>1110</td>
<td>Cornfield</td>
<td>Flat area</td>
<td>0°</td>
<td></td>
<td></td>
<td>1.63</td>
<td>NA</td>
<td>2.6 (3.1–2.0)</td>
<td>NA</td>
</tr>
</tbody>
</table>

* LOI (loss on ignition approximates soil organic matter) in percentage compared to the total mass of the soil, the average, and range.

# the percentages of different sizes of soil particles (20–200 μm, 2–20 μm, and < 2 μm).

§ bulk density and pH are the average values of soil in the whole cores. NA: not measured.

Fig. 1. Sampling sites in the Heimugou Catchment of the Beiluohe River Basin in the Loess Plateau in northwest China.

Fig. 2. Diagram of the sampling sites G1, G2, G3, and G4 in the grassland slope in the Heimugou Catchment. (a) illustrating the process of the deposition of eroded soil at the site G3 on the middle of the grassland slope; (b) a photo of sampling site G3 showing the vegetation coverage and terrain.
loaded to a 2-mL TEVA resin column preconditioned with 40 mL of 3.0 M HNO₃. After rinsing with 80 mL of 3.0 M HNO₃ and 40 mL of 6.0 M HCl to remove uranium, thorium and other interfering elements, Pu on the column was eluted with 20 mL of 0.1 M NH₄OH-HCl-2.0 M HCl solution by reducing Pu(IV) to Pu(III). The eluate was evaporated to dryness at 200 °C, and the residue was dissolved with concentrated HNO₃. After heating at 200 °C to decompose NH₄OH-HCl, the solution was evaporated to dryness. The residue was dissolved with 4 mL of 0.5 M HNO₃. Plutonium isotopes (239,240Pu, 241Pu, and 242Pu) in the sample solution were measured using a triple quadrupole ICP-MS (Agilent 8800). NH₃-He was applied as the reaction gas to eliminate the interferences of 238UH⁻ and 238UH²⁻. The measurement sensitivity for 239Pu and 240Pu was 710 cps/ppt. The chemical yields of plutonium in the chemical separation were measured to be 75–95%. Based on using the procedure blank, the detection limits of the analytical methods for 239Pu and 240Pu were estimated to be 2.0 × 10⁻³ and 3.0 × 10⁻⁴ Bq/g, respectively.

2.3. Estimation of soil erosion rate

The soil erosion rate was estimated by the comparison of the 239,240Pu inventory in an investigated site with that in the reference sites without obvious soil erosion and accumulation. As various degrees of soil erosion occurred in all sample sites, we used a reference site from the Dongzhuanggou catchment of the Loess Plateau (as discussed in 3.2) nearby the studied area. The assumptions of this approach are: (1) the plutonium isotopes in the study area only originated from the global fallout; and (2) the sampling sites and reference sites have the same 239,240Pu deposition and depth distribution (Alewell et al., 2017). The 239,240Pu inventory in soil core (Bq/m²) was calculated using the following equation:

\[
I = \frac{1}{A} \sum_i M_i C_i
\]

where \( A \) is the cross-sectional area (m²) of the soil core, \( M_i \) is the mass of the \( i \)-th depth increment of a soil core (kg), and \( C_i \) is the 239,240Pu concentration (Bq/kg) of the \( i \)-th depth increment.

The Modelling Deposition and Erosion rates with Radio-Nuclides (MODERN) model was used to calculate soil erosion rates in this work (Arata et al., 2016a,b). Different from the previous models (e.g. the Proportional Model (Zapata, 2002), the Profile distribution Model (Portes et al., 2018; Walling and Quine, 1990), the Inventory Method (Lal et al., 2013; Portes et al., 2018), the Mass Balance Model (Zapata, 2002) and the Diffusion and Migration Model (Meusburger et al., 2018), the MODERN conversion model could freely define the depth profile of plutonium at the reference site, which is more flexible to adapt to the natural scenarios. Besides, MODERN model allows simulation of different disturbing activities (e.g. tillage, erosion, and deposition) at the reference site, thus assuring the comparability of reference and sampling sites.

The detailed calculation method using the MODERN model in this work are presented in the Supporting Information. Two stepwise functions for the depth profile of 239,240Pu inventory at the reference site were established for two different scenarios of the studied sites (Fig. S5). For unploughed sites (forest and grassland sites), the stepwise function was based on the original depth profile of 239,240Pu inventory determined at the reference site. Whereas for the ploughed sites (apple orchard and cornfield), considering the homogenized effect of ploughing on the vertical distribution of 239,240Pu, the corresponding stepwise function was adapted from that for uncultivated sites by assuming an average inventory value at all the layers above the ploughing depth (20 cm in this study).

To estimate the thickness of eroded soil, the 239,240Pu accumulative inventory at the sampling site was calculated for the whole depth profile. The MODERN model searched in one of the two established stepwise functions for reference site (unploughed or ploughed, depending on the scenario of the eroded site) to target a depth where the sum of all inventories in this increment and those below is equal to the 239,240Pu accumulative inventory of the sampling site. With the calculated thickness of soil loss (\( x^* \), in cm) at the sampling site by MODERN, erosion rate \( Y \) in t/ha/yr could be estimated by the following equation:

\[
Y = 10 \times \frac{x^* \times xm}{d \times (t_f - t_0)}
\]

where \( xm \) is the mass depth (kg/m²) of the sampling site, \( d \) (cm) is the whole depth increment of soil core at the sampling site, \( t_0 \) and \( t_f \) are the sampling year (2020) and the reference year (1963), respectively.

3. Results and discussion

3.1. Level and distribution of plutonium in the soil profiles

The 239,240Pu activity concentrations in all soil profiles collected in the Heimuogu Catchment range from 0.002 to 0.34 Bq/g (Fig. 3). The peaks of 239,240Pu concentration present at the depth of 10–20 cm in the uncultivated soil profiles (G1–G4, F1, and F2), followed by an exponential decline with depth in the deeper layers. The cultivated soil cores (A1 and A2) showed relatively homogeneous distributions of 239,240Pu in the ploughing layer of 0–20 cm.

The 239Pu/239Pu atomic ratios (Fig. 4) in all soil profiles vary within 0.154–0.217 (excluding the results with high uncertainty in the deep layers) and have a mean value of 0.184 ± 0.011 (1σ), which agrees well with the typical ratio (0.18 ± 0.014) of global-fallout originated plutonium from atmospheric nuclear weapons tests (Kelley et al., 1999). Similar 240Pu/239Pu atomic ratios were reported in the other soil profiles collected in the Loess Plateau by Zhang et al. (2019) (0.186 ± 0.017) and Cao et al. (2019) (0.189 ± 0.043), suggesting that the global fallout is the dominant source of plutonium isotopes in this region.

The distributions of the 239,240Pu inventories in each layer for the investigated sites with the total inventory in the entire soil column are shown in Fig. 5. A large variation was observed for the total inventories of 239,240Pu from 33.87 ± 2.62 to 82.66 ± 4.98 Bq/m² in the investigated soil cores collected in the Heimuogu Catchment region, which are significantly lower than the reported levels for the sites at similar latitudes in the United States, South Korea, Italy, and China (84.5–231 Bq/m², Table 2) (Lee et al., 1996; Ketzerer et al., 2002; Xu et al., 2015; Portes et al., 2018; Raab et al., 2018; Ni et al., 2018; Cao et al., 2019; Zhang et al., 2019). These values are also much lower than the observed level at a reference site in Qingyang (35.7 N, 107.5 E; 111 ± 5 Bq/m²) in the Loess Plateau near the sampling sites of this work (Zhang et al., 2019), indicating that remarkable soil erosion occurred in the study region.

Among the investigated soil profiles, the total 239,240Pu inventories in the forest sites (61.00 ± 3.12 Bq/m² at site F1 and 79.04 ± 3.97 Bq/m² at site F2) are higher than those in the grassland sites (36–49 Bq/m² at sites G1, 2, and 4) except for site G3 with the maximum inventory (82.7 Bq/m²). The sites G1, G2, G3, and G4 are located in a hilly grassland from top to the bottom (Fig. 2). The total 239,240Pu inventories at sites G1, G2 and G4 are comparable (around 42 Bq/m²), which is only about half of that at site G3. These three sites (G1, G2, and G4) show relatively low 239,240Pu inventories and 239,240Pu mainly presents in the uppermost 30 cm layer of soil, indicating an erosion of the upper layer of the soil no matter at the flat or the slope sites. Compared to the other sites in the grassland (G1, G2, G4) with gentle slopes (<20°), site G3 is at a steeply convex spot (40°) at the middle of the grassland with a deeper 239,240Pu depth distribution (0–50 cm). Its peak value of 239,240Pu inventory occurred at 20 cm depth in the soil core, which is different from the typical exponential declined trend or peaked value at the subsurface (3–5 cm depth) followed by an exponential declined trend of 239,240Pu inventory with depth (Alewell et al., 2017). These features suggest that
Fig. 3. Depth distributions of $^{239,240}$Pu concentrations in eight studied soil cores collected from the Heimugou Catchment.

Fig. 4. Depth profiles of $^{240}$Pu/$^{239}$Pu atomic ratios in eight studied soil cores collected from the Heimugou Catchment. The gray column shows the typical average of $^{240}$Pu/$^{239}$Pu ratio of the global fallout of $0.18 \pm 0.014$. (Kelley et al., 1999).
there might be an accumulation of soil eroded from the upper part of the grassland slope at site G3. The low total 239,240Pu inventories at two farmland sites (40.14 ± 2.71 at A1 and 33.87 ± 2.62 Bq/m² at A2) and the relatively homogeneous 239,240Pu distribution in these two soil cores indicate a high soil erosion level and significant disturbance of the soil profile by the tillage activities in the 20 cm topsoil of these sites.

3.2. Soil erosion rates in the Heimugou Catchment

Based on the depth distribution of 239,240Pu inventories, the soil erosion rates at each site were estimated using the MODERN model in comparison with the reference site. Because of the overall low 239,240Pu inventories at all investigated sites in this work (including the undisturbed flat-top sites with forest or grass coverage), an alternative reference site (Re) in the Loess Plateau in Qingyang was used (Zhang et al. 2019). This site is located in another watershed (Dongzhuanggou), which is 175.2 km away from the studied area and has a similar climate (annual average precipitation of 556 mm) and soil type (Loess). This site has been well protected by vegetation conservation measures since 1954 without obvious soil erosion or deposition. Considering the similar environmental conditions and clear vegetation conservation history, the Re site is the best available reference soil profile for this research. The reference soil profile sample was collected without visible soil erosion and deposition and analyzed for 239Pu and 240Pu. An exponentially declining depth profile of 239,240Pu concentrations in a soil core sampled from a flat natural grassland at this reference site has been reported (Zhang et al. 2019), and the total inventory of 239,240Pu in this soil core was estimated to be 111 ± 5 Bq/m² (Table 2 and Fig. S3), which is significantly higher than those observed in the investigated area and comparable with the values of other similar latitude regions in Table 2. However, the investigations of deposition and soil depth profiles of plutonium isotopes (239Pu and 240Pu) at reference sites in the hilly-gully region of the Loess Plateau are still limited, and more relevant data will be supplied to calibrate the soil erosion rates evaluated by the plutonium

Table 2
Comparison of the total inventories of 239,240Pu estimated in the Heimugou Catchment of the Loess Plateau with those reported in the reference sites of the different locations in the middle latitude in the North Hemisphere.

<table>
<thead>
<tr>
<th>District</th>
<th>Site</th>
<th>Latitude/Longitude (° N/° E)</th>
<th>Precipitation mm/a</th>
<th>Land types</th>
<th>239-240Pu inventory (Bq/m²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>America</td>
<td>Wind River Range</td>
<td>42.8°N, 109.2°W</td>
<td>1100</td>
<td>Forest</td>
<td>149-231</td>
<td>Portes et al. 2018</td>
</tr>
<tr>
<td>America</td>
<td>Lake Erie</td>
<td>42.2°N, 81.2°W</td>
<td>1396</td>
<td>Stream sediments</td>
<td>108</td>
<td>Ketterer et al., 2002</td>
</tr>
<tr>
<td>South Korea</td>
<td>Euiwang</td>
<td>37.3°N, 127.0°E</td>
<td>1460</td>
<td>Forest</td>
<td>102</td>
<td>Lee et al. 1996</td>
</tr>
<tr>
<td>Italy</td>
<td>Sila Mannif upland</td>
<td>39.4°N, 6.5°E</td>
<td>1000-1800</td>
<td>Grassland/Forest</td>
<td>86.5-176</td>
<td>Raab et al. 2018</td>
</tr>
<tr>
<td>Northeastern China</td>
<td>Dalian</td>
<td>38.9°N, 21.4°E</td>
<td>600-800</td>
<td>Grassland/Forest</td>
<td>84.5-90.0</td>
<td>Xu et al. 2015</td>
</tr>
<tr>
<td>Northeastern China</td>
<td>Chengde</td>
<td>42.3°N, 117.3°E</td>
<td>512</td>
<td>Grassland</td>
<td>138.4</td>
<td>Ni et al. 2018</td>
</tr>
<tr>
<td>Loess Plateau China</td>
<td>Yan’an</td>
<td>36.8°N, 109.3°E</td>
<td>505</td>
<td>Grassland</td>
<td>66</td>
<td>Cao et al.2019</td>
</tr>
<tr>
<td>Loess Plateau China</td>
<td>Qingyang</td>
<td>35.7°N, 107.5°E</td>
<td>556</td>
<td>Grassland</td>
<td>111 ± 5</td>
<td>Zhang et al. 2019</td>
</tr>
<tr>
<td>Loess Plateau China</td>
<td>Luochuan</td>
<td>35.7°N, 109.5°E</td>
<td>533</td>
<td>Grassland</td>
<td>36-83</td>
<td>This study</td>
</tr>
</tbody>
</table>

(Inventory of 239,240Pu in each layer is calculated by 239,240Pu concentration multiplied by the bulk density and the depth of the corresponding interval).

Fig. 5. Depth distribution of 239,240Pu inventories in eight studied soil cores collected from the Heimugou Catchment. (Inventory of 239,240Pu in each layer is calculated by 239,240Pu concentration multiplied by the bulk density and the depth of the corresponding interval).
The estimated soil erosion depth, rate and intensity in the studied sites in the Heimugou Catchment.

<table>
<thead>
<tr>
<th>Forest</th>
<th>Grassland</th>
<th>Arable land</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>$^3$H</td>
<td>$^{14}$C</td>
</tr>
<tr>
<td>F1</td>
<td>0.5</td>
<td>37.6</td>
</tr>
<tr>
<td>F2</td>
<td>0.4</td>
<td>37.55</td>
</tr>
<tr>
<td>G1</td>
<td>5.1</td>
<td>10.1</td>
</tr>
<tr>
<td>G2</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>G4</td>
<td>32.5</td>
<td>40.5</td>
</tr>
</tbody>
</table>

4. Key factors influencing soil erosion rate

A large variety of soil erosion rates at different sites was estimated in the investigated area using the $^3$H tracer. Although the loose soil (loess) and concentrated precipitation (60 %–70 % in the summer) in the Loess Plateau could aggravate the soil erosion rates, the similar climate conditions in this relatively small watershed in the investigated area could not cause such a large variation in soil erosion rates.

The steep slope in the Heimugou Catchment (typically 20–60 °) generally favors water erosion by increasing the velocity and flow rate of runoff (Fang et al., 2015; Wang et al., 2019), whereas the sampling sites in this study (except for the site G3) have relatively gentle and similar slopes (< 20 %), which has a limited impact on the variation of the soil erosion ratio in these sites.

The different land utilization and types of vegetation coverage in the Heimugou Catchment might be the key factors responsible for the different soil erosion rates. Increased soil erosion rates were observed for the sites in an order of forest < grassland < arable land in the Heimugou Catchment. The lowest soil erosion rates (5.1–7.6 t/ha/yr) were observed at sites of the forest (F1 and F2), followed by grassland (G1, G2, and G4) with relatively low erosion rates of 10.1–13.0 t/ha/yr. This is probably owing to the fact that forests and grassland can effectively reduce the intensity of the kinetic energy of raindrops and water flows (Lacombe et al., 2018; Zhang et al., 2019) as well as the wind speed above the soil surface (Li et al., 2005; Wolfe and Nickling, 1993). The interlaced roots of vegetation with its exudates and microflora in the forest and grassland can also increase the cohesion and fixation of soil particles (Amekzeta, 1999; Hudek et al., 2017; Musso et al., 2020; Pintaldi et al., 2018), inducing a suppression on soil erosion. Half soil erosion rates in the forests compared to that in the grassland should result from the different seasonal variabilities in vegetation coverage between these two types of land. The forest sites have relatively constant vegetation coverage throughout the whole year. The dominant species of tree in the forest in this region is the locust, a perennial deciduous tree species with a large forest canopy and extensive litter, which effectively protects the surface soil from erosion by raindrops and wind, even in the winter. Whereas natural grassland can only maintain high vegetation coverage in the growing season (i.e., from late spring to autumn), and the withering of grass in other seasons (i.e., winter) leads to the decrease of grass coverage, exposure of bare soil surface, and therefore increased...
wind erosion occurring in the winter (Hou et al., 2020). The higher erosion rates at the grassland sites than those at the forest sites were also reported by other studies in the Loess Plateau and Sichuan Basin (Fu et al., 2009; Li et al., 2009). The highest soil erosion rate (32.5–40.5 t/ha/yr) was observed at the cultivated land sites (A1 and A2). The apple orchard (site A1) was mainly covered by low-density trees (about 12 m²/tree) and less other vegetation (e.g., grass). The cornfield (site A2) is only covered by cultivated plants in April to October. The less vegetation coverage and not well-developed root system in the surface soil of the cultivated land compared to the natural grassland and forest cause higher soil erosion by water and wind. The low content of organic matter in the cultivated land (Table 1 and Fig. S4) arising from the low vegetation coverage hampers the aggregation of soil particles and water infiltration, exacerbating water-induced erosion (Comporti et al., 2013). The studies in the upper Min River watershed and the Loess Plateau also showed that vegetation coverage has a considerable influence on the soil erosion rate (Jin et al., 2021; Zhou et al., 2008).

3.4. Re-location of the eroded soil in the grassland slope

The highest total inventory of $^{239,240}$Pu (82.7 Bq/m³) and the deepest distribution of $^{239,240}$Pu (50 cm) in the soil core was observed at site G3 in the natural grassland over all investigated sites in the Heimugou Catchment (Fig. 5). The accumulated inventory and distribution of $^{239,240}$Pu in the 20–50 cm section at site G3 are similar to the 0–30 cm sections at sites G1, G2, and G4 (Fig. 6). Based on the assumption that there were the same initial $^{239,240}$Pu distributions in all soil profiles, there might be a similar soil erosion to the other grassland sites that occurred at site G3 in the early date but accompanied by deposition of 20 cm eroded soil at the top of soil core afterwards (Fig. 6). The significant accumulation of the eroded soil at site G3 might be attributed to the convex terrain where the fine particles eroded by the downward-flowing stream from the upper slope were deposited and accumulated (Fig. 2a and 2b). This is supported by the significantly larger fractions of the average fine soil particle content (<2 μm: 9.3 %; and 2–20 μm: 59.2 %) in the soil profile at site G3 compared to those at sites F1, F2, G1, and G2 (<2μm: 6.2–8.1 %; and 2–20 μm: 37.1–46.3 %) (Fig. 7). Fine soil particles, compared to heavier coarse soil particles, could be easily removed by the inertial force of water flow (Wang and Shi, 2015), resulting in a deposition of the eroded fine particles at site G3. This is also supported by the observation that the eroded sediment contains 2.7–18.9 % more high-fine particles (<2 μm) than the on-site soil (Poesen and Savat, 1981; Tuo et al., 2014; Wang and Shi, 2015). This indicates that the convex slope could trap the eroded soil particles and reduce the overall loss of soil on the slope. This also agrees with the previous investigation in another catchment in the middle Loess Plateau (Zhang et al., 1990), where nearly twice $^{137}$Cs inventory in the soil cores at the lower site with the convex terrain was observed compared with the upper side of the same slope. This support that the convex terrain is effective for deposition of the eroded soil from the upper part of the slope. An experimental study also indicated that an undulant microrelief consisting of mounds and troughs is more effective to mitigate soil loss than a smooth surface (Zhao et al., 2021). However, the total $^{239,240}$Pu inventory at site G3 is still lower than that at the reference site, indicating that the deposition of eroded soil particles at site G3 from the upper slope may have only occurred in the later stage after the reclamation because the severe soil erosion eroded most of the $^{239,240}$Pu inventories in the 1950s–1970s or even until the 1980s, while the deposition layers of G3 have relatively low $^{239,240}$Pu inventories.

In the Heimugou Catchment, most of the eroded soil particles might be flushed to the bottom of the catchment along the steep slopes by the surface runoff after heavy rainstorms, leading to a large amount of soil deposition at the bottom of the catchment. Due to the typically interlaced structure of plateau, gully, and ridge in the Loess Plateau, the surface soil from the sloping areas is often moved by water flow and wind to the low-lying locations and deposited in the hilly-gully regions of the Loess Plateau (Hessel and Van Asch, 2003; Wei and Shao, 2007). The eroded soil particles, especially the fine soil particles might be also flowed to the rivers in each catchment and then to the Yellow River, and eventually be deposited in the estuarine area of the Yellow River in the Bohai Sea (Zhu et al., 2004; He et al., 2016).

4. Conclusion

The soil erosion in the Heimugou Catchment, a typical watershed located in the middle of the Loess Plateau, was investigated using a $^{239,240}$Pu tracer. Land reclamation and deforestation in the 1950–1970s resulted in a wide and relatively severe soil erosion (with erosion rates of 5.1–40.7 t/ha/yr.) in this region. And the soil and water restoration practices (such as the Green to Grain project) implemented since the 1980s by recovering the vegetation coverage through returning the reclaimed sloping farmland to forest and grassland significantly suppressed soil erosion rates. Compared with the arable land, forest and grassland with higher vegetation coverage in most seasons of the whole year are prone to resist soil erosion, confirming the effective practice in
the Loess Plateau over the past 2-3 decades. The convex microtopography can play an important role in the resistance of soil loss in the slope area, which provides a practical strategy for the mitigation of soil loss in the Loess Plateau.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

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