Preliminary experiments to assess the effectiveness of magnetite powder as an erosion tracer on the Loess Plateau

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ABSTRACT

Soil water erosion monitoring is essential for long-term soil conservation and ecological restoration on the Loess Plateau region of China. Traditional approaches, such as runoff plots and water weirs in a watershed, provide reliable spatially averaged soil erosion data but cannot validate process-based erosion prediction models for dynamic soil erosion evaluation. Erosion tracer techniques are capable of quantitatively determining spatial distribution of soil erosion. Ideal tracers are expected to provide highly contrasting values compared with background ones, and be analyzed efficiently and acquired cost-effectively. In this laboratory study, magnetite powder was selected as an erosion tracer to test. The tracer was implanted into loessial soils from the Loess Plateau using a wet soil-tracer mixing procedure. The effectiveness of magnetite powder as an erosion tracer was evaluated in aspects of basic magnetic features between the tracer and soils, distribution under different soil aggregate sizes, mobility along soil profiles, and detachment of tracer-labeled loessial soils by shallow surface flow along a slope. Results showed that magnetite powder was bound tightly to loessial soil aggregates, with no noticeable vertical mobility under long-term leaching conditions, and almost synchronous detachment with the eroded soils. Furthermore, the tracer is an inexpensive tracer (approximately 0.08 US$/kg), which has higher magnetic susceptibility over two or three orders of magnitude than ordinary soils and high sensitivity of analysis (< 1% measuring error). It can also provide quick measurement (< 15 s) with equipment expenditure at relatively low price (approximately 5000 US$). The work demonstrates that magnetite powder as a promising erosion tracer will be great potential on the Loess Plateau region. Effectiveness of the magnetite powder tracer under simulated and natural rainfall conditions in this region still need to be testified in the future studies.

1. Introduction

As a key area of food and fossil energy production in the Northwest China, the Loess Plateau suffers severe human-induced soil erosion due to intensive agricultural cultivation and destruction of natural vegetation during the past hundreds of years (Tang, 2004). Soil erosion dramatically changes the landscape of this region from flat ground to gully system, and it becomes one of the most serious environmental problems hindering economic sustainability and life quality of local people (Zhao et al., 2013).

Soil water erosion monitoring and prediction are essential for long-term soil conservation and ecological restoration on the Loess Plateau. In the past 50 years, increasingly researches on water erosion (Tang, 2004) have been conducted at slope, watershed and region scales in this region, which provides valuable data for developing and modifying erosion models. However, most of these studies were based on spatially averaged soil erosion data due to imperfect traditional approaches for dynamic spatial patterns of soil erosion, such as runoff plots and water weirs in watersheds (Lal, 1994). This restricted accurate understanding of the spatial and temporal variations of soil redistribution processes at slope and watershed scales. Spatially distributed soil erosion data are important for better understanding of erosion dynamics, and evaluation of the impacts of local agricultural productivity and vegetation recovery on soil erosion and deposition processes. Moreover, they can be helpful for validating process-based erosion models (i.e. Water Erosion Prediction Project model, WEPP) (Li et al., 2017), dynamic monitoring of soil erosion, assessments of soil conservation practices and government-led land use policy in the region.

Tracers are recognized as useful tools to obtain spatially distributed soil erosion data (Zhang et al., 2001; Zapata, 2002). Various

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types of tracers, including radionuclide (e.g., $^{137}$Cs, $^{210}$Pb, or $^7$Be) tracers (Zapata, 2002), rare-earth oxide tracers (Liu et al., 2004; Zhang et al., 2003, 2017), noble element (e.g., Au or Ag) tagged natural grains (Wheatcroft et al., 1994), and exotic magnetic materials (e.g., magnetic plastic bead) (Ventura et al., 2001, 2002) have been proven to be effective in obtaining spatially distributed soil erosion data. However, each type of these tracers has its own limitation, which can be referred to Zhang et al. (2001, 2003), Guzmán et al. (2010, 2013), and Armstrong et al. (2012).

According to the suggestions from Liu et al. (2001) and Zhang et al. (2001), ideal erosion tracers should be difficult to dissolve in water, not easily absorbed by plants, harmless to eco-environment, possess low soil background values, and has a strong binding with soil particles or aggregates. Additionally, the analytical precision of the tracers needs to be high enough and the cost needs to be low enough. From a worldwide perspective, previous studies focused on the selection of ideal tracer on soil erosion research which was the prerequisite for the application of erosion tracer techniques. For magnetic tracers, various types have been tested, such as steel nuts (Lindstrom et al., 1992), magnetic plastic beads (Ventura et al., 2001, 2002), and different mixtures of fine soils, magnetic powder and fly ash with cement (Hu et al., 2011). However, selective transportation of these tracers caused by their density, size and shape significantly differ from soils in the erosion process, which limited their erosion tracing ability. Even though the binding and synchronous movement problems of the tracer with soil aggregates was solved by adding strong magnetic heated sediment or soils to natural soils (Parsons et al., 1993; Armstrong et al., 2012), the relatively high cost and limited types of original soils in heated soil technique restrict its use in wider areas.

To our knowledge, magnetite powder is close to an ideal tracer among existing erosion tracer. The magnetite powder is pure black powder, commonly used as auxiliary material in the process of coal mining or as pigment. The powder belongs to low-cost minerals commonly processed as silt-sized particles. Its commercial retail price is very cheap (roughly 0.08 US$·kg$^{-1}$) in China. Furthermore, the magnetite powder is almost pure ferrimagnetic minerals and its extremely high magnetism is three or four orders of magnitude than most natural soils (Mullins, 1977; Thompson and Oldfield, 1986; Yu and Lu, 1991; Dearing, 1994). More importantly, magnetic susceptibility measurement is rapid (< 15 s) and highly accurate (approximately 1% measuring error) (Dearing, 1994). However, reports on understanding the silt-sized magnetite powder as a soil erosion tracer is still insufficient. Using it as a water erosion tracer has only been attempted by Guzmán et al. (2010, 2013), who successfully conducted simulated experiments on soils from agriculture and field experiments in olive orchard plots in Southern Spain. Their pilot studies demonstrated that the magnetite powder tracer was an efficient tracer, and beneficial for providing precise evaluation of soil erosion rate and spatial distribution in remote areas lacking runoff plots system and measuring weir for sediment yield at a catchment outlet. As an emerging erosion tracer, it is imperative to assess the feasibility of this erosion tracer in more regions.

Existing erosion tracers applied on the Loess Plateau include environmental radionuclides, such as $^{137}$Cs (Zhang et al., 1989, 1991; Yang et al., 1999, 2006) and $^7$Be (Liu et al., 2009, 2011; Liu et al., 2016) and rare earth oxides (Tian et al., 1992, 1994; Liu et al., 2001, 2004). Studies involving magnetic tracer techniques for water erosion have not been reported up to now. The authors believe if the silt-sized magnetite powder can label the erosive loessial soils with similar texture of this tracer (Zhang et al., 2015) to inexpensively and timely quantify soil loss and spatial patterns of soil erosion, it will play an important role on efficiently obtaining the spatially distributed soil erosion data in this region.

For erosion tracers, good binding ability and synchronous mobility of erosion tracer with targeting soils is indispensable in the practicality of tracer technology. Thus, this paper presented the preliminary laboratory results using magnetite powder as an erosion tracer in loessial soils of the Loess Plateau. The objectives of this paper were to (1) evaluate the binding ability of the tracer with loessial soils by revealing the particle distribution of the tracer on different-sized soil aggregates, (2) evaluate its vertical mobility in long-term soil percolation and detachment capability during surface soil scouring process, and (3) summarize its characteristics and application conditions.

2. Materials and methods

2.1. Characteristics of soils and magnetic tracer

Four typical soils distributing from north to south on the Loess Plateau of northwest China (Fig. 1) were collected from the topsoil of
Soil percolation test

Lyses of tagged soils were completed in triplicate. With 5 di-
machine in a 20-min run, which equipped with a set of nylon sieves.

Basic features of the tracer were in accordance with Guzmán et al.

Distribution was performed using an 8841 electric vibrating sieve

2.4. Determination of soil aggregate size distribution

(Dearing, 1994).

Table 2

<table>
<thead>
<tr>
<th>Soil code</th>
<th>Soil particle composition(%)</th>
<th>Texture</th>
<th>Organic matter (%)</th>
<th>Bulk density (g cm⁻³)</th>
<th>(\chi_f (\times 10^8 \text{ m}^2 \text{ kg}^{-1}))</th>
<th>(\chi_{lf} (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clay</td>
<td>&lt; 0.002 mm</td>
<td>Silt</td>
<td>0.002-0.05 mm</td>
<td>Sand</td>
<td>0.05-2 mm</td>
</tr>
<tr>
<td>SM</td>
<td>5.7</td>
<td>34.8</td>
<td>59.5</td>
<td>Sandy loam</td>
<td>0.44</td>
<td>1.4</td>
</tr>
<tr>
<td>AS</td>
<td>9.2</td>
<td>54.3</td>
<td>36.5</td>
<td>Silt loam</td>
<td>0.53</td>
<td>1.2</td>
</tr>
<tr>
<td>CW</td>
<td>19.4</td>
<td>66.2</td>
<td>14.4</td>
<td>Silt loam</td>
<td>1.09</td>
<td>1.2</td>
</tr>
<tr>
<td>YL</td>
<td>33.6</td>
<td>55.2</td>
<td>11.2</td>
<td>Silt clay loam</td>
<td>2.30</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Notes: * Indicates soil texture is identified using the USDA classification scheme (Soil Taxonomy).

Table 1

Sampling information and basic properties of the original soils from Shenmu (SM), Ansai (AS), Changwu (CW), and Yangling (YL).

<table>
<thead>
<tr>
<th>Soil code</th>
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<td>1.3</td>
</tr>
</tbody>
</table>

Notes: * Indicates the commercial price of magnetite powder for sale in China in recent years.

cropland (Table 1). These four soils were designated as Shenmu soil (SM), Ansai soil (AS), Changwu soil (CW) and Yangling soil (YL). Basic properties of the original soils were analyzed (Table 1). The magnetic tracer used was magnetite powder, magnetic iron oxide (Fe₃O₄). The collected soils were air-dried, and plant roots and other non-soil materials in the soils were removed. The soils were passed through a 2 mm plastic sieve, then fully mixed with magnetite powder. The soil-tracer mixture in dry state were then stirred into mud state by step-by-step adding deionized water. Finally, the tagged soils with tracer were air-dried, and then grinded lightly before passing through a 5 mm plastic sieve. This tagging procedure is named as a wet soil-tracer mixing method in the following sections.

2.2. Tagging procedure of soils with tracer

The collected soils were air-dried, and plant roots and other non-soil materials in the soils were removed. The soils were passed through a 2 mm plastic sieve, then fully mixed with magnetite powder. The soil-tracer mixture in dry state were then stirred into mud state by step-by-step adding deionized water. Finally, the tagged soils with tracer were air-dried, and then grinded lightly before passing through a 5 mm plastic sieve. This tagging procedure is named as a wet soil-tracer mixing method in the following sections.

2.3. Magnetic susceptibility measurement

Each soil sample (including original and tagged soils) was air-dried, disaggregated and passed through a 2 mm nylon sieve. Specific mass magnetic susceptibility (\(\chi_f\)) was determined at a low frequency (0.47 kHz) and a high frequency (4.7 kHz) using A Bartington® magnetic susceptibility meter MS2* with a dual frequency sensor MS2B* (Dearing, 1994).

2.4. Determination of soil aggregate size distribution

For the original and tagged soils, the analysis of aggregate size distribution was performed using an 8841* electric vibrating sieving machine in a 20-min run, which equipped with a set of nylon sieves with 5 different sizes (viz. 5000, 2000, 500, 200, 50 μm). All the analy-
eses of tagged soils were completed in triplicate.

2.5. Soil percolation test

To test the mobility of the magnetic tracer in soil profiles under the condition of long-term percolation, plastic columns (8 cm in inside diameter and 25 cm in height) were prepared to simulate soil profiles of a 20 cm depth in the field. All the original and tagged soil samples were sieved through a 5 mm nylon sieve. The bottom of the columns was covered with a piece of non-woven textile fabrics (the mesh was 0.5 mm). Then, the columns were gently and uniformly filled with untagged soils in 9 layers with a 2 cm height. Finally, one layer of tagged soil was set above the untaged soil layers, separated by the non-woven textile fabrics.

A long-term indoor percolation simulation for four tagged soils was implemented based on the procedure designed in the previous studies (Zhang et al., 2001; Guzmán et al., 2010). The "long term" refers to approximately 10 years of annual rainfall on the Loess Plateau region (Zhao et al., 2013). Specifically, to simulate 201 deionized water leaching through soil profiles with 50 cm² area and 20 cm deep, equivalently cumulative 400 cm (volume in depth per specific 50 cm² area) leachate in percolation test, 2.5 l deionized water was firstly passed through soil column. A soil percolation test was restarted with another 2.5 l deionized water after the soil column was air dried for three days. All tests were repeated 8 times and lasted approximately two or three months depend on various soil infiltration capacities. After all the tests were finished, each 2 cm soil layer was cut apart separately from the soil column containing certain soil moisture with a plastic knife, air dried, and passed through a 2 mm plastic sieve to determine its magnetic susceptibility. All the tests repeated in triplicate.

2.6. Soil scouring test

The experiment was conducted using a plastic hydraulic flume to test the separation synchronism feature of the tracer in the tagged soils with surface flow along a slope. Fig. 2 shows the schematic diagram of the flume and sample box. In each test, the hydraulic flume was set at 10% slope. The flow discharge of tap water supply was controlled at 0.5 × 10⁻³ m² s⁻¹ and the running time was set to 120 s. The original and tagged soils were air-dried, sieved through a 5 mm screen, and packed into sample boxes. Then, these soils in the specific sample boxes were pretrained with deionized water to saturation before the test. At last, the original and tagged soil samples after the test were air-dried, sieved (≤ 2 mm) again, and analyzed for soil magnetic susceptibility. The tests repeated ten times.

2.7. Microscope observation

To identify the homogeneity of tagged soils, distribution photos (Fig. 3) of the tagged soil aggregates using a professional optical microscope (Olympus-BX51*) were analyzed. First, one drop of trans-
parent nail polish was added onto the center of the slide glass to form a very thin microscopic section. Then the drop was lightly pressed into flate state using a coverslip. A little powder of tagged soils was casted onto the flat nail polish after removing the coverslip. Finally, through gently pressing the powder on the nail polish to form a cloudiness soil sample on the slide glass, a new coverslip was put onto the slide glass for observing and photographing under the microscope.
2.8. Data analysis

Descriptive statistics for all original soils were calculated, including the total number of samples, mean, standard deviation, and variation coefficient. t-tests were conducted to identify significant differences of $\chi_{lf}$ values between original soil layers and tagged soil layers after soil percolation test, and those of $\chi_{lf}$ values and loss weight in soils before and after soil scouring test. Significant differences of $\chi_{lf}$ values and soil weight under various soil aggregate sizes were analyzed using a one-way ANOVA. Statistical analyses were performed using SPSS 17.0 software (SPSS Inc, 2008).

3. Results and discussion

3.1. Features of soils and magnetite powder tracer

3.1.1. Features of original soils

The basic features of original soils from SM, AS, CW, and YL are...
presented in Table 1. Soil particle size distribution, organic matter content and magnetic susceptibility values ($\chi_{fl}$ and $\chi_{lf}$) (Table 1) showed that the four original soils have gradual transition from high latitude to low latitude on the Loess Plateau, indicating these soils are representative regional loessial soils on the Loess Plateau. From SM to AS, CW, YL, the magnetic susceptibility values ($\chi_{fl}$) of original soils increased, varying from $29.2 \times 10^{-8}$ $\text{m}^3 \text{kg}^{-1}$ to $144.6 \times 10^{-8}$ $\text{m}^3 \text{kg}^{-1}$, which were in the range of $\chi_{lf}$ values in most natural soils worldwide (Dearing, 1994).

### 3.1.2. Features of magnetite powder tracer

Basic properties of the tracer are given in Table 2. The magnetic tracer had high mass magnetic susceptibility value ($\chi_{fl}$ = $38.519 \times 10^{-8}$ $\text{m}^3 \text{kg}^{-1}$), more than two or three orders of magnitude compared to the four original soils (Table 1). This result was in the same order of magnitude as reported by Guzmán et al. (2010), Mullins (1977) and Dearing (1994). The texture of magnetite powder was silt-sized predominantly, consistent with the soil particle size distribution of the magnetic tracer applied in the research work of Guzmán et al. (2010). It was close to the silt loam (AS and CW soils) and silt clay loam (YL soils) texture of the original loessial soils (Table 1).

Compared with the widely used $^{137}$Cs tracer, the magnetite powder as an erosion tracer has technical advantages in aspects of analyzing efficiency, measuring accuracy, expenditure and maintenance costs of the instrument and land area (Table 3). Additionally, the magnetic powder is cost-effective and easy to acquire, compared with the current highly-watched artificial rare earth element tracing technique (Liu et al., 2004; Zhang et al., 2001, 2003, 2017). For example, the commercial price of magnetite powder is approximately 0.08 US$/kg in China in recent years. It is widely used in the process of coal mine production, belonging to mineral commodities. By contrast, the prices of rare earth oxides, as scarce mineral resource, range from 30 to 1000 US$/kg in China. In general, the magnetic tracer is acquired inexpensively, and analyzed conveniently and rapidly. Its magnetism ($\chi_{fl}$ values) are two or three orders of magnitude higher than the background values in most of natural soils. These advantageous features of magnetite powder are basis of this erosion tracer for widespread use in the future.

### 3.2. Distribution of magnetic tracer in different-sized soil aggregates

#### 3.2.1. Magnetic features of different-sized aggregates in original soils

Fig. 4 presents the magnetic susceptibility and weight distributions of original soils under different aggregate sizes. The variation of the magnetic susceptibility values in the four original soils were almost consistent under various aggregate sizes, except for $< 0.05$ mm aggregates (Fig. 4a), indicating that magnetic minerals in CW and YL soils were homogeneous, and the magnetism in SM and AS soils had only a slight accumulation in $< 0.05$ mm aggregates (Fig. 4b). This was due to their very low clay content and organic matter content (Table 1) which weakened aggregation in SM and AS soils. This phenomenon was in agreement with the previous study by Guzmán et al. (2010). Moreover, the soil mass in different-sized aggregates was unevenly distributed in SM, AS, CW and YL soil samples (Fig. 4b), supporting the

<table>
<thead>
<tr>
<th>Items</th>
<th>Environmental radionuclides measurement (take $^{137}$Cs as an example)</th>
<th>Soil magnetic susceptibility measurement (take magnetic powder tracer as an example)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement error</td>
<td>$&lt; \pm 10%$ (Zapata, 2002)</td>
<td>$&lt; \pm 1%$ (Dearing, 1994)</td>
</tr>
<tr>
<td>Single analyzing time</td>
<td>$&gt; 30,000$ s (Zapata, 2002)</td>
<td>$&lt; 15$ s (Dearing, 1994)</td>
</tr>
<tr>
<td>Quality of sample required</td>
<td>$&gt; 200$ g (Zapata, 2002)</td>
<td>$&lt; 10$ g (Dearing, 1994)</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>$&gt; 50,000$ US $</td>
<td>$&lt; 5000$ US $</td>
</tr>
<tr>
<td>Land area of equipment</td>
<td>A dedicated lab</td>
<td>$1$ m$^2$ desktop</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>Relatively high</td>
<td>Very cheap</td>
</tr>
</tbody>
</table>
tracer with the tagged loessial soils by shallow surface flow along a slope. Table 4 presents the results of the magnetic susceptibility differences and weight loss in the four original and tagged soils suffering soil detachment and transportation by surface flow. For original samples of the four soils, the proportions of $\chi_{lf}$ difference ($n = 10$) fell into the range from 0.3% to 2.6% after the soil scouring test. Nearly no significant differences of the $\chi_{lf}$ values in original soil samples and residual ones were observed before and after the test, although the proportions of soil mass loss varied greatly (Table 4). Variation coefficients (C.V.) of the $\chi_{lf}$ values ($n = 3$) in original soils ranged from 0.6% to 2.4%, and was at the same variation level as the proportions of $\chi_{lf}$ difference. Thus, the above results fully indicate that almost no selective magnetic grains of the four original loessial soils occurred during the process of soil detachment by surface flow. For tagged soils, C.V. of the $\chi_{lf}$ values ranged between 0.3% and 0.7% ($n = 3$) before the test and ranged between 1.0% and 1.9% ($n = 10$) after the test. The value slightly increased in the $\chi_{lf}$ variation, while the weight of soil loss varied significantly during soil detachment of surface flow. From the point of view of magnetic measurement, these results imply that detached magnetite powder in tagged soils was almost synchronized with soil aggregates and was not sensitive to disturbance of surface flow. Guzmán et al. (2010) observed no significant differences of $\chi_{lf}$ values existed between tagged soils and sediments after rainfall simulations at micro-plot scale using magnetite powder tracer, which supported the above results based on the scouring test.

Taking into account the findings in the preliminary experiments of binding ability, long-term vertical mobility and separation capability of the tracer in tagged soils, the emerging magnetite powder tracer can be considered as an ideal erosion tracer for loessial soils on the Loess Plateau region, compared with the ideal tracer standards for water erosion proposed by Liu et al. (2001) and Zhang et al. (2001). Additionally, this magnetic tracer has been applied successfully to assess spatial variability of water erosion rates in an Olive Orchard at plot scale in Southern Spain (Guzmán et al., 2013), which has set a good example to advance the tracer from research to practice in the study region in future.
4. Conclusions

This study summarizes the following points of the results: (1) aggregate analysis shows the magnetite powder was homogeneous in the tagged loessial soils using a wet soil-tracer mixing method; (2) long-term leaching migration of the tracer indicates that no noticeable mobility of the magnetite powder along the profiles of the four study soils occurred; and (3) soil scouring test suggests that the tracer in the tagged soils was detached and scoured by surface flow with soil aggregates.

The above laboratory results demonstrate that magnetite powder has great potential as an efficient tracer for water erosion research. Considering the low cost, convenient and reliable measurement, the tracer is of great potential in obtaining erosion rates and spatial patterns in areas lacking infrastructural erosion plots and long-term soil erosion data. However, some concerns of application conditions need to be further validated before practical usage. For example, the potential possibility of magnetite powder altering the erodibility of original soils needs to be tested. The applicability of this tracer method to erosion types (sheet erosion or rill erosion) requires to be identified. The disturbance from pedoturbation of earthworms and insects to tagged soil layer is a concern for long-term future erosion monitoring. In sum, future work will be needed to testify the effectiveness of the magnetite powder as an erosion tracer under simulated and natural rainfall conditions on the Loess Plateau region.

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