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# Factor Selection Study to Determine the Sediment Source of a Small Watershed in the Loess Plateau Based on the Multi-element Tracer Technique

**Ningning Zhang*(***) and Puling Liu*(**)†**
*State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China
**Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China
***University of Chinese Academy of Sciences, Beijing 100049, China
†Corresponding author: Puling Liu

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## ABSTRACT

Tracer techniques, such as the multi-element tracer technique, have been studied in recent decades to determine their effectiveness in estimating the sediment sources in the Loess plateau. The first step in studying sediment sources using the multi-element tracer technique is to screen for indicating factors; however, few studies have presented a reference of the trace elements that can be used in the study of sediment sources in the Loess plateau. Furthermore, because the loess deposition resulted from the long-term operation of wind power and loess is generally homologous, significant differences usually do not occur among the concentrations of the loess' chemical elements. To determine obvious differences in the chemical element concentrations, additional factors must be selected. For our study site, we selected a typical small closed watershed in the Peng-yang region of the Ningxia Province in China, and 20 cm surface soil samples were collected at each of the following five geographical locations: (i) ridge, (ii) hill slope, (iii) shoulder line of the valley, (iv) channel slope and (v) area in front of the dam. A neutron activation analysis was then performed, and 31 major soil constituents were detected in the standards and soil samples. The results showed that marked differences occurred among the concentrations of Eu, Fe, Al, Co, Cs, Hf, Sc, Th, Cr, Rb and Mn. And combining a previous study, we suggest that the soil nutrient index, soil magnetic susceptibility and soil concentrations of Al, Eu, Cs, Hf, Sc, Co, Th, Cr, Rb,$^{137}$Cs, $^{7}$Be, $^{210}$Pb and $^{226}$Ra can be used as indicating factors in the study of sediment sources in the Loess plateau.

## INTRODUCTION

The study of sediment sources in the Loess plateau has been a popular and complex research topic for many years. After the 1960s, researchers attempted to distinguish between the sediment sources through a series of investigative methods, such as the runoff plot observation method (Betson & Marius 1969, Hadley & Schumm 1961), large area survey method (Xiong 1990) and hydrological data analysis method (Leopold 1968). In the 1970s, scholars renewed their attempts to study sediment sources by using the "tracer method" (Walling & Peart 1979), which was gradually accepted by researchers. With a large number of relevant studies, researchers determined that using single factor tracer technology produced numerous limitations in the study of sediment sources. Therefore, in 1988, Burch (Burch 1988) first put forward a $^{7}$Be and $^{137}$Cs compound method to determine and predict the sediment sources of catchment areas. Subsequently, the use of multiple tracers became a viable research strategy (Olley et al. 1993, Wallbrink et al. 1999), and the multi-element tracer technique was developed.

The first step to using the multi-element tracer method to study sediment sources is confirming the obvious differences in content of "tracer element" between different potential sediment sources. Here, we apply "tracer element" as a more general concept and assert that when researching soil erosion using tracer technology, any component that functions as a stable tracer material can be used as an indicating factor. Recently, the earth's physical and chemical properties (Peart & Walling 1988), mineral elements (Wall & Wilding 1976), mineral magnetic (Walling & Peart 1979), sediment particle colours (Grimshaw & Lewin 1980), plant pollen (Brown 1985), stable isotopes (Douglas et al. 2003) and atmospheric precipitation isotopes (Olley et al. 1993, Wallbrink et al. 1999) have been referred to as tracer factors to continuously trace sediment sources.

In recent decades, numerous researchers in China have evaluated different experimental methods and techniques to determine the sediment sources of the Loess plateau. However, because the loess is generally homologous and the deposition is the result of long-term wind power operations, the sources have obvious homologous characteristics. Therefore, significant differences have not been found in the nuclide concentrations in the horizontal and vertical loess, and the use of tracer methods to research the sediment sources of the Loess plateau watershed has attracted the attention of numerous researchers. In the late 1980s, Zhang et al. (1989) used $^{137}$Cs for the first time as a tracer to study the Loess plateau watershed's sediment source in China, and the preliminary research results were nearly identical to that of the measured sediment source ratio. Subsequently, studies that used single nuclide tracer sediment sources increased gradually in China, and many of the questions related to the sediment sources of the studied watersheds were explained (Peart & Walling 1988, Tian et al. 1992, Wang et al. 1991, Yang et al. 1997). However, dramatic variability in the distribution of nuclides is a universal issue when applying the single nuclide tracer method (Sun et al. 2009). The multi-element tracer technique can reduce this variation, while simultaneously improving the precision of measurements (Song & Liu 2002, Zhang & He 2004). Zhang et al. (1989) studied the sediment sources of the pond dam library of the Wu-jia gully watershed in the Yan-ting region using both $^{137}$Cs and $^{210}$Pb as tracers, whereas Yang et al. (1997) selected the contents of total N, low frequency magnetic susceptibility and concentrations of $^{137}$Cs, $^{226}$Ra, etc. as combined tracer factors to trace the relative contribution of 4 source types from individual rainfall in the Loess Plateau (Yang & Xu 2010). This study used the statistical analysis method for the first time in the selection of tracer factors in China.

However, there are few reports related to the selection of factors to trace the sediment source of a small watershed in the Loess plateau based on the multi-element tracer technique. Therefore, in this paper, we selected a typical small closed watershed in the Peng-yang region of Ningxia Province in China and collected surface soil samples for five geographical locations: (i) ridge, (ii) hill slope, (iii) shoulder line of the valley, (iv) channel slope and (v) area in front of the dam. A neutron activation analysis was then used to measure the concentrations of the elements contained in the soil samples. Finally, we analysed the trace element content and screened the elements whose content had obvious differences from that of the different sediment sources. The aim of this study was to broaden the optional range of the tracer factors while using multi-element tracer technology to research the sediment source of the Loess plateau watershed. We expect these data to provide technical support for future research that uses multi-element tracer techniques to determine the sediment sources of the Loess plateau.

## MATERIALS AND METHODS

**Study area:** A small closed watershed that is typical of the loess of the Chinese Loess plateau was selected for soil sample collection, and it is located near the Peng-yang County village Yang-he (Fig. 1) at roughly 35°41'-36°17'N and 106°32'-106°58'E. The study site has an approximate area of 0.5 km$^2$, with an altitude of 1248-2418 m, and the continental monsoon climate of this region produces an average annual temperature of 7.4 to 8.5°C and average annual rainfall between 350 and 550 mm. Below the shoulder line of the valley is a region used for agriculture. Soil erosion, sediment delivery and siltation have been identified as problems that occur during precipitation events.

**Soil sampling:** Based on the watershed survey, sampling occurred at key collection points. To ensure that the collected samples were representative of the soil found in the different geomorphic partitions of the watershed, the entire watershed was divided into the following five potential sources of sediment: ridge, hill slope, shoulder line of the valley, channel slope and the area in front of the dam. Three points for each geomorphic partition were selected from which soil samples were collected. Note that the three points are distributed evenly along the horizontal contour, with the exception of the location in front of the dam. The three sampling points near the dam are set in a flat triangular position. The soil samples were collected using a 6 cm diameter soil auger and taken from a depth of 20 cm at the potential source. The soil samples were then loaded into valve bags that were labelled and taken back to the lab.

**Sample processing and determination:** An agate mortar was employed to pulverize the soil samples, which were then mixed well and passed through a 100-mesh screen. Approximately 150-200 mg of each sample was placed into small polyethylene vials that were sealed and placed within a second sealed polyethylene container for irradiation. All the analyses were conducted under the primary accuracy standard NBS SRM-1633A except for Cl, which used NBS SRM-1646. In addition, all of the samples were analysed under the secondary standards NBS SRM-1632A and 1646 and a Chinese standard soil sample, NBS GSS-8, which was provided by the Institute of Geophysical & Geochemical Exploration (IGGE), China. Although the flux in the SLOWPOKE reactor can be controlled to within 1-2% over long periods, the secondary standards were analysed with every batch of samples to guarantee analytical quality. All the standards were packed and irradiated using the same methods as for the samples.

***Irradiation and counting*:** The experiment was conducted at a neutron flux of $1.0\times10^{11}$ n.cm$^{-2}$.sec$^{-1}$ in the SLOWPOKE-2 reactor at the University of Toronto. We determined Al, Ca, Cl, Mg, Ti, Na, V and U through their short-lived radionuclides; the elements were measured over an

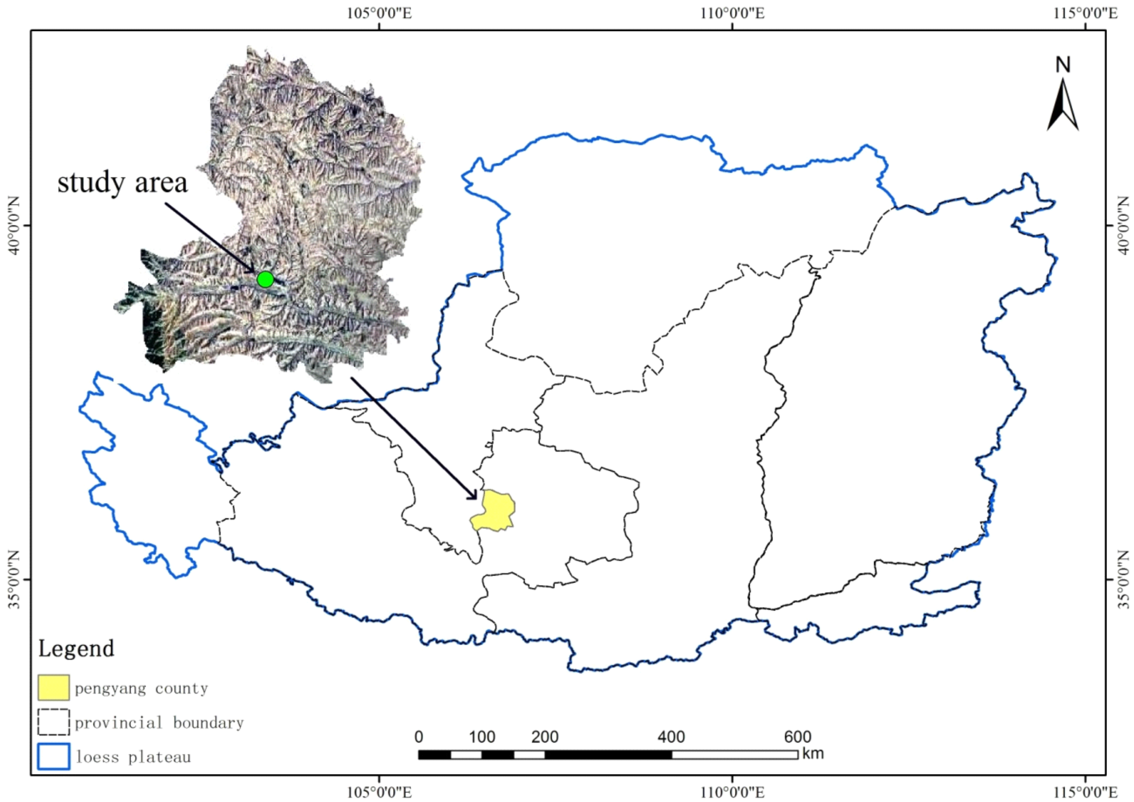

Fig.1: Location of the study area.

irradiation period of 5 minutes, decay time of 15-20 minutes and counting for another 5 minutes. Sixteen hour irradiations were used for elements that yield longer-lived radionuclides. After cooling periods of 5-7 days and 14-20 days, we counted the samples twice to determine the longer-lived radionuclides. Using this method, we measured 31 major soil constituents. The short-lived nuclides were counted at the SLOWPOKE site using a hyper-pure germanium detector (resolution of 1.8 KeV at 1332 KeV) in conjunction with a Canberra 8180 analyser, whereas a coaxial Ge detector (sensitive area of 93 cm$^3$, efficiency of 21.6%, and resolution of 1.7 KeV at 1332 KeV) was used for the other nuclides.

***Interference and corrections*:** We selected suitable cooling intervals and interference-free photo-peaks to avoid interference in the gamma ray spectrometry. Special attention was necessary for the fast neutron reaction of $^{27}$Al (n, p) and $^{24}$Mg. A correction factor for this reaction was found to be 0.18 μg Mg per μg Al in a sample. The precision of the three replications for most of the elements in the samples was less than 10%. We evaluated the accuracy of the determination by comparing our values for the SRM standards NBS-1632A and 1646 and Chinese soil standard with those in published articles that were considered satisfactory (Table 1). The relative difference between our values and the values given for most elements of GSS-8 was less than 10%. Only the errors for Ce, Cl and Sb were in excess of 20%.

**Data processing:** After sample processing and determination, we analysed the concentration of micro-elements in the soil samples and applied the Kruskal-Wallis H-test to determine the concentration using Spass19.0. The information on the concentration of the micro-elements in each geomorphic unit were summarized, and the differences between the geomorphic regions were analysed.

## RESULTS

**The average concentrations of micro-elements in the soil samples in different regions of the watershed:** To ensure the representativeness of each test sample, all the samples from the different regions were measured three times. After averaging the three concentrations, we determined the average concentration of each element in the sample; the results are given in Table 1.

**Difference analysis of the elemental contents in the soils from different positions within the watershed:** Tracing sediment sources through multiple elements is based on signifi-

Table 1: Concentration of trace elements in a single location (in µg/g, unless noted otherwise).

| | Ridge | | | Hill slope | | | Shoulder | | | Channel slope | | | Dam | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ele. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| Lu | 0.454 | 0.47 | 0.399 | 0.422 | 0.489 | 0.522 | 0.549 | 0.38 | 0.498 | 0.379 | 0.489 | 0.421 | 0.63 | 0.693 | 0.536 |
| Tb | 0.73 | 0.87 | 0.88 | 1.15 | 1.31 | 0.64 | 0.98 | 1.08 | 1.06 | 0.84 | 0.88 | 1.2 | 0.91 | 1.52 | 1.13 |
| Eu | 1.04 | 1.12 | 1.14 | 1.53 | 1.31 | 1.15 | 1.1 | 1.14 | 1.16 | 1.28 | 1.22 | 1.17 | 1.49 | 1.26 | 1.17 |
| Ta | 1.278 | 1.482 | 0.882 | 0.967 | 0.876 | 1.024 | 1.114 | 1.127 | 1.002 | 1.133 | 0.996 | 1.057 | 1.034 | 1.26 | 1.051 |
| Sb | 1.69 | 1.48 | 1.83 | 1.75 | 1.81 | 1.46 | 1.04 | 1.53 | 1.56 | 1.59 | 1.67 | 1.37 | 1.38 | 1.53 | 1.68 |
| Fe% | 2.71 | 2.74 | 2.75 | 2.83 | 2.9 | 2.91 | 2.94 | 3 | 3.02 | 3.1 | 3.12 | 3.13 | 3.22 | 3.23 | 3.47 |
| Yb | 2.77 | 3.35 | 2.49 | 3.74 | 3.07 | 2.71 | 2.81 | 3.03 | 3.68 | 2.81 | 3.12 | 3.3 | 2.1 | 2.86 | 3.15 |
| U | 3.32 | 2.7 | 2.98 | 2.58 | 3.78 | 3.49 | 2.65 | 4.35 | 3.99 | 4.37 | 3.11 | 3.39 | 3.95 | 3 | 3.66 |
| K% | 3.99 | 2.08 | 3.08 | 1.77 | 1.82 | 1.83 | 2.89 | 1.6 | 2.93 | 2.09 | 2.38 | 1.71 | 1.81 | 1.8 | 3.57 |
| Al% | 5.39 | 5.57 | 5.45 | 5.42 | 5.54 | 5.58 | 5.65 | 5.84 | 5.42 | 5.76 | 6.03 | 5.89 | 5.83 | 5.94 | 5.94 |
| Cs | 6.18 | 5.66 | 4.68 | 5.39 | 6.17 | 4.89 | 5.65 | 5.53 | 5.65 | 6.97 | 6.6 | 6.19 | 6.32 | 7.38 | 6.85 |
| Ca% | 5.7 | 6.42 | 5.76 | 6.89 | 6.25 | 5.83 | 6.52 | 5.46 | 7.76 | 5.53 | 5.49 | 5.71 | 6.85 | 5.61 | 6.97 |
| Sm | 6.03 | 5.94 | 6.83 | 5.89 | 6.13 | 6.03 | 6.08 | 5.92 | 6.09 | 6.61 | 6.64 | 7.03 | 6.26 | 6.48 | 6.73 |
| Hf | 7.48 | 7.13 | 6.67 | 6.64 | 7.15 | 6.73 | 6.47 | 5.89 | 6.45 | 6.05 | 5.48 | 5.77 | 5.67 | 5.34 | 6.03 |
| Sc | 9.94 | 10.55 | 9.9 | 10.72 | 10.68 | 10.68 | 10.61 | 11.22 | 11.34 | 11.32 | 11.6 | 11.69 | 11.82 | 12.34 | 12.3 |
| Co | 10.45 | 9.98 | 10.25 | 11.23 | 11.21 | 11.61 | 11.67 | 11.94 | 11.48 | 12.18 | 11.18 | 12.98 | 12.9 | 12.83 | 13.46 |
| Th | 11 | 11.33 | 10.8 | 12.05 | 12.42 | 11.91 | 11.33 | 12.15 | 11.96 | 12.14 | 11.76 | 12.58 | 12.95 | 12.94 | 12.9 |
| As | 15.34 | 13.83 | 17.74 | 15.19 | 13.92 | 10.95 | 13.94 | 13.29 | 15.7 | 15.16 | 14.91 | 17.68 | 16.53 | 16.01 | 18.44 |
| Nd | 26.63 | 32.2 | 31.41 | 30.39 | 32.88 | 25.29 | 30.92 | 33.3 | 27.03 | 24.03 | 21.89 | 28.77 | 32.67 | 30.27 | 25.86 |
| La | 34.07 | 35.07 | 37.66 | 33.71 | 38.05 | 33.6 | 35.42 | 32.86 | 32.88 | 36.34 | 37.45 | 39.29 | 34.18 | 37.63 | 38.93 |
| Zn | 45.83 | 42.37 | 56.56 | 83.75 | 87.39 | 44.92 | 79.1 | 69.73 | 65.1 | 67.41 | 61.23 | 75.87 | 73 | 65.43 | 115.7 |
| Cl | 38.61 | 116.2 | 14.4 | 81.74 | 133.3 | 100.7 | 118.1 | 78.71 | 59.92 | 88.33 | 50.15 | 92.76 | 176.2 | 225.1 | 67.98 |
| Cr | 69.2 | 63.17 | 61.1 | 89.42 | 74.63 | 77.07 | 70.22 | 69.18 | 66.28 | 67.83 | 72.56 | 71.66 | 70.7 | 72.05 | 73.83 |
| Ce | 62.11 | 72.58 | 62.91 | 115.1 | 80.2 | 77.05 | 76.87 | 74.78 | 74.77 | 65.8 | 71.21 | 80.72 | 85.81 | 73.05 | 70.23 |
| V | 71.22 | 74.33 | 72.54 | 79.25 | 70.71 | 71.93 | 65.8 | 80.09 | 65.36 | 81.8 | 77.75 | 77.27 | 70.36 | 84.8 | 82.12 |
| Rb | 85.58 | 94.66 | 87.12 | 102 | 97.44 | 103.2 | 95.97 | 91.93 | 98.94 | 94.42 | 101.5 | 102.6 | 114 | 106.6 | 109.5 |
| Ba | 402.5 | 561.4 | 481.9 | 415.8 | 547.3 | 582.5 | 514.4 | 498.1 | 539.5 | 584.3 | 502.9 | 623 | 418.4 | 441.2 | 821.6 |
| Mn | 650.7 | 616.8 | 649.9 | 601.6 | 626.7 | 642.1 | 634 | 653.2 | 618.7 | 652.8 | 702.9 | 699 | 664 | 717.7 | 689.5 |
| Ti | 3834 | 4051 | 3940 | 3860 | 4070 | 3676 | 3764 | 3706 | 4066 | 3984 | 4088 | 4057 | 4169 | 4120 | 3708 |
| Na | 12614 | 12196 | 13299 | 11924 | 12506 | 12253 | 12926 | 12396 | 12422 | 13656 | 13039 | 12611 | 12352 | 11858 | 11659 |
| Mg | 13231 | 13921 | 17218 | 15462 | 16354 | 16141 | 12019 | 14318 | 14899 | 14060 | 17796 | 16069 | 18746 | 18839 | 20706 |

Note: 1, 2, 3; 4, 5, 6; 7, 8, 9; 10, 11, 12, and 13, 14, 15 refer to the respective sampling points at the different locations (ridge, hill slope, shoulder line of the valley, channel slope and area in front of the dam) within the watershed.

cant differences between the different potential sediment sources for the same element. In addition, the precision of this method improves as additional visible differences are observed. Consequently, the Kruskal-Wallis H-test was applied to the soil micro-element concentrations from the different sediment source areas, and the results are presented in Table 2. In Table 2, we also summarized the descriptive statistical analysis results, including the maximum, minimum and average values, for the concentrations of the same element at different positions within the watershed. In addition, the results of the Kruskal-Wallis H-test used to discern the different source types in the watershed are presented in Table 2. A total of 11 individual elements passed the Kruskal-Wallis H-test, which yielded test statistics in excess of the critical value with a p-value of less than 0.05.

## DISCUSSION

There are numerous factors that influence soil geochemical elements (Hawkes & Webb 1962, Mattigod et al. 1990). The Loess plateau's soil is homologous, which leads to a relatively uniform concentration of geochemical elements. However, because of the impacts of nature and human activities over a long period of time, the trace element contents in different parts of the studied watershed exhibit differences. In this paper, we applied the Kruskal-Wallis H-test to the contents of 31 measured elements from soil samples in different regions of the research watershed, and the results showed that differences occurred in our soil samples.

Table 2 indicates that statistical analysis of the concentrations of the 31 elements, which was performed using Spass19.0, fell within the 95% confidence interval ($p=0.05$). Consequently, the concentrations of Eu, Fe, Al, Co, Cs, Hf, Sc, Th, Cr, Rb and Mn passed the Kruskal-Wallis H-test, with p-values of 0.045, 0.009, 0.046, 0.035, 0.021, 0.014, 0.032, 0.029, 0.025, 0.028, and 0.042, respectively. Therefore, these 11 trace elements can be used as tracer factors to study the sediment source of small watersheds in the Loess plateau. Twenty other elements failed the Kruskal-Wallis

Table 2: Results of the descriptive statistical analysis and Kruskal-Wallis H-test for the concentrations of soil micro-elements in the different sediment source areas.

| Fingerprinting property (µg/g) | Mean | Std. Deviation | Minimum | Maximum | Chi-Square | Sig. |
|---|---|---|---|---|---|---|
| Lu | 0.49 | 0.09 | 0.38 | 0.69 | 7.76 | 0.101 |
| Tb | 1.01 | 0.23 | 0.64 | 1.52 | 4.37 | 0.359 |
| Eu | 1.22 | 0.14 | 1.04 | 1.53 | 9.75 | 0.045* |
| Ta | 1.09 | 0.16 | 0.88 | 1.48 | 4.43 | 0.351 |
| Sb | 1.56 | 0.20 | 1.04 | 1.83 | 3.45 | 0.486 |
| Fe% | 3.00 | 0.21 | 2.71 | 3.47 | 13.50 | 0.009* |
| Yb | 3.00 | 0.43 | 2.10 | 3.74 | 1.39 | 0.845 |
| U | 3.42 | 0.59 | 2.58 | 4.37 | 2.80 | 0.592 |
| K% | 2.36 | 0.75 | 1.60 | 3.99 | 3.63 | 0.458 |
| Al% | 5.68 | 0.22 | 5.39 | 6.03 | 9.68 | 0.046* |
| Cs | 6.01 | 0.76 | 4.68 | 7.38 | 10.35 | 0.035* |
| Ca% | 6.18 | 0.69 | 5.46 | 7.76 | 4.23 | 0.375 |
| Sm | 6.31 | 0.37 | 5.89 | 7.03 | 7.64 | 0.106 |
| Hf | 6.33 | 0.65 | 5.34 | 7.48 | 11.50 | 0.021* |
| Sc | 11.11 | 0.76 | 9.90 | 12.34 | 12.56 | 0.014* |
| Co | 11.69 | 1.04 | 9.98 | 13.46 | 10.57 | 0.032* |
| Th | 12.01 | 0.68 | 10.80 | 12.95 | 10.81 | 0.029* |
| As | 15.24 | 1.94 | 10.95 | 18.44 | 6.23 | 0.182 |
| Nd | 28.90 | 3.57 | 21.89 | 33.30 | 4.43 | 0.351 |
| La | 35.81 | 2.23 | 32.86 | 39.29 | 5.57 | 0.234 |
| Zn | 68.89 | 18.85 | 42.37 | 115.70 | 5.90 | 0.207 |
| Cl | 96.15 | 53.53 | 14.40 | 225.10 | 4.27 | 0.371 |
| Cr | 71.26 | 6.54 | 61.10 | 89.42 | 11.10 | 0.025* |
| Ce | 76.21 | 12.58 | 62.11 | 115.10 | 7.33 | 0.119 |
| V | 75.02 | 5.96 | 65.36 | 84.80 | 3.90 | 0.420 |
| Rb | 99.03 | 7.84 | 85.58 | 114.00 | 10.90 | 0.028* |
| Ba | 528.99 | 105.12 | 402.50 | 821.60 | 2.57 | 0.633 |
| Mn | 654.64 | 34.35 | 601.60 | 717.70 | 9.90 | 0.042* |
| Ti | 3939.53 | 167.83 | 3676.00 | 4169.00 | 3.27 | 0.514 |
| Na | 12514.07 | 541.99 | 11659.00 | 13656.00 | 8.40 | 0.078 |
| Mg | 15985.27 | 2368.47 | 12019.00 | 20706.00 | 8.93 | 0.063 |

Note: *denotes significance at $p = 0.05$.

H-test; as a result, they cannot be used as tracers for our research.

In addition to the results achieved here, numerous reports on sediment source research using single factor tracer technology have demonstrated that $^{7}$Be, $^{210}$Pb and $^{226}$Ra are widely accepted as indicators of trace sediment sources and that the technology is also relatively mature (Mabit et al. 2008, Schuler et al. 1991, Wallbrink et al. 1998, Walling et al. 1999, Walling & Woodward 1992). In addition, Yang and Xu have used composite fingerprint recognition technology to study the sediment sources of the northwestern region of China's Loess plateau, and their research has employed the content total nitrogen and organic matter, low frequency magnetic susceptibility, high frequency magnetic susceptibility and concentrations of $^{137}$Cs· $^{210}$Pb· etc. in the soil as tracers, and obtained good results (Yang & Xu 2010).

## CONCLUSION

Because of the homogeneous characteristics of the Loess plateau's soil, the selection of the appropriate tracer factors is more difficult. Based on the results of this paper and previous research, the options of tracer factors can be broadened by using the multi-element tracer technique in a wide range; therefore, we suggest that the soil nutrient index, soil magnetic susceptibility and Al, Eu, Cs, Hf, Sc, Co, Th, Cr, Rb, $^{137}$Cs, $^{7}$Be, $^{210}$Pb and $^{226}$Ra concentrations be used as optional tracer factors for the study of sediment sources using the multi-element tracer technique.

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