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ORIGINAL PAPER

# Ecological, environmental risks and sources of arsenic and other elements in soils of Tuotuo River region, Qinghai-Tibet Plateau

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**Abstract** Against the backdrop of global warming, the pollutants that were once "temporarily stored" in the permafrost are gradually being released, posing significant impacts on the environment. This has become an internationally focused hot topic. In this study, the contents of 11 elements such as As, Ti, Cd, Cr, Co, Mn, Cu, Pb, Ni, Zn and V in soil samples from 128 sampling points in the freeze–thaw area of the Tuotuo River in the source region of the Yangtze River on the Qinghai-Tibet Plateau were determined to evaluate the possible sources, contamination status and ecological, environmental and health risks of these elements. The mean values of As, Cd, Pb and Zn were higher than the corresponding Tibet soil background values. Among fourteen PTEs, As, Cd and Pb had the highest average values of enrichment factor and pollution index, indicating that freeze–thaw area soils showed moderate enrichment and pollution with As, Cd and Pb. Mean ecological risk factor (ER) of Cd was 109 and other PTEs mean ER values $<40$, whereas ecological risk index (RI) values of all PTEs ranged from 59.5 to 880 and mean RI values was 152, indicating moderate ecological risk in study area. Explanatory power $q$ value of total S (TS) content was 0.217 by GeogDetector, indicating TS was the most significant contributing factor to RI. Correlation analysis and PCA analysis showed that Cr, Cu, Ni, Co, Mn, Ti, V were mainly originated from natural sources, Cd, Pb and Zn from traffic activity, As from long-distance migration-freeze–thaw.

**Keywords** Freeze–thaw area · Global climate change · Potential toxic elements · Soil pollution · Risk assessment · Geographic detector

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## Introduction

Soil is the material basis of human survival. Due to the characteristics of potential toxic elements (PTEs) in soil, such as strong latent ability, slow migration rate, difficult degradation and strong concealment, it has become the primary problem concerning human health that needs to be solved urgently (Aytop, 2023, 2023a, 2023b; Aytop et al., 2023a; Aytop et al., 2023b; Gong et al., 2022a; Huang et al., 2020; Nagajyoti et al., 2010; Singh et al., 2011). The survey shows that the point exceeding rates of Cd, As, Cr, Cu, Pb, Zn and Ni in the soil of China in 2014 were 7.0%, 2.7%, 1.1%, 2.1%, 1.5%, 0.9% and 4.8%, respectively (Gong et al., 2022b). Therefore, the PTEs pollution and its potential harm in Chinese soil cannot be ignored. In recent years, domestic research on PTEs in soil has mainly focused one the Pearl River Delta, the old industrial base in the northeast, the Yangtze River Delta, central, southern and southwest China (Yu et al., 2021). For the western region, especially the unique geographical location of the Qinghai-Tibet Plateau (QTP) in the world, there is still less research on potentially toxic elements in soil. Especially in the context of global warming, permafrost as a "temporary reservoir" of pollutants, the "secondary release" of soil PTEs and their environmental effects have become a hot issue of international concern. However, there are few reports on the PTEs in the freeze–thaw soil of the QTP.

The QTP is known as the "roof of the world" and "the third pole of the world", with an average elevation of more than 4000 m (Chen et al., 2020; Peng et al., 2023). The QTP is considered to be the area with the least human interference except the north and south poles, and is less polluted by human beings, so it is called the last pure land in China. But recent research shows that the situation is not optimistic (Wu et al., 2016). The rapid industrialization of South Asia, Southeast Asia and East Asia has had an important impact on the PTEs in the soils of the QTP in the past few decades (Kang et al., 2016a, 2016b; Wang et al., 2022). Especially in recent years, with the climate change, the development and utilization of natural resources and the gradual acceleration of the development of the secondary and tertiary industries, its soil system has been polluted by PTEs to a certain extent (Kang et al., 2016a, 2016b; Wang et al., 2022), the main pollution sources include traffic sources, application of pesticides and chemical fertilizers, religious activities and large-scale sacrificial activities (Du et al., 2021; Guan et al., 2018; Huang et al., 2019; Wu et al., 2016; Yin et al., 2019; Zhang et al., 2018). In addition, permafrost degradation is also significant source of PTEs in the QTP, and has a significant impact on the global circulation of PTEs and the regional environment, and this impact will continue to strengthen (Ashu et al., 2022; Kevin et al., 2020; Mu et al., 2020).

The Qinghai-Tibet Plateau (QTP) contains abundant permafrost resources, which is a natural laboratory for studying high-altitude life evolution, cycling processes and human-land relationships. Under the background of climate warming, the permafrost layer in the QTP region has been degrading at a rate of 3.6 cm/year (Chen et al., 2020, 2023; Peng et al., 2023). Pollutants (such as PTEs, persistent organic pollutants and microplastics) released in the history of human activities can be dispersed globally through atmospheric circulation, enriched in cryosphere low temperatures, and trapped in permafrost as "temporary reservoirs" of pollutants(Ashu et al., 2022; Grannas et al., 2013; Kang et al., 2019; Kevin et al., 2020; Lu et al., 2022; Schuster et al., 2018). Under the background of climate warming, permafrost degradation forms freeze–thaw zones or thermal karst landforms, which changes the geomorphology, hydrological process and soil environment in permafrost areas, leading to the activation and release of organic carbon and PTEs closely associated with it to the environment, thus affecting the migration and transformation of PTEs in soil in permafrost areas and enhancing the environmental exposure risk of PTEs (C et al., 2020; Sun et al., 2023; Turetsky et al., 2020). Assessment of the distribution characteristics of PTEs in permafrost degraded frozen-thawed areas is an important part of a comprehensive understanding of the geochemical cycle of PTEs on the global scale and the risk of environmental exposure. However, at present, there is a lack of information about the distribution and risk assessment of PTEs in soils in the freeze–thaw area of the QTP. Therefore, the study filled this significant gap by assessing the distribution of PTEs and their potential effects on ecological, environment and human health in the frozen-thawed area of the Tuotuo River in the source of the Yangtze River.

The Tuotuo River source area is located in the core area of the ecological security barrier of the QTP and in the permafrost region in the hinterland of the Yangtze River source. Freeze–thaw cycle occurs frequently, which is the most sensitive and precursory area of global climate change response. However, the first and second scientific research work on the QTP did not give much consideration to the permafrost in this region, but our investigation and evaluation of the ecological environment of the Tuotuo River region in the past two years found that the degradation of the permafrost area in this region was intensified, the thickness of the freeze–thaw active layer in the permafrost region increased year by year, the freeze–thaw disaster showed an increasing trend, and there were obvious pollution anomalies in soil As, Pb, Cd and Zn(Gong et al., 2024). It has a certain impact on the quality of soil ecological environment in this region. In this paper, 11 PTEs (As, Ti, Cd, Cr, Co, Mn, Cu, Pb, Ni, Zn and V) in the surface soil of the Tuotuo River freeze–thaw zone were selected as the objects, and the enrichment factor (EF), geological accumulation index ($I_{geo}$), pollution index (PI), synthetic pollution index (SPI), potential ecological risk index (ER) and geographic detector were used to analyzed the distribution, source and ecological risk characteristics of heavy metals in the soil. The specific purpose of study is to (1) evaluate the distribution characteristics of PTEs in soil; (2) determine the possible sources of PTEs by multivariate statistical methods, (3) use multiple indicators to evaluate the eco-environmental risks of PTEs. Clarify the risk characteristics of PTEs in the study area, and then support and serve the construction of Tuotuo River Park in Sanjiangyuan National Park.

## Materials and methods

### Overview of the study area

The study area is located in the hinterland of the QTP, the northernmost part of Anduo county (90° 32° 47.62″ -91° 49° 13.06″ E, 33° 23° 16.46″ -34°41° 31.47″ N) (Fig. 1).The climate belongs to the cold semi-arid and semi-humid climate transition zone. The annual average gale days is more than 110 days, the annual average pressure is 584.3mb, the annual average temperature is − 4.2 °C, and the freezing period is from September to April of the following year. The temperature and pressure are low, the temperature difference between day and night is large, the radiation is strong, the climate of the basin is dry and cold, the precipitation is little, and the natural environment is bad. There are a small number of herdsmen in the study area, and their grazing animals are mainly yaks and sheep, with no obvious agricultural activities.

### Soil sample collection, processing and analysis

Field sampling to be completed in 2022. The sampling locations were shown in Fig. 1. According to the 1:250,000 land mass geochemical evaluation specification (DZ/T0295-2016), the sampling density was 1 point/4 $km^2$, and the distance between sampling points was required to be greater than 2 km. Use GPS to determine the center point, and combine 3–5 sub-samples in equal parts within 100 m around

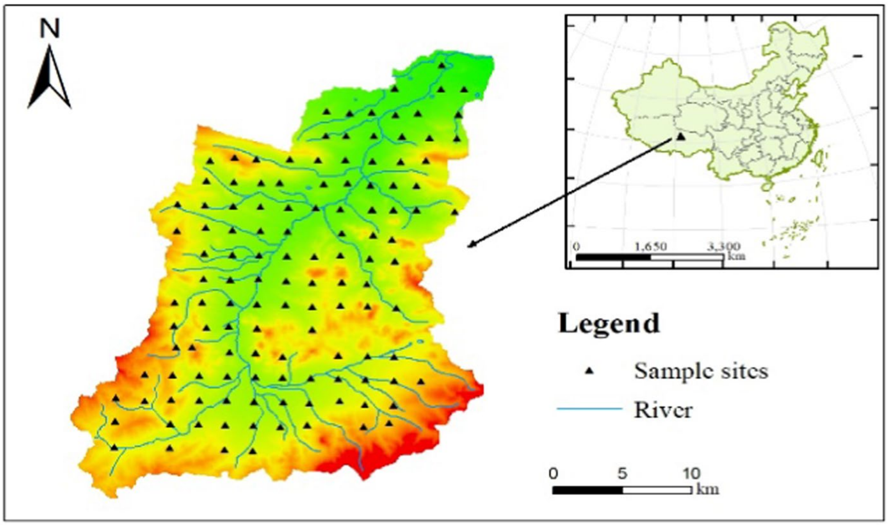


**Fig. 1** The location of the study area and sampling sites (Map were generated with software ArcMap10.8 http://www.esri.com/)

the central sampling point to form a mixed sample, the sampling depth is 0–25 cm. The collected samples can be air-dried at room temperature. After drying, gently knock it with a mallet, impurities such as worms, stalks, roots, and stones were removed, fully mixed, using the quartet to retain 0.5 kg of the sample and put into the sample bag. A total of 125 samples were sent to the laboratory for analysis. The pH value was determined by ion selective electrode method (Analysis methods for regional geochemical sample-part 34: determination of pH by ion selective electrode method, DZ/T0279.34-2016). The soil sample was extracted with water without carbon dioxide, the ratio of soil to water was 1:2.5, and then thoroughly stirred after adding water, the pH glass electrode was inserted into the extract and measured directly. The content of soil $C_{org}$ was determined by potassium dichromate volumetric method (Analysis methods for regional geochemical sample-part 27: determination of organic carbon contents by potassium dichromate volumetric method, DZ/T0279.27-2016). The $C_{org}$ in the soil was oxidized by the method of external heating in the oil bath, and the remaining potassium dichromate was titrated with the standard solution of iron, and the content of $C_{org}$ in the sample was calculated by the amount of potassium dichromate consumed. N content in soil was determined by Kjeldahl distillation volumetric method (Soil testing-part 24: determination of total nitrogen in soil-automatic kjeldahl apparatus method, NY/T1121.24-2012). Soil material was boiled and oxidized with $H_2SO_4$ in the presence of $K_2SO_4$, $CuSO_4$ and Se, so that the N in the sample was converted to $(NH_4)_2SO_4$, and then alkalized with NaOH, heated distillation to escape ammonia, absorbed by $H_3BO_3$, titrated with HCl standard solution, and the N content in the sample was calculated. The content of As in soil was determined by hydride generation-atomic fluorescence spectrometry (Analysis methods for regional geochemical sample-part 13: determination of arsenic, antimony and bismuth contents by hydride generation-atomic fluorescence spectrometry, DZ/T0279.13-2016). Soil material was digested by aqua regia. The fluorescence intensity of As was determined by atomic fluorescence spectrometer in HCl (1 + 9) solution with thiourea-ascorbic acid as reducing agent. The contents of Ti, Mn, V, Cr, P, K and Sc were determined by X-ray fluorescence spectrometry (Analysis methods for regional geochemical sample-part 1: determination of 24 components including aluminum oxide etc. by pressed power pellets-X-ray fluorescence spectrometry, DZ/T 0279.1-2016). The standard curve constant and matrix correction coefficient of a series of standard samples were obtained by the method of powder compression, and the interference and matrix effects were corrected by background subtraction. The contents of Co, Cu, Pb, Zn, Ni and Cd were determined by inductively coupled plasma mass spectrometry (Analysis methods for regional geochemical sample-part 3: determination of 15 elements including barium, beryllium, bismuth etc. by inductively coupled plasma mass spectrometry, DZ/T 0279.3-2016). The soil material was digested HF, $HNO_3$ and $HClO_4$, dissolved with aqua regia and then moved into polyethylene test tubes, shaken at constant volume. The clarified solution was separated, diluted with $HNO_3$(3 + 97) to 1000 times, and the element quantity to be measured was quantitatively analyzed by calibration curve method.

In order to ensure strict quality control, 2 national first-class standard substances and 1 duplicate sample were inserted into every 50 samples, the calculation accuracy and precision were required to be precision $\leq 0.17$, accuracy $\leq 0.10$, the relative deviation (RD) of repeatability test $\leq 40\%$, and the pass rate was required to be greater than 95%. After the analysis was completed, the abnormal test was carried out on the mutation high point and mutation low point in the analysis result according to the proportion of 3%, and the pass rate should be greater than 90%. The accuracy of each element was $< 0.03$ and the precision was $< 7.5\%$. The pass rate of each element was above 95%, and the pass rate of abnormal test was above 93%. Accuracy, precision, repeatability and anomaly inspection meet the quality inspection requirements of the 1:250,000 land mass geochemical evaluation specification (DZ/T0295-2016).

## Environmental risk assessment

### *Enrichment factor (EF)*

The enrichment factor (EF) was proposed by Zoller when studying the source of chemical elements in pollutants over Antarctica(Zoller et al., 1987). EF refers to the ratio of the content of trace elements in the environmental medium to the background value of trace elements in the study area. It is an important parameter to evaluate the enrichment degree of trace elements. It can further distinguish the man-made and natural sources of PTEs. EF can be calculated based on the following equations:

$$EF = [M_i/M_{Sc}]_S / [M_i/M_{Sc}]_B \tag{1}$$

where $[M_i/M_{Sc}]_S$ is the content ratio of the PTE *i* to Sc in soil samples, the content of Sc and PTEs in the sample were determined simultaneously, $[M_i/M_{Sc}]_B$ is the ratio of Tibet soil background values (1990) (Table 4). Sc in soil has no significant anthropogenic sources, so Sc is chosen as the reference element(Zhang et al., 2019). The enrichment degree of PTEs in soil is divided according to different grades, as shown in Table 1.

### *Geo-accumulation index ($I_{geo}$)*

Geo-accumulation index ($I_{geo}$) is Muller index, it is usually used to evaluate the pollution intensity of individual PTEs (Muller, 1969; Qiao et al., 2019).

$$I_{geo} = \log_2\left(\frac{C_i}{K \times B_i}\right) \tag{2}$$

where $I_{geo}$ is the soil accumulation index of PTE *i*; C*i* is the measured value of soil PTE *i*; B*i* is the reference value, and the Tibet soil background value of QTP is selected (1990) (Table 4); *k* is the correction coefficient, generally 1.5. The evaluation standard of $I_{geo}$ index were shown in Table 2.

### Pollution index (PI) and synthetic pollution index (SPI)

Using PI and SPI to assess HMs contamination levels in soil. PI and SPI can be calculated based on the following equations:

$$PI = \frac{C_i}{S_i} \tag{3}$$

$$SPI = \sqrt{\frac{\left(\frac{C_i}{S_i}\right)_{max} + \left(\frac{C_i}{S_i}\right)_{ave}}{2}} \tag{4}$$

where PI is the contamination index of element *i* and SPI is the synthetical score of each PTE to the composite pollution. $S_i$ is the evaluation standard of the *i* element, and the background values of soil in Tibet were chosen as the standard (1990) (Table 4). The pollution categories of PI and SPI can be divided into 4 grades: ≥ 6, 3–6, 1–3 and < 1, representing very high pollution, considerable pollution, moderate pollution and low pollution, respectively (Varol et al., 2020).

### Ecological risks assessment

#### *Potential ecological risk factor (ER)*

ER is used to assess the potential ecological risk of individual PTEs in soils (Hakanson, 1980), ER can be calculated based on the following equations:

$$ER = TR_i PI_i \tag{5}$$

**Table 1** Enrichment factor method evaluation grading standard

| Enrichment degree | Minimal enrichment | Moderate enrichment | Significant enrichment | Very high enrichment | Extremely high enrichment |
|---|---|---|---|---|---|
| EF | < 2 | 2–5 | 5–20 | 20–40 | ≥ 40 |

**Table 2** The evaluation standard of $I_{geo}$ index

| Pollution degree | Unpolluted | Mild polluted | Moderate polluted | Moderate-heavy polluted | Heavy polluted | Heavy-extreme polluted | Extremely heavy polluted |
|---|---|---|---|---|---|---|---|
| $I_{geo}$ | < 0 | 0–1 | 1–2 | 2–3 | 3–4 | 4–5 | ≥ 5 |

where $TR_i$ is the toxic-response factor of PTE ($i$), they are 30, 10, 5, 5, 2 and 1 for Cd, As, Pb, Cu, Cr and Zn, respectively(Hakanson, 1980), TR of Ni, Co, V, Mn and Ti are 5, 5, 2, 1 and 1 (Xu et al., 2008). $PI_i$ is the contamination index of PTE($i$). The ER classes were shown in Table 3 (Varol et al., 2020).

Potential ecological risk index (RI)

RI is a method to evaluate soil multi-element ecological risk. It can be calculated based on the following equations (Hakanson, 1980; Varol et al., 2020).

$$\mathrm{RI} = \sum_{i=1}^{n} ER = \sum_{i=1}^{n} \left(\mathrm{TR}_i \times \mathrm{PI}_i\right) \quad (6)$$

where $\sum_{i=1}^{n} ER$ is the potential ecological risk factor of PTE ($i$)and $n$ $i$ the number of PTEs. The RI classes were shown in Table 3(Varol et al., 2020).

Geographical detector

Geographic detector is a tool for detecting and utilizing spatial differentiation, and measures the contribution of independent variables to dependent variables by calculating the ratio of the sum of variance of each variable and the sum of variance of the dependent variable after classification(Dong et al., 2021). The specific calculation principle is as follows (Wang & Xu, 2017):

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \quad (7)$$

where the range of $q$ is [0,1], the higher the value of $q$, the greater the influence of the independent variable X on the dependent variable Y. h = 1…, L is the classification number of independent variable X, $N_h$ and N are the number of units in the layer and the whole area, respectively; ${\sigma_h}^2$ and $\sigma^2$ are the variances of the classification h and the factor variable Y within the area, respectively.

In this study, factor detector was applied to quantitatively detect the degree of influence of various pollution sources. Therefore, the RI was Y, and the following factors were X and GeogDetector was used to analyse the spatial correlation between RI and the anthropogenic and natural factors recorded for individual sampling site. Then, 19 factors were selected: pH, total carbon (TC), total phosphorus (TP), organic carbon ($C_{org}$), total nitrogen (TN), total sulfur (TS), normalized vegetation cover index (NDVI), elevation ($X_1$), slope ($X_2$), aspect($X_3$), soil parent materials($X_4$), soil types($X_5$), soil erosion degree($X_6$), distance from railway($X_7$), distance from national highway G109($X_8$), distance from county road($X_9$), distance from rural area($X_{10}$), distance from lake($X_{11}$), distance from river ($X_{12}$).

Data analysis

Descriptive statistics were implemented in SPSS 26 and Microsoft Excel 2010. Using Origin 2019b to carry out drawing. Pearson correlation analysis reveals the relationship between PTEs. Principal component analysis (PCA) was conducted to identify sources of PTEs in soils.

## Results and discussion

The contents and distribution of PTEs in freeze–thaw area soils

The soils of all sampling sites are alkaline (pH > 7.5), the range of soil pH is 8.02–10.3, the average value is 8.67, higher than the background value of soil pH in Tibet and the geochemical baseline values of soil in Lhasa(1990; Cheng et al., 2014). The mean

**Table 3** The evaluation standard of ER

| Risk assessment | Low potential ecological risk | Moderate potential ecological risk | Considerable potential ecological risk | High potential ecological risk | Very high potential ecological risk |
|---|---|---|---|---|---|
| ER | < 40 | 40–80 | 80–160 | 160–320 | ≥ 320 |
| RI | < 150 | 150–300 | 300–600 | – | ≥ 600 |

**Table 4** Soil PTEs content statistics in freeze–thaw area of Tuotuo river

| | | As | Cd | Cr | Cu | Ni | Pb | Zn | Co | Mn | Ti | V | Sc | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mg/kg | | | | | | | | | | | | |
| Tuotuo River freeze–thaw area | Minimum | 10.2 | 0.083 | 41.0 | 8.71 | 12.1 | 17.9 | 38.3 | 4.49 | 229 | 2231 | 33.2 | 3.92 | This study |
| | Maximum | 157 | 2.18 | 110 | 87.2 | 48.4 | 584 | 582 | 17.0 | 1088 | 4024 | 118 | 16.1 | This study |
| | Mean | 32.0 | 0.29 | 66.0 | 17.3 | 27.8 | 49.2 | 88.5 | 9.18 | 515 | 3158 | 60.4 | 7.7 | This study |
| | Standard deviation | 23.1 | 0.24 | 11.9 | 7.77 | 7.51 | 52.0 | 57.7 | 2.57 | 155 | 472 | 15.8 | 2.3 | This study |
| | Median | 25.1 | 0.25 | 65.9 | 16.5 | 26.9 | 40.7 | 75.7 | 8.87 | 507 | 3098 | 58.1 | 7.4 | This study |
| | Coefficient variation | 72.2 | 79.8 | 18.0 | 44.8 | 27.0 | 106 | 65.2 | 28.0 | 30.1 | 14.9 | 26.3 | 29.8 | This study |
| The risk screening values for China soil contamination (GB 15618–2018, pH > 7.5) | | 25 | 0.6 | 250 | 100 | 190 | 170 | 300 | | | | | | |
| Geochemical baseline values of soil in Lhasa | | 20 | 0.13 | 42 | 23 | 21 | 31 | 70 | 10 | 619 | 3320 | 67 | 9 | Cheng et al. (2014) |
| Background values of soil in Tibet | | 19.7 | 0.081 | 76.6 | 21.9 | 32.1 | 29.1 | 74 | 11.8 | 625 | 3400 | 76.6 | 10.2 | (1990) |
| Chinese soils | | 1.9 | 0.05 | 63 | 38 | 57 | 15 | 86 | 32 | 780 | 659 | 99 | 11 | Li (1994) |
| Worldwide soils | | 6.83 | 0.41 | 59.5 | 38.9 | 29 | 27 | 70 | 11.3 | 488 | 7038 | 129 | 11.7 | Kabata-Pendias (2011) |
| Upper continental crust (UCC) | | 4.8 | 0.09 | 92 | 28 | 47 | 17 | 67 | 17.3 | 774 | 3840 | 97 | 14.0 | Rudnick and Gao (2004) |

concentrations of C, $C_{org}$, N, P and S were 2.26%, 0.96 mg/kg, 997 mg/kg, 727 mg/kg and 297 mg/kg.

Table 4 lists the basic statistical data of 11 kinds of PTEs in the soil of the freeze–thaw area of Tuotuo river. Ti and Mn were the most abundant elements and were consistent with their contents in upper continental crust (UCC) (Rudnick & Gao, 2004). The abundant of Cd was less. In general, the average contents of all PTEs except As were below the pollution risk screening value of soil (GB15618-2018). The maximum contents of As, Cd, Pb and Zn were 6.28, 3.63, 3.44 and 1.94 times higher than their corresponding pollution risk screening value. In particular, contents of As in 64 samples (50%) and Cd in 7 samples (5.5%) exceeded their pollution risk screening values. Studies pointed out that the coefficient variation was proportional to the degree of interference from external factors such as human activities (Gong et al., 2022b). The high coefficient variation of As, Cd, Pb and Zn in study area indicates that they may be affected by some external interference factors.

Comparison with Lhasa geochemical baseline values of PTEs, contents of Cu, Ti, Mn, Co and V were slightly lower, but the contents of As, Cd, Zn, Cr, Ni and Pb were higher, which were 1.26–2.23 times higher than their corresponding baseline values (Cheng et al., 2014). Also, the contents of As, Cd, Pb and Zn were 1.62, 3.58, 1.69 and 1.20 times higher than their corresponding mean values in soil background values of Tibet (1990).

When compared with mean contents of PTEs in Chinese soils (Li, 1994), the contents of Zn and Cr were close to their respective soil values in China, Cu, Ni, Co, Mnand V were lower than their respective Chinese soils values, while As, Cd, Pb and Ti were 16.84, 5.80, 3.28 and 4.79 times higher than their respective Chinese soils values. Comparison with worldwide soil values of PTEs (Kabata-Pendias, 2011), the contents of Cr and Mn were of the same order of magnitude, As, Pb and Zn were 4.69, 1.82 and 1.26 times of their respective world soil values, respectively, while other five PTEs were lower than their corresponding world soil. In comparison with UCC values of PTEs (Rudnick & Gao, 2004), As, Cd, Pb and Zn were significantly larger than the corresponding values of UCC, other 7 PTEs were lower than corresponding values of UCC. The contents of As and Pb in the soil of the study area were higher, which were different from the corresponding background values of UCC (Rudnick & Gao, 2004), the world (Kabata-Pendias, 2011) and China (Li, 1994).

Figure 2 shows the spatial distribution of soil PTEs and Sc in the study area. As can be seen from the figure, Co, Cr, Mn, Ni, Ti, Mn and Sc exhibit similar distribution characteristics, Cd and Cu exhibit similar distribution characteristics, similar distribution features mean that the source may be consistent. Pb and Zn exhibit similar distribution characteristics, it was speculated that it may be caused by traffic pollution sources. While As exhibit different distribution characteristics from other PTEs, it was speculated that it may be caused by long-distance migration and freeze–thaw release.

Evaluation of environmental risk

Figure 3 shows the results of EF, $I_{geo}$, PI and SPI. Among fourteen PTEs, As, Cd and Pb had the highest mean EF (Fig. 3a) values ($2 < EF < 5$), meaning that As, Cd and Pb were moderate enrichments in soil, while the mean EF values of other PTEs were less than 2, showed the minimal enrichments.The average $I_{geo}$ (Fig. 3b) values followed the descending order: Cd > Pb > As > Zn > Ti > Cr > Ni > Mn > V > Co=Cu, the mean $I_{geo}$ values of the other 10 PTEs except Cd were < 0, indicating that the soil in the freeze–thaw zone were unpolluted by other PTEs, but soils were unpolluted to moderately polluted by Cd. Cd showed the highest average values of PI (Fig. 3c) ($3.64 \pm 2.90$), demonstrating considerable pollution with Cd, the PTEs of Pb, As and Zn showed the

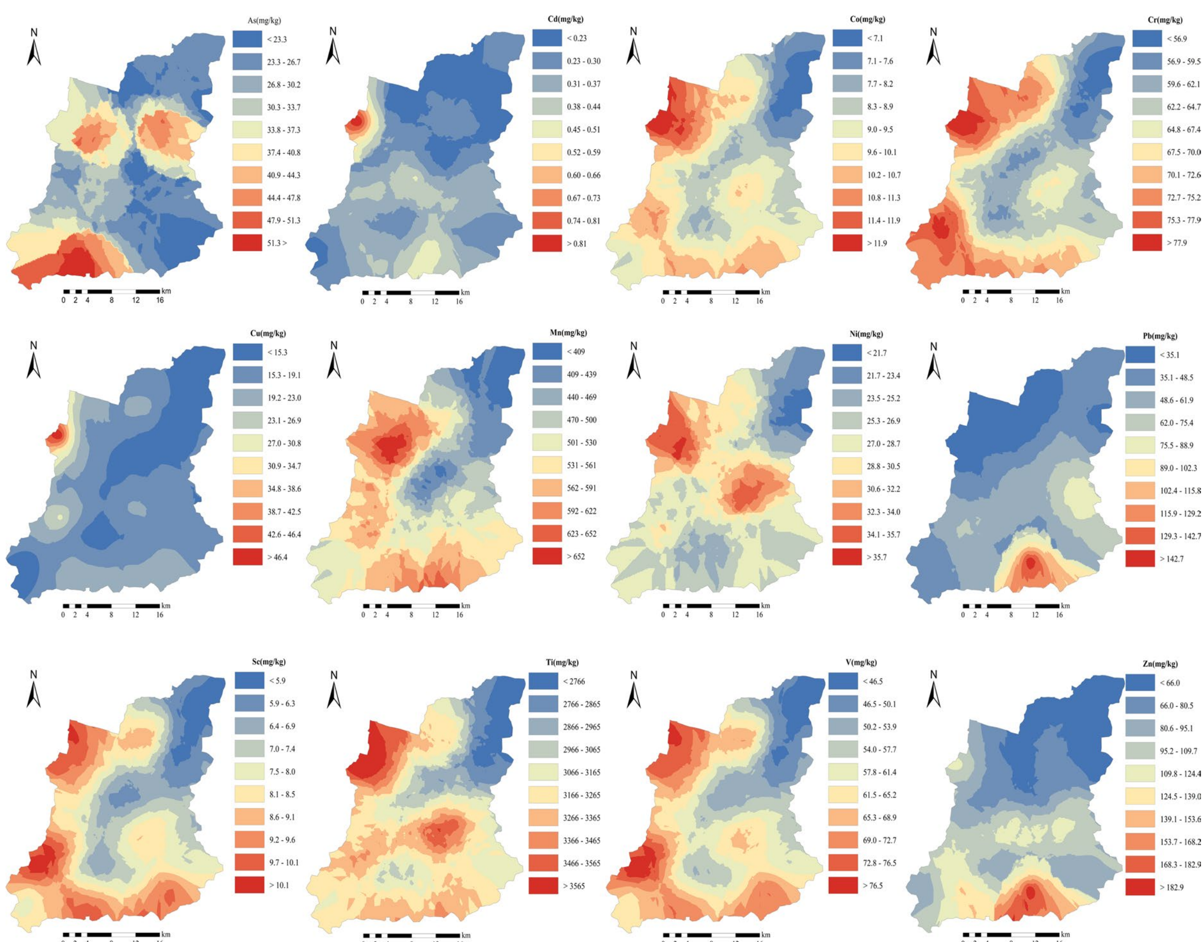


**Fig. 2** Spatial distribution of the soil PTEs and Sc. (Map were generated with software ArcMap10.8 http://www.esri.com/)

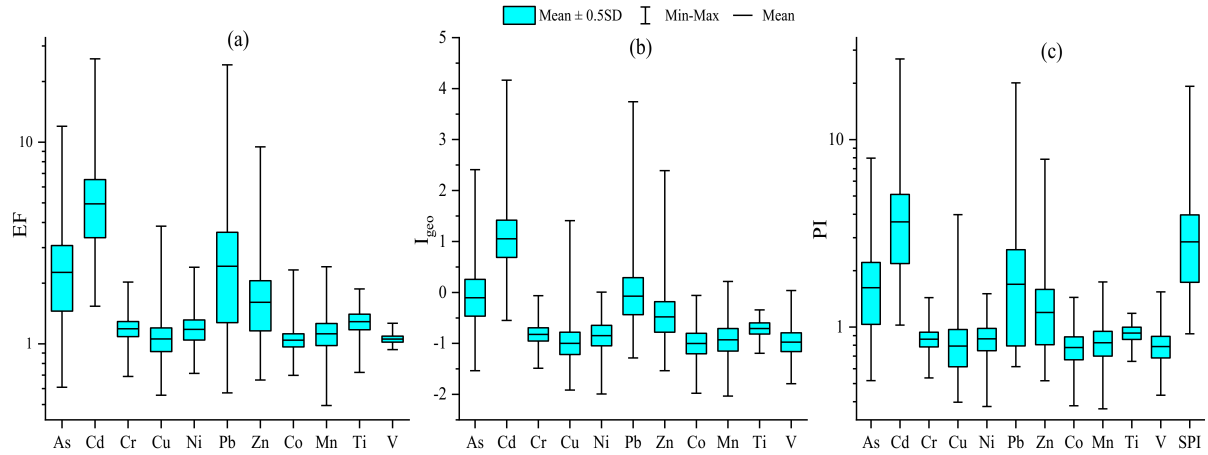


**Fig. 3** The EF (**a**), $I_{geo}$ (**b**), PI and SPI (**c**) for PTEs in soils of Tuotuo River freeze–thaw area

second highest average PI values (1 < PI < 3), demonstrating moderate pollution with Pb, As and Zn, however, the mean PI of other PTEs < 1 (Fig. 3c), meaning than soils were low pollution by other PTEs. The mean SPI values (2.86 ± 2.21) for fourteen PTEs, demonstrating moderate pollution with all PTEs. Wang et al. (2022) reported that the degradation of permafrost increases the risk of PTEs release to the QTP. In addition, PTEs in the QTP may be generated from geogenic/pedogenic associations and long-distance atmospheric transmission or anthropogenic activities of local (Du et al., 2021; Olson et al., 2018; Wang et al., 2022). Thus, As, Cd, Zn, Pb and As pollution in Tuotuo river freeze–thaw area soils can be closely related to the geogenic/pedogenic associations and atmospheric transmission.

Evaluation of ecological risk

The basic statistics of ER and RI were given in Fig. 4. The average ER (Fig. 4a) values followed the descending order: Cd(109) > As(16.2) > Pb(8.45) > Ni(4.33) > Cu(3.96) > Co(3.89) > Cr(1.72) > V(1.58) > Zn(1.20) > Ti(0.93) > Mn(0.82), Cd highest mean ER values (80 < ER < 160), indicating that soils had considerable potential ecological risk Cd, other PTEs showed low potential ecological risk with mean ER values < 40. However, the samples with ER values higher than 40 of Cd, As and Pb respective accounted for 96.1%, 3.1% and 0.8%, indicating that Cd in the study area has significant ecological risks, As and Pb have certain ecological risks, other PTEs had low ecological risk. Mean value of RI was 152 and

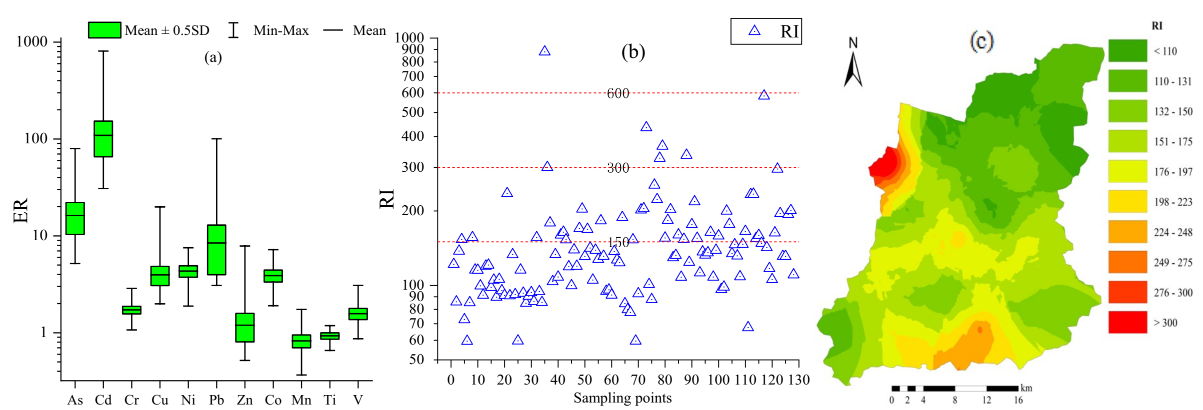


**Fig. 4** The ER (**a**) and RI (**b** and **c**) for PTEs in soils of Tuotuo River freeze–thaw area

the range of RI values were 59.5 to 880, the samples with RI values higher than 150 accounted for 36.7%, indicating that demonstrating moderate ecological risk in this study. According to the spatial distribution characteristics of RI (Fig. 4c), low RI risk areas were mainly distributed in the northeast of the study area, while high RI risk areas were mainly concentrated in the south and northwest of the study area, which was similar to the spatial distribution characteristics of most PTEs (Fig. 2).

## Factors affecting the ecological risk of soil PTEs according to GeogDetector

The explanatory power *q* value of 19 factors to RI by factor detector was shown in Fig. 5. When using GeogDetector to analyze the influencing factors, if the independent variable is a numerical variable, it must be transformed into a type variable. In this study, the influencing factors of numerical variables were classified by natural breakpoint method. Various factors contribute to RI as follows: TS (0.217) > $X_{12}$ (0.140) > $X_5$ (0.129) > $X_9$(0.125) > $X_{11}$ (0.122) > $X_1$ (0.119) > $X_6$ (0.109) > $X_{10}$ (0.095) > $C_{org}$ (0.089) > $X_7$ (0.081) > TC (0.0803) > $X_3$ (0.0801) > $X_2$ (0.074) > TN (0.070) > $X_4$ (0.057) > $X_8$ (0.053) > NDVI (0.047) > pH (0.040) > TP (0.037). Soil TS was the most significant factor. Related studies showed that PTEs have a tendency to combine preferentially with sulfur-containing functional groups (Hesterberg et al., 2001). The complexation of sulfur-containing amino acids with Cd in soil has an important effect on the migration of Cd. Soil cystine and cysteine participate in the methylation of PTEs, and the mobility and activity of methylated Cd and As were enhanced (Sun et al., 2014). In this study, TS, elevation ($X_1$), distance from river ($X_{12}$), distance from lake ($X_{11}$) and soil types ($X_5$) were natural influencing factors. Under the background of climate change, the alternating freeze–thaw process in permafrost regions was bound to be accompanied by soil water phase transformation and transfer, thus profoundly affecting soil physical and chemical properties and biological processes (Chai et al., 2014), aggravating the possibility of soil and water loss, and the water flow in rivers and lakes changes (Cruse et al., 2001). In addition, the degree of freeze–thaw was also different with different elevations (Li et al., 2023). It means that freeze–thaw process had a very important effect on the RI of soil PTEs in the study area.

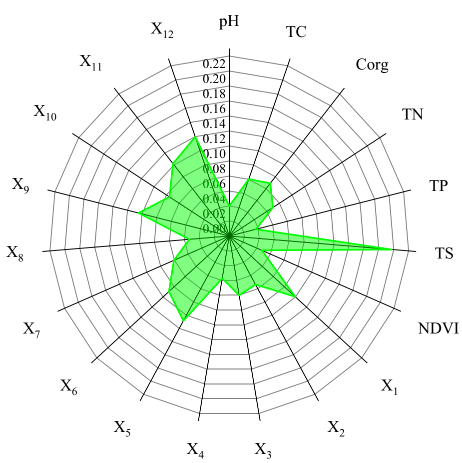


**Fig. 5** The *q* value of influencing factors affecting ecological risk of soils PTEs in Tuotuo River freeze–thaw area

## Multivariate statistical methods

### *Correlation analysis*

The results of correlation analysis showed that there was a significant correlation among most PTEs ($P < 0.05$) (Fig. 6). The soil PTEs with high correlation coefficient may be interdependent and have a common source (Dong et al., 2018; Pan et al., 2016; Varol et al., 2020). The results showed that significant positive correlations existed among Cr, Cu (except Cu-Mn), Ni, Co, Mn, Ti, V and Sc ($r > 0.5$, $p < 0.01$), indicating that these PTEs and Sc in Tuotuo river freeze–thaw area soils were from similar sources. There was a very significant correlation between Cd, Pb and Zn ($p < 0.01$), and the correlation coefficients were 0.41 (Cd–Pb), 0.68(Cd-Zn) and 0.83 (Pb–Zn), respectively, indicating that the sources of Cd, Pb and Zn were similar. Whereas, the As showed weak or no correlation with other PTEs and Sc, meaning that the source of As was different from that of other PTEs.

### Principal component analysis (PCA)

The PCA results of PTEs in soils were showed in Table 2. The Bartlett's sphericity test value $p < 0.0001$ and KMO score of 0.806 meaning that the data set was a suitable for PCA. The eigenvalues of three

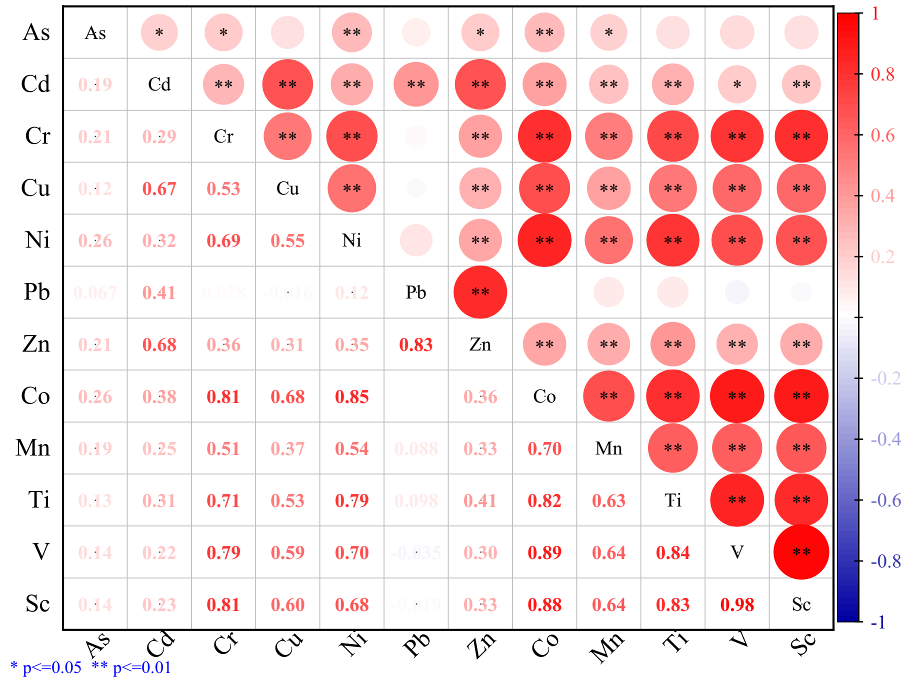


**Fig. 6** Pearson correlation of PTEs and Sc in soils of Tuotuo River freeze–thaw area

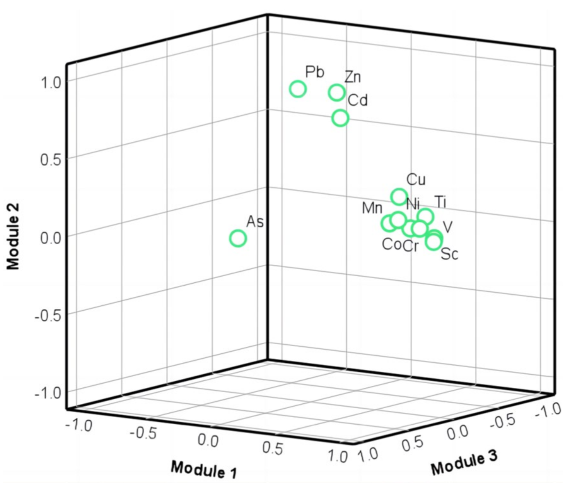


**Fig. 7** The component diagram of principal component analysis

factors (6.42, 2.05 and 1.00), the cumulative contribution rate was 78.6%, which could basically explain the information contained in the soil PTEs.

According to the component diagram of the PCA (Fig. 7), the first principal component (PC1) had strong positive loadings ($\geq 0.677$) on Cr, Cu, Ni, Co, Mn, Ti, V and Sc, and PC1 accounted for 53.5% of the total variance. The mean values of Cu, Co, Ti, V, Ni, Cr and Mn were slightly lower than their respective background values of soil in Tibet. Also, these 7 PTEs exhibited extremely significant positive correlations with each other ($r > 0.51$, $p < 0.01$) (Fig. 6). In addition, these 7 PTEs exhibited lower PI, EF and $I_{geo}$ values and lower coefficients of variation (Table 4). Therefore, they were mainly controlled by natural sources.

The second principal component (PC2) explained 17.1% variance contribution rate, the strong loadings on Pb (0.893), Zn (0.919) and Cd (0.756). The average values of Pb, Zn and Cd were higher than their corresponding background values of soil in Tibet, and showed significant positive correlations with each other (Fig. 6). Cd, Pb and Zn were mainly released through the incomplete combustion of automobile fuel and the wear and tear of tires (Wang et al., 2017; Zhang et al., 2015). Related research shows that the Qinghai-Tibet highway and railway distributed in the northeast-southwest direction were important sources of Cd, Pb and Zn in the surface soil of the QTP (Wang et al., 2022; Yang et al., 2020; Zhang et al., 2015). Therefore, PC2 is mainly affected by traffic factors.

The third principal component (PC3) explained 8.03% variance contribution rate, the strong loadings on As (0.980). The average values of As was higher than background values of soil in Tibet, and showed weak or no correlations with other PTEs and Sc. Sheng et al. (2012) pointed out that the high content of As in Tibetan soil may be related to widely distributed arsenic-rich rocks, but there was no correlation between As with soil parent material index elements Ti and Sc in this study (Table 5).

Guo et al. (2016) pointed out that As and other PTEs in lake sediments of the QTP were greatly affected by soil and atmospheric deposition in the basin. Zhu et al.(2020) analyzed pollutants in lake sediments in the southern QTP and found that the source of pollutant As was mainly caused by the release of glacial meltwater, which corresponded to climate warming. With climate change, pollutants released from the degradation of the cryosphere (glaciers, permafrost, ice and snow) are collected by meltwater into lakes, and then transferred to the surrounding soil through evaporation, runoff transport and other behaviors (Ci et al., 2020; Wang et al., 2022; Zhang et al., 2021). It can be seen that a warming climate may promote the secondary release of pollutants from glaciers and permafrost into the atmosphere, along with meltwater discharge, and other processes. Although the Himalayan mountains in the southern part of the QTP impede atmospheric transport, the transport of As cannot be completely blocked (Wang et al., 2016). The mountain-valley wind pattern may promote the trans-Himalayan transport of pollutants (Cong et al., 2015). Atmospheric circulation patterns also affect remote plateau areas (Yang et al., 2014). For example, Cong et al. (2007) pointed out that South Asia may be the source of PTEs pollutants such as As in Namtso atmospheric particulates. Therefore, PC3 in this study can be defined as a long-distance migration-freeze–thaw.

## Conclusions

Among PTEs of As, Cd, Cr, Cu, Ni, Pb, Zn, Co, Mn, Ti and V, only the average content of As was above the soil pollution risk screening value (GB15618-2018). The As, Cd, Pb and Zn were 1.62, 3.58, 1.69 and 1.20 times greater than their respective Tibet soil background values. Based on average $I_{geo}$ values, freeze–thaw area soils were uncontaminated to moderately uncontaminated by Cd, and soils were uncontaminated by other PTEs. According to mean

**Table 5** PCA results of PTEs in soil

| Variable | As | Cd | Cr | Cu | Ni | Pb | Zn | Co | Mn | Ti | V | Sc | Eigenvalues | % of variance | Cumulative % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PC1 | 0.124 | 0.284 | **0.844** | **0.677** | **0.811** | -0.100 | 0.264 | **0.948** | **0.701** | **0.884** | **0.951** | **0.948** | 6.42 | 53.5 | 53.5 |
| PC2 | 0.095 | **0.756** | 0.105 | 0.275 | 0.168 | **0.893** | **0.919** | 0.121 | 0.127 | 0.168 | 0.014 | 0.036 | 2.05 | 17.1 | 70.6 |
| PC3 | **0.980** | 0.076 | 0.103 | −0.013 | 0.191 | −0.001 | 0.087 | 0.149 | 0.129 | −0.005 | −0.002 | −0.012 | 1.00 | 8.03 | 78.6 |

Bold indicates significant load elements

EF values, soils had moderate enrichments of As, Cd and Pb, however, other PTEs showed slight enrichments. In terms of average PI values, soil had demonstrating considerable pollution with Cd, had moderate pollution with Pb, As and Zn, and had low contamination with other PTEs. According to ER values, soil had considerable potential ecological risk Cd, while other PTEs showed low potential ecological risk. Combined with RI values, the study area was at a moderate level of ecological risk. Based on GeogDetector results, TS was the most significant contributing factor to RI, and freeze–thaw process had a very important effect on the RI of soil PTEs. The correlation and PCA analysis showed that Cu, Co, Ti, V, Ni, Cr and Mn were mainly controlled by natural sources, Cd, Pb and Zn by traffic activity. It is worth noting that the source of As was mainly caused by the long-distance transport and settlement of PTEs in the atmosphere caused by human activities, and the "secondary release" of As during the freeze–thaw process.

Overall, this study provides useful information for identifying possible sources, environmental risks and health risks of soil PTEs pollution in the freeze–thaw area on the QTP, which will be useful for formulating targeted policies and measures for its reduction by PTEs of the soil environment of the QTP. This research can also provide a reference for the study of the environmental behavior of PTEs in the soil of high-altitude freeze–thaw areas under the background of global warming, and provide decision-making support for the construction of Tuotuo River Park in Sanjiangyuan National Park.

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**Data availability** The authors declare that all data supporting the findings of this study are available within the article.

**Declarations**

**Conflict of interest** The authors declare no competing interests.

**Ethical approval** This article does not contain any studies with human participants, or animals by any of the authors.

**Consent to participate** Informed consent to participate was obtained from all individuals included in the study.

**Consent to publication** Consent to publish has been received from all participants of the study.



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