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## Distribution, pollution, and ecological risks of rare earth elements in soil of the northeastern Qinghai–Tibet Plateau

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### ABSTRACT

Information on rare earth elements (REEs) in soils of the Qinghai–Tibet Plateau is very limited. Therefore, this study performed field sampling to explore the concentrations, contamination degree, and potential ecological risks of REEs in soil of the northeastern Qinghai–Tibet Plateau. Concentrations of total REEs (TREEs) ranged from 95.82 to 544.01 mg/kg with average value of 241.81 mg/kg. Light REEs accounted for 72.3%–84.2% of TREEs, whereas Ce was the dominant element. Four methods were employed to evaluate the pollution of soil REEs. About 45.7% of sampling sites exhibited uncontaminated to moderately contaminated levels based on geoaccumulation index values of TREEs. Over 95.7% of sampling sites exhibited deficiency to minimal enrichment based on enrichment factor values of TREEs. The pollution load index evaluation results illustrated that about 85.7% of sampling sites possessed moderate levels of pollution, more serious than those evaluated by modified degree of contamination method. The potential ecological risk indexes of soil REEs in study area ranged from 11.02 to 40.55, showing low risk levels. This study provided important information on REEs in soils of the northeastern Qinghai–Tibet Plateau for soil pollution prevention and control at the high-elevation areas.

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rare earth elements; the Qinghai–Tibet plateau; characteristic parameters; pollution; ecological risk

## Introduction

Rare earth elements (REEs) are generally defined as a homogenous group of 17 elements with identical physic-chemical properties including scandium (Sc), yttrium (Y), and 15 lanthanides with atomic numbers from 57 to 71 (Hu *et al.* 2006; Khan *et al.* 2017), exhibiting similar environmental behaviors. REEs comprise light rare earth elements (LREEs) and heavy ones (HREEs). Elements such as lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm) does not exist naturally in crust of the earth, samarium

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(Sm), and europium (Eu) belong to LREEs while the remaining belong to HREEs (Hu *et al.* 2006).

REEs naturally originate from weathering of the parent materials (Hu *et al.* 2006), actually relatively abundant in the upper continental crust (Caspari *et al.* 2006; Cidu *et al.* 2013; Hu *et al.* 2006; Long *et al.* 2010) and soil (Khan *et al.* 2017; Liang *et al.* 2014). REEs have been widely used in industry, agriculture, and medical technology for decades (Pagano *et al.* 2015a,b; USEPA 2012). Thus, through wide anthropogenic inputs, REEs have accumulated in soil, water, plant, and atmosphere due to their low mobility (d'Aquino *et al.* 2009; Fiket *et al.* 2017; Li *et al.* 2013a; Liu *et al.* 2018; Zhang and Shan 2001), although they naturally exist in such environments with low concentration (Li *et al.* 2013a).

REEs possess the environmental persistence (Laveuf *et al.* 2012; Tang and Johannesson 2006), bioaccumulation (Censi *et al.* 2013; Fiket *et al.* 2017; Fu *et al.* 2014; Wang *et al.* 2008), and chronic toxicity (d'Aquino *et al.* 2009; Pagano *et al.* 2015a,b), although toxicity of REEs is not as strong as that of the environmental toxic elements (Hu *et al.* 2006; Laveuf and Cornu 2009). However, information on environmental behaviors and ecological effects of REEs is still limited (Šmuc *et al.* 2012), especially for high-elevation regions such as the Qinghai–Tibet Plateau.

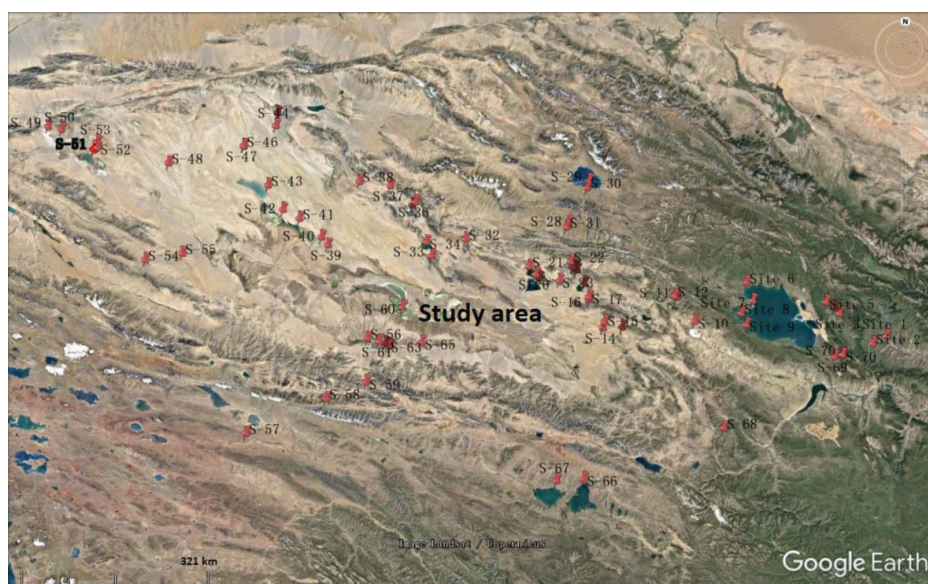
Soil is an important sink to receive nutrients and pollutants, thus playing critical function for ecosystems. In recent decades, soil pollution has attracted more and more attention (Foti *et al.* 2017; Li *et al.* 2013a; Marquès *et al.* 2017; Tepanosyan *et al.* 2017). However, information on soil pollution by REEs is scarce. Therefore, it is necessary to pay attention to the pollution posed by REEs, especially for vulnerable zones such as the Qinghai–Tibet Plateau.

The Qinghai–Tibet Plateau, called as the third pole and roof of the world, has shown unexpected inorganic and organic pollution (Wu *et al.* 2016a, 2016b). Interestingly, the previous studies on REEs in the Qinghai–Tibet Plateau mainly focused on providing proof for the elevation of this area (Li *et al.* 2013b; Wang *et al.* 2014) or discussing distribution of REEs in wet deposition (Guo *et al.* 2017). Research on pollution of REEs in soil of the Qinghai–Tibet Plateau is still very limited. It is necessary to discuss the potential impacts posed by REEs in soil since they are important components of soil, especially in the Qinghai–Tibet Plateau that is an ecologically fragile region in China. Therefore, it is important to study the soil pollution by REEs in the Qinghai–Tibet Plateau due to their potential environmental influences. The objectives of this study are to explore the distribution of REEs in soil of the northeastern Qinghai–Tibet Plateau, discuss the REEs soil pollution of the study area, and provide comprehensive information on REEs in soils for the soil pollution prevention and control in the high-elevation area.

## Methods and materials

### *Study area and analysis of REEs in soil*

Compared with the other regions of the Qinghai–Tibet Plateau, the northeastern region is the most disturbed by anthropogenic activities (Müller 2017; Wu *et al.* 2018). Therefore, the present study selected this region as the study area and 70 sampling sites were determined (Figure 1). The study area is located on 34°–39° N, 90°–102° E with an elevation of 2468–4543 m. The study area has a mean annual temperature of –5.7–8.5°C and annual



**Figure 1.** Map of study area and sampling sites.

precipitation of 50–450 mm. Sampling sites covered typical agricultural regions, pastoral areas, industrial zones, mining areas, tourism sceneries, and roadsides of the highways. Field sampling was carried out from May 31 to June 13, 2016. The topsoil sample (0–20 cm) was carefully collected by stainless steel shovel, *in situ* homogenized, and stored in the sample bags for the following preparation in the laboratory. The soil sample was air dried at the room temperature, and then passed through 0.074 mm nylon-sieve for chemical analysis. According to soil texture analysis, the major soil type of samples was sandy clay loam.

Soil total organic carbon (TOC) was determined using a multi N/C 3100 analyzer (Analytik Jena AG, Germany) after removing inorganic carbon. Soil pH was measured using the supernatants with water-soil ratio of 2.5:1 by a pH meter (Shanghai INESA Scientific Instrument Co., China).

Before instrumental analysis, 50 mg of soil sample was first put into a microwave digestion PTFE (poly tetra fluoroethylene) vessel, and followed by adding 2 mL of 37% HCl, 3 mL of 65% HNO<sub>3</sub>, and 2 mL of 65% HF. The PTFE vessel was placed into the microwave digestion system (MDS-6G, SINEO Microwave Chemistry Technology Co., Shanghai, China) and soil sample was digested for 1 h. After the digestion solution naturally cooled down, 2 mL of 65% HClO<sub>4</sub> and 15 mL of 65% HNO<sub>3</sub> were added into the solution, which was then evaporated at 180°C to dry. The digestion samples were re-dissolved by 2.0 mL of 65% HNO<sub>3</sub> and added with 2% HNO<sub>3</sub> to a final volume of exactly 100 mL for analysis. Total 16 REEs including Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu were analyzed using an Agilent7900 inductively coupled plasma mass spectrometry (ICP-MS, Agilent Inc, USA). Standard solutions of individual REEs were purchased from Alfa Aesar (Thermo Fisher Scientific, USA). Method detection limits of REEs in soil are listed in [Table 1](#). Two quality control samples spiked by standard REE solution were analyzed for every 10 real soil samples to assure the data quality. The recoveries of REEs in spiked quality control samples ranged from 96.1% to 107.3%.

**Table 1.** Statistical summary of pH, TOC, and rare earth element (REE) concentrations of soil samples ( $n = 70$ , g/kg for TOC and mg/kg for all REEs) and method detection limits (MDL, mg/kg) of REEs in soil samples.

	Sc	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy
MDL	3.41	1.03	1.11	2.42	0.36	1.57	0.41	0.12	0.42	0.07	0.31
Mean	10.97	23.83	43.65	87.41	10.10	37.62	7.24	1.67	6.77	0.90	4.81
SE	0.34	0.63	1.74	3.41	0.40	1.49	0.25	0.16	0.22	0.03	0.13
Minimum	4.06	11.31	13.62	27.70	3.23	12.87	3.02	0.85	3.02	0.37	2.09
Median	10.76	23.94	42.36	84.72	9.84	35.83	7.03	1.46	6.56	0.88	4.76
Maximum	19.71	46.46	107.74	216.02	24.73	91.53	16.46	10.77	14.32	1.74	9.42
	Ho	Er	Tm	Yb	Lu	LREE	HREE	TREE	TOC	pH	
MDL	0.09	0.29	0.03	0.30	0.04						
Mean	0.93	2.74	0.38	2.43	0.36	187.68	54.13	241.81	10.07	8.33	
SE	0.02	0.07	0.01	0.06	0.01	7.28	1.34	8.46	1.85	0.06	
Minimum	0.42	1.23	0.18	1.23	0.20	71.24	24.59	95.82	0.42	7.39	
Median	0.93	2.79	0.38	2.45	0.37	181.78	54.36	235.99	4.59	8.27	
Maximum	1.78	5.17	0.71	4.47	0.65	458.27	92.20	544.01	76.93	10.02	

Note: LREE includes La, Ce, Pr, Nd, Sm, and Eu; HREE includes Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc, and Y; TREE includes LREE and HREE; SE refers to standard error; TOC means total organic carbon.

### Characteristic parameters of soil REEs

Characteristic parameters of soil REEs include  $(La/Yb)_N$ ,  $(La/Sm)_N$ ,  $(Gd/Yb)_N$ ,  $Ce/Ce^*$ , and  $Eu/Eu^*$ . The parameters are generally calculated based on the North American Shale Composition (NASC) normalized values as follows (Gromet *et al.* 1984; Fiket *et al.* 2017; Zhao *et al.* 2017):

$$(La / Yb)_N = \frac{(La_{sample} / La_{reference})}{(Yb_{sample} / Yb_{reference})} \tag{1}$$

$$(La / Sm)_N = \frac{(La_{sample} / La_{reference})}{(Sm_{sample} / Sm_{reference})} \tag{2}$$

$$(Gd / Yb)_N = \frac{(Gd_{sample} / Gd_{reference})}{(Yb_{sample} / Yb_{reference})} \tag{3}$$

$$Ce / Ce^* = \frac{(Ce_{sample} / Ce_{reference})}{\sqrt{(La_{sample} / La_{reference}) \times (Pr_{sample} / Pr_{reference})}} \tag{4}$$

$$Eu / Eu^* = \frac{(Eu_{sample} / Eu_{reference})}{\sqrt{(Sm_{sample} / Sm_{reference}) \times (Gd_{sample} / Gd_{reference})}} \tag{5}$$

where  $element_{sample}$  and  $element_{reference}$  stand for the concentration of rare earth element in soil sample and that in reference material, respectively. For the concentrations of rare earth elements in reference material refer to Taylor and McLennan (1985).

### Evaluation on soil pollution by REEs

Soil pollution by REEs was evaluated using four methods including geoaccumulation index ( $I_{geo}$ ), enrichment factor (EF), modified degree of contamination ( $mC_d$ ), and pollution load index

(PLI). These methods evaluate the soil pollution by REEs from different aspects. It is difficult to determine the final evaluation results before performing all assessments using different methods. Therefore, it is necessary to employ these methods to evaluate soil pollution by REEs.  $I_{geo}$  mainly shows the pollution intensity of individual rare earth element as follows (Müller 1969):

$$I_{geo} = \log_2 \frac{C_x^i}{1.5 \times C_b^i} \quad (6)$$

where  $C_b^i$  and  $C_x^i$  represent the background concentration (mg/kg) of the  $i$ th target rare earth element and its concentration (mg/kg) in the soil sample, respectively. Background concentrations of REEs refer to MEPC (1990).

EF is also used to quantify pollution and enrichment level of individual rare earth element (Chester and Stoner 1973; Clark *et al.* 2014), calculated using the following equation:

$$EF = \frac{\left( \frac{C_x^i}{R_{soil}} \right)}{\left( \frac{C_b^i}{R_b} \right)} \quad (7)$$

where  $R_b$  and  $R_{soil}$  refer to soil background concentration (mg/kg) of the reference element and the concentration (mg/kg) of corresponding element in soil sample, respectively. Elements Al, Fe, Mn, Ti, Sc, or Ca can be used as acceptable EF reference element (Salmanighabeshi *et al.* 2015). Ti was chosen as reference element by this study (Salmanighabeshi *et al.* 2015; Wu *et al.* 2018) because its contents in soil samples were determined accurately with REEs at the same time by ICP-MS and relatively high to offset the uncertainty caused by relatively low concentrations of reference element.

$mC_d$  is a comprehensive index to evaluate the soil pollution degree, defined using the following equation (Abraham and Parker 2008; Wu *et al.* 2016a):

$$mC_d = \frac{\sum_{i=1}^n \frac{C_x^i}{C_b^i}}{n} \quad (8)$$

where  $n$  stands for the number of pollutants.

Another comprehensive assessment method PLI is calculated as follows (Bhuiyan *et al.* 2010; Ćujić *et al.* 2016):

$$PLI = \left( \frac{C_x^1}{C_b^1} \times \frac{C_x^2}{C_b^2} \times \dots \times \frac{C_x^n}{C_b^n} \right)^{\frac{1}{n}} \quad (9)$$

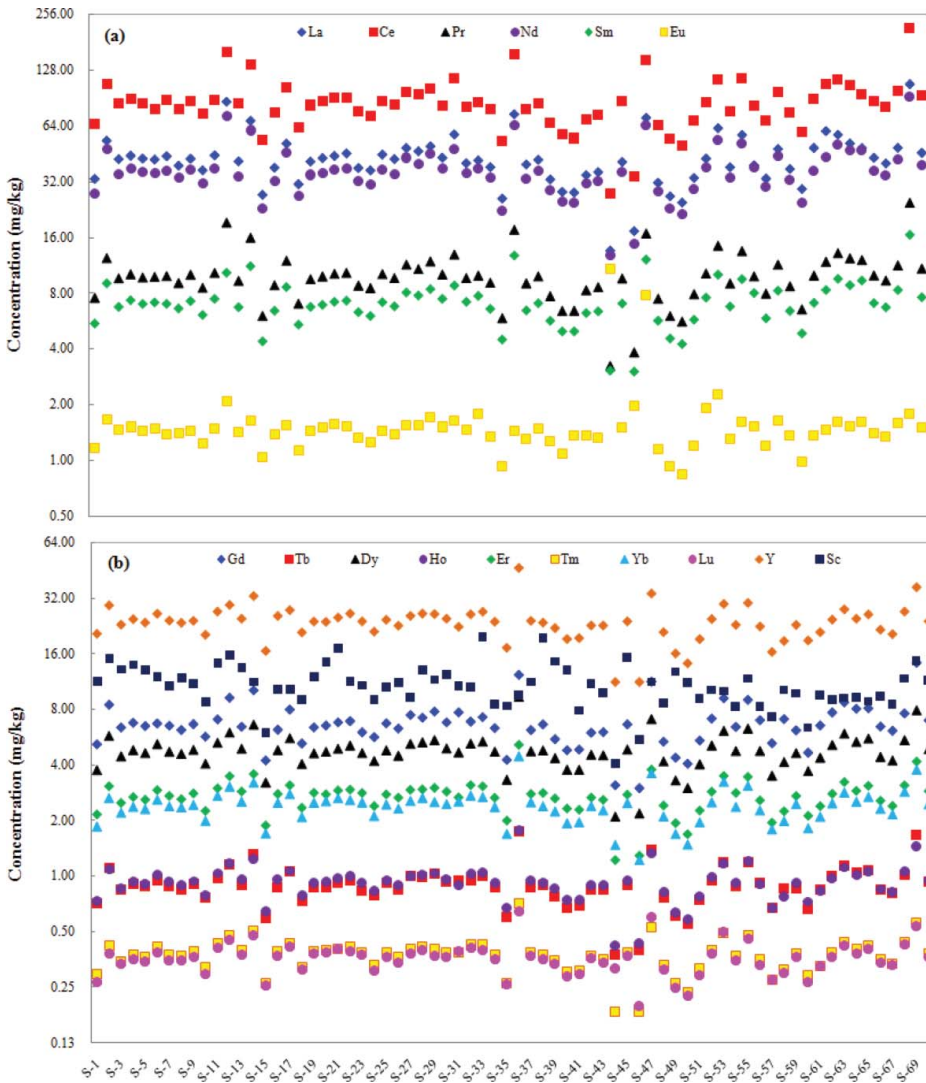


Figure 2. Concentrations of individual rare earth elements in soil samples.

**Ecological risks of REEs in soil**

Ecological risks posed by REEs in soil of the study area were evaluated using potential ecological risk index (PERI) (Hakanson 1980; Madiseh *et al.* 2009). The following equation shows calculation of PERI:

$$PERI = \sum_{i=1}^n T_x^i \times \frac{C_x^i}{C_b^i} \tag{10}$$

where  $T_x^i$  refers to the biological toxicity factor of an individual rare earth element. It is difficult to obtain  $T_x^i$  values for all REEs from the references. Thus, for more rigorous consid-

eration, this study used biological toxicity factor of typical heavy metal Zn ( $T_x^i = 1$ , Hakanson 1980) as  $T_x^i$  value for all REEs.

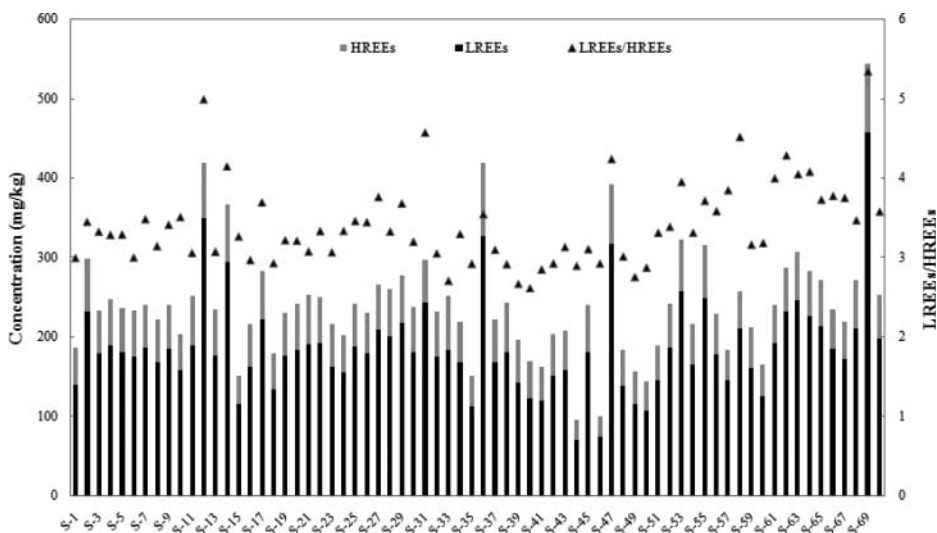
### Statistical analysis

The comparison of concentrations of different rare earth elements in soils was performed using analysis of variance (ANOVA) with calculation of the least significant differences (LSD,  $p = 0.01$ ). All data and artworks were processed in Microsoft Excel 2016.

## Results and discussion

### Distribution of REEs in soil of the study area

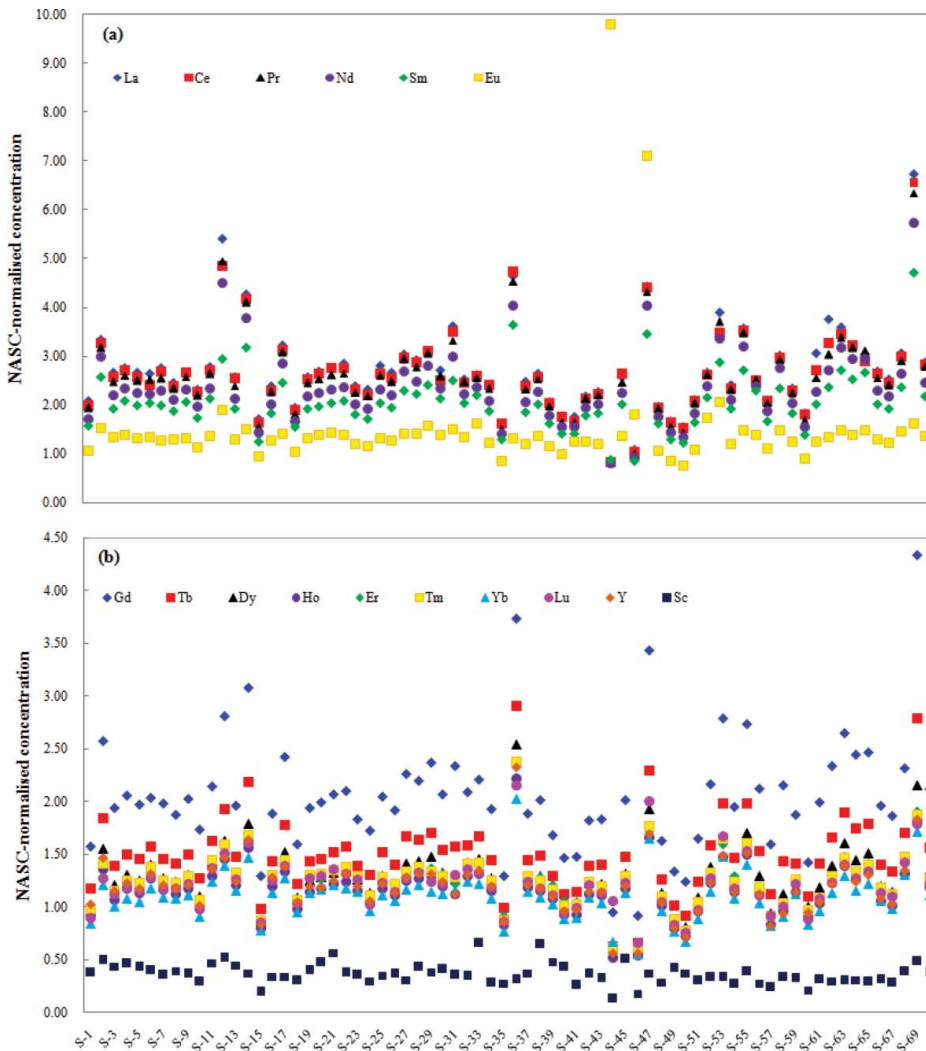
Soil TOC ranged from 0.42 to 76.93 g/kg while pH varied from 7.39 to 10.02, showing significant spatial variations (Table 1). Concentrations of REEs in soil of the study area also exhibited drastic spatial/elemental variations (Table 1 and Figure 2). Based on the results of ANOVA, no significant difference existed between the concentrations of Sc & Pr, Sm & Gd, Tb & Ho, and Tm & Lu. The rest of REEs showed the significant difference. Ce was the dominant element for all sampling sites, ranging from 27.70 to 216.02 mg/kg with the average concentration of 87.41 mg/kg while La and Nd also contributed with considerable proportion to the concentrations of REEs in soil, with average concentrations of 43.65 and 37.62 mg/kg, respectively (Table 1 and Figure 2). These all three dominant elements belonged to LREEs. Y, Sc, and Gd were three dominant HREEs with the average concentrations of 23.83, 10.97, and 6.77 mg/kg, respectively (Table 1 and Figure 2). The average concentration of REEs followed the order of Ce>La>Nd>Y>Sc>Pr>Sm>Gd>Dy>Er>Yb>Eu>Ho>Tb>Tm>Lu. Coefficients of variation (CV) of individual REEs ranged from 20.68% (Lu) to 81.41% (Eu). Except Eu



**Figure 3.** Concentrations of rare earth elements in soil samples and ratio of LREEs/HREEs (light rare earth elements/ heavy rare earth elements).



that showed significant heterogeneity according to CV, the remaining REEs in soil of the study area exhibited relatively good homogeneity of distribution. Concentrations of Tm and Lu were the lowest among all REEs with average values of 0.38 and 0.36 mg/kg, respectively. Concentrations of total REEs (TREEs) in soil were in the range of 95.82–544.01 mg/kg with the mean value of 241.81 mg/kg (Table 1 and Figure 3). The average concentrations of TREEs were similar with those of mining and smelting areas (Briki *et al.* 2016; Wiche *et al.* 2017) and significantly higher than those in soils of China and other countries (Mihajlovic and Rinklebe 2018; Sadeghi *et al.* 2013; Wei *et al.* 1991). Except S-44, concentrations of REEs from all other sites exceeded 100 mg/L, showing the wide occurrence and relatively high abundance of REEs in soil. Interestingly, sampling sites with relatively high concentrations of REEs (>280 mg/kg) were mainly industrial/mining areas except S-69 that located nearby a



**Figure 4.** NASC-normalized concentrations of individual rare earth elements in soil samples.

traffic way and near a tourism park. It was assumed that anthropogenic activities especially chemical industry, mining, and oil extraction might make great contribution to accumulation of REEs in soil. LREEs served as the main composition of REEs in the study area, accounting for about 72.3%–84.2% of TREEs (Figure 3).

### Characteristic parameter of REEs in soil

Ratios of LREEs/HREEs in soils ranged from 2.6 (S-40) to 5.3 (S-69) with the average value of 3.4 (Figure 3) to reveal that LREEs were predominant over HREEs in soil of the study area, which was similar to results reported by Fiket *et al.* (2017). NASC-normalized concentrations of individual REEs ranged from 0.14 (Sc) to 9.79 (Eu) with average values of 0.37 (Sc) to 2.73 (La), showing different inner distribution pattern of the apparent concentrations (Figure 4). La, Ce, and Pr were dominant elements based on NASC-normalized concentration while Sc served as the least influencing element (Figure 4). Distribution of NASC-normalized REEs characteristic parameters including  $(La/Yb)_N$ ,  $(La/Sm)_N$ ,  $(Gd/Yb)_N$ ,  $Ce/Ce^*$ , and  $Eu/Eu^*$  is shown in Figure 5. Ratio of  $(La/Yb)_N$  reflects fractionation and enrichment of LREEs and HREEs, with  $(La/Yb)_N > 1$  showing enrichment of LREEs (Yang 2012).  $(La/Yb)_N$  ranged from 1.26 to 3.92 with the average value of 2.44, showing considerable enrichment of LREEs in soil. The ratios of  $(La/Sm)_N$  and  $(Gd/Yb)_N$  can serve as indicators to illustrate the fractionation degree of LREEs and HREEs, respectively (Yang 2012; Zhao *et al.* 2017).  $(La/Sm)_N$  were in the range of 0.98–1.84 with mean value of 1.31, suggesting that LREEs possessed fractionation to some extent.  $(Gd/Yb)_N$  ranged from 1.41 to 2.53 with average value of 1.85, showing that HREEs possessed more significant fractionation than LREEs.  $Ce/Ce^*$  and  $Eu/Eu^*$  generally represent anomaly of elements Ce and Eu (Gill *et al.* 2018; Yang 2012; Zhao *et al.* 2017).  $Ce/Ce^*$  values of soil samples slightly fluctuated across 1,

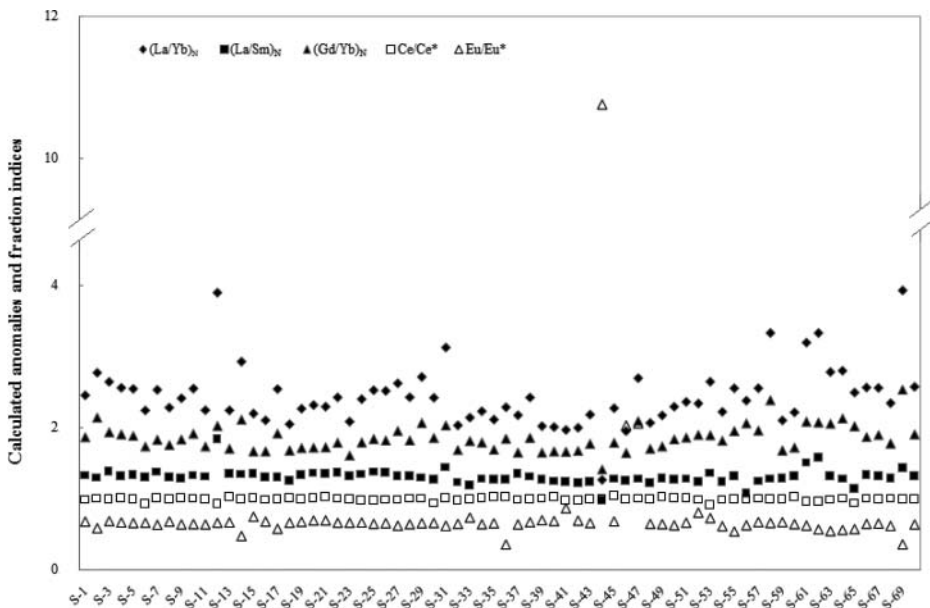
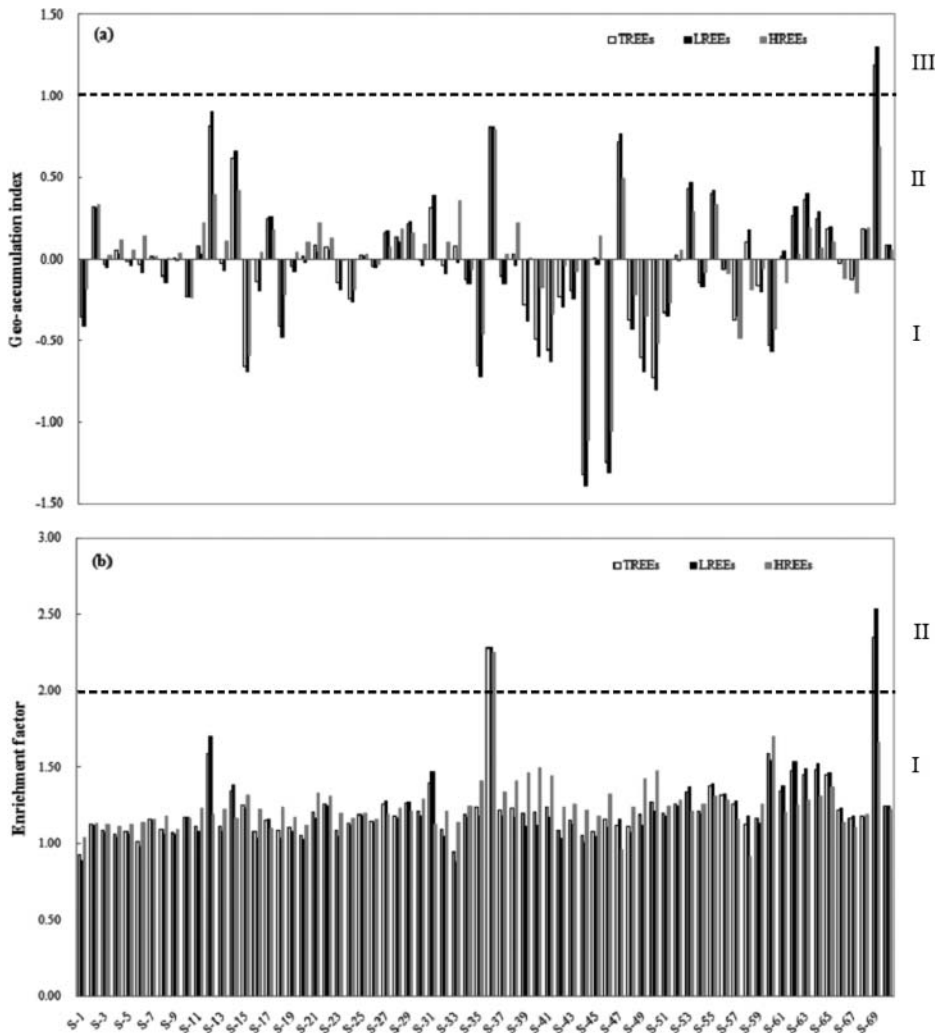


Figure 5. Characteristic parameters of rare earth elements in soil samples.

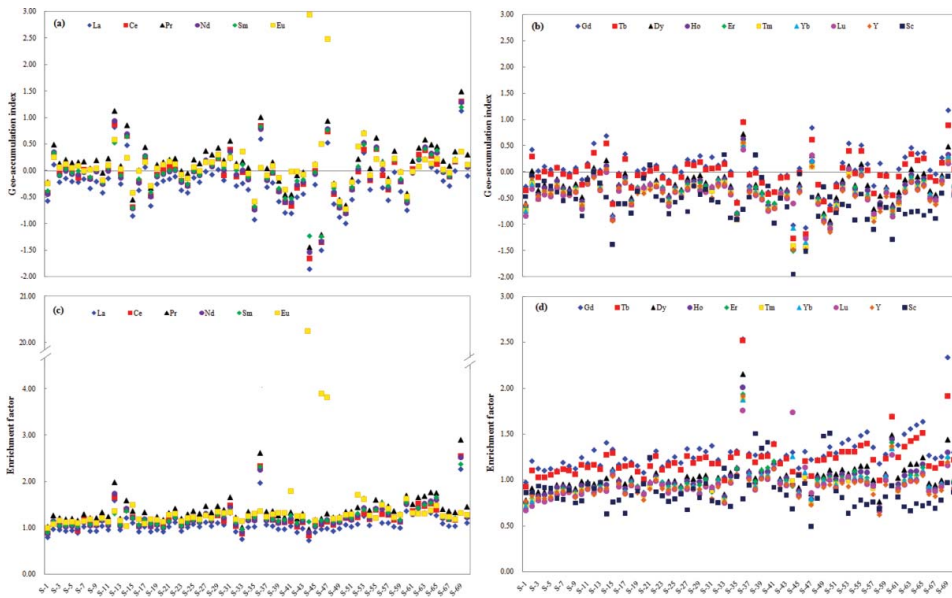
suggesting that Ce was non-anomaly on the whole. Except 3 samples including S-44, S-47, and S-48, Eu/Eu\* values of the remaining soil samples were less than 1, showing that Eu in most of soil samples possessed negative-anomaly. Eu/Eu\* value of S-44 exceeded 10, suggesting Eu in this site occurred significant positive-anomaly.

### Soil pollution by REEs of the study area

Soil pollution by REEs of the study area was evaluated by four approaches (Figures 6–8). Based on evaluation criterion (Ćujić *et al.* 2016),  $I_{Geo}$  values of TREEs in soil samples showed



**Figure 6.** Geoaccumulation indexes and enrichment factors of rare earth elements in soil samples. TREEs, LREEs, and HREEs refer to total rare earth elements, light rare earth elements, and heavy rare earth elements.  $I_{Geo}$  classes I, II, and III refer to uncontaminated, uncontaminated-to-moderately contaminated, and moderately contaminated, respectively; EF classes I and II refer to deficiency to minimal enrichment and moderate enrichment, respectively.

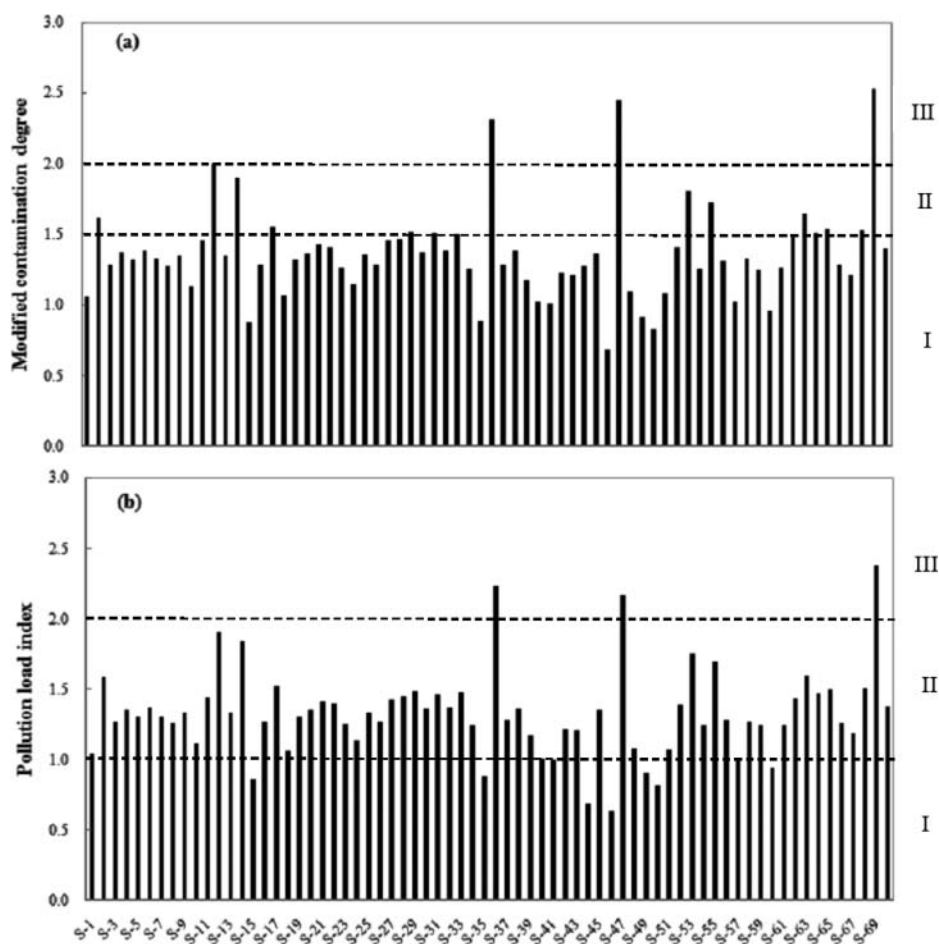


**Figure 7.** Geoaccumulation indexes and enrichment factors of individual rare earth elements in soil samples.

that about 52.9%/45.7%/1.4% of sampling sites exhibited uncontaminated/uncontaminated-to-moderately-contaminated/moderately-contaminated levels (Figure 6a). Pollution patterns based on  $I_{Geo}$  of LREEs were similar with those of TREEs while 40%/60%/0% of sampling sites exhibited uncontaminated/uncontaminated-to-moderately-contaminated/moderately-contaminated levels based on  $I_{Geo}$  values of HREEs (Figure 6a). Among LREEs, Pr exhibited the most serious pollution with about 30%/67.1%/2.9% of sampling sites possessing uncontaminated/uncontaminated-to-moderately-contaminated/moderately-contaminated levels, and then followed by Eu with about 38.6%/58.6%/2.9% of sampling sites possessing uncontaminated/uncontaminated-to-moderately-contaminated/moderately-contaminated levels (Figure 7a). La showed the lightest pollution among LREEs with about 80%/18.6% of sampling sites exhibiting uncontaminated/uncontaminated-to-moderately-contaminated levels. Gd exhibited the most serious pollution among HREEs with about 37.1%/61.4%/1.4% of sampling sites possessing uncontaminated/uncontaminated-to-moderately-contaminated/moderately-contaminated levels, and then followed by Tb (Figure 7b). Ho, Er, Tm, Yb, Lu, Sc, and Y showed the similar pollution patterns with over 87% of sampling sites exhibiting uncontaminated levels.

According to criterion (Ćujić *et al.* 2016; Wen *et al.* 2017), EF values of TREEs in soil samples showed that TREEs in most of sampling sites (>95.7%) were in status of deficiency to minimal enrichment (Figure 6b). LREEs and HREEs in soils also exhibited the same enrichment patterns with TREEs. EF values of individual rare earth elements ranged from 0.49 (Sc at S-47) to 20.34 (Eu at S-44), exhibiting more variable enrichment patterns than those of TREEs (Figures 7c and 7d). Eu was more easily concentrated in soil than other REEs, with EF values ranging from 1.00 to 20.34.

Evaluation results of  $mC_d$  based on criterion (Abraham and Parker 2008) suggested that about 77.1%, 18.6%, and 4.3% of sites showed nil to very low degree of



**Figure 8.** Modified contamination degree and pollution load index of rare earth elements in soil samples. Modified contamination degree classes I, II, and III refer to nil-to-very low degree of contamination, low degree of contamination, and moderate degree of contamination, respectively; pollution load index classes I, II, and III refer to low level of pollution, moderate level of pollution, and high level of pollution, respectively.

contamination, low degree of contamination, and moderate degree of contamination (Figure 8a). Interestingly, PLI evaluation results based on criterion (Ćujić *et al.* 2016) showed that about 10%, 85.7%, and 4.3% of sampling sites possessed low, moderate, and high levels of pollution, respectively (Figure 8b). Difference in calculation and pollution evaluation criterion (Abraham and Parker 2008; Ćujić *et al.* 2016) might be the main reason for difference in evaluation results of PLI and  $mC_d$  methods. Based on the worst-case scenario, REEs in soils of the study area mainly caused moderate pollution. Several sites including S-36, S-47, and S-69 exhibited high pollution due to relatively high soil concentrations of several REEs (Tb, Ho, Tm, Lu, and Eu) and relatively low background concentrations (<1 mg/kg) of these REEs. Generally speaking, REEs in the study area still incurred non-negligible pollution although pollution posed by individual element seemed not serious.

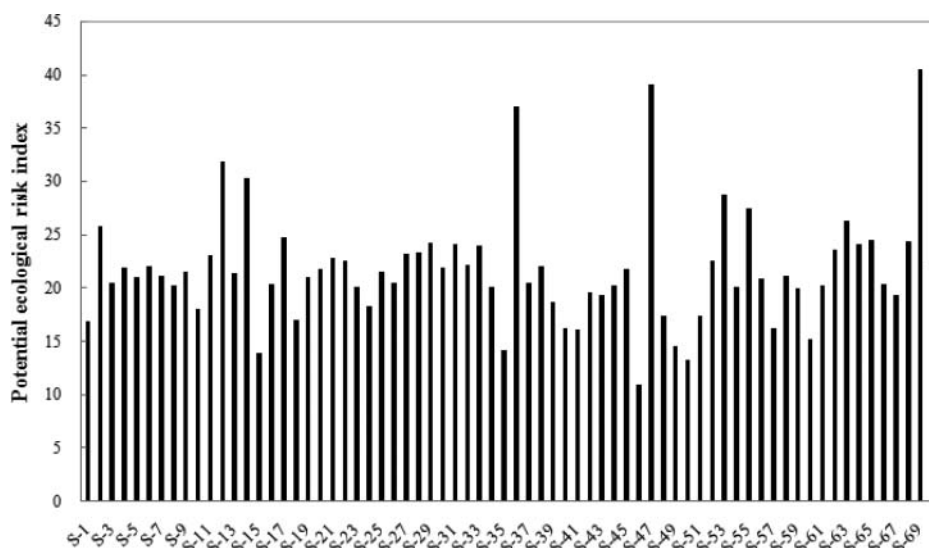


Figure 9. Potential ecological risks of rare earth elements in soil samples.

### Ecological risks posed by REEs in soils

Ecological risks exerted by REEs in soils of the study area were evaluated using PERI (Figure 9). PERI of REEs in soils ranged from 11.02 to 40.55. According to the evaluation criterion (Madiseh *et al.* 2009), the ecological risks of soil REEs in study area were at low levels (when PERI < 150). Concentrations of individual REEs in soils were not high enough so that ecological risks were not high. Elements including Pr, Gd, Nd, Sm, Eu, and Dy were main contributors for ecological risks. It is reasonable to infer that the ecological risks of REEs in soils might be underestimated because the biological toxicity factor  $T_x^i$  of each element was set at 1 in this study. Actually, REEs were frequently reported to possess toxicity (d'Aquino *et al.* 2009; Pagano *et al.* 2015a,b) so that true  $T_x^i$  of each element might be greater than 1 to make the calculated ecological risk higher than that of this study. Therefore, more research work on the ecological risk assessment for REEs in soils needs to be performed in the future.

### Conclusions

Concentrations of REEs in soils of the northeastern Qinghai–Tibet Plateau showed significant spatial/elemental variations. The average concentration of total REEs in soil of the study area was 241.81 mg/kg with maximal value of 544.01 mg/kg, higher than those in soil of China and other countries. LREEs were the dominant REE group in the study area, accounting for 72.3%–84.2% of TREEs in soils. Ce was the dominant element with the average concentration of 87.41 mg/kg. LREEs were easier to concentrate in soil of the study area than HREEs while HREEs possessed more significant fractionation than LREEs by comparing characteristic parameters. About 52.9%/45.7% of sampling sites exhibited uncontaminated/uncontaminated-to- moderately-contaminated levels according to  $I_{Geo}$  values of TREEs in soils. Soil TREEs in most of sampling sites (>95.7%) showed deficiency to minimal enrichment based on  $EF$  values. Evaluation results of  $mC_d$  suggested that about 77.1% and 18.6%

of sites showed nil to very low and low degree of contamination. However, the PLI evaluation results showed that about 10%/85.7% of sampling sites possessed low/moderate levels of pollution, more serious than those of  $mC_d$ . PERI values of REEs in soils ranged from 11.02 to 40.55, illustrating that the ecological risks posed by REEs in soils of the northeastern Qinghai–Tibet Plateau were at low levels.

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