



Effect of soil properties and environmental factors on chemical compositions of forest soils in the Russian Far East

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Abstract

Purpose Forest ecosystem acts as a significant sink and source of elements; however, the dynamics of trace elements (TEs) in soils of boreal zone are still poorly characterized. Data on relationships of TEs, major elements (MEs), soil properties, and parent rock geochemistry in boreal forest of Northeast Asia are scarce. Therefore, the objectives of this study were to evaluate the origination of TEs in forest soils and identify soil properties and ecosystem processes controlling accumulation and profile distribution of TEs.

Materials and methods Dystric Cambisols and underlying parent rocks have been sampled within hilly landscape covered by Gmelin larch (*Larix gmelinii* (Rupr.) Rupr.) forests in Amur region (Russia). This paper considers 10-selected soil characteristics, total concentrations of 19 TEs, and 10 MEs measured by ICP-MS and RFA analysis. Factor analysis has been employed to highlight underlying relationships hidden in a complex data of element concentration and soil characteristics. Origination of TEs was assessed by using an enrichment factor (EF) considering concentration of TEs in soil in comparison to underlying parent rocks using Ti as a reference element.

Results and discussion A group of biophile Zn, Mo, Sn, and Pb were enriched in the upper soil horizon, and depleted in mineral compared to parent rocks. Beryllium, Sc, Cr, Cu, Ga, Ge, Ta, Th, and U were depleted in both horizons. Ni and Cs show highest enrichment in both studied soil horizons. Frequently occurring forest fires affect soil characteristics and TEs dynamic only in the upper part of soil profile. Factor analysis revealed potential effect of exchangeable Na and soil pH on accumulation of the elements in the upper horizon, as a result of ash deposition by fire.

Conclusions The studied TEs primarily originate from underlying parent rocks. Accumulation versus leaching of TEs in Dystric Cambisols might be element specific and affected by fire-derived ash. Our work shows that the upper horizon of forest soils could act as a significant sink of group of TEs. Therefore, long-term observations of TEs dynamic in soil profiles are needed to elucidate biogeochemical cycles in frequently burned forests of Northeast Asia. The present study for the first time has established an important wide data set of TEs concentration in Dystric Cambisols of natural boreal forests in the Russian Far East.

Keywords Boreal forest · Cambisols · Geochemistry · Major and trace elements · Soil properties

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1 Introduction

Forests among other terrestrial ecosystems play a key role in hydrological and biogeochemical cycles. Major and trace elements (MEs and TEs) as a part of these cycles are transporting through forest ecosystem compartments (Bergkvist et al. 1989; Tyler and Olsson 2001). In this regard, forest soils act as a main pool for accumulation and transformation of different substances. Soil pool of elements is determined by rock weathering which is predominant in natural

landscapes. However, industrial and densely populated territories act as a significant source of elements to net soil pool of neighboring ecosystems. In this matter, revealing the origination of elements is critical to understanding modern soil formation process in forest ecosystems.

Until now, majority of studies concerning TEs dynamic in forest ecosystems have aimed to assess contamination from artificial sources (Blaser et al. 2000; Weiss et al. 2002; Sterckeman et al. 2006). Other investigations characterizing natural concentrations of TEs in forest soils have been performed in well-studied regions such as Europe (Tyler 2004), Mediterranean region (Ballesta et al. 2010), and Chinese montane forests (Zhang et al. 2002; Wang et al. 2009). Much less is known about origination, accumulation, and distribution of TEs along soil profile during pedogenesis in natural forests of the Russian Far East. This region is known to receive influence from neighboring industrial areas (Galloway and Cowling 2002). That is why, it is important to know the origination of TEs in forest soils of the region. However, little is known even about basic concentrations of TEs and MEs (but see Timofeeva et al. 2018). Very few studies consider soil geochemistry in comparison to local parent rocks to reveal element origination in soil. This knowledge is critical for the understanding of ecosystem functioning and element cycling.

Most studies considering chemical composition of forest soils have paid attention to very limited numbers of elements which belong to special geochemical group or those elements whose fate is critical in plant nutrition, or to toxic metals. Nearly, all these studies were devoted to 5–10 elements. Thus, previous investigations on geochemical characteristics of the forest soils in the Russian Far East focused on a small number of lithophile elements (Timofeeva et al. 2018), heavy metals (Zharikova 2017), or rare earth elements (Bryanin and Sorokina 2015). These studies have not clearly shown the origin of these elements by considering chemical composition of parent rocks. At the same time, these investigations have not reported such TEs as Li, Be, Cr, Co, Ni, Cu, Zn, Mo, Pb, Sn, Ge, Cs, Ta, Th, and U. However, Cr, Cu, Pb, and Zn are known to be the most dangerous elements in the biosphere (Kabata-Pendias and Szeke 2015). Other elements with unclear grouping or ambiguous biochemical function are poorly reported in literature. That is why, such knowledge is important to clarify the concentrations of these elements in forest soils of the Russian Far East.

At the same time, important source of TEs in forest soils could be the byproducts of forest fires, such as ash. Fire byproducts such as ash and charcoal do not affect only plant and biota but also significantly alter soil properties. These substances change soil physical and physico-chemical characteristics, such changes are well known and widely reported in literature (e.g., Neary et al. 1999; Certini 2005). Due to climate features, fire is the most frequent and severe forest disaster in the studied region (Makoto et al. 2007). Hence, forest

soils are developed under permanent fire influence as a factor of regional pedogenesis. While plant response to fire and soil property alteration have been addressed in the studied area (Makoto et al. 2011; Bryanin et al. 2018), TEs dynamic in frequently burning forests is remaining poorly understood.

The TEs are actively involved in soil formation processes and their concentrations vary in soils within wide limits in different ecosystems (Kabata-Pendias and Szeke 2015). As soil profile differentiates into horizons during weathering and pedogenesis, TEs also come to specific vertical distribution in soil profile. Forest soils have their own peculiarities of pedogenesis: regular input of organic matter causes high microbial activity in the top layer and as a result, creates different substances of acidity nature influencing TEs mobility. In humus horizons, biophile TEs enrichment occurs due to litter accumulation and decomposition (Tyler 2005). However, further distribution of TEs in soil horizons highly depends on soil properties. Thus, in mineral soils, TEs concentrations are influenced by parent rock chemical composition and soil texture. Among soil properties, content of organic carbon (C), pH, and CEC are the most important parameters controlling TEs migration and accumulation in natural soils (Tyler and Olsson 2002; Kabata-Pendias and Szeke 2015).

Therefore, the objectives of this study were to evaluate the origination of TEs in the soils in Northeastern Asia forests. At the same time, we analyzed soil characteristics. By summarizing this analysis, we can clarify the element's origination and influence of soil characteristics on distribution of TEs along soil profile. We investigate TEs concentrations and distribution within Dystric Cambisol profiles developed on lower Paleozoic igneous rocks in unmanaged boreal forests of the Russian Far East, which have been burned continuously by forest fires. To investigate origination of TEs in soils, we put special attention to element concentrations in parent rocks. We consider total concentrations of 19 TEs which is to our knowledge, the first attempt to characterize such a wide range of elements for Dystric Cambisols in the Russian Far East.

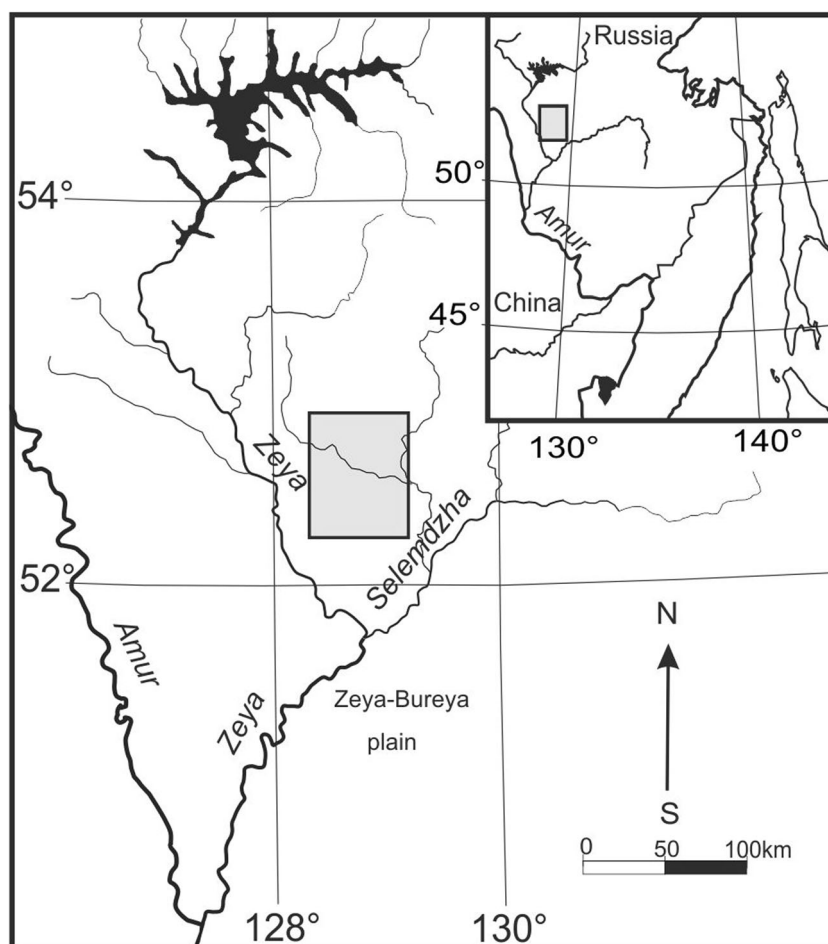
2 Materials and methods

2.1 Site description

The study area is located in the Orlovka River basin (52°37'N, 129°25'E) in the central part of Amur region (Fig. 1). The territory covers 352 km² and refers to southern boundary of boreal forest zone with hilly landscapes formed by lower Paleozoic igneous rocks.

The study area is covered by forests of Gmelin larch (*Larix gmelinii* (Rupr.) Rupr.) mixed to white birch (*Betula platyphylla*). The territory is natural and never contaminated, located far from roads, settlements, and pollutant sources. The climate is continental with monsoon features: a humid and hot

Fig. 1 Location of the study area



summer followed by cold and snowless winter. The study area is the sporadic permafrost soil region, with a mean annual temperature of about $-1.6\text{ }^{\circ}\text{C}$ and a mean annual precipitation of 466 mm (Amur Center for Hydrometeorology and Environmental Monitoring 2015). All these natural factors provide the conditions for the formation of coarse humic soils of the brown soil series according to the Russian soil classification. Following the World Reference Base for Soil Resources, the studied soils refer to Dystric Cambisols (WRB 2015). The studied soils are developed on igneous parent rocks whose genesis and geochemistry have been exhaustively characterized by A. Sorokin and co-authors (Sorokin et al. 2015, 2017).

2.2 Sampling and analytical procedures

Dystric Cambisols were sampled from seven soil profiles established on southern hill slopes of similar inclination and under the same forest type. According to the World Reference Base for Soil Resources, the soil profiles were divided by horizons which have been morphologically described and sampled (WRB 2015). An average soil sample with a weight of $\sim 1\text{ kg}$ was collected from each horizon. Samples were

carefully mixed, and all gravel, roots, twigs, and litter were removed by hand sorting. Samples then were air dried, crushed, mixed thoroughly, ground using mortar, and sieved under 2 mm. Parent rock samples were collected under every soil profile. Proportion (wt%) of detrital fragments in soil was estimated in field by washing of 1 kg soil on sieve with mesh size of 2 mm. Content of C was analyzed using the combustion method with a TOC-L analyzer, on a module for solid sample measurement, SSM-5000A (Shimadzu, Japan). Soil pH was measured electrometrically from a 1:2.5 soil to KCl solution using Hanna HI 2215 (HANNA Instruments Deutschland GmbH, Germany). During the measurement for the suspension, the pH was stable. The CEC as the sum of extractable Ca^{2+} , Mg^{2+} , K^{+} , Na^{+} , Al^{3+} , and H^{+} was analyzed after extracting mineral soil samples (2.5 g) with 1 M NH_4Cl to full cation displacement. To determine particle size distribution, pipette method was used. All basic soil analyses were performed according to Pansu and Gautheyrou (2006). Soil texture classes were characterized according to the guidelines from the World Reference Base for Soil Resources (WRB 2015).

Chemical composition was analyzed in humus and mineral compartments of the soil profile (i.e., A and Bw horizons).

Concentrations of MEs were measured in powdered solid soil samples by X-ray fluorescence analysis (XRF) of 1050–1100 °C. The measurements were carried out on a S4 Pioneer X-ray spectrometer (Bruker AXS GmbH, Germany). The intensities of the analytical lines were corrected for the background, and for the effects of absorption and secondary fluorescence. Total concentrations of Li, Be, Sc, V, Cr, Co, Ni, Cu, Zn, Ga, Ge, Rb, Mo, Sn, Cs, Ta, Pb, Th, and U were measured by inductively coupled plasma mass spectrometry (ICP-MS) at the Institute of Tectonics and Geophysics (Khabarovsk). The samples were dissolved by acid decomposition. The measurements were conducted in a standard regime on an Elan 6100 DRC (Perkin-Elmer, USA), whose sensitivity over the whole mass scale was calibrated using standard reference solutions that contained all elements to be analyzed in the samples. The relative measurement error for MEs and TEs was 3–10%.

2.3 Statistical analyses

The data was tested for normal distribution by applying Shapiro–Wilk’s normality test. For variables which do not fit to normal distribution, Box-Cox transformations were applied. Pearson product-moment correlation coefficients were calculated to examine the relations among the variables. Factor analysis (FA) was applied to identify the following: (a) the relationships among the studied variables and (b) the main factors differentiating TEs in soil horizons. The FA was performed upon correlation matrix of ten MEs, 19 TEs concentrations, and ten soil properties. Prior FA-normalized data were scaled and the analysis was done upon the correlation matrix by using package “psych” version 1.7.8 (Revelle 2017). The first three components were retained and rotated using Varimax rotation; the latter redistributes the variance in each variable so that each contributes strongly to one factor and little to the others (Sharma 1996). All statistic calculations were performed in R Studio (version 1.1.383) (R Development Core Team 2017). To characterize TEs, we used conventional method of normalization of element concentrations to upper continental crust composition (Taylor and McLennan 1995).

To evaluate origination of TEs in the soil profile, we calculated the enrichment factor for TEs against the composition of the parent rocks and using Ti as one of the stable elements during weathering. Following equation was used:

$$EF_{Ti} = \frac{[E]_S/[Ti]_S}{[E]_R/[Ti]_R}$$

where E is the content of any element, S refers to the soil horizon (A or Bw), and R refers to parent rock underlying the same soil profile.

3 Results

3.1 General soil parameters

The soil profile of the studied Dystric Cambisols consists of five horizons: O-A-ABw-Bw-BwC (Table 1). The upper O horizon is represented by fresh forest litter mixed to partially charred organic matter of low decomposition stage. The A horizon lies in limits of 3–6 cm and contains charcoal, ash, and charred wood. Mineral soil layer is weakly differentiated to subhorizons. The overall profile thickness does not exceed 50 cm with considerable amount of detrital fragments from the depth of 16 cm increasing to about 80% in the lower horizon, underlined by unweathered parent rock.

Soil texture varied from fine sandy loam in upper and middle soil horizons to coarse sandy loam in the lowermost BwC horizon. The content of clay and silt was highest in the middle part of the soil profile and lowest in BwC horizons due to increasing of detrital fragments and related sandy fractions. Soil pH varied in wide ranges from neutral in the upper part of the soil profile, then gradually decreased with depth to very acid in the lower BwC horizon (Table 1). The CEC values (cmol kg^{-1}) of soils were high in the upper layer and decreased considerably to bottom one. Remarkably, contribution of exchangeable Na^+ ions to CEC in upper horizons varied from 6.9 to 5% decreasing significantly in the mineral horizon. Majority of organic matter was stored in the upper 15 cm layer with high content of C (up to 28%) and decreased in mineral soil to low content (less than 1%).

3.2 MEs and TEs concentrations

The concentrations of MEs and TEs in soil horizons and parent rocks were summarized in the Electronic supplementary material (Table S1). As the soil properties are vertically differentiated, the concentrations of MEs markedly varied within the soil profile. In the humus horizon, distinct accumulation of MnO and P_2O_5 was observed, while mineral soil (Bw horizon) was enriched by Fe_2O_3 , SiO_2 , and Al_2O_3 (Fig. 2a, b). Other elements had ambiguous vertical distribution pattern: contents of Na_2O , CaO, and MgO were slightly accumulated in the humus horizon and decreased with depth.

Concentrations of TEs varied in wide ranges (mg kg^{-1}): Li from 12.7 to 53.1, Be from 0.9 to 2.8, Sc from 4.5 to 25.9, V from 43.2 to 246.6, Cr from 27.4 to 119.4, Co from 6.8 to 28.4, Ni from 9.2 to 37.2, Cu from 2.2 to 76.1, Zn from 90.9 to 292.6, Ga from 10.7 to 20.2, Ge from 1.06 to 1.5, Rb from 39.7 to 152.1, Mo from 0.57 to 4.5, Sn from 0.53 to 11.6, Cs from 2.4 to 11.0, Ta from 0.36 to 1.36, Pb from 1.03 to 22.6, Th from 4.1 to 10.5, and U from 0.85 to 4.40.

Concentrations of TEs normalized to the upper continental crust (UCC) composition (Taylor and McLennan 1995) are shown in Fig. 3. Content of TEs in the studied soils was

Table 1 Main properties of Dystric Cambisols

	O <i>n</i> = 7	A <i>n</i> = 8	ABw <i>n</i> = 7	Bw <i>n</i> = 9	BwC <i>n</i> = 8
Thickness (cm)	3 (0.5)	4 (0.4)	10 (1)	15 (2)	18 (2)
Bottom boundary (cm)	3 (0.3)	6.8 (0.8)	16.3 (1.7)	28.7 (2.4)	46.8 (3.7)
Rockiness (wt%)	0	0	43.1 (14.2)	67.8 (3.9)	78.8 (4.1)
pH (KCl)	6.6 (0.3)	5.7 (0.3)	4.4 (0.3)	3.6 (0.1)	3.7 (0.1)
Clay (wt%)	0	31.5 (2.6)	33.1 (2.9)	36.4 (2.8)	24.6 (4.2)
Silt (wt%)	0	9.8 (0.6)	10.4 (1.4)	11.1 (0.7)	7.8 (1.8)
Ca ²⁺ (cmol kg ⁻¹)	82.4 (9.2)	35.1 (3.3)	12.5 (2.0)	6.5 (1.8)	8.8 (2.3)
Mg ²⁺ (cmol kg ⁻¹)	17.1 (1.7)	10.3 (1.3)	5.2 (0.9)	3.8 (0.9)	4.5 (1.3)
K ⁺ (cmol kg ⁻¹)	0.2 (0.02)	0.1 (0.02)	0.07 (0.02)	0.03 (0.01)	0.02 (0.01)
Na ⁺ (cmol kg ⁻¹)	5.2 (2.9)	2.38 (1.3)	1.2 (0.5)	0.95 (0.4)	0.5 (0.3)
H ⁺ (cmol kg ⁻¹)	0.25 (0.03)	0.20 (0.02)	0.1 (0.02)	0.2 (0.05)	0.3 (0.02)
Al ³⁺ (cmol kg ⁻¹)	0.02 (0.01)	0.01 (0.01)	0.2 (0.06)	2.2 (0.8)	0.7 (0.2)
CEC (cmol kg ⁻¹)	105.3 (11.8)	48.1 (5.0)	19.3 (2.9)	13.6 (2.2)	14.8 (3.5)
V (%)	100 (0.1)	100 (0.2)	98 (0.5)	75 (9.4)	88 (5.7)
Organic C (%)	27.7 (2.3)	15.0 (1.2)	4.2 (0.9)	1.6 (0.3)	0.8 (0.1)

Data in table are means and standard errors in brackets

almost lower than that for UCC with exception of Zn showing distinct accumulation in both studied horizons. In the mineral Bw horizon, TEs showed higher variation compared to the upper horizon. In spite of relatively high variation of distribution, patterns of TEs were fall into value field of world Cambisols (Kabata-Pendias 2011). Negative anomaly of Be and Ni and positive for Zn and Ta were the exceptions from this pattern. These anomalies were observed in all the studied horizons.

3.3 Enrichment factors

Enrichment factors (EF) for all soil horizons were calculated for every studied horizon using the data in Table S1 (Electronic supplementary material) and titanium as reference. Mean EF are given in Table 2. For beryllium, Sc, Cr, Cu, Ga,

Ge, Ta, Th, U, V, and rubidium EF were below or close to 1. The other group of TEs consisted of Zn, Mo, Sn, and Pb showed clear enrichment in the upper A soil horizon, while the mineral Bw horizon was depleted by these elements. Cobalt, Li, Ni, and Cs tended to accumulate in both A and Bw horizons. Different TEs showed completely different patterns of enrichment/depletion.

3.4 FA

For both soil horizons, FA separated three factors cumulatively explaining 82% and 75% of the total variance in A and Bw horizons respectively. In the upper humus horizon, Factor 1 was comprised of majority of TEs among which Sc, V, Co, Cu, Ga, and Ge had positive correlation, while Cr, Rb, Mo, Sn, Cs, and Pb had negative correlation to Factor 1 (Fig. 4a).

Fig. 2 Upper continental crust (UCC)-normalized MEs concentrations in A humus (a) and Bw (b) mineral soil horizons. Lines in figure show chemical composition of individual samples. The composition of UCC was given from Taylor and McLennan (1995)

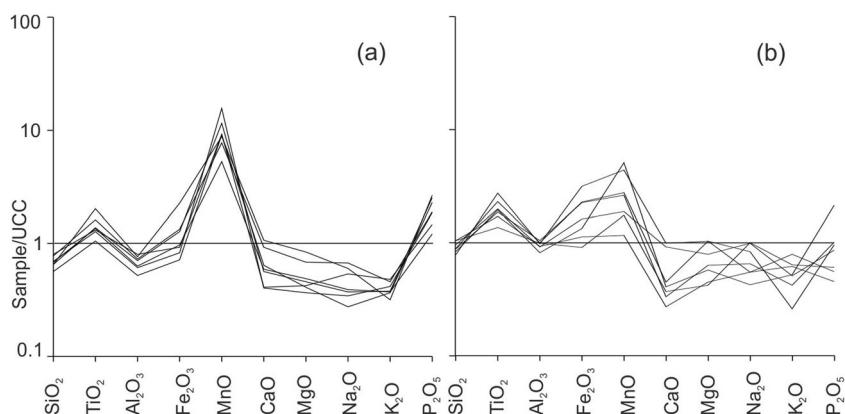
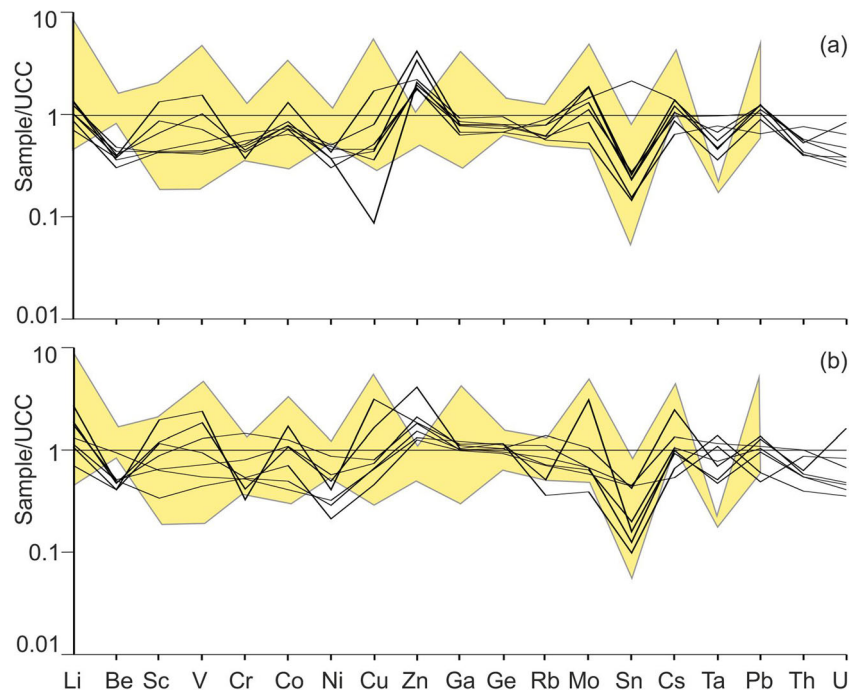


Fig. 3 Upper continental crust (UCC)-normalized TE concentrations in A humus (a) and Bw (b) mineral soil horizons. Yellow field is the range of TE concentrations in the world's Cambisols (Kabata-Pendias 2011; Kabata-Pendias and Szeke 2015). Lines in figure show chemical composition of individual samples. The composition of UCC is cited from Taylor and McLennan (1995)



Oxides of Al, Fe, Ti, Ca, Mg, and Na had been included in the first factor with high loadings. Strong positive correlation to the first factor was observed for exchangeable Na⁺ ions, pH, and C. Silt and clay concentration had negative loadings to the

Factor 1. The second factor included Be, Th, and Zn together with exchangeable cations and CEC. The third factor in the upper horizon included Li, Ni, and Al oxide with positive and exchangeable H with negative loadings. Uranium and Mn oxide had the lowest communality among tested variables in the upper soil horizon; their variances were poorly explained by separated factors.

Table 2 Mean (*n* = 7) enrichment factor (EF_T) for soil horizons

Element	Soil horizons	
	A	Bw
Li	1.81	1.67
Be	0.71	0.63
Sc	0.68	0.69
V	1.09	1.17
Cr	0.48	0.40
Co	1.35	1.72
Ni	2.91	2.21
Cu	0.47	0.60
Zn	1.62	0.84
Ga	0.53	0.51
Ge	0.54	0.52
Rb	0.98	0.71
Mo	1.48	0.68
Sn	1.26	0.87
Cs	3.23	2.21
Ta	0.82	0.56
Pb	1.57	0.96
Th	0.79	0.65
U	0.47	0.47

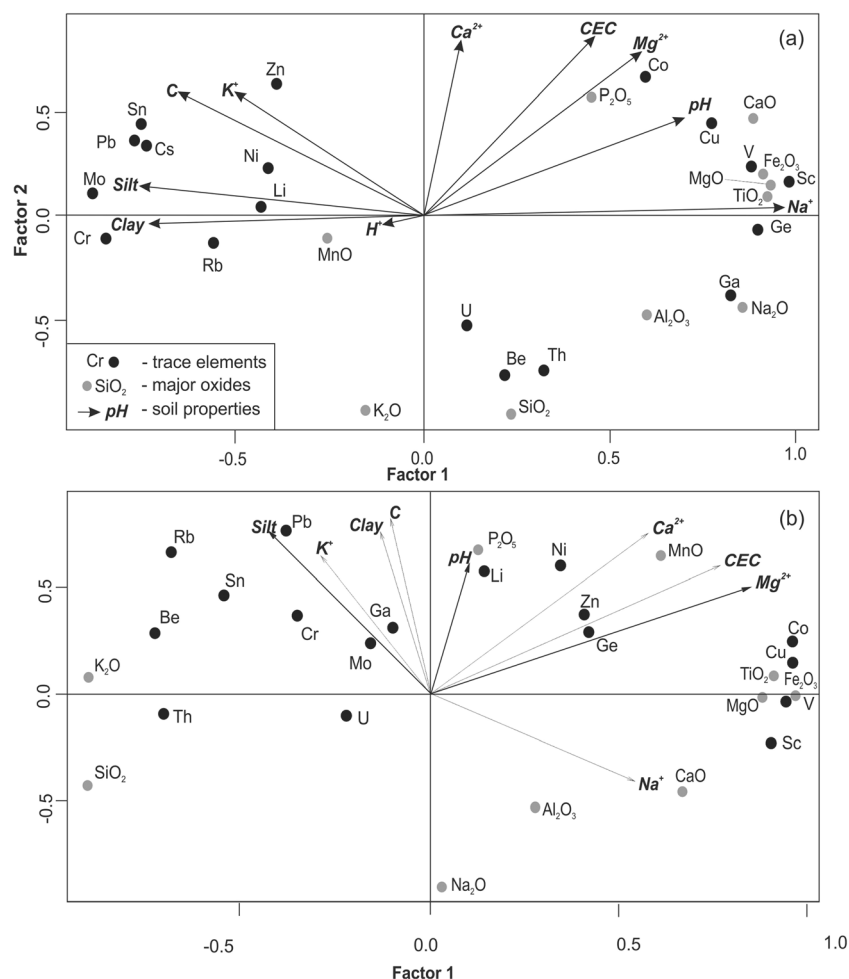
In the mineral Bw horizon, the first factor was comprised of Be, Sc, V, Co, Cu, Rb, Sn, Th, and oxides of Si, Ti, Fe, Mg, K, and CEC accounting for 37% of the total variance (Fig. 4b). Soil C content along with clay and silt content and exchangeable Ca was strongly associated with Li, Ni, Cs, Pb, and Na₂O. Exchangeable Na⁺ combined to the third factor with Li, Zn, Mo, and oxides of Al. Apart from that, Cr, Ga, Ge, and U had small communality values and were not adequately explained by three separated factors in the Bw horizon.

4 Discussion

4.1 Features of element content and origination

Element concentrations undergo vertical differentiation during pedogenesis and weathering (Zhang et al. 2002; Tyler 2004). In our study, concentrations of MEs and TEs showed distinct differentiation between the upper humus horizon and mineral soil layer. There was no element among TEs and MEs with stable distribution along the soil profile. Even Al, which is considered to be the stable element (Weiss et al. 2002), was distinctly enriched in the mineral soil

Fig. 4 Varimax rotated factor analysis ordinations for A (a) and Bw (b) soil horizons



horizon. Clear differentiation of TE concentrations suggests that elemental composition of soil is much influenced by pedological and environmental processes. In our study, the middle part of the soil profiles was enriched by clay minerals and major oxides especially Fe and Al, which influence TE accumulation. Same results are described in a study of European podzol, the most similar soil to the studied ones (Tyler 2004). We found low variation of TE concentrations in the humus horizon compared to mineral soil. The latter could be attributed to biogeochemical effect of plant and microbial communities which produce and decompose forest litter.

Simultaneous sampling and analysis of soils and parent rocks allowed us to reveal origination of the major part of the studied TEs. Our calculations of EF (Table 2) suggest lithological origination of most TEs. Nevertheless, in the same environmental conditions, there were two groups of TEs with different enrichment/depletion patterns. A group of biophile elements consisted of Zn, Mo, Pb, Sn, and Co showed distinct enrichment in the upper A horizon and depletion in the mineral Bw. This finding is supported by the comparison to UCC

(Fig. 3). The other group was depleted along the whole soil profile. We found high EF for Ni and Cs which cannot be clearly explained by weathering of local parent rocks. It is known that Ni in humid climate is easily complexed to organic substances and bound to clay minerals (Kabata-Pendias and Szeke 2015). In spite of high enrichment in comparison to local parent rocks, concentrations of Cs fitted to global Cambisol composition and UCC (Fig. 3), suggesting that Cs tends to accumulate in this soil type around the world. Cesium accumulates in organic horizon during litter decomposition and its mobility decreases in neutral and alkaline environment (Rafferty et al. 2000). Many investigations have showed that the solubility of Co, Ni, and Zn decreases in neutral and alkaline soil pH (Bergkvist et al. 1989; Liodakis et al. 2009; Pereira et al. 2012). Interestingly, concentrations of Ni in the studied soils were even lower than that in world's Cambisols. We must admit that found high EF could not be uniquely determined as pollution. Given that the study area is quite remote from industry and high population area, future investigations are needed to attribute the origination of these two elements in forest soils in the Russian Far East.

4.2 Influence of soil properties and environmental factors

Soil properties significantly affect TEs dynamics in soil profile (Tume et al. 2006; Wang et al. 2009). Thus, sorption capacity of soil is determined by element retention on the surface of minerals, organic macromolecules, and exchangeable cations (Vega et al. 2004). On the other hand, soil pH acts as a driver of element mobility. Our results revealed neutral pH (6.6) and high content of exchangeable Na in the humus horizon (Table 1). These outstanding soil characteristics do not match with characteristics of Cambisols recently reported by Timofeeva et al. (2018). The upper horizon of Dystric Cambisols is usually thick organic layer of 8–10-cm depth formed by organic matter of different decomposition stages with acidic environment within whole soil profile where pH ranged from 3.9 to 4.3 (Tyler and Olsson 2002; Timofeeva et al. 2018).

One possible reason of this altered soil pH could be frequent forest fires. Fires in the studied region occur annually and their byproducts, i.e., charcoal and ash, have altered soil physical and chemical characteristics (Bryanin and Sorokina 2015; Bryanin and Makoto 2017). As a result, the upper horizon is represented by thin organic layer, relatively high pH, and abundant Na⁺ ions. The latter tend to be accumulated in soil due to regular ash input (Escudey et al. 2015). All these soil parameters resulted in decreasing mobility of Sc, V, Co, Cu, Ga, and Ge and their accumulation in the upper part of soil profile. This assumption is supported by FA (Fig. 4a) where this group of TEs along with soil pH and Na were included into one factor. In addition, pronounced accumulation of MnO, Zn, and P₂O₅ in the upper horizon could also be attributed to ash deposition (Makoto et al. 2012). This process was proved by research of ash-amended soils in pine forest in northwestern Spain (Omil et al. 2007), and pine plantations in North Estonia (Mandre 2006). As shown in investigation of leaching properties of forest ashes (Lioudakis et al. 2009), mobility of Cr and Pb in neutral and slightly alkaline environment drastically increase and these elements are completely released from ashes. Our data is in line with this finding: pH, Cr, Pb, and Mo have combined to one factor with high negative loadings suggesting same processes as described above (Fig. 4a). In the mineral horizon, FA defined similar grouping of TEs but explanatory soil parameters differed from those in the upper horizon. In mineral soil, TEs combined to C and CEC along with MEs oxides. Our data also showed distinct acid barrier on the border of humus and mineral horizons where acidity drastically changed from pH 5.7 to pH 3.6. In such very acid environment, mobility of some TEs significantly increased, at the same time, higher clay content along with CEC provided retention of TEs in the middle layer. Furthermore, abundance of detrital fragments in the mineral horizon acted as a source of new portions of TEs. All this

coexisting processes in the mineral soil horizon explain accumulation a variety of TEs.

5 Conclusions

Our investigation for the first time has established an important wide data set on TEs concentrations in Dystric Cambisols developed under natural boreal forests of the Russian Far East. Soil's TEs composition reflects the composition of the parent rocks and does not display pollution history. However, soil formation process and frequent forest fires might affect vertical distribution of these elements in soil profiles. Accumulation of group of TEs is controlled by exchangeable Na and soil pH. Neutral and even slightly alkaline conditions created by fire-derived ashes resulted in retention and accumulation of group of TEs in upper horizons. Future investigations are needed to reveal the element's ecological toxicity in conditions of recent changing of the climate such as increasing forest fires in the Russian Far East.

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