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Influence of Trace Elements Translocation from Cryoconite on Local Soil Pollution Level at the Mount Elbrus Region

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Abstract. Cryoconites are supraglacial organomineral sediments that can accumulate various pollutants and release them into downstream ecosystems during the melting period. The influence of cryoconites on the pollution of local soils was studied in many mountainous regions, including the Tibetan Plateau, the Alps, and others. However, this information is lacking for the Caucasus Mountains and, particularly, their highest peak – Mount Elbrus, even though it is an important region for agriculture and tourism. We studied the content of Cu, Zn, Pb, Ni, and Cd in cryoconites at the Garabashi and Maliy Azay glaciers as well as in the soils of adjacent gorges. The content of trace elements was studied by atomic absorption spectroscopy, and pollution indices were calculated further. Our findings showed that sediments mostly accumulate trace elements in the cryoconite holes at the Garabashi Glacier (Zn max. 80.00 mg/kg, Cu max. 31.20 mg/kg, Ni max. 31.20 mg/kg, Pb max. 41.90 mg/kg, Cd max. 0.54 mg/kg). The highest content of trace elements in local soils of the Terskol Gorge, especially Zn (65.40 mg/kg) and Cd (max. 0.47 mg/kg), was found at the grazing meadow and wetland at the Terskol River floodplain while all trace element more polluted more remote soils at the Baksan Gorge. According to indices of geoaccumulation and ecological risk, most of the samples were unpolluted, while the pollution index indicated a high pollution load with Zn and Cu. These results showed that local anthropogenic activities increase trace element content in samples. Soils of wetlands and floodplains act as a natural geochemical barrier for translocated pollutants. High pollution by Zn and Cu is probably associated with metal-sulfite mineral ores at the Baksan Gorge and the transfer of polluted material. Currently, this pollution may not affect local ecosystems; however, it should be taken into account for the development of agriculture. Therefore, cryoconites play an important role in the geochemical flows of the Mount Elbrus periglacial zone, which should be taken into account in future human activities and the conservation of mountain ecosystems.

Keywords: supraglacial sediments · mountain soils · trace elements · pollution indices · Caucasus Mountains

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1 Introduction

The problems of global climate change and chemical pollution are among the most important issues in the scientific community at present. At the same time, mountainous and polar regions are the most sensitive to anthropogenic pollution. Its sources usually include traffic emissions, burning of fossil fuels for heating and other purposes, mining, construction, and agricultural activities. Black carbon, one of the most common pollutants, plays a significant role in climate and ecosystem changes. It is deposited from the atmosphere in cold areas, which leads to the formation of specific sediments on the surface of glaciers – cryoconites.

Cryoconites are dark-colored organomineral sediments that are common in glacial zones of the Earth. They contain black carbon, mineral particles, and organic components [1]. They can be located in cryoconite holes, in crevasses, and on the glacier surface. These glacial sediments can accumulate various pollutants, including heavy metals. During the warm season, various substances and elements can be translocated to the periglacial zone with meltwater flows. This migration can affect geochemically subordinate landscapes, both increasing their pollution levels and accelerating the development of local soils and soil-like bodies.

The research took place in the Elbrus region, one of the most high-mountainous areas of the Caucasus Range, where mountain glaciers are covered with cryoconites and subject to anthropogenic impact. Migration of various elements from the glacier surface to the periglacial zone of Elbrus can affect the pollution state of local ecosystems, which becomes especially relevant in connection with the development of tourism near Mount Elbrus and active agricultural activities. Thus, the purpose of this study is to estimate the pollution of glacial and periglacial zones of Mount Elbrus with some trace elements and the role of supraglacial sediments in the pollution of mountainous soils.

2 Materials and Methods

Cryoconites and moraines were sampled in different locations from two glaciers on the southern slope of Mount Elbrus: the Malyi Azau Glacier and the Garabashi Glacier. Soils were taken at the Terskol Gorge and the Baksan Gorge.

Sampled soils were defined as Molic Leptosol, Umbric Leptosol, and Eutric Histosol [2] at the Terskol Gorge, immediately adjacent to Mt. Elbrus. In the more remote part of the the glaciers, Leptic Umbrisol with Haplik Chernozem were sampled at the Baksan Gorge. Concentrations of copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), and cadmium (Cd) were determined in the studied samples by atomic absorption method [3]. Analysis of variance (ANOVA) and Spearman's rank correlation coefficient were used for statistical processing of the obtained data.

We used several pollution indices to interpret trace elements' content in studied materials correctly. The categorization of calculated indices is given in the mentioned sources. The Geoaccumulation index (Igeo) is a useful tool for estimation of pollution load with a single element and can be calculated as follows [4]:

$$Igeo = \log_2\left[\frac{C_n}{B_n \times 1.5}\right]$$

Here, Cn is the actual value of trace element in the sample; Bn is a natural geochemical background value; 1.5 is an empirical coefficient.

Another sensitive index is the Pollution Index (PI), which is calculated as follows [5]:

$$PI = \frac{C_n}{B_n}$$

We used local background values of the Caucasus mountain region from the previous study [6].

Pollution load index (PLI) is an index for assessment of the pollution load with all trace elements, which is calculated using the following equation [7]:

$$PLI = \sqrt[n]{PI_1 \times PI_2 \times \cdots \times PI_n}$$

Here, PI is a Pollution index value and n is the number of analyzed trace elements.

Comprehensive potential ecological risk (RI) for all trace elements is usually calculated in order to estimate potential risk for ecosystems caused by toxicity of elements [8]:

$$RI = \sum\nolimits_{i=1} Tr \times PI$$

Here, Tr is a biological toxic factor of individual trace elements, and PI is a Pollution index.

Tr was determined as follows: Cu = 5, Zn = 2, Ni = 5, Pb = 5, Cd = 30. RI categorization looks as follows: low risk ($RI < 45$), moderate risk ($45 \leq RI < 90$), strong risk ($90 \leq RI < 180$).

3 Results

3.1 Trace Elements Content

According to the results, the studied samples were mainly polluted with zinc (max. 64.40 $mg*kg^{-1}$). On the other hand, more remote from the glaciers soils at the Baksan Gorge were more polluted than these samples with almost all trace elements (Cu max. = 31.60 $mg*kg^{-1}$, Zn max. = 68.00 $mg*kg^{-1}$, Ni max. = 43.00 $mg*kg^{-1}$, Pb max. = 16.50 $mg*kg^{-1}$, Cd max. = 0.76 $mg*kg^{-1}$). A statistically significant difference between the content of trace elements in sediments and mountainous soils was observed only for Cu ($p < 0.05$); its content was higher in cryoconites. The results of Spearman's test showed a high positive correlation between all studied trace elements.

The results of our studies of trace element content are presented in Table 1.

3.2 Pollution Indices

The calculation of the Igeo index revealed that almost all samples were classified as unpolluted (Igeo <0). Only one cryoconite material was slightly polluted with Zn, Cu, and Cd. Slight pollution was also typical for almost all samples from the Baksan Gorge.

Table 1. Mean values of trace elements content in studied materials at the glacial zone and the Terskol Gorge.

Sample type and site	Sampling depth, cm	Cu, mg*kg^{-1}	Zn, mg*kg^{-1}	Ni, mg*kg^{-1}	Pb, mg*kg^{-1}	Cd, mg*kg^{-1}
Cryoconite, the Malyi Azau Glacier	0–5	2.76	7.11	1.48	<0.10	0.14
	0–5	4.04	6.12	1.76	< 0.10	0.10
	0–5	10.29	36.07	11.63	11.49	0.57
	0–5	4.29	4.28	1.30	< 0.10	0.1
Cryoconite and moraine, the Garabashi Glacier	0–5	4.64	5.46	1.80	< 0.10	0.05
	0–5	22.07	55.40	21.07	26.03	0.37
	0–5	5.34	8.66	1.70	< 0.10	0.07
	0–5	3.81	4.95	1.41	< 0.10	0.19
	0–5	4.38	9.01	3.91	2.81	0.27
	0–5	5.34	3.67	1.13	< 0.10	0.11
Soil, the Terskol Gorge	0–10	2.37	8.42	2.02	1.32	0.12
	10–20	1.88	7.43	1.71	< 0.10	0.12
	20–35	1.89	7.43	1.62	0.24	0.11
	35–40	2.14	7.66	1.75	0.15	0.12
Soil, left bank of the Terskol River	0–7	7.75	64.40	6.35	8.23	0.41
	7–13	4.40	54.20	5.09	7.53	0.29
	13–25	2.35	49.73	3.06	7.62	0.23
Histosol, the Terskol Gorge	0–10	4.62	31.30	6.48	5.72	0.38
	10–30	4.46	19.07	9.43	5.10	0.40

On the other hand, the calculation of the PI index showed different results. According to these calculations, some cryoconite samples from the Garabashi Glacier, as well as soil on the left bank of the Terskol River, were highly polluted with Zn and moderately polluted with Cd. Moreover, some cryoconite samples were contaminated with Cu and moderately polluted with Pb. Sediments at the Malyi Azau Glacier and other soil study sites were predominantly unpolluted or slightly polluted. Soils from the Baksan Gorge were mainly characterized as highly polluted.

The complex PLI index (Fig. 1) showed that only a few samples from the Garabashi Glacier were polluted with all trace elements together. However, samples from the left bank of the Terskol River and Histosols were close to the threshold value. The RI index (Fig. 1) indicated moderate risk in few cryoconite samples at the Garabashi Glacier and some soil samples at the Terskol Gorge, while other samples had low ecological risk. Moderate pollution and ecological risk were typical for the soils of the Baksan Gorge.

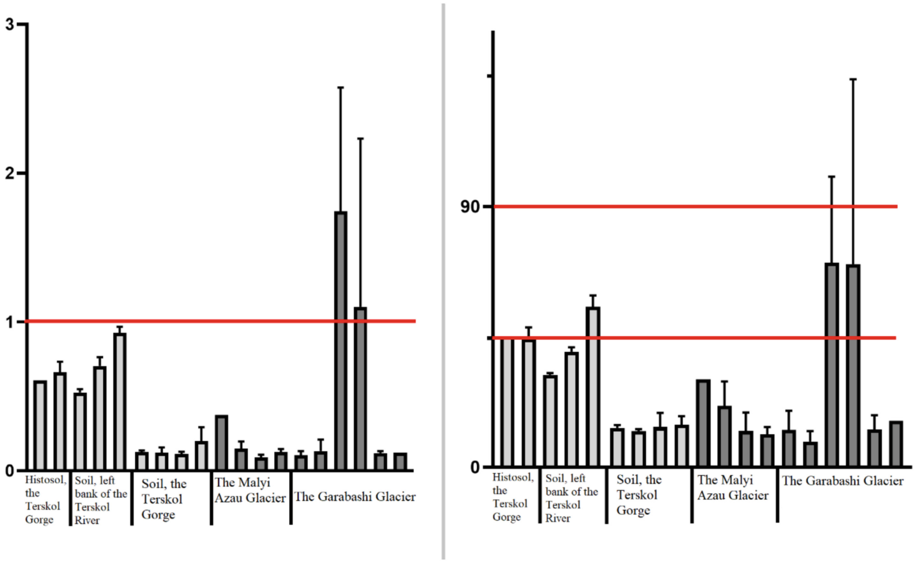

Fig. 1. Calculated mean values of PLI index (on the left) and RI index (on the right) of studied samples in the glacial and periglacial zones at the Terskol Gorge with standard deviations. The red line indicates the categorizations.

4 Discussion

Among the studied samples, soils of the Baksan Gorge accumulated the highest concentrations of trace elements, associated with proximity to settlements and highways and a high level of anthropogenic pressure in general. However, top horizons, especially in the river floodplain study site, were more polluted, which may indicate additional transfer of pollutants with water streams.

High-altitude sites are located far from settlements and major highways, which causes their lower degree of pollution. Cryoconites actively accumulated various heavy metals, which is also proved by pollution indices; lead content was the highest among all studied materials. In addition, high concentrations of zinc and some other heavy metals in some sites were noted. However, the content of pollutants in cryoconites varied between samples, presumably due to the proximity of sites with high concentrations to tourist infrastructure facilities: cable cars, parking lots, automobile roads, and cafes. It was especially noticeable at the Garabashi Glacier, which is the most popular among tourists. Another evidence of the dominant role of the influence of human activities on the pollution level is a high positive correlation between all trace elements, according to Spearman's test, which is not typical for background and indicates the complex source of pollution. Mountains represent the natural barrier for long-range atmospheric transfer; therefore, autochthonous input is the main source of glacial sediments. Besides tourism and construction activities, another important local source of pollutants is the Tyrnyauz ore deposit at the Baksan Gorge with mining tailings. Pollutants from these mining tailings, especially zinc, and copper, may be translocated to the glacial surface and local soils via aeolian transfer, affecting pollution load.

On the other hand, a previous study [9] showed that atmospheric dust may be transferred from Western Asia and Northern Africa. Due to high background concentrations and anthropogenic activities in these regions, this dust was enriched with trace elements, especially copper, zinc, and cadmium. In our previous study at the Elbrus region [10], we also found a high level of pollution with zinc and copper, which was associated with both local and allochthonous input of material.

Translocation of polluted material from glacial surface leads to migration of elements to geochemically subordinate landscapes. Thus, in the periglacial soils of the Terskol Gorge, zinc was the dominant trace element, while the accumulation of some other elements was noted in the upper horizons. Even though most soil samples showed a low level of ecological risk, additional anthropogenic load may increase risks for vulnerable local ecosystems. Moreover, zinc and copper have a higher migration capacity despite their lower toxicity. Their transfer to the foothill areas may lead to additional pollution of the Baksan Gorge soils, which are actively used for agriculture.

Therefore, it is important to continue monitoring sediments and soil pollution in the context of climate change and tourism development. Moreover, additional studies are needed to correctly understand the migration routes of pollutants from the supraglacial to the periglacial zone. The results of this and future studies could be useful for the sustainable development of tourism and agriculture in the Elbrus region.

5 Conclusions

- We measured the content of five trace elements in cryoconites and soils in the Elbrus mountainous region and calculated pollution indices for them.
- Cryoconites efficiently accumulated trace elements, especially zinc and lead.
- The translocation of polluted cryoconite material influences the pollution level of local soils.
- Mining, tourist facilities, traffic emissions, and allochthonous input of atmospheric dust are likely the main sources of pollutants.
- Possible ecological risks should be taken into account for the future development of tourism and agriculture.

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