Naryan-Mar city: Zn is as high as 28 μg/l^3 in the river water 3 km downstream of Iskateli neighborhood (northern outskirts of the city), which is almost three times the maximum permissible concentration (MPC) for fisheries waters (10 μg/l^3).

CONCLUSIONS

Landscape-geochemical studies in the lower reaches of the Yenisei and Pechora rivers discharging into the Arctic basin have confirmed the possibility of tracing radionuclide and heavy metal contamination of landscape systems due to global- and regional-scale sources. Delta front island systems can act as barriers to riverine transport of contaminants. The observed accumulation patterns of elements in different components of chemically conjugated landscape systems can be used for reference in pollution tracing and monitoring.

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BIOGEOCHEMISTRY OF PERMAFROST LANDSCAPES IN WEST SIBERIA: IMPLICATIONS FOR ECOLOGY AND SUSTAINABILITY

D.V. Moskovchenko

Institute of Northern Development, Siberian Branch of the Russian Academy of Sciences,
PO box 2774, Tyumen, 625003, Russia; land@ipdn.ru

The study concerns with biogeochemistry of landscapes in the Yamal Peninsula, including the trace-element composition of different soils and abundances of plant nutrients. The sustainability of plant-soil systems in permafrost terrains has been recognized to have two major controls: the biosorption activity of plants and contents of biogenic elements in soils. The former factor stabilizes the material composition of landscapes and shows up especially in zonal systems. The other factor controls the rate of revegetation in industrially disturbed areas, the azonal soils being best provided with mineral nutrients.

The vegetation cover has been universally accepted to be the principal control in processes responsible for the sustainability of permafrost landscapes [*Tyrtikov, 1974; Meltser, 1994; Tsibulsky, 1995; Moskalenko, 1996; Ermokhina, 2009*]. Vegetation, and peat derived from it, stabilize the thermal regime of soils and thus prevent permafrost from degradation. On the other hand, vegetation is the most changeable

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landscape component prone to surficial and subsurface impacts. Thus, investigation into the structure and functions of plant biota is a basic approach in estimating the ecology and sustainability of tundra landscapes.

The patterns of vegetation depend directly on soil chemistry. Lichens prevail in sandy tundra soils with low peat contents [*Dobrinsky, 1995*], willow shrub communities grow mostly on marine sediments with highly saline soil waters [*Ermokhina, 2009*]. Vegetation on soils depleted in major and trace elements is poor, and such landscapes are weakly sustainable. Thus, the sustainability of plant-soil systems is, to a large extent, a function of their chemical structure meant as the spatial and composition patterns of leaching and enrichment zones [*Glazovskaya, 1988*]. The structure of landscape-geochemical systems results from a long evolution with its general trend following Vernadsky's law of increasing biogeochemical energy in living matter [*Vernadsky, 1980*].

The biogeochemistry of permafrost plant-soil systems has been studied in soil and plant samples collected through environmental profiling in the Arctic and Subarctic tundra of the Yamal Peninsula (Bovanenko and Tambei oil fields). Sampling was along landscape profiles (sequences or catenas) that traverse different geomorphic levels and, correspondingly, record different ecological conditions. Another objective was to explore soil composition changes at development sites (petroleum wells and clusters).

According to data on the biotic component of the landscape sequences, the endmembers commonly have a simple structure of cenoses and low biodiversity. For instance, the driest and wettest Subarctic tundra biotopes miss shrubbage. Plant communities growing on depleted and relatively dry sandy soils show less diverse taxonomic compositions than those on wetter and richer loamy soils of sedge-shrub-sphagnum tundra [*Moskalenko, 2006*]. The Yamal tussock and sphagnum bogs have reduced spectra of life forms [*Telyatnikov, 2003*], their simplified biotic structure being evidence of nutrients and energy shortage and poor self-regulation.

Therefore, we explored the compositions of plants and soils in different ecological sequences. Plants are known to be more active element absorbers in zonal watershed tundra ecosystems than in very wet or very dry areas. The biosorption activity for trace elements is the highest in shrubs (*Betula nana*, *Salix glauca*, *S. lanata*), the edificators of Subarctic tundras, but is low in grasses, sedges, and sphagnum that dominate the intra-zonal systems [*Dobrinsky, 1995*]. The same trends appear in the topsoil peat compositions. Biosorption is the most active in zonal tundra soils in flat watersheds. The highest contents of Mn and Zn, which are the most rapidly accumulated elements, are in peat from yernik (dwarf birch)-lichen-green moss tundra. Hydromorphic subacid soils show weaker biosorption and higher lateral migration of substances and lower contents of biogenic elements in peat (Table 1). The total coefficient of biological accumulation (ratio of average measured element concentrations to their average in soil) is the highest in zonal tundra systems of flat watersheds.

Thus, vegetation in the latter systems, which reflect the most faithfully the environment features ("invariant" systems according to V. Sochava), has the highest geochemical activity developed in the course of long evolution. This fact shows up in the biogeochemical structure of soils, namely in high compositional diversity of organic topsoils and poor element enrichment in the mineral horizons. This is biological accumulation preventing elements from transport in water that stabilizes the composition of a

Table 1. **Trace-element compositions of peat topsoil (Bovanenko oil field)**

Soils, geography, vegetation	Element									Rk
	Mn	Cr	Ba	Sr	Ni	Co	Cu	Zn	Pb	
Peat-gley soils of watersheds in tussock shrub-lichen-green moss tundra, $n = 32$	$\frac{3.0}{3650}$	$\frac{0.7}{124}$	$\frac{2.1}{1834}$	$\frac{0.8}{169}$	$\frac{0.6}{61}$	$\frac{1.1}{25}$	$\frac{0.8}{46}$	$\frac{2.3}{202}$	$\frac{1.1}{24}$	2.0
Peat-gley soils of watershed slopes in grassy willow tundra, $n = 6$	$\frac{2.6}{3167}$	$\frac{0.6}{120}$	$\frac{1.7}{1467}$	$\frac{1.3}{262}$	$\frac{0.7}{68}$	$\frac{1.3}{28}$	$\frac{0.8}{44}$	$\frac{1.3}{112}$	$\frac{0.9}{19}$	1.8
Bog soils of swales in shrub-sedge-moss tundra, $n = 8$	$\frac{1.2}{1483}$	$\frac{0.6}{113}$	$\frac{1.7}{1500}$	$\frac{1.1}{225}$	$\frac{0.7}{73}$	$\frac{1.0}{23}$	$\frac{0.8}{47}$	$\frac{1.0}{82}$	$\frac{1.1}{25}$	1.6
Transitional bog soils in carex-eriophorum-sphagnum tundra, $n = 4$	$\frac{1.7}{2050}$	$\frac{0.6}{120}$	$\frac{1.9}{2000}$	$\frac{0.8}{150}$	$\frac{0.7}{70}$	$\frac{1.4}{30}$	$\frac{1.0}{55}$	$\frac{0.9}{80}$	$\frac{1.1}{25}$	1.8
Alluvial soils of near-terrace floodplain, $n = 6$	$\frac{1.3}{1500}$	$\frac{0.6}{120}$	$\frac{1.7}{1500}$	$\frac{1.0}{200}$	$\frac{0.6}{60}$	$\frac{0.5}{10}$	$\frac{0.5}{30}$	$\frac{0.5}{40}$	$\frac{0.7}{15}$	1.1

Note. *n* is the number of samples; Rk is the total biological accumulation (ratio of average measured concentrations of elements to their average soil abundance). Element composition of soils: numerator is the ratio of element concentration in soil to that in soil parent material; denominator is the average measured element concentration, ppm.

Table 2. **Chemical composition of soils in Arctic tundra (Yamal Peninsula)**

Soil	pH_{KCl}	pH_{H_2O}	Organic matter	N_{total}	P_2O_5	K_2O	CEC	TAB
			%		ppm		mmol/100 g	
Peat-gley tundra	4.8	5.9	45.2	0.23	63	240	1.5	4.7
Supra-permafrost gley	5.0	6.6	0.55	0.03	114	225	1.5	0.5
Podzol	4.9	6.5	1.2	0.04	98	231	1.6	1.2
Bog-tundra	4.0	5.5	14.5	0.38	80	190	2.8	8.9
Fen	4.4	5.5	23.2	0.44	33	232	1.2	8.6
Alluvial	5.2	6.5	3.1	0.17	178	286	2.1	6.9

Note. CEC is the cation exchange capacity; TAB is the total absorbed bases.

landscape, the biotic component thus being the crucial intrinsic factor of its self-regulation and stabilization.

Comparison of peat compositions in different climate zones shows that the tundra soils are depleted in many trace elements. Average contents of Zn, Ni, Pb, Cu, and Co in forest peatland are, respectively, 940, 180, 120, 89, and 45 mg per kg of ash [*Dobrodeev, 1990*], which is much higher than in the Yamal peat. The trace-element depletion in the tundra peat is due to prolonged biological cycles and intense leaching. The low intensity of biological cycles in tundra landscapes and the related low self-regulation are responsible for their vulnerability to industrial disturbance [*Perelman and Kasimov, 1999*].

Soils in northern West Siberia are deficient in many plant nutrients necessary for rapid and efficient revegetation in disturbed areas [*Vasilievskaya et al., 1986*]. Technogenic loads at development sites change dramatically the geochemical framework of landscapes. Specifically, soils at drilling sites are contaminated with petrochemical products, Ba, Sr, and Pb [*Moskovchenko, 1998*]. Disturbance to peat topsoil reduces the store of organic matter, potassium, and nitrogen. Mechanic damage and pollution cause degradation or extermination of plant communities, while the remediation efficiency depends on the availability of mineral nutrients.

According to agrochemistry data for the Yamal soils, zonal tundra peat-gley soil systems are depleted in P and have low cation exchange capacity (CEC) and total absorbed bases (TAB). Depleted compositions are observed in podzol soils of flat watersheds and gley soils in areas of sporadic permafrost. On the contrary, soils of intra-zonal systems have high concentrations of mineral plant nutrients. Alluvial soils have highest P and K enrichment, while peat in bog-tundra and fen soils is the richest in nitrogen (Table 2). This is vegetation in the overwetted areas that shows the highest recovery potential. Revegetation is the most rapid in thin peatbogs [*Liverovsky et al., 1980*] or in fens and water-filled swales [*Moskalenko and Shur, 1975*].

Thus, the sustainability of zonal and azonal plant-soil systems has different controls that depend on the chemical composition of soils. The sustainability of zonal systems, meant as capability of preserving their structure, depends on how efficient the vegetation is in the use of material and energy resources. This efficiency is expressed quantitatively in high biological accumulation of elements in peat. The sustainability as an ability of rapid recovery after being industrially disturbed ("elasticity") is the maximum in azonal systems and depends on the contents of plant nutrients in soils.

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