Natural Biogeochemical Cycling in Polar Ecosystems

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Abstract Natural biogeochemical cycling in polar and tundra ecosystems is described. The review of literature and new data allow the author to show the approaches to biogeochemical cycling ranking in severe climate conditions based on active temperature coefficients.

Keywords Biogeochemical cycling • Polar ecosystems and ecoregions • Biogeochemical ranking • Biogeochemical regionalization

1 Introduction

In the Northern hemisphere, the area of arctic and tundra ecosystems is 3,756,000 km^2. In the southern hemisphere, these ecosystems are virtually absent. Most of the ecosystems are in Russia, Finland, Sweden, Norway, Greenland, Alaska (USA) and Canada.

These arctic and tundra zone is not really favorable for any human economic activities, especially for agriculture due to lack of heat (cumulative temperatures > 5 °C are less than 1000 °C), low soil temperatures (no higher than 10–14 °C at a depth of 10 cm), high soil acidity and amorphy, poor agrophysical properties, meagerness of humus and nourishment, and low biological activity of soils. This is compounded by short vegetation season (60–70 days) and likely frosts in summer months. As for the warm season, there is no clearly defined period with mean daily temperature of >10 °C. The forest tundra climate is severe having short and cool summers, the active season for vegetation is no longer than 50 days with temperatures of >10 °C and cumulative temperatures for the period amounting to 700–

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800 °C. The soils are undeveloped, tight, waterlogged and poorly aerated, have high acidity and low temperatures, which in total results in low biological activity, since the plant nutrients in the soil are scarce.

It is well known that the Russian Federation accumulates the major natural gas reserves and the largest part of these reserves is located in Polar region with severe natural conditions and vulnerable environment. Monetization of these reserves and gas supplies to both domestic and foreign consumers require using sustainable development approaches based on unified environmental, social and economic principles. These principles should be the grounds for industrial activity of all gas companies.

Accordingly, on a basis of sustainable development principles no harmful influence should be given to natural ecosystems during gas and oil production. This means that the anthropogenic loads must be in the limits of natural deviations of biogeochemical food chains (Bashkin 2002). Thus the aim of this paper is to describe the natural features of biological and biogeochemical cycling in polar ecosystems.

2 Biological and Biogeochemical Cycling in the Arctic Regions

2.1 Biological Cycling

In lowland tundra, the biological cycle occurs in conditions of long polar day: the long summer time is effective for photosynthesis due to the high energetic light and plants have adapted to this. “Long day plants” are poorly developed in low latitudes with short day. Thanks to the long day the amount of solar radiation in the lowland tundra is the same as in southern taiga, but the temperature in summer is much lower. Low air temperature and soils limit biological cycle, these are the cause of many features, in particular, development of xeromorphic plants. Deficiency of heat is related with so called “waves of life”: in years with warmer summers increasing the annual production of living matter. Some plants bloom only in favorable years, such as fireweed in the Arctic tundra.

Biomass in the Arctic tundra varies widely—from 0.40 to 3.00 t/ha, most of it concentrated in the roots (70–80 %). In shrub tundra these values can be much higher. Plants grow slowly: lichens for the year increase by 1–10 mm, the juniper on the Kola Peninsula with a trunk diameter of 83 mm has 544 annual rings. However, it affects not only the adverse influence of low temperatures, but also the poverty of the environmental nutrients. The annual increase is 1.0 t/ha for the Arctic tundra and 25—for shrub one.

Due to the low temperature decomposition of remains of organisms in the tundra is slow, many groups of microorganisms do not function or work very poorly (bacteria that break down cellulose, etc.). This leads to the accumulation of organic matter on the surface and in the soil. In the litter accumulates 2.5—83.5 t/ha with an annual litter fall of $n \times 10^{-1}$–5.0 t/ha. The value of the ratio of the total mass of the annual litter fall, which characterize the intensity of decomposition of plant residues (innerecosystem biological cycle, C_b) ranges from 100 to 17. This contributes to the accumulation of organic matter in the upper layers of the soil profile.

2.2 *Biogeochemical Cycling*

2.2.1 Arctic Ecosystems

Depending on the absorption of macro- and microelements by the plants the involvement of these chemical elements in biogeochemical cycling is in different ways. The ratio of the concentration of elements in plants to their concentration in water extracts from soil-forming rocks (the value of the coefficient B_x by Kasimov 1995), shows that in the Arctic ecosystems iron and manganese to the greatest extent are absorbed by plants. The coefficient of biological absorption, A_x (Perelman and Kasimov 1999) can serve as an indicator of this absorption. The magnitude of A_x for Fe and Mn are in the range from $n \times 10^2$–$n \times 10^3$, whereas for Zn, Cu and Ni, these values equal approximately to $n \times 10^1$. It should be emphasized that high concentrations of iron and manganese are usually determined in dead organic matter (mortmass) of peat bogs (Perelman and Kasimov 1999).

The removal of elements from soil solution by plant uptake, leaching and remobilization in the composition of soil organic matter is balanced by a new entry of chemicals that support the permanence of biological and biogeochemical cycle. The main inputs of chemical elements in Arctic ecosystems is due to the marine aerosols deposited on the surface of the soil and weathering of rocks. For example, on the island of Spitsbergen atmospheric inputs of various elements are characterized by the following values (Table 1).

You can compare these values with the flows of the considered metals in biogeochemical cycles. Biological productivity of the Arctic ecosystem, developing on low terraces of the Spitsbergen Island, is shown in Table 2.

Table 1 Air intake elements in the ecosystem of the island of Spitsbergen, mg/year for 100 mm of precipitation (Dobrovolsky 1994)

Element	Fe	Mn	Zn	Cu	Ni
Input	27,500	800	31,100	900	300

Table 2 Biological productivity of the Arctic ecosystems of the Spitsbergen island (Manakov 1972)

Productivity	ton/ha
Total biomass of living plants	2.9
Total mortmass	9.6
Net annual production	0.6

It can be noted for comparison that the annual increase in the biomass of polar willow (Salex arctica) on the Islands of the Canadian archipelago, located at 75°N, is about of 0.03 t/ha (Warren 1957).

Biogeochemical flows of chemical elements in Arctic ecosystems are given in Table 3. For iron and manganese they are much higher than their inflow with atmospheric precipitation. At the same time, the supply of copper balances its annual consumption, and for zinc is even in excess. All these metals are essential elements and their flow from rainfall can be considered as a positive factor for the functioning of polar ecosystems. Excessive intake of lead, for which an unspecified physiological and biochemical functions, can be considered as pollution. However, a significant amount of lead can be quickly immobilized in the composition of dead organic matter and derived from the biogeochemical cycle.

For subordinate landscapes the input of the nutrient elements is due to the lateral inflows from surface and subsurface runoff. Ecosystems of marshy glacial valleys can get significant amounts of additional nutrients from overlying geochemically subordinate landscapes. This increases the productivity of the respective wetland ecosystems in 3–4 times in comparison with the eluvial landscape ecosystems, and the consequent biogeochemical fluxes of elements. For example, accumulation of elements in dead peat organic matter of waterlogged valleys was estimated as the follows: Fe, $n \times 10^{1}$ kg/ha, Mn, 1–2 kg/ha, Zn, 0.1–0.3 kg/ha, Cu, Pb and Ni, $n \times 10^{-2}$ kg/ha.

2.2.2 Biogeochemical Cycling in Tundra Ecosystems

Tundra landscapes and associated ecosystems occupy the northern strips of the Eurasian and North American continents bordering the Arctic seas. The climatic conditions of the tundra will allow ecosystems to achieve higher productivity. In

Table 3 Biogeochemical flows of chemical elements in ecosystems of the Spitsbergen island (Dobrovolsky 2003)

Metals	Mean plant content, ppm on dry mass	Metal fluxes, g/ha/year			Precipitation input[a], g/ha/year
		In living plants	In mortmass	In annual plant increase	
Fe	2000.0	5800.0	19,200.0	1200.0	82.5–110.0
Mn	150.0	435.0	1440.0	90.0	2.4–3.2
Zn	60.0	174.0	576.0	36.0	93.3–124.4
Cu	6.3	18.3	60.5	3.8	5.1–6.8
Ni	4.3	12.5	41.5	2.6	0.9–1.2
Pb	3.7	10.7	35.5	2.2	2.7–3.6
Co	1.0	2.9	9.6	0.6	0.9–12

[a]Note: Admission with atmospheric deposition was calculated at 300 and 400 mm per year in accordance with annual precipitation on the island of Spitsbergen and the content of metals in sediments is shown in Table 1

Table 4 The partition of biomass in tundra ecosystems, t/ha (Rodin and Bazilevich 1965)

Biomass type	Living plant biomass	Mortmass	Net annual production	Annual litter fall
Mass	28	83	20.4	20.3

tundra ecosystems the higher activity of biogeochemical cycles of various elements is observed as compared with the Arctic ecosystems. The mosses, lichens and herbaceous plant species are predominant in the northern part of the tundra, and shrubs—in the southern part.

The biomass of tundra ecosystems varies from 4–7 t/ha for moss-lichen tundra to 28–29 t/ha of dry weight in shrub tundra. In the northern tundra, the ratio of live and dead biomass approximately equal to 1:1, and to the south, living biomass is smaller than dead plant remains mass. The average values of the organic matter distribution in tundra ecosystems are shown in Table 4.

Edaphic microflora is more diverse in tundra ecosystems, and the number of microbial cenosis is characterized by higher values than in the soils of arctic ecosystems. The number of bacteria varies from 0.5×10^6 to 3.5×10^6 cells per gram in the upper soil layers.

The content of ash elements and nitrogen is characterized by similar values in the biomass of tundra ecosystems. The highest concentrations, >0.1 % of dry weight, are typical for Ca, K, Mg, P and Si. It is possible to note an increased content of iron, aluminum and silicon in the aboveground parts of plants (Vasilevskaya 1996, 1998).

Tundra ecosystems are formed on different soils. In conditions of well-drained slopes and watershed surfaces brown acidic tundra soils are formed. Characteristic features of these soils are the accumulation of undecomposed plant residues and the formation of the peat horizons. The underlying soil layers are poorly differentiated. The humus content in the thin humus horizon varies from 1 % to 2.5 % with a predominance of soluble fulvic acids. This determines the acidic reaction of soil, pH < 5.0. Acidic geochemical conditions favor the migration of many metals, phosphorus, nitrogen and several alkaline-earth elements. Migration of chemical elements mainly occurs in the form of the Me-organic or P-organic complexes.

In low relief with poor permeability of soil and grounds there is often a shortage of oxygen, which leads to the formation of tundra gley soils (*Gelic Regosol*). Gley horizon of these soils enriched (in order) by inclusions of precipitated gels of oxides of trivalent iron.

Biogeochemical cycle of nitrogen is about 50 kg/ha/year. Similar values are shown for the amounts of mineral elements, 47 kg/ha/year. The corresponding values of various macro- and micronutrients are given in Table 5. The fluxes of chemical elements per area unit in tundra ecosystems are not proportional to the uptake by plants. Some elements such as Zn and Cu, are selectively absorbed, other elements, Ti, Zr, V or Y, are adsorbed passively, depending on their concentration in soils.

Where soluble mineral compounds come to the landscapes from the outside, biogeochemical cycling increases, the vegetation becomes more luxuriant, the role of flowering plants increases and the role of mosses and lichens is reduced. Such conditions are created in the floodplains of some rivers, enriching in a flood period

Table 5 Annual biogeochemical fluxes of chemical elements in dwarf shrub-moss tundra ecosystem (Dobrovolsky 1994)

Element	Symbol	Plant uptake fluxes, kg/ha/year
Nitrogen	N	50
Iron	Fe	0.188
Manganese	Mn	0.226
Titanium	Ti	0.031
Zinc	Zn	0.028
Copper	Cu	0.0071
Zirconium	Zr	0.0070
Nickel	Ni	0.00188
Chromium	Cr	0.00165
Vanadium	V	0.00141
Lead	Pb	0.00116
Yttrium	Y	0.00070
Cobalt	Co	0.00047
Molybdenum	Mo	0.00043
Tin	Sn	0.00024
Gallium	Ga	0.00005
Cadmium	Cd	0.00003
Mean plant ash content, %		2.0
Total ash elements uptake by plants, kg/ha/year		47

by fertile silt, on the rookeries, at space camps, on the flat bottoms of lakes around the Arctic foxes' holes, etc. In some tundra ecosystems the high thickets of flood-plain grass create the impression of the more southern areas. Tundra wet meadows also have a high grass, they are characterized by an abundance of grasses, the presence of legumes that are missing in the offline landscape. Respectively meadow tundra ecosystems also develop along streams and rivers at the bottom of former lakes, pipelines, etc.

In Kamchatka peninsula the dense grass cover is characteristic for the tundra ecosystems, which periodically covered by volcanic ash. Therefore, climate is not the direct cause of the wide development of mosses and lichens in acidic gley southern tundra—the main reason is owing to the low content of nutrients in the soil and low speeds of depressive biogeochemical cycle.

2.3 *Biogeochemical Regionalization of Polar Ecosystems*

Depending on climate, geological bedrock, soil and vegetation cover, hydrology, and topography, the global ecosystem is divided into various ecoregions and ecozones (see for example, Bailey 1998). Within of these structural units of the biosphere, the spatial organization of the global ecosystem is manifested in the form of characteristic features of the biogeochemical cycles of different elements. This equally applies to the ecosystems.

2.3.1 Parameterization of the Biogeochemical Cycle

Biogeochemical cycles in different ecosystems are largely determined by the biota, especially the processes of primary productivity and decomposition of dead organic matter. Biogeochemical cycles represent the cumulative display settings of the circulation of substances between the various components of the biosphere—soils, surface and ground waters, sediments, biota and the atmosphere (Fig. 1).

Soil, geobotanical, geological, and overall ecosystem regionalization is the basis of biogeochemical zoning (Fortescue 1980; Glazovskaya 1997, 2002; Bazilevich 1993; Ermakov 1993; Bashkin and Bailey 1995; Bashkin and Kozlov 1999; Perelman and Kasimov 1999; Bashkin 2002, 2004, 2006, 2008, 2009; Kasimov and Klige 2006). The combination of these types of regionalization with quantitative indicators of biological, geochemical and hydrochemical cycle allows us to calculate the velocity of the biogeochemical cycle. It is shown that in the most parts of the Earth's surface the actual length of the various processes that determine the circulation of chemical elements (chemical, biological, microbiological, geochemical, and biogeochemical processes) depends on the duration of the winter period, when the intensity of these processes is significantly reduced or completely suspended within 6–10 months. It is also known that the effect of any pollutants on these processes occurs only during the spring and summer time. The duration of this impact can be characterized by the active temperature factor, C_t, which is the ratio of the sum of active temperatures >5 °C to the total amount of annual temperatures.

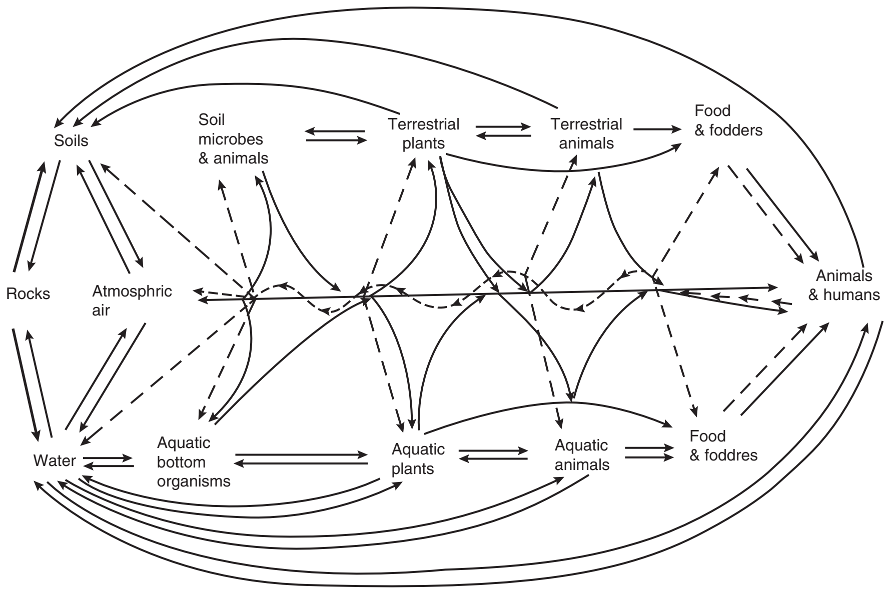

Fig. 1 The general scheme of biogeochemical food webs in terrestrial ecosystems

For the influence of temperature on the processes of biological absorption of elements is proposed using the coefficient of biogeochemical cycles, C_x, which is calculated as the product of the coefficient of inner ecosystem biological cycle, C_b, which is equal to the ratio of litter mass to the mass of annual litter fall and the rate of active temperatures:

$$C_x = C_b \times C_t.$$

Its use allows taking into account the influence of the period of active temperatures on the rate of biogeochemical cycles in different ecosystems. The coefficient of biogeochemical cycling can be used for correction of the values of inner ecosystem biological cycle, C_b.

Table 6 shows the combination of soil temperature and biogeochemical conditions in various polar and tundra geographic regions of the Earth. It is represented ecosystem types, soil types according to the classification of FAO, the coefficients of inner ecosystem biological cycle, C_b, active temperature, C_t, and biogeochemical cycles, C_x.

To understand these approaches it is necessary to pay attention to the principles of the global regionalization of the parameters used.

The coefficients of active temperatures, ranked in accordance with the main climatic zones are shown in Table 7.

The coefficients of biogeochemical cycles, C_x, for all geographic regions were ranked to determine the type of biogeochemical cycle and these grades are

Table 6 The coefficients of inner ecosystem biological cycle (C_b), active temperatures (C_t) and biogeochemical cycles (C_x) in different soil-ecosystem and geographical regions of the Earth

			Index	No			
Ecosystems	FAO main soil types	Geographic regions (Glazovskaya 1978)	See Glazovskaya 1984		C_b	C_t	C_x
Primitive Arctic desert and tundra	Litosols, Regosols	North American	1_1	1	75.0	0.07	5.3
		Eurasian	1_2	2	75.0	0.07	5.3
Tundra	Cryic Gleysols, Histosols, Humic Podzols	North American	2_1	3	18.0	0.15	2.7
		Eurasian	2_2	4	18.0	0.15	2.7

Table 7 Ranking of indicators of a temperature mode to assess the duration of biogeochemical reactions

Rank	Temperature regime	Coefficient of active temperature, C_t
1	Arctic	<0.25
2	Boreal	0.26–0.50
3	Sub-Boreal	0.51–0.80
4	Mediterranean	0.81–0.99
5	Subtropical and Tropical	1.00

Table 8 Ranking of indicators of the biogeochemical cycle to estimate rates of migration in different ecosystems (Bashkin 2002)

Rank	Biogeochemical cycling	Coefficient of biogeochemical cycling, C_x
1	Very intensive	<0.4
2	Intensive	0.5–1.4
3	Moderate	1.5–2.5
4	Depressive	2.6–4.9
5	Very depressive	>5.0

shown in Table 8. Five types of biogeochemical cycle are selected: very intensive, intensive, moderate, depressed, and very depressed.

Intensive and very intensive type of biogeochemical cycle occurs in tropical and desert ecosystems where rapid biological turnover under conditions of high temperature of the growing season. The moderate type of circulation is typical for steppe, forest-steppe and sub-boreal forest ecosystems, whereas in the boreal taiga forests the depressive type of biogeochemical cycle is dominated. Very depressive type is in tundra and arctic ecosystems.

Using the above described approaches, let us to consider arctic and tundra ecosystems on different continents.

2.3.2 Regionalization of the Biogeochemical Cycle

Eurasia

On the vast territory of Eurasia in all climatic zones are all types of ecosystems, from Arctic deserts to tropical rain forests (Fig. 2).

Primitive Arctic desert and tundra ecosystems are found in the Eurasian geographical region, which occupies the most Northern part of the Asian Arctic and includes the northern large island of the North Land and a number of small neighboring islands. Biogeochemical cycle in these ecosystems is characterized by Arctic hydrothermal regime, including very low temperatures, little annual rainfall (50–150 mm) and primitive shrub, algae and lichen vegetation. Biogeochemical cycling can be defined as very depressed, which includes a long period of mineralization of organic residues (from 10 to 50 years or more), and a short relative period of annual active temperatures >5 °C (C_t is equal to 0.05–0.10). The predominant soils are *Regosols* and *Litosols*, in the crevices, Histosols.

Tundra ecosystems are widespread in the Eurasian geographical region on gley and podzolic soils (*Podzols Distric*, *Cryic Gleysols*, *Histosols*, *Regosols and Litosols*). Biogeochemical processes in these soils are characterized with low quantity of heat, short but intense period of active temperatures (the average value C_t is equal to 0.15), wide distribution of permafrost and a small amount of precipitation, low biological and microbiological activity and low rate of chemical weathering.

The average value of C_b is equal to 18 (15–50), in combination with low annual mean temperature it leads to a very depressive type of biogeochemical cycle. However, the prolonged winter period contributes to the accumulation of various pollutants in the snow cover with their explosive impact on the ecosystem during the spring-summer period.

North America

In the North, in the Arctic and the subarctic zones, the annual radiation balance is 0–10 kcal/cm^2 (Glazovskaya 1978; Bailey 1998; Bashkin 2002).

Tundra ecosystems (North American tundra geographic region) cover the northern coast of the continent and adjacent islands of the American archipelago (Fig. 2).

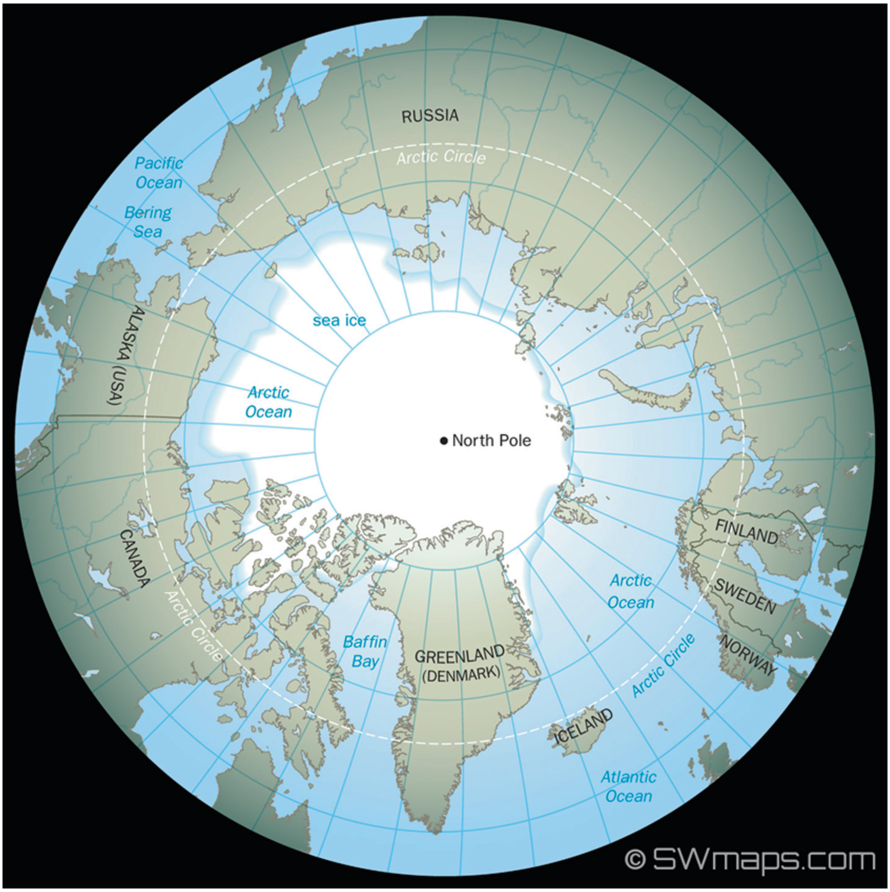

Fig. 2 Northern polar region of Earth (SWmaps.com)

In the North this region is bordered by the Arctic deserts and in the South—boreal taiga forests ecosystems. As in Eurasia, the southern boundary of tundra ecosystems varies with the height above the sea level. On the Labrador peninsula, washed by cold currents, and on the coast of cold Hudson Bay, tundra ecosystems penetrate as far South as 54°N. To the West of Hudson Bay, with an increase in the continentality of climate, the boundary between tundra and boreal taiga forest ecosystem is shifted to the North. On the Meridian of the Great lakes it lies slightly North of the Arctic circle, near the estuary of the Mackenzie river, the boundary extends a maximum North—to 68.5°N. The Northern part of Alaska is occupied by tundra ecosystems, and along the coast of the Chukchi Sea the border of the tundra shifts back to the South. Biogeochemical cycling in these tundra ecosystems is similar to those described for the Eurasian continent (see Table 6).

3 Conclusions

Thus, the natural biogeochemical cycling is described for understanding the natural parameters in polar and tundra ecosystems. The review of literature and new data allow us to show the approaches to biogeochemical cycling ranking in severe climate conditions based on active temperature coefficients. Finally, the given data base is a key for managing environmental pollution in gas industry impacted ecosystems on a basis of their biogeochemical ranking and biogeochemical regionalization.

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