CHAPTER 6

ARCTIC AND TUNDRA CLIMATIC ZONE

1. GEOGRAPHICAL PECULIARITIES OF BIOGEOCHEMICAL CYCLING AND POLLUTANT EXPOSURE

In the Northern Hemisphere the area of arctic and tundra landscapes with plant species' ecosystems is 3,756,000 km^2. In the Southern Hemisphere similar landscapes are completely absent. Most of these landscapes occur in northern Eurasia (Russia, Fennoscandia), Greenland, Alaska, and Canada.

The climate conditions of Arctic and Tundra ecosystems are the main factor influencing many peculiarities of biogeochemical cycling. Because of the severity of the climate the vegetation season is very short. During the arctic summer the temporary melted soil layer is less than 40–45 cm and the deeper layers of ground are permanently frozen. These permanently frozen grounds are called permafrost. The existence of permafrost mainly determines the qualitative and quantitative parameterization of biogeochemical cycles of all elements. We can say that the biological and biogeochemical cycles are restricted both temporally and spatially in Arctic ecosystems.

The major restricting factor is the ocean. Both continental coastal areas and areas of islands are exposed to cold oceanic currents. The Arctic oceanic basin is separated from the warm influence of the currents from the Atlantic and Pacific Oceans owing to the existence of both narrow channels like the Bering Strait and submarine ranges. The average precipitation is from 100–200 mm (North American areas) to 400 mm (Spitzbergen Island) and the average temperature of January is between -30 °C and -38 °C (Figure 1).

The low precipitation and freezing water stage during 10–11 months per annum have led to the development of arid polar and tundra landscapes. The characteristic features of these landscapes are the alkaline soil reaction (pH 7.5–8.0) and even the occurrence of modern carbonate formations.

1.1. Landscape and Vegetation Impacts

In accordance with the local maximum of precipitation and the relative low winter temperatures, the most favorable climate conditions for biogeochemical processes and pollutant exposure are in the western part of Spitzbergen Island. Three types of landscapes with corresponding ecosystems are widespread (Dobrovolsky, 1994).

On the wide shore terraces of fjords and on the slopes of hills and low mountains, the Arctic Tundra ecosystems occur. The mosses and lichens are predominant with

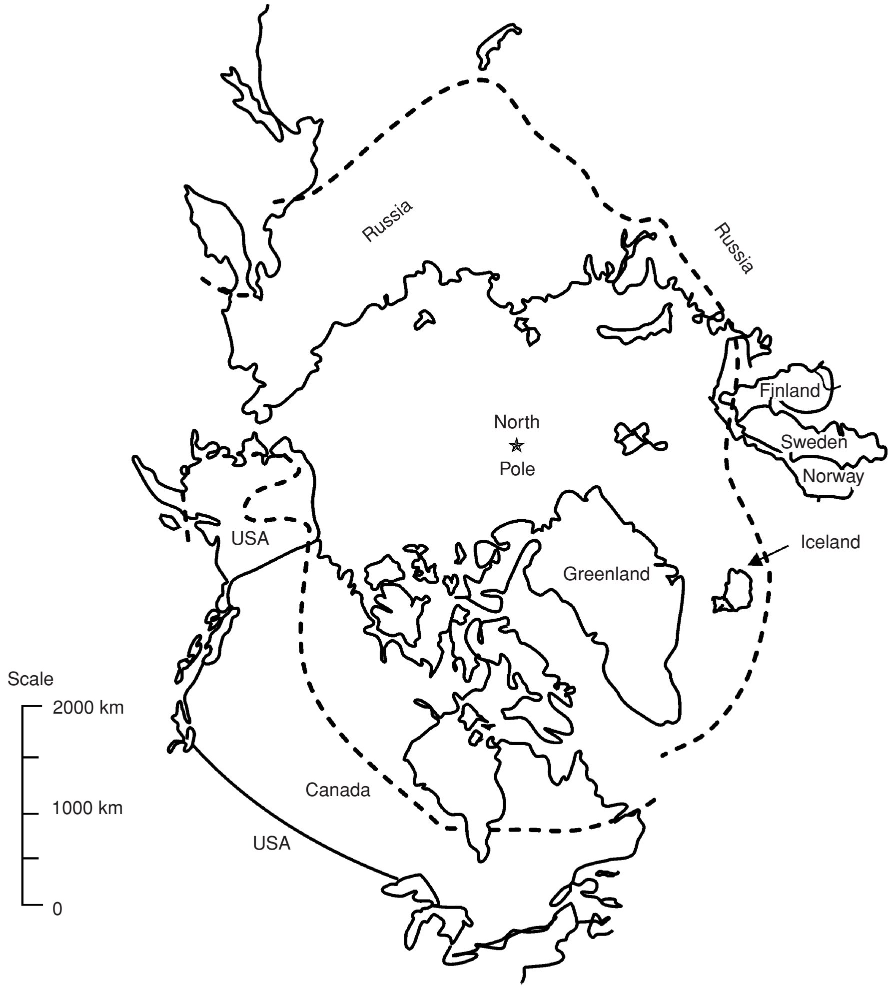

Figure 1. Polar and Tundra ecosystem area in the Northern Hemisphere.

the twigs of willow (*Salix polaris*), varieties of rockfoils (*Saxifraga oppositifoila, S. polaris, S. caespitosa*, etc.), dryad (*Dryas octopetala*), specimens of arctic poppies, buttercups, cinquefoils, various tufted rushes (*Juncus*) and grasses. In some areas the vegetation forms a continuous covering and in others it is confined to depressions enclosing cryogenic polygons. The plant mat covers the soil surface. Most soils are Brown Arctic Tundra soils having only A and C genetic horizons.

The vegetation becomes sparse at the high plateau over 400–500 m above sea level (a.s.l.). The surface coverage is mainly less than 10%. The short grown mosses are predominant. They occupy the depressions with shallow soil accumulation. Lichens

Table 1. Chemical composition of different plant species in Spitzbergen island ecosystems (after Dobrovolsky, 1994).

	Content, ppm by dry plant weight								
Plants	Ca	K	Na	Fe	Mn	Zn	Cu	Pb	Ni
Lichen	1,170	2,000	633	137	6.2	10.0	2.5	7.8	<1.5
Moss	758	2,170	867	1,240	13.9	8.3	5.2	5.8	1.7
Rockfoils	1,460	10,000	1,833	1,751	44.3	50.8	8.8	<1.5	2.6
Arctic willow	1,375	6,670	658	401	87.8	176.2	8.0	3.7	3.7
Cotton grass	683	20,000	442	Nil	Nil	90.0	7.3	2.5	2.5
Rush	400	667	2,000	1,380	286.0	63.5	5.8	1.5	4.3
Alpine sorrel	1,550	8,330	2,000	3,480	172.0	24.5	8.9	1.8	16.7
Heather	9,580	22,500	10,500	1,659	106.2	35.6	10.5	1.5	3.7
Laminaria	6,000	4,330	2,033	203	15.0	16.6	3.7	1.5	1.5

grow on mosses and large rock fragments. Only separate specimens of rushes and rockfoil occur. The soils are of the Arctic coarse skeleton type.

The rank *Hyphnum* and *Sphagnum* mosses are mainly represented on the flat variously waterlogged bottoms of glacial valleys. Cassiopes (*Cassiope tetragona*), tufted grasses and rushes grow in the relatively dry sites of these valleys. The given conditions favor peat formation; however, the permafrost layer restricted this process and the peat layer is mainly less than 40 cm. The small thermokarts lakes place in the wide valley and they are bordered by sedges (*Carex nordina, C. rupestis*), cottongrass (*Eriophorum*) and nappy plant species.

The ash of peat forming plant species contains a predominant amount of silicon. This element is particularly abundant in the *Sphagnum,* where its content achieves 36% by ash weight. Iron and aluminum are the next abundant. The first is accumulated during the peat formation process. The accumulation of calcium and potash is more pronounced than sodium, and the sulfur content is also remarkable. A large amount of mechanically admixed mineral particles (40–80% by ash weight) is found in mosses. This is due to the deposition of fine dispersed mineral material from snowmelting waters and atmosphere dust deposition (Table 1).

1.2. Pollutant Exposure and Chemical Composition of Plants

Let us consider the influence of various exposure factors on the chemical composition of plant species in the arctic islands. It seems the most influential factor is the distance from the ocean shore. For example, in arctic willow growing a few meters from the tide line, the content of Zn, Cu, Pb, and Ni was higher than that of the same plant

Table 2. The trace element composition of the Spitzbergen snowmelting water, ppb (Evseyev, 1988).

Trace metal	Fe	Mn	Zn	Cu	Pb	Ni	Co
Content	27.5	0.80	31.1	1.7	0.9	0.3	0.3

species growing about 1 km from the coast line and sheltered from the sea by a morain hill. The coastal plants contain also more sea salt cations like Na, Ca, K, and Mg.

The enrichment effect of the ocean is mainly related to the chemical composition of aerosols, which determine the chemical composition of snow. For the northern areas of the Eurasian continent and the western areas of Spitzbergen Island we can estimate the average values of sea salt deposition in snow from 3,000 to 5,000 kg/km^2. The predominant chemical species in the snow water are chlorides (anions) and sodium and calcium (cations). The content of trace elements (heavy metals) is negligible. Their origin is connected with long-range trans-boundary air pollution from industrial centers of North America, Russia and Europe. This was shown for the Greenland glaciers, where the statistically significant growth of zinc and lead in the recent probes in a comparison with ancient ice cores has been attributed to the environmental pollution (Bashkin, 2002).

The role of air aerosols in the biogeochemical cycle of various nutrients in the Arctic ecosystems has been studied in Spitzbergen Island. The supply of oceanic aerosols is very important in these conditions since the interaction between plant roots and soil or mineral substrates is depressed during a long part of the year. According to the monitoring data the following results are typical for the Spitzbergen snow melting water (Table 2).

For a comparison, the mobile forms of trace metals were extracted from the local geological rocks, as water-soluble and 1.0 N HCl-soluble forms. The results are shown in Table 3.

We can see that the content of trace metals in water extraction is very low. This means that the direct involvement of these metals in biogeochemical cycles is very restricted. The significant increase of metal contents in acid-soluble form was shown only for Fe, Mn and, partly, for Zn. These data testify the importance of atmospheric deposition for the Arctic ecosystems as a source of nutrients.

The supply of sea salts and trace metals via precipitation appears to contribute to the elevated content of water-soluble forms of alkaline and earth–alkaline elements and trace metals in the uppermost soil layer.

1.3. Influence of Soil on Pollutants Exposure

A high amount of various nutrients and trace metals is retained in peat and dead plant residues and thus temporarily eliminated from the biogeochemical cycles and pollutants exposure to human and ecosystem health. The period of this elimination depends on the solubility of these metals. It has been shown (Dobrovolsky, 1994) that

Table 3. Content of mobile forms of trace elements in rocks of Spitzbergen Island, number of rocks = 10 (after Dobrovolsky, 1994).

	Trace metal content, ppb						
Statistics	Fe	Mn	Zn	Cu	Pb	Ni	Co
Extractant—water							
M	5.71	0.54	0.53	0.11	0.05	0.07	0.03
σ	4.64	0.28	0.21	0.08	0.02	0.08	0.03
V, %	81	52	40	73	40	107	100
Extractant—1.0 N HCl							
M	1,266.6	408.8	7.41	4.64	4.23	0.83	1.04
σ	949.3	148.0	2.40	2.46	2.23	1.07	0.45
V, %	75	36	32	53	53	129	43

the soluble forms of such metals as iron and zinc accounted for about 70% and 50% of the total contents of these metals in solution, correspondingly, in the upper peat layer with living plants. In the underlying peat layer, the percentage of soluble forms tended to decrease. A similar tendency was recorded for soluble forms of carbon: on leaching from upper to lower peat layer, the concentration of soluble form decreases twice as much in the terrace and still greater, in waterlogged depression.

Electrodialysis of the soluble forms of iron has revealed the predominance of electroneutral forms. A similar distribution has been shown for carbon. The hypothesis that the organic iron-containing complexes are responsible for water-soluble forms of iron in polar peat ecosystems seems logical. Amongst the soluble zinc forms, the percentage of electroneutral forms is somewhat lower that that of charged forms, with the anions present in a larger amount in the upper peat layer.

However, only the smallest part of soluble metals is involved in the biological cycle. Most of these are either lost to water runoff, or retained in the peat organic matter. The latter is the source of gradual remobilization but the whole mineralization may last up to 50 years or even more. The total accumulated retained amount of macro- or trace metals in organic matter of peat is tens and hundreds of time higher than the concentration of annually released soluble forms, which are available for plants.

2. BIOGEOCHEMICAL CYCLES AND EXPOSURE ASSESSMENT IN POLAR ZONES

2.1. Biogeochemical Cycles

The different metal uptake by plants is accompanied by a different involvement of these trace metals and macronutrients in the biogeochemical cycles. A comparison of

Table 4. Airborne input of various trace metals in the Spitzbergen island ecosystems, mg/yr per 100 mm of precipitation (after Dobrovolsky, 1994).

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

the metal concentrations in plant tissues and the metal concentrations in the aqueous extracts from soil-forming geological rocks shows that iron and manganese are the most actively absorbed by plants. The plant to soil metal ratio can be an indicator of this absorption. These values for Fe and Mn are in a range of $n \times 10^2$ to $n \times 10^3$. This ratio is about $n \times 10^1$ for Zn, Cu, and Ni. It is noteworthy that the high concentrations of iron and manganese tend to even increase in the dead organic matter of peat.

The systematic removal of elements by runoff and the reimmobilization from solution by organic matter are continuously counterbalanced by the new input of chemical species, which maintain both biological and biogeochemical cycles. The main sources of water-soluble elements are oceanic aerosols deposited on the land surface and the weathering of rocks. The airborne input of the trace metals may be ranked as follows for the Spitzbergen island ecosystems (Table 4).

We can compare these values with those characterizing the fluxes of trace metals in biogeochemical cycles. The biological productivity of the Polar Tundra ecosystem grown on the low terrace in the region of Barentsberg, Spitzbergen Island, is shown in Table 5.

To be noted for comparison, the annual growth increase for arctic willow (*Salex arctica*) in Cornwallis Island in the Canadian Arctic Archipelago, 75°N, is a mere 0.03 ton/ha (Warren, 1957). The corresponded trace metal fluxes are shown in Table 6.

2.2. Exposure to Airborne and Ground Pollutants

We can see that for iron and manganese the annual fluxes of trace metals are an order of magnitude higher than airborne input. For copper this input is sufficient to supply the annual uptake, and for zinc is even in excess. All these trace metals are essential elements and their input with deposition can be considered as positive for

Table 5. The biological productivity of the Polar Tundra Low Terrace ecosystem.

Productivity	Ton, ha
Total mass of living plants	2.9
Mass of dead plant matter	9.6
Annual net primary productivity	0.6

Table 6. Fluxes of trace metals in the Spitzbergen Island ecosystems (after Dobrovolsky, 1994).

Trace metal	Mean content in plant species, ppb by dry weight	Trace metal fluxes, g/ha/yr			Airborne input*, g/ha/yr
		In living plant organisms	In dead organic matter	In net annual production	
Fe	2,000.0	5,800.0	19,200.0	1,200.0	82.5–110.0
Mn	150.0	435.0	1,440.0	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

* The airborne input was calculated per 300 and 400 mm per year in accordance with annual precipitation rates in the western Spitzbergen coast and trace metal rates shown in Table 4.

the ecosystem's behavior. The excessive deposition input of lead is rather dangerous owing to the unknown physiological and biogeochemical role of this element in plant metabolism. However, the significant amounts of lead can be immobilized in dead organic matter and excluded from biological turnover.

The other output from watershed and slope landscapes positions is related to the surface and subsurface runoff of trace metals. The ecosystems of waterlogged glacial valleys, geochemically subordinate to the above mentioned landscape, can receive with surface runoff an additional amount of various chemical species. This results in 3–4-fold increase of plant productivity in comparison with elevated landscapes and in corresponding increase of all biogeochemical fluxes of elements, which are shown in Table 6. For instance, the accumulation of trace metals in dead peat organic matter of waterlogged valley was assessed as the follows: Fe, $n \times 10^1$ kg/ha, Mn, 1–2 kg/ha, Zn, 0.1–0.3 kg/ha, Cu, Pb, Ni, $n \times 10^{-2}$ kg/ha.

3. BIOGEOCHEMICAL CYCLES AND EXPOSURE ASSESSMENT IN TUNDRA ZONES

The tundra zone and corresponding tundra ecosystems occupy the northernmost strip of the continental area of Eurasia and North America bathed by the seas of the Arctic basin. The climate conditions of the tundra zone provide for a higher productivity of ecosystems and higher activity of biogeochemical cycles of various elements as compared with the Arctic ecosystems. The mosses, lichens, and herbaceous plant species are predominant in the northern part of the Tundra ecosystems and shrubs are prevalent in the southern part.

The edaphic microflora is diversified, and the microbial community is more numerous than that of the arctic soils. The bacterial population varies from 0.5×10^6 to 3.5×10^6 specimens per gram in topsoil horizon.

3.1. Plant Uptake of Pollutants

The ash contents of the total trace elements and nitrogen are similar in Tundra ecosystem biomass. The highest concentrations, >0.1% by dry ash weight, are typical for Ca, K, Mg, P, and Si. We can note the increase of iron, aluminum and silicon contents in the underground parts of any plants.

The uptake of trace metals depends on both from the plant species and metal. Such elements as titanium, zirconium, yttrium, and gallium are poorly absorbed owing to their minor physiological role in plant metabolism. Rockfoils (Genus *Saxifraga*) and mosses (genus *Bryophyta*) are especially sensitive to alternations of trace metal concentrations. The bryophytes are capable of sustaining higher concentrations of some trace metals as compared to vascular plants (Shacklette, 1962). Some species of mosses can accumulate enormous amounts of trace elements and can serve as indicators of copper metal ore deposits with elevated copper contents.

3.2. Tundra Soils and Exposure to Pollutants

The Acidic Brown Tundra soils (Distric Regosol) are formed under the conditions of the free drainage commonly encountered in slopes and the watershed relief positions. The characteristic features of these soils are related to the accumulation of non-decomposed plant residues and the built-up peat layers. Below the peat horizon the soil profile differentiation is indistinct. In the thin indistinct humus horizon underlying the peat layer, the humus content is from 1 to 2.5% with predominance of soluble fulvic acids. This presents an acid reaction of soils, with values of soil pH <5.0. The acid geochemical conditions facilitate the migration of many trace elements, phosphorus, nitrogen and many earth–alkaline metals. The migration of chemical species is mainly in the form of Me–organic or P–organic complexes. This facilitates the exposure of humans and ecosystems to different pollutants.

The deficiency of oxygen is very common in lowland plains with an impeded drainage. This is favorable to the formation of Gley Tundra soils (Gelic Regosol) with a grey gleyic horizon. This horizon includes the gray and rusty spot-like inclusions of precipitated gels of Fe^{3+} oxides. These oxides are the geochemical barriers in the pollutants biogeochemical cycles and they can retard significant amount of various chemical species.

3.3. Exposure to Pollutants and Productivity of Tundra Ecosystems

The biomass of Tundra ecosystems gradually increases from 4–7 ton/ha for moss–lichen tundra to 28–29 ton/ha by dry weight for low-bush tundra. In the northern tundra, the plant biomass and dead organic matter are eventually shared. Southwards this percentage tends to diminish, and low-bush living biomass is smaller than dead plant remains mass. A typical feature of the Tundra ecosystems plant species is the prevalence of underground matter (roots) up to 70–80% of the total biomass.

Table 7. The partition of Tundra ecosystem biomass, ton/ha (after Rodin and Bazilevich, 1976).

Biomass types	Plant living biomass	Dead organic matter	Annual net production	Annual litterfall
Mass	28	83	20.4	20.3

The average mass distribution of Tundra ecosystems is as shown in Table 7.

The biogeochemical turnover of nitrogen is about 50 kg/ha per year. A similar value was shown for the turnover of total mineral elements, 47 kg/ha/yr. The relevant values for various trace and macroelements are shown in Table 8.

Table 8. Annual fluxes of chemical species in the Low-Bush Moss Tundra ecosystem (after Dobrovolsky, 1994).

Chemical species	Chemical species symbol	Plant uptake fluxes, kg/ha/yr
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
Average ash content of plant species, %		2.0
Total uptake of ash elements by vegetation, kg/ha/yr		47

The flux of chemical elements per unit area in tundra ecosystems is not proportional to the plant uptake. Presumably, some elements, like Zn and Cu, are taken up selectively, whereas other trace elements, like Ti, Zr, V, or Y, are absorbed passively, depending on their content in the environmental media.

Finally, this determines the actual and potential exposure of living organisms to pollutants' impact.