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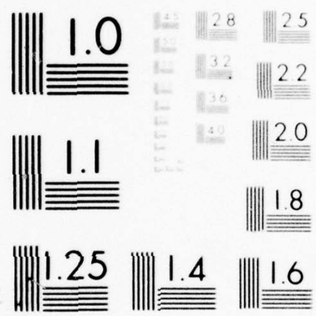

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NATIONAL BUREAU OF STANDARDS 1963

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November 1976

SENSITIVE SUBARCTIC

V.V. Kryuchkov

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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This book will acquaint the reader with the special features of nature in the Subarctic, a huge region occupying 20 percent of the Soviet Union's territory, where nature is extremely vulnerable and easily destroyed. Normal temperature variations in the Subarctic that would be almost unnoticeable in southern zones and areas lead to changes in relief and intensify ground creep on slopes. This book contains a large amount of factual material -- the result of more than 20 years of research in the Far North on the part of the author.

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[Book by Vasiliy Vasil'yevich Kryuchkov, USSR Academy of Sciences, Izdatel'stvo Nauka, signed to press 10 May 1976, 26,500 copies]

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[Text] **ANNOTATION**

This book will acquaint the reader with the special features of nature in the Subarctic, a huge region occupying 20 percent of the Soviet Union's territory, where nature is extremely vulnerable and easily destroyed. Normal temperature variations in the Subarctic that would be almost unnoticeable in southern zones and areas lead to changes in relief and intensify ground creep on slopes. This book contains a large amount of factual material -- the result of more than 20 years of research in the Far North on the part of the author.

INTRODUCTION

At the present time intensive development work is being done in the Far North -- primarily the Subarctic -- in connection with the large reserves of useful minerals (such as cupronickel ores, apatites, coal, tin, and so on) that are found there. The Far North's biological resources are also considerable: it yields about 45-50 percent of this country's furs and 30 percent of its fish (in inland, fresh-water bodies); it has about 2.5 million households and more than 600,000 wild deer, boars and waterfowl, berries and mushrooms. Nevertheless, the natural conditions of the continental Subarctic have been studied less than the natural conditions of marine water areas and the more southerly natural zones. We cannot even talk about the lag in the rates of development for regions in the Far North. There is an intolerable gap between the development rate and scientific research, which is the basis for substantiating any industrial and economic projects for exploiting resources and for predicting the consequences of development.

It is a well known fact that every period of interaction between society and the environment requires appropriate information about the latter. Right now we are feeling the inadequacy of our knowledge about nature in the Far North and the processes taking place in this region.

In recent years, during the industrial development of the Subarctic we have collided with the facts of the extraordinary vulnerability and instability of its natural territorial complexes. At the present time it has become known that in the track of a cross-country vehicle that has destroyed the vegetative cover, there can appear a thermokarst-erosion gully that then enlarges intensively not only during periods of rain, but also in dry, warm weather as the result of the thawing of subsurface ice.

At one time there were suggestions that at industrial points in the Far North (Monchegorsk, Kirovsk, Vorkuta, Noril'sk), some cooling occurs in connection with the unavoidable pollution of the atmosphere with dust. The actual picture proved to be somewhat more complicated. It was not possible to avoid pollution of the atmosphere, soil, and snow. However, the pollution caused not only a slight reduction in solar radiation (that insignificant because of the constant winds that cause renewal of the air masses), but also a change in the underlying surface's albedo, which in the final account resulted in warming of the industrial centers and a slight increase in the length of the snowfree period and growing seasons in comparison with the natural, unchanged territorial complexes -- the ecosystems.

In contrast to the more southerly zones, in the Subarctic we do not have centuries of experience in industrial development, and this also makes the exploitation of the Far North's natural resources more complicated.

During the development process the most severe changes are undergone by the soil mantle and vegetative cover, with particular emphasis on arboreal vegetation, which affects the condition and dynamics of the northern boundary of the forests -- one of the main natural borders on our planet. The northern forest boundary, which is a derivative of many natural (including anthropogenous) factors, is itself a large border that more or less refracts the component parts of nature (winds, snow redistribution, soil freezing, fauna, and so on), which in turn influences the economic activities of man.

The reasons for the lack of forests in the tundra zone and the dynamics of the northern forest boundary have only recently begun to interest a small number of specialists in the fields of botany and geography, and have not been taken into consideration in practice. Right now our knowledge of these questions is exerting an ever increasing influence on the economic activities of man. Here are just a few examples. Is the northern forest boundary advancing or retreating and, in connection with this, is the forest-covered area in the Far North expanding or contracting? Statements in the press on this problem are contradictory. Is it possible to plant varieties of trees and shrubs at populated points in the tundra zone? The role of such plantings in improving the microclimate, removing dust from the atmosphere, reducing noise, and so forth is commonly known.

Is it possible to create forest belts along roads in the tundra zone? On railways in the Vorkuta area forest belts are more effective than wooden screens in protecting the tracks from snow drifts. In the final account, forest belts are more economically profitable than wooden screens. The answers to these questions also depend on the level of our knowledge about the lack of forestation in the tundra zone and the processes taking place in it. Considering the increasing intensity of development of the Subarctic, including the tundra and forest-tundra zones, as well as the extraordinary vulnerability and instability of this region's ecosystems, with the passage of time it will be more and more difficult to analyze the problem of the tundra zone's lack of forestation. For example, because of the plowing up of the steppes and forest-steppes, the reasons for the lack of forestation of the steppes and the interrelationships of forest and steppe vegetation are not clear and, apparently, never will be.

Substantial contributions to the study of the North were made by such Russian scientists as N.Ya. Ozeretskovskiy and V.F. Zuyev, who visited the northern part of our country in the second half of the 18th Century; A. Shrenk, who traveled in 1837 through the northeastern part of European Russia; A.F. Mindenford, who explored northern and eastern Siberia in 1842-1845; G.I. Tanfil'yev, who studied a large area from Mezenskaya Bay to the lower reaches of the Pechora River in 1892. Many other investigators also occupied themselves with the study of the North. Although these were but brief visits, frequently made without adequate supplies, they yielded new material about the mysterious North and half-lifted the veil of secrecy. One pioneer in the mastery of the North was A.V. Zhuravskiy, who raised the question of settling the North and creating seeded meadows and forest plantations in the tundra even before the Great October Socialist Revolution.

Academician A.A. Grigor'yev (1883-1968) made a great contribution to the study of nature in the Subarctic. His book "The Subarctic" appeared in 1946, was reissued in 1956, and in 1970 was published in "Collected Theoretical Works." This work correlates not only the original research of A.A. Grigor'yev, but also the large amount of materials accumulated up until that time. Grigor'yev pointed out the basic regularities of the Subarctic on the example of the Eastern European Subarctic, which he regarded as typical for the Subarctic of all Eurasia.

B.N. Gorodkov (1890-1953) devoted his entire life to investigating the Far North. He formulated the beginning of the fractional division of the taiga on a zonal basis that is now generally accepted. Gorodkov was very concerned with questions of the dynamics of the Far North's vegetation. He introduced the concept "polar desert" as a vegetation type.

In 1927, M.I. Sumgin (1873-1942) -- one of the founders of geocryology -- published the first complete report on "Perpetually Frozen Ground in the USSR."

Most Soviet scientists who are engaged in studying the Subarctic were pupils of these great investigators and are continuing their work.

At the present time, we are obtaining ever more evidence of the instability and extraordinary vulnerability of nature in the Subarctic. This applies to both its separate components (permanently frozen ground, soils, vegetation, fauna) and it natural complexes as a whole (that is, the ecosystems).

In 1970, USSR Academy of Sciences' Corresponding Member P.F. Shvetsov wrote: "On the tundra there is nothing that resembles the preconceived notion that in the Far North everything is covered with permanent frost from the time of the Ice Age, while the topography is fixed and changes only over the course of geological periods. As a matter of fact, in the industrially developed regions of the Subarctic man changed nature not in millennia, but in 30 years. In order to convince oneself of this, it is sufficient to compare the contemporary relief, the depth of occurrence and brokenness of the permafrost layer, and the vegetative cover in the vicinities of Vorkuta and Noril'sk with those that were recorded in 1937."[1]

In the Subarctic, small temperature deviations result in considerably more serious consequences than in any other part of the globe. The Subarctic has a special rhythm and regime of natural processes distinct from those seen under the conditions in the middle latitudes. This special character means that nature in the Subarctic is highly vulnerable and unstable, responsive and delicate. In telling about these special features of the Subarctic the author remembered that one picture is worth a thousand word, so in this book the text is accompanied by many photographs and figures.

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[1]Shvetsov, P.F., "Toward a Plan of Research in the Subarctic for the Development of Scientific Principles for Transforming It and Predicting Changes in Its Nature," IZV. VGO [Bulletin of the All-Union Geographic Society], No 5, 1970, 419.

WHAT IS THE SUBARCTIC?

Special Features of Light Conditions and Climate

Because of its high-latitude location, the Far North inherently has different lengths of night and day at different times of the year (Figure 1); this means that insolation[1] is not uniform in this area. The amplitude of the annual pattern of this inequality increases, as is well known, as the geographical latitude does. In one band, there is a continuous day lasting for half a year, from the spring to the fall equinoxes. The night lasts for approximately the same amount of time. The number of days when the sun does not set during the summer decreases toward the south, and at the latitude of the Arctic Circle there is theoretically only one day (the day of the summer solstice) when the sun does not go below the horizon.

Because of the lengthening of the day, the total possible radiation in high latitudes during the summer period exceeds the total radiation in low latitudes. However, because of the high reflective capacity of the ice cover's surface and great cloudiness, the amount of absorbed radiation turns out to be comparatively small.

The absorbed radiation is considerably less than the total possible radiation that could be absorbed under a cloudless sky. The amount of it depends on the albedo (the reflecting capacity of the underlying surface), as a result of which it changes during the year and from place to place, depending on the state of the surface. For instance, on Dikson Island the absorbed radiation is 33.4 kcal/cm^2 per year, while in Salekhard it is 45.6 kcal/cm^2 per year. There is snow on the ground in the Far North from October to June; that is, the underlying surface

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[1]Insolation is the influx of solar radiation onto the surface in the form of direct, reflected, and scattered rays.

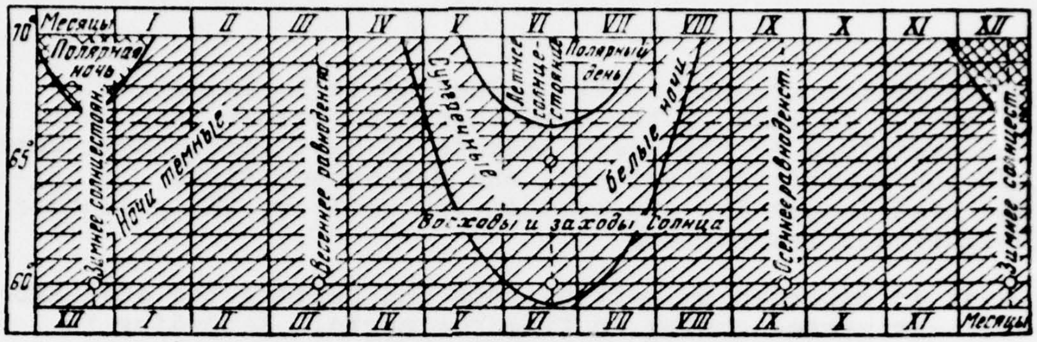

Figure 1. Periods of solar illumination in the Far North (59-70° N. Lat.).

Key:

1. Months
2. Polar night
3. Winter solstice
4. Dark nights
5. Spring equinox
6. Polar day
7. Summer solstice
8. Twilight and white nights
9. Sunrises and sunsets
10. Fall equinox

has the same properties for the greater part of the year. During this time, less than 25-30 percent of the total incoming radiation is absorbed. The disappearance of the snow lowers the albedo. The next significant variable is the radiation balance, the calculation of which takes into consideration not only the losses of reflected short-wave radiation, but also the output of radiated heat as the result of effective radiation, which depends on the temperature, absolute humidity of the air, and carbon dioxide content. Cold air masses contain less water vapor, which increases effective radiation. The reduced carbon dioxide content in Arctic air masses during the summer months[1] also contributes to an increase in effective radiation. In the Arctic and Subarctic, the annual effective radiation totals are 26-40 kcal/cm^2.

The radiation balance expresses those reserves of solar energy that are expended on evaporation and heating the Earth's surface and the air. The more heat consumed for evaporation, the less there remains to heat the ground and air. In the Arctic and Subarctic, heat expended on evaporation is the main item of consumption, and exceeds the magnitude of the heat exchange between ground and air. In June in the Far North, the magnitude

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[1]The reduced CO_2 content is explained by the fact that in Arctic waters during the summer, with 24-hour illumination, phytoplankton that assimilate carbon dioxide grow rapidly and abundantly. Therefore, air masses arriving from the Arctic in the summer contain about 0.016 percent CO_2 instead of the usual 0.03 percent [5].

of the radiation balance is twice what it is in August, although in all regions of the area August is warmer than June. This is explained by the great amounts of heat consumed in June to heat the excessively wet soil and for evaporation. In August the heat losses for evaporation are smaller, which results in a higher air temperature.

Much heat is expended on melting snow and heating the soil and the cold air masses coming in from the north. According to calculations made by Academician A.A. Grigor'yev, the following amount of heat is expended for melting snow. When the snow is 70 cm thick and its density is 0.35 per 1 cm^2 of surface, 24.5 g of water is generated; when it is 60 and 40 cm thick, 21 and 14 g, respectively, are produced. In the first case, 1,960 cal are required to melt the snow, in the second -- 1,680, and in the third -- 1,120; that is, the melting of the snow cover, which takes place primarily in May, requires more than half of this month's radiation energy base (the radiation balance for May is 1.0-3.5 $kcal/cm^2$). Therefore, the average monthly temperatures for May are negative, even in the southern regions of the Subarctic. In June, July, and August much heat is expended for the thawing and heating of the soil. Grigor'yev's calculations (1970) show that if the moisture (ice) content in the soil is 0.3 g per 1 cm^3 of soil (that is, 30 g for a 1-meter column of soil with a cross-section of 1 cm^3) and the latent heat of fusion of 1 g of ice is 80 cal, then the thawing of soil to depths of 0.5, 1.0, and 1.5 m requires 1,200, 2,400, and 3,600 cal, respectively. According to the calculations presented by M.I. Budyko in [4], 4.5 $kcal/cm^2$ are consumed for thawing and heating soil in the Subarctic, while 9 kcal are expended on evaporation.

It is for just this reason that summer temperatures in the North are quite low: even in the southern regions of the Subarctic, the average temperature in July is 11.5-12.0° at Magadan and 12-13° at Salekhard. The negative or low winter radiation balance values cause the low negative temperatures in the Arctic and Subarctic.

A small amount of precipitation -- from 200 to 500 mm -- falls in the Far North; in the Kola sector of the Subarctic the figure is a little higher. Winter evaporation is very low -- much less than the amount of precipitation. During the period of positive temperatures, again more precipitation falls than evaporates, except for a number of regions in the Eastern Siberia sector. In the Western European part of the North, the excess of atmospheric precipitation over evaporation is, according to Grigor'yev's data, approximately equal to a 70-mm layer of water in the southern Subarctic and up to a 120-mm layer near its northern boundaries. Frozen soils act as a water-resistant horizon that does not transmit moisture and increases bog formation. Frozen soils usually contain ice. When soils thaw to a depth of 1 m and when they contain moisture in the form of ice that totals 0.3 g/cm^3, 30 cm^3 of liquid moisture forms per square centimeter of thawed soil; that is, almost twice as much as the amount of atmospheric precipitation that falls during the warm period. Thus, waterlogging and swampiness of the ground in connection with a short and cold summer during which little moisture evaporates is a resultant special feature of the Subarctic.

The heavy excess of precipitation over evaporation in the Subarctic causes not only abundant swampiness, but also a great number of lakes and high summer water levels in the rivers. The area occupied by lakes in the Subarctic zones -- tundra, forest tundra, northern taiga -- is the highest when compared to other zones. The total annual runoff of the Subarctic's rivers is also the highest: 140-400 mm, which even reaches 600 mm in the Kola sector. In the southern part of the taiga, the runoff totals 100-200 mm.

The low temperatures in the Subarctic cause there to be little moisture in the atmosphere -- 1-3 g/m^3, on the average. Water vapor, as is the case with any gas, possesses elasticity (pressure), which can be expressed in millimeters of mercury or millibars. The absolute winter air humidity in the Subarctic is 0.7-1.5 mb, while in the summer (July and August) it is 8-13 mb. The relative air humidity expresses the ratio of the actual water vapor pressure in the atmosphere to the saturated water vapor pressure at the same temperature, and is given as a percentage. As a result of the low temperatures, it is high -- 65-95 percent -- in the Subarctic at all times of the year.

The Arctic Ocean's "breathing," especially during the summer when winds blow from the cold expanses of the Arctic onto the heated and moisturized continent, causes moisture condensation and the formation of fogs and freezing rains. This happens frequently, so that freezing rains and fog are common in the Subarctic summer. However, torrential rains and thunderstorms rarely occur in the Subarctic.

The Subarctic is a region with the greatest daily and annual temperature ranges (daily -- up to 15-20°, annual -- up to 60-70°) and the most abrupt weather changes. When there is a north wind from the Arctic Ocean, a clear sunny day with a temperature of 18-20° can change in an hour to rainy and windy weather with a temperature close to zero.

Now, a few words about climatic fluctuations. It is a well known fact that there exist climatic fluctuations with periodicities of 2-5, 11, 22, 80-90, 180, 600, 1,800 years and so on. In the opinion of climatologists Ye.S. Rubinshteyn and L.G. Polozova [14], the 2-year cycle of fluctuations in various meteorological indicators is explained by self-oscillations of the atmosphere; that is, its intrinsic fluctuations caused by the varying thermal regime of the oceans and continents, the change of seasons, and other geophysical causes. The 11-, 22-, and and 80-90-year climatic fluctuations are caused by respective cyclic fluctuations in solar activity. Many climatologists think this to be the case. It is also known that the range of climatic fluctuations is much greater in the high latitudes than in the lower ones. For example, the warming observed from the beginning of this century (and particularly from 1920) to the end of the 1940's was at its highest in the high latitudes. The overall planetary warming equaled several parts of a degree. In the high latitudes it exceeded 2-3°. This was written about by V.Yu. Vize in 1940, Rubinshteyn and Polozova in 1966 [14], and S.P. Khromov in 1968. It was again confirmed at the Conference on Problems of Climatic Change that was held at the Main Geophysical Observatory (Leningrad) on 27-29 February 1968 and the Symposium on the Cenozoic History of the Polar Ocean (1-6 April 1968, Leningrad).

Apparently, the initial warming was also insignificant in the Far North. However, it extended the duration of the open-water period somewhat, and this in turn led to a lowering of the albedo, an increase in the radiation balance, and even greater warming; that is, the shrinkage of sea ice and the retreat of inland ice, an increase in the sea water's temperature, the appearance of herring in the Kara Sea, some increase in the growth of plants, and the penetration into the North of insects. Actually, warming by only 1° in the high latitudes means a northward advance of the thermal boundaries for plants and animals of more than 100 km. The animals reacted more quickly to the warming: small invertebrates inhabiting the upper part of individual plants, the soil surface, grasses and undergrowth, lakes, streams. This could not help but be reflected in the larger animals; in particular, the birds, since they feed on the invertebrates. Plant growth increased, which affected the herbivorous animals and, consequently, the beasts of prey.

This warming had a very substantial effect on the thawing of perpetually frozen soils (permafrost) and thermokarst processes.

Similar phenomena have also occurred in the distant past, during the so called Middle Holocene[1] thermal optimum; that is, a period of warming that took place approximately between 6,000 and 5,000 years ago. It was greatest within the limits of 50-70° N. Lat. The warming had considerably less effect in the southern latitudes. This was again confirmed at the Conference on Thermal Reclamation of the Northern Latitudes, particularly in the materials of V.P. Grichuk[2].

The Subarctic reacts to cooling with the same sensitivity and dynamicity as to warming as the result of those same features we mentioned above. It has now been established that an initial reduction of temperature in the subpolar latitudes of only 0.3° was able to (which means that it can happen again) bring the ice cap to life. Here is how Academician K.K. Markov describes this process: "Assume that a small degree of cooling allowed an insignificant ice cap to be born. This cap itself cools the atmosphere, contributing to its own further growth. The ice caps' self-expansion finally created such scales of climatic cooling that they exceeded the initial cooling of the atmosphere many times. . .The ice cap, by gradually expanding, was finally able to reduce the temperature of the air above and around it by 25°C!"[3]

This feature of the Far North must always be taken into consideration when developing any projects that can affect the thermal regime in the high latitudes.

This property of the high-latitude (Arctic and Subarctic) natural territorial complexes, of reacting quite sensitively to small climatic deviations and then causing large physico-geographical changes, explains the fact that the continental glaciations that have taken place in the history of the Earth occurred in the high latitudes, while in the low latitudes the temperature was always close to what it is today.

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[1]The Holocene is the modern, post-Ice-Age geological epoch; that is, the most recent and not yet finished segment of the Quaternary Period of the Earth's geological history. The beginning of the Holocene is considered to be the end of the last continental glaciation in northern Europe, which occurred about 10,000 years ago.
[2]See TEPLOVAYA MELIORATSIYA SEVERNYKH SHIROT [Thermal Reclamation of the Northern Latitudes, Collection of Works], Moscow, Izd-vo Nauka, 1973.
[3]Markov, K.K., PALEOGEOGRAFIYA [Paleogeography], Moscow, Izd-vo MGU [Moscow State University], 1960, 164.

It is a known fact that the Earth's separate modes of motion and its orbital parameters are periodic and not constant, which is one of the causes of climatic fluctuations.

The Yugoslav geophysicist M. Milankovich calculated that a reduction in the angle of inclination of the Earth's axis of only 1° would reduce the annual amount of incoming radiation at the equator by 0.35 percent, while at latitude 45° it would increase by 0.03 percent. As one moves to the north, the amount of incoming radiation increases sharply, particularly during the summer. For instance, at latitude 70° the summer increase would be 3.18 percent, while the total annual increase here would be 2.49 percent. A further decrease in the Earth's axis's angle of inclination would cause even greater changes in the subpolar latitudes[1]. The actual changes in the axis's angle of inclination will be no greater than 3° in the next 40,000 years.

An increase in temperature in the high latitudes usually leads to a decrease in zonal contrasts on Earth and a substantial change in overall atmospheric circulation: it is weakened in the northern hemisphere, the subtropical anticyclones are displaced northward, and aridity increases in the middle latitudes -- the grain-growing regions of the Volga basin, the Ukraine, and so forth, which was observed as recently as the warming period from the 1920's to the 1940's.

The character of changes in nature is directly proportional not only to the amplitude of the temperature deviation, but also to its duration. For example, the warming in the first half of the 20th Century, which lasted only a few decades, did not result in such substantial changes as took place during the climatic Middle-Holocene optimum, which lasted at least about 2,000 years (and, apparently, even longer). The temperature change in the Middle Holocene was the same as in this century: 2-3° in high latitudes, significantly less (but of much longer duration) in low latitudes. During the recent warming period,

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[1]If the Earth's axis were perpendicular to the plant of its orbit, then on Earth there would be no seasons and there would exist zones with constant, unchanging climatic conditions: subpolar zones of eternal cold and ice, a burning equatorial zone, and zones of gradual transitions between them. A reduction in the angle of inclination of the Earth's axis to its orbital plane would lead to a decrease in the annual radiation total in the equatorial zones and an increase in it in the polar zones; that is, it would smooth our the difference between the equator and the poles.

therefore, only the most mobile components of nature underwent a slight change: air masses, ice, and animals to some extent, while plant growth increased. However, there was no reorganization of plant communities (phytocenoses), for example, because the period was too short, while during the Middle Holocene thermal optimum there was substantial reorganization of the phytocenoses, although -- once again -- only in the high latitudes. Forest-tundra phytocenoses formed where today there is only tundra, and in the area of the present forest tundra there were taiga phytocenoses.

Thus, the dynamicity of nature in the Subarctic, its sensitivity to even small deviations, and its instability -- all of these are caused, in the final account, by its climatic peculiarities, which in turn depend on the Subarctic's high-latitude location and the proximity of many components of nature (including ecosystems) to critical parameters.

Perpetually Frozen Soils (Permafrost)

An excess of winter freezing of the ground over summer thawing leads to the formation of permanently frozen soils. The protracted winter with low temperatures that occurs in a great part of the Subarctic contributes to this regime: the frozen layer is always thicker than the seasonal summer thawing layer. The existence of such a regime for thousands of years causes the formation of permanently frozen strata to depths of several dozen and even hundreds of meters. The freezing of the ground in the Subarctic, with its excessive moisture, has finally resulted in the formation of subsurface ice that is enclosed in the frozen soil. The subsurface ice content is especially high in areas where tectonic subsidence of the relief has occurred. In a number of regions in Western Siberia and the Yano-Indigirskaya and Kolymskaya depressions and other areas, subsurface ice constitutes 50-70 percent of the soil volume in the top 50-100 m layer (Figure 2). According to calculations made by USSR Academy of Sciences' Corresponding Member P.F. Shvetsov [26], the melting of this ice would lead to settling of the surface to below sea level. In some places, such melting goes on before our very eyes. For example, in 1936 in the Laptev Sea, Vasil'yevskiy Island -- which was 7 km long in 1823 -- melted. This island consisted of loamy mineral soils and ice. Where it once was, there is now a submerged shoal. Semenovskiy Island melted in 1956. It is also possible that the mysterious Sannikov Land suffered the same fate. The Lyakhovskiy and Medvezh'i Islands and Ayon Island apparently separated from the continent quite recently as the result of melting. An interesting picture of the sea's advance into northern lowlands with high subsurface ice contents was recorded by the well known

Figure 2. Ice vein exposed as the result of soil caving-in during undermining of river bank. The ice extends into the earth at least 7-9 m.

Arctic investigator N.N. Zubov. Here is what he wrote in his book "In the Center of the Arctic": "In 1946, while flying over Laptev Strait, I asked the pilot to hold a course parallel to the island's coast. . .Continuous cave-ins extended along the entire coast. . .The fresh landslides were characterized by the snowy white color of fossil ice. Without a doubt, what happened to Vasil'yevskiy Island will happen to Bol'shoy Lyakhovskiy Island."[1]

The area occupied by permafrost constitutes up to 25 percent of the Earth's land surface and about 40-47 percent of the USSR's area. In contrast to land glaciation (Antarctica, Greenland, Franz Josef Land, and so on), territories with permanently frozen soils containing ice (independently of the abundance of the ice) are assigned by geocryologists to the category of subsurface glaciation. In the Subarctic the quantity of subsurface ice is the greatest in comparison with the other zones and, according to B.I. Vtyurin's calculations, reaches 2-10 million m^3/km^2 in the upper levels (5-30 m). The great iciness of the Subarctic's soils causes thermokarst; that is, melting of the ice and surface settling or even caving, depending on the abundance of ice and the nature of its

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[1]Zubov, N.N., V TSENTRE ARKTIKE [In the Center of the Arctic], Moscow-Leningrad, Izd-vo Glavsevmorputi, 1948.

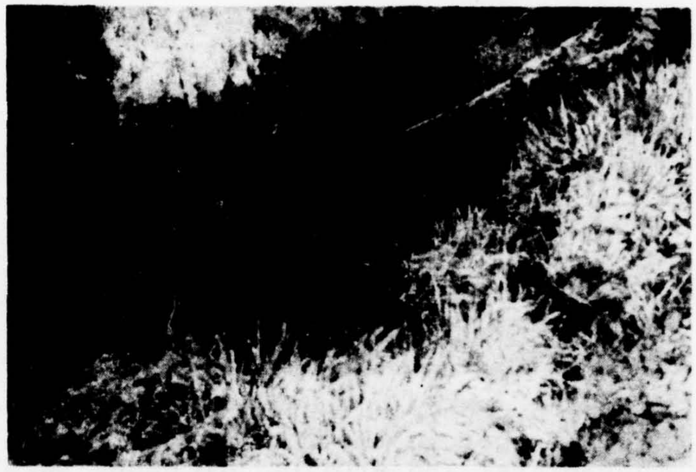

Figure 3. Thermokarst sink formed at location of melted ice vein.

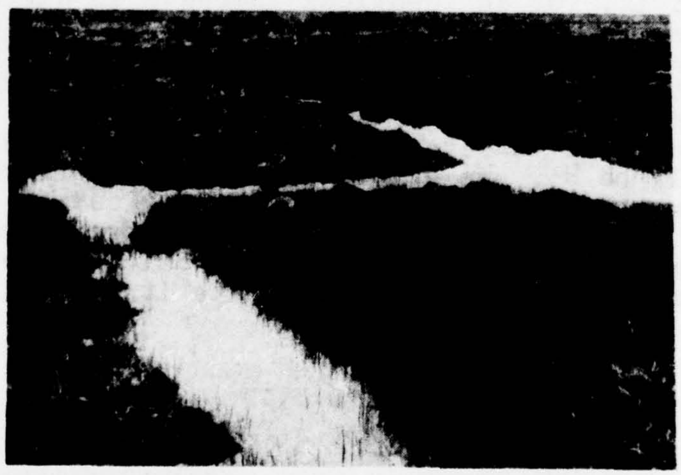

Figure 4. Melting and formation of thermokarst subsidences filled with water abvoe ice veins. (Photograph by Yu.T. Uvarkin.)

melting (Figures 3-5). Thermokarst usually appears where the depth of the seasonal summer melting exceeds that previously established and reaches the subsurface ice or severely icy rock. In connection with this, it is of interest to discuss the regularity established by P.F. Shvetsov [27]. He proved that during warming, the temperature increase in the soil and, consequently, the density of the heat flow in the soil's upper

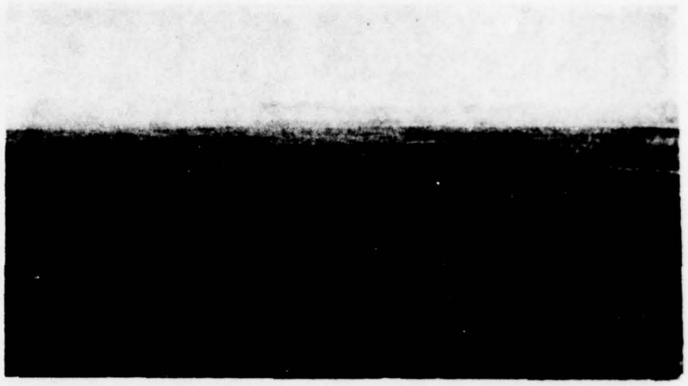

Figure 5. Polygonal-block relief in the tundra zone, in the formation of which thermokarst and erosion processes participated.

layer grow larger during the same periods of time from south to north; that is, for an identical increase in air and ground surface temperature, the increase in the thickness of the seasonally thawed layer will be great in the north than in the south. Let us designate the average depth of summer thawing in the more northerly regions with shallow seasonal thawing as H_1, while the average thawing depth in those areas with deeper thawing will be H_2. We will assume that the increase in the average summer air temperature during the summer months (June-August) is the same for the entire physicogeographical province (the Eastern or Western Siberian Subarctic, and so forth) during the warming periods, and designate it by Δt°. For $H_2 > H_1$ we have

$$\frac{\Delta t^{\circ}}{H_2} < \frac{\Delta t^{\circ}}{H_1},$$

from which

$$\Delta q_1 = K\frac{\Delta t^{\circ}}{H_1} > \Delta q_2 = K\frac{\Delta t^{\circ}}{H_2},$$

where Δq = heat flow increment, K = the rock's coefficient of internal thermal conductivity.

Since the depth of thawing is a function of the downward heat flow q, then the increase in thawing depth caused by the increase in the ground surface's temperature will be identical in both cases; namely, $\Delta H_1 > \Delta H_2$ (for the same time period).

Thus, the main condition for intensive development of thermokarst -- great iciness -- exists. The main cause of this process -- the increase in seasonal thawing depth that encompasses icy rock or ice -- is also present: normal temperature fluctuations (2-3, 11-year, and so on). On the basis of the indicated regularity, the increase in summer thawing during warming periods will always be greater in the tundra and forest tundra than in the taiga. This means that the thermokarst processes and solifluction current of the soils in the tundra and forest tundra will always be more intense than in more southerly zones.

The most common thermokarst forms are: thermokarst lakes, sinks (swampy and dry), and baydzharakhi[1]. If technogenetic (that is, caused by man) factors are added to these natural processes, in the Subarctic this frequently has catastrophic consequences: caving and destruction of roads and buildings, the formation of thermokarst lakes and the sinking into these lakes of buildings, roads, bridges, telegraph posts, and so on. All of these is indicative of the extraordinary lack of equilibrium of the soil and ground complex -- a phenomenon that is unique to the Subarctic.

Let us examine some causes of thermokarst that are related to the productive and domestic-economic activities of people. This primarily means contamination of the ground surface with dust, which lowers its albedo and thereby leads to a change in the conditions of heat exchange between the ground and the atmosphere. Dust-covered ground heats more intensively and the seasonally thawed layer increases, reaching the subsurface ice. It melts, which leads to surface settling and formation of a pond, which warms up even more strongly than the ground surface; that is, self-intensification of the process is seen.

Destruction of the plant cover as the result of economic development of the territory causes an even more intense manifestation of thermokarst in the Subarctic. Many confirmations of this can be seen along the so called "dead" railway in the northern part of Western Siberia that runs from Salekhard to the east along the Pravaya Kheta River (Figures 6, 7). It was built from 1949 to 1953, according to light-duty specifications. It has been in a preserved state, without repair, for more than 20 years.

Along the entire railway, in a belt several hundred meters wide the vegetative cover was disturbed or completely destroyed, which resulted in an abrupt change in the conditions for heat

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[1]Baydzharakhi are round hummocks 0.5-10 m high that form during the melting of subsurface ice. They are usually found on the shores of thermokarst lakes and sinks.

Figure 6. Section of the "dead" railway to the east of Salekhard. In this spot a thermokarst lake formed where the vegetative cover was destroyed. Rails, structures, and telegraph posts sank into it. (Photograph by N.I. Mukhin.)

exchange between the soil and ground complexes and the atmosphere in this band. The creation of structures and embankments or ditches caused a redistribution of the snow cover, which also contributed to the change in the freezing and thawing processes. At certain locations there was severe heating of the ground as the result of blackening of the surface with lubricating materials and, in particular, the lighting of wood fires. In those places were embankments were raised, the upper limit of the permafrost was elevated. For an embankment 2.0-2.5 m high, the frozen ground level under it was raised 0.3-0.5 m. In a number of places this complicated the water runoff process and resulted in the formation of a chain of dam-type (not thermokarst) lakes 1-3 m in depth, under which small taliks have begun to form. All of this taken together caused the appearance of swellings, subsidences, and thermokarst lakes and the expansion of the dam-type lakes, as a result of which the roadbed became unusable and in many places even sank beneath the surface of the thermokarst lakes or was covered with sand. Several buildings even sank into the water. The thermokarst processes and the expansion of the lakes continues. The poured roadbed is spreading and more or less settling, although in some places it is heaving upward.

Taliks exist in a number of forested places where there is a thick snow cover (in the vicinity of Salekhard, for example).

Figure 7. Section of unused railway east of Salekhard. The disturbance of heat exchange in the permafrost led to melting of the subsurface ice under the roadbed and its settling. (Photograph by A.I. Dement'yev.)

After the forests were cut down on these taliks, the snow began to blow away when the roadbed was being laid. This always results in deeper winter freezing, and in similar situations has led to the appearance of permafrost in the location of the taliks.

At the present time, several scientists are proposing the construction of suspended monorails as the main means of transport in the North. They are much cheaper than railways and several times cheaper than highways, while their trains are considerably faster than those on regular railroads, especially under the conditions encountered in the North. To this we should add that the construction of a monorail suspended on supports will cause substantially less damage to nature. When the proper precautions are taken, the vegetation and soil almost do not suffer during the erection of the line. Such a transportation system will not become drifted with snow, either.

Ignorance of and failure to allow for the specific nature of permafrost (cryogenic) phenomena are also frequently displayed in other situations. It is a well known fact that in connection with the erection of high-voltage power transmission lines and the building of roads, a right of way is cut. In forests where there is no permafrost, this strip is usually overgrown by a thick birch or aspen grove, and the measures for its maintenance include, in particular, the systematic cutting of this regrowth. It is another matter altogether when permafrost is present. Destruction of the vegetation along a road causes intensified thawing, especially in icy soils, and the appearance of thermokarst sinks; that is, it results in an abrupt change in the natural complex. Even a cross-country vehicle that has traveled only a few times over the same place destroys the tundra's grassy-mossy cover, as a result of which the mineral soil is laid bare and a thermokarst-erosion gully forms (Figure 8). Plants in turf constitute a good heat insulator. For example, on the tundra in Yakutiya on a sunny July day with an air temperature of 15-20°, the soil temperature at a depth of 10 cm is 2-3°, and at a depth of 45-55 cm the permafrost layer begins. When the grassy-mossy cover is disturbed, heat exchange in the soil changes sharply, the ground begins to thaw to a greater depth, and ice veins are transformed into slump holes and trenches. In a place where there was previously a temporary dirt road, a thermokarst erosion strip forms, the width of which can eventually reach several dozen meters. The growth of such a thermokarst-erosion gully continues all summer, in any weather -- during rain and during dry, warm weather, when ice melts intensively, as a result of which there is an increase in the flow of the mud mass. During the winter, such gullies must evidently be filled in with construction debris, slag, and soil.

Under the conditions prevalent in the Subarctic, with its permanently frozen ground, tracked vehicles do a great deal of harm to northern ecosystems. During geological, geophysical, and other prospecting work it is necessary to use machines that are suited to the conditions in the North, but they should be equipped with large, pillow-shaped tires that exert little pressure on the ground and do not destroy the vegetative soil cover.

Complexes of antierosion agrotechnical measures have been developed for the forest steppe, steppe, and other zones: sowing

Figure 8. Thermokarst-erosion gully that formed in the path of a tracked cross-country vehicle. The vegetative cover was destroyed and the mineral soil laid bare. Subsurface ice is visible in the outcrop on the left.

fields to grass, afforestation, outlining with series of embankments, and so forth. For Subarctic regions, where the clay, loam, and sandy-loam soils are in a frozen state and permeated with ice, these measures do not suffice. In such regions there can be no more or less permanent dirt roads. After several passages over the same point, a road must be abandoned and shifted to one side. For a number of populated points the problem of access roads has now become extremely serious. The development of such regions must first of all be accompanied by the construction of permanent causeways made of gravel and rock waste, under which the permafrost would be preserved. Otherwise, a populated point will eventually be deprived of access roads, and their construction on land deformed by thermokarst-erosion processes will be extraordinarily complicated, and if such a state of affairs occurs the populated point itself will usually be in miserable shape. Even more unfortunate situations have occurred, where surveyors and builders did not take into consideration the direct and straightforward relationship between the network of polygons on the land surface and the presence of ice veins in the underlying ground. The result of this was that, because of melting of the ice, the section on which a settlement was built turned into a swamp, with slump holes and deep channels.

Research done in the 1950's showed that only 70-80 percent of the buildings in Vorkuta were in a stable state, while the rest

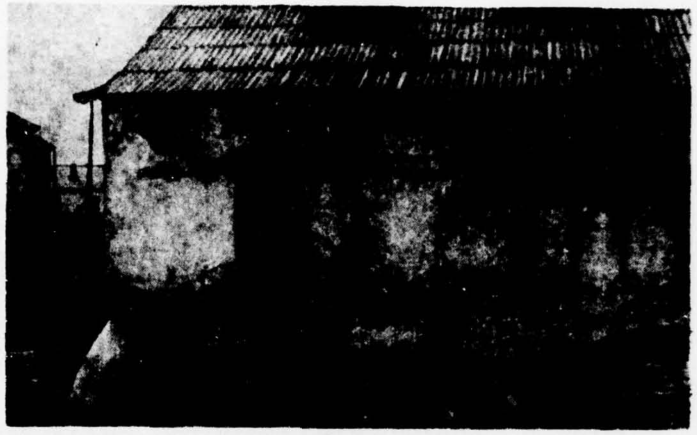

Figure 9. Building being destroyed as the result of nonobservance of the principle of preserving the permafrost during construction.

damaged to one extent or another. Almost all of the deformations were caused by uneven settling during the ground thawing period (Figure 9), which is explained -- in the opinion of P.F. Shvetsev -- by the coincidence of intensive construction in the 1940's and 1950's (increased coal mining, more furnaces, rock dumps, contamination of the surface with dust, redistribution of the snow, and so on), which caused a change in ground-atmosphere heat exchange, with several brief (2-3 years) natural increases in the temperature of the ground surface. The superimposing of these two processes led to thawing of the permafrost and uneven settling, with deformation of the structures located in the given sections.

Cases of restoration of the frozen rock strata (under Vorkuta, for example) have been noted, in addition to the cases of degradation. As is known, Vorkuta is located in the subzone of underbrush tundras. The permafrost in its vicinity has a temperature close to zero; that is, it is unstable. Here the seasonally thawed layer is 1-2 m thick, sometimes more; taliks are present. The underbrush (yerniki [translation unknown], or thickets of dwarf birch, and willow groves), which retains the snow, plays a large role in maintaining the temperature close to zero, since the snow prevents severe freezing of the ground. However, the underbrush was removed during development and the plowed field remains bare during the winter; that is, there is almost no snow on it.

Figure 10. Swelling hummock with ice nucleus on swampy plain composed of permafrost. Its height is about 10 m.

Under these conditions the temperature of the frozen rock stratum begins to drop and the thickness of the seasonally thawed layer decreases, which has a negative effect on agriculture. In those places where taliks are present, there are permafrost layers that do not thaw during the summer. Plants that could previously be cultivated here no longer grow on these sections.

We have discussed only a few of the features of permafrost -- its instability and lack of equilibrium, which lead to deformation of the surface and a rapid change in the entire natural complex. At the same time, it is known that permafrost, by severely cooling the soil, retards biochemical processes as well as the growth and development of plants. It is water-resistant and, simultaneously with a decrease in evaporation, contributes to universal swamp formation in cold soils. All of these features are exhibited to the greatest degree in the tundra, forest tundra, and northern taiga; that is, in the Subarctic zones.

The Subarctic has unique zonal relief forms (Figure 10).

Zonal Microrelief Forms

Polygonal-mottled microrelief forms (mottled tundras, medallion tundras, small-hummock tundras with patches, muddy circles, polygonal tundras, polygonal soils, nongraded circles, rock circles, polygons, structural soils, and so forth) have long been indisputably ranked among the zonal microrelief forms of the Arctic and Subarctic.

D.A. Dranitsyn wrote on this subject in 1914, A.A. Grigor'yev in 1925, and B.N. Gorodkov, M.I. Sumgin, S.P. Kachurin, and others in the 1920's and 1930's. The formation of polygonal-mottled forms is a very complicated phenomenon. This is why there is still no unified point of view among scientists about the reasons for their formation. At the present time there are about 30 hypotheses explaining the polygonal and mottled nature of the microrelief in the high latitudes. The number of articles, chapters in books, and collections of works on this subject is more than 400.

The greater part of the hypotheses are based on the fact that soil volume changes during freezing and thawing because of so called frost sorting, which is possible when the soil is sufficiently moist. As a result, the stones in the ground are pushed upward and to the sides, forming rock polygons, circles, and (on slopes) stone tracts. When the seasonally thawed layer of ground freezes, its volume increases. Objects located in the ground -- stones, building foundations, poles -- are also lifted upward unless they are sunk several meters into the permafrost. An empty space forms under the uplifted objects that, during thawing, is filled with a flowing, silty mass. Such processes, when repeated from year to year, finally result in a situation where the stones, posts, and other objects are expelled and "frozen out" onto the surface. In the absence of any material in large pieces, sorting of the silt takes place in a manner quite similar to the process involved in sorting the former. Therefore, there is no fundamental difference between "nonstructural" patches and polygons and "structural" rock polygons, rings, and similar forms in the genetic sense.

Field observations and the study of sources in the literature indicate that there are many causes of vegetative cover degradation and exposure of the mineral soil. After the uncovering of the mineral soil, however, silt and rock sorting must begin in it (Figure 11). In this respect there is actually no difference between "structural" (stones are present in the ground) and "nonstructural" (no stones in the ground) forms. Experimental research carried out both in the Soviet Union and abroad has fully confirmed the fact of ground sorting as a function of its freezing and thawing. At the same time, it is absolutely indisputable that if the appearance of patches and polygons depended on these processes alone, then in all zones of the temperate belt where the ground freezes, patches and rock polygons would have appeared: larger in some zones, smaller in others, but in all of them. They are found only in the Arctic and Subarctic, as well as on level or slightly tilted sections in high mountain areas.

Many years' worth of microclimatic observations in the Khibiny Mountains from the mountain tundra to the forest zone, which we made in accordance with the International Geophysical Year's

Figure 11. Stones ejected ("frozen out") onto the ground surface that have formed a circle in a spot where a cross-country vehicle destroyed the vegetation.

program, indicate that ground freezing and thawing take place in all vertical bioclimatic zones. Here there is no permafrost. At the same time, it is a known fact that stone polygons form in the mountain tundra but not the forest belt. Within the limits of the forest belt in the Khibiny Mountains, stone polygons are seen only on the bottoms of drained lakes; these bottoms are very damp -- there is a thin layer of water in them during the spring, but in summer the water disappears. As is the case for the mountain tundras with polygons in this area, so for the damp bottoms of the drained lakes inside the forest belt, vegetation is typically very sparse or completely absent. There is no continuous network of plant roots in the soil layer here. It is a curious fact that in the tilled sections of Murmanskaya Oblast and Kareliya, several years after the stones are removed from a plowed field, they again appear on the surface. This is the result of frost sorting in sections from which the natural tree and brush growth has been removed.

All of this indisputably indicates that plant roots arranged parallel to the surface and concentrated in dense networks in the uppermost soil layer neutralize the yearly effects of freezing and thawing, thereby nullifying the frost sorting process. Thus, although the fact of frost sorting as the result of freezing and thawing cannot be disputed, it alone cannot be the explanation of the appearance of patches and polygons. We must find reasons for the stripping of the ground's vegetative cover, as well as the reasons why this state is maintained.

For instance, on the mountain tundra plateaus in the Khibiny Mountains and the bottoms of the drained lakes in the forest belt there are various reasons for the absence of plants, although the final result is the same -- stone polygons.

Many theories are based on the fact that patch-medallions and stone polygons form only in the presence of permafrost that thaws to a great depth. This group of hypotheses, in contrast to the others, more or less bears the stamp of official recognition. It is a well known fact that the participants at the International Geological Congress who took an excursion to Spitzbergen in 1911 agreed to recognize the unconditional relationship of patch formation and the existence of a permafrost horizon. In mentioning this event, in 1936 the pedologists O.A. Polyntseva and Ye.N. Ivanova wrote that until the present time (the middle of the 1930's, that is), most investigators hold this viewpoint. It was held to, as is known, by V.N. Sukachev, K. Trol', M.I. Sumgin and his followers S.P. Kachurin, N.I. Tolstikhin, V.F. Tumel', and others. At the present time, B.N. Dostovalov and V.A. Kudryavtsev fully adhere to this hypothesis[1]. It should be noted that all of the named authors belong to that group of investigators for whom permafrost is the main object of study. This fact, of course, influenced their hypotheses. In actuality, permafrost (as is now well known) is not a necessary condition for the formation of patches and stone polygons. Geographic comparisons have confirmed this conclusion: patches and stone polygons are found in Iceland and the northern part of the Kola Peninsula in sections where there is no permafrost, but at the same time are not found in the deciduous forests of Western Siberia with their linked moss and underbrush cover, where the soils have developed under permafrost conditions and thaw to a depth of 50-100 cm in the summer.

The basis of the next group of hypotheses is that the formation of patches and polygons is caused by frost splitting of the ground (Figure 12, A, B). It has been fully proven that during severe cooling and freezing, there appear ruptural deformations in the ground that lead to the formation of cracks. In connection with this, mineral soil is usually saturated with moisture during the autumn. After the onset of negative temperatures the ground freezes together and becomes a monolithic, cemented frozen stratum. The dimensions of the polygons in homogeneous soil serve in their own way as a gauge of the maximum gradients: large rectangular blocks form when the temperature

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[1]Dostovalov, B.N., and Kudryavtsev, V.A., OBSHCHEYE MERZLOTOVEDENIYE [General Geocryology], Moscow, Izd-vo MGU, 1967.

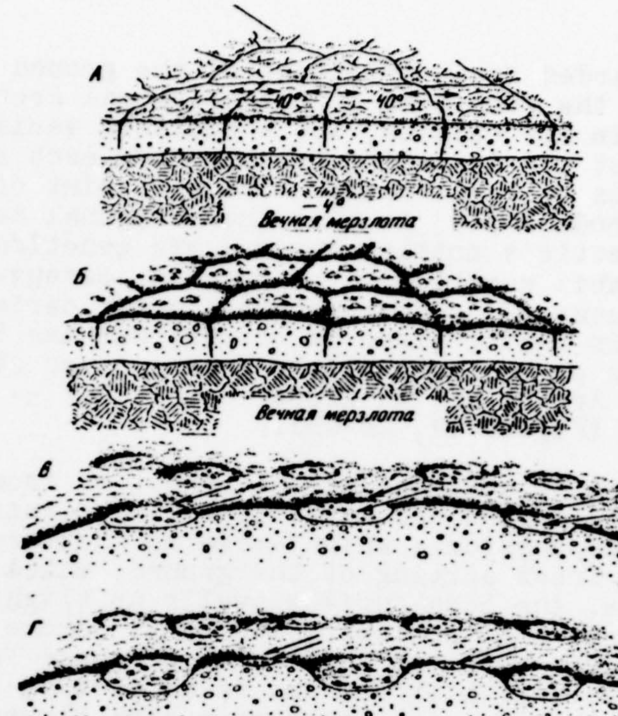

Figure 12. A,B = diagram of formation of cracked and mottled tundra. The numbers indicate the winter ground temperature on the surface and at some depth. As a result of the temperature gradients, splitting of the ground occurs (A). Vegetation appears along the cracks and in the depressions (B). C,D = diagram of formation of eolian-mottled tundra. Because of wind erosion of the fine earth, the surface of a patch sinks and the number of stones increases (C). At a certain depth, there appear in the depressions areas of relative calm into which fine earth is blown from adjacent sections; the old patches start to be overgrown and new ones emerge on the hummocks between them (D). The arrows indicate wind direction.
Key:
1. Permafrost

gradients are small; when the gradients increase, these rectangular units split in two again and again, forming ever smaller blocks. Rectangular blocks do not form in heterogeneous soils, although the dependence of the polygons' dimensions on the temperature gradients is preserved.

B.N. Gorodkov regarded frost splitting of the ground as the original cause of the formation of the polygonal Arctic deserts. Mottled tundras, in his opinion, are a southern variant of the Arctic deserts that are indistinguishable from each other at the northern limits of their range. The viewpoint of V.B. Sochava and B.N. Gorodkov [15] is that the polygonal Arctic deserts and the Subarctic's mottled tundras are genetically related. We consider this position to be correct, because although there are many causes of ground exposure, under certain conditions the processes taking place in ground that has been stripped of plants or has very little ground cover give the same effect under Arctic and Subarctic conditions -- polygonal-mottled complexes (Figure 12, AB-CD).

After the formation of polygons as the result of frost splitting of the ground, mosses and a few flowering plants are concentrated in the depressions, which serve as shelters from the wind. Because of frost sorting of the ground, which causes its volume to increase, the bare surface swells up slightly and the effects of the winds and snow corrasion on it become more intense. In Gorodkov's opinion, the result of these factors plus the soil's low levels of nitrogen and salts is that the polygon's inner bare surface is not overgrown with flowering plants, although blue-green algae and fine mosses are found there. In the Arctic tundra, vegetation along the cracks occupies 10-20 percent of the surface. In connection with this, Gorodkov wrote that two types of habitats have been created in the Arctic tundras: one -- on the bare patches -- is subject to all the unfavorable conditions of the Arctic climate in winter and summer; the other -- in the frost cracks -- is protected and fertilized by plant and animal remains. On Kotel'nyy Island Gorodkov observed how sections of polygonal tundra denuded of plants were covered with a solid vegetative cover near the commercial hunting station, where they were fertilized by drainage water. In the Khibiny Mountains, on Mount Yukspor near the meteorological stations, we observed the overgrowth of stone polygons (primarily by grasses) previously devoid of plants. The cause was the same: fertilization by drainage water, leftover food, and so forth.

The material that has been accumulated up until now indicates that the adduced hypothesis (or group of hypotheses along this line: frost splitting is the original cause of polygonal-mottled formations) correctly represents the genesis of patches and medallions; that is, the so called mottled tundras (polygonal is the term Gorodkov uses) in the Arctic tundra. As we move southward (in the typical and southern tundra subzones and the forest tundra), this process becomes more and more subordinate. Here there are other reasons for the formation of

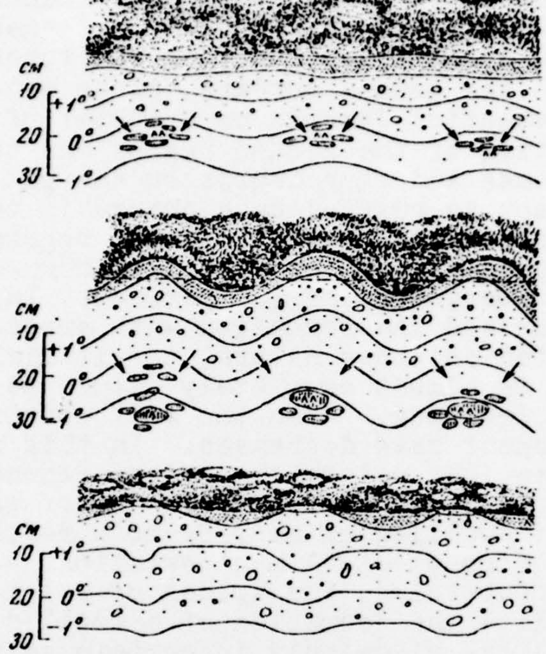

Figure 13. Diagram of formation of mottled tundras as the result of ground swelling and the appearance of ice lenses (^^). The lines indicate isotherms; the arrows, the direction of migration of the moisture toward the freezing front. The upper part of the hummocks above the dotted line (middle drawing) will eventually be destroyed as the result of degradation of the vegetation.

mottled tundras. Therefore, the hypotheses along this line (formation of polygonal-mottled tundras as the result of splitting of the ground) in no way refute the others.

The next group of hypotheses explains the formation of mottled tundras by ground swelling with subsequent degradation of the plant growth on the hummocks and the formation of bare patches of mineral soil (Figure 13). It is a well known fact that ground swelling is related to intensive migration of moisture toward the freezing front. Irregular freezing, in turn, is caused by uneven distribution of the vegetation, unevenness of the microrelief, and so on. Ice lenses form under sections that freeze more quickly than others; here the surface swells up. In time, the conditions on the growing hummocks become unfavorable for plants (a thin snow cover or complete removal of it by wind, summer dryness, and so forth). Plant degradation begins, continuing until it is completely ruined and the mineral soil is laid bare; that is, a patch is formed. Under the influence of wind erosion and swelling the tubercle is destroyed and leveled to the ground surface, after which regrowth begins. Further evolution depends on a number of conditions: either frost sorting of the ground begins and there is a concentration of stones and rock debris on the patch's surface and at its edges, which is related to a change in the hydrothermal regime and severe conditions that prevent regrowth, or it is overgrown. In such an area, new swelling hummocks are most often formed after overgrowth of the patches. The process of moisture migration and ice formation with subsequent swelling is best represented in those natural territorial complexes where the ground is almost completely saturated with moisture by the moment of freezing. When the soil moisture is reduced, the moisture movement rate decreases. In this case, as in the two preceding ones, the saturation of the ground with moisture is a mandatory condition for the formation of the microrelief. The dependence of swelling on many factors results in a great diversity in its morphological manifestations -- from large hummocks to microtubercles, the apices of which are destroyed and thereby initiate the formation of a mottled tundra complex. This process can take place only in certain sections in the southern tundra and forest tundra and can scarcely be observed in the Arctic tundra and Arctic desert, with their shallow thawing and upper layer dryness (in part, as the result of jointing and good aeration).

All authors who wrote about the formation of mottled tundras as the result of swelling processes did not work in the Arctuc tundras, but in the more southerly ones.

It is necessary to mention that the process of ground swelling, as is the case with frost sorting, is restrained to a considerable extent by the roots of underbrush and tree cover. In connection with this, the following example is of interest. In 1965, at the northern forest boundary (in the vicinity of the settlment of Kular in the Yakut ASSR) we observed that in sections where the thin forest had been burned off only a few years before, swelling hummocks had started to form. The frozen roots of the trees were being forced up as a result of the swelling. There was no such swelling in a number of areas where the thin forest had not been burned, although the location and nature of the soils were identical.

Yet another group of hypotheses, the first of which was advanced by V.N. Sukachev in 1911, is also of interest. Sukachev suggested that patches and medallions form as the result of the eruption of very wet, flowing soil onto the surface, this soil

Figure 14. Patch formed as the result of eruption of flowing mass onto the ground surface on a slope. In the lower part of the elongated patch, the excreted and [illegible] soil lies on still fresh, undecomposed vegetation -- mosses, lichens, undergrowth.

having been under great hydrostatic pressure during freezing from above. This viewpoint has a great number of both adherents and opponents.

A substantial addition for the understanding of this phenomenon (patch formation caused by a small mud volcano) can be made if

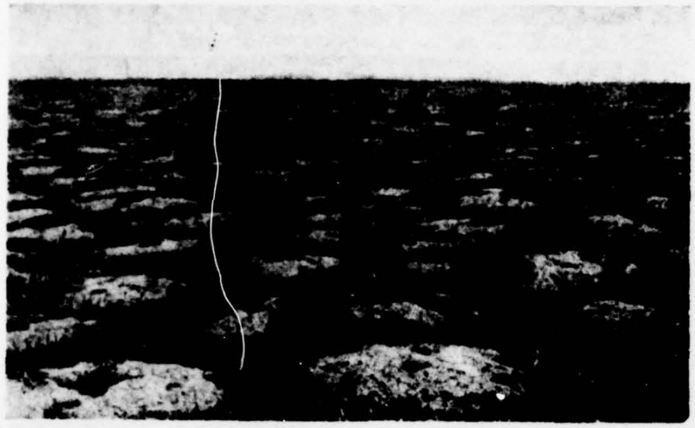

Figure 15. Mottled (medallion) tundra.

we remember the phenomenon of thixotropism, which is characteristic of tundra soils. Thixotropism means the capacity of a relatively dense, finely dispersed soil to change into a fluid, flowing state under the effect of an additional load. When the load is removed, the soil again resumes its thickened state. According to A.I. Popov [13], the freezing of ground from above causes stress that, having reached a critical value, leads to disruptions of the water-soil bonds; that is, to a flowing-fluid state in even unfrozen soil and to convective deformations in the soil. The conversion of soil into a liquified thixotropic state can also take place as the result of crack formation. The impulse generated at the moment of crack formation in still unfrozen soil is a force sufficient to result in the disruption of the water-soil bonds, causing a liquefaction effect in the soil. This is what Popov thinks, and the author of this book agrees with this viewpoint.

In the settlement of Kular at the end of June 1965, we observed the following phenomenon, which was caused by thixotropy of the soil. After the snow had melted away and the ground had dried, an old road to a borehole -- which had not been traveled in 1965 -- appeared as a more or less packed strip devoid of vegetative cover. Thawing in this strip reached 50-80 cm. In a number of adjacent areas with an undisturbed vegetative ground cover, the soil thawed to a depth of only 20-40 cm. On 29 June 1965 at 1700 hours, several trucks passed along this road, first in one direction and then, after an hour, in the other. By midnight the roadbed had already lost its density and packed solidity, sagged under the weight of a man, and had a certain amount of springiness. In the morning, patches and bands of extrusive, fluidly flowing soil appeared on the roadbed.

All of this makes it possible to state that we cannot eliminate the phenomenon of eruption of liquefied soil to the surface. This process apparently occurs primarily in the southern tundra and the northern forest tundra, and not even everywhere there, but under certain conditions and in specific natural territorial complexes (Figures 14, 15).

Yet another cause of patch formation is known: soaking as the result of water stagnation in the spring and subsequent degradation of the vegetation in small depressions (Figure 16). This takes place approximately as follows. Meltwater stagnates in small depressions 20-30 cm in diameter. After the snow disappears the soil still remains frozen for some time and does not let water pass through it, so that rainwater also accumulates in the depressions at this time. The algae, undergrowth, and lichens in the depressions die. Last of all, the sedges and mosses die. After the plants die off, a brownish peaty mass remains. Abrupt changes in the ecological conditions, from extraordinary overmoisturization to parching, prevent plants from establishing themselves in these areas; the peaty layer breaks down (it is mineralized, or blows away) and the mineral ground is exposed in the center of the depression. This is a young patch, with its surface being 5-15 cm lower than the organic layer and below even the soil's mineral surface. Such depressions are frequently crossed by plant roots. From the onset of water stagnation to the exposure of the mineral ground, it apparently takes several decades. Under a young patch, stones at all depths (if there are any) are distributed uniformly, but this is not always the case. One frequently sees patches where the material present in larger pieces has accumulated in the upper part of the profile. These are sections that were already in the patch stage, were then overgrown, and now have again evolved into the stage of a mineral patch.

In comparison with areas with ground cover, there is a sharp change in the hydrothermal regime in a patch devoid of vegetative cover, and the amplitudes of the temperature fluctuations increase. Ground sorting begins, which has been neutralized up until this time by the vegetative cover. As the result of ground sorting, the volume of it in the patch increases and the patch's surface becomes convex. On the convex surface the ecological regime is changed substantially in comparison with the sunken surface. In the southern tundra, in contrast to the Arctic, patches are usually overgrown. Depressions in which water stagnates were formerly hummocks. A new cycle begins: plant degradation in an expanding and deepening depression and overgrowth of the mineral patch with mosses and lichens followed by undergrowth; Siberian larch or scrub alder sometimes

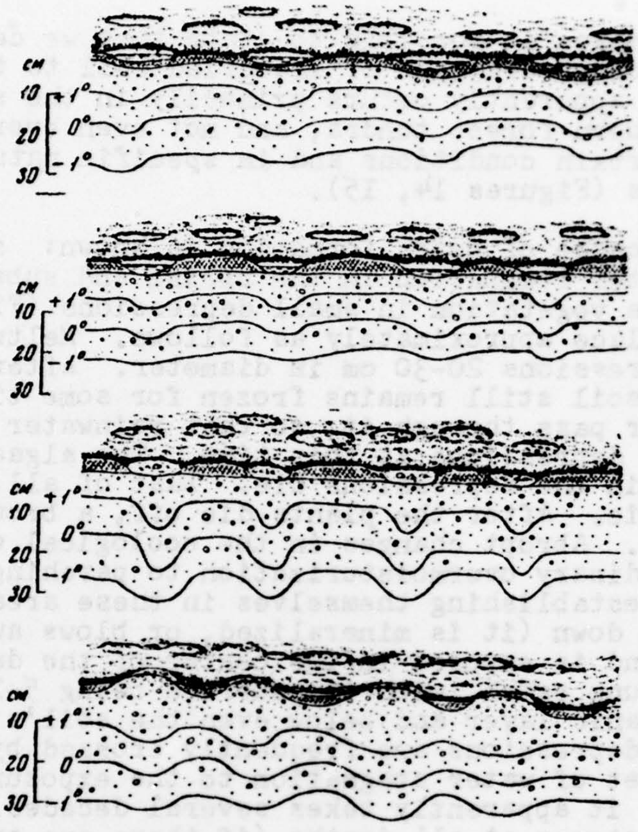

Figure 16. Diagram of formation of mottled tundras as the result of water stagnation in depressions. From top to bottom -- sequential stages of patch expansion, plant cover degradation, and exposure of mineral ground.

sometimes appear on the patches. Natural complexes of these mottled tundras are confined to flat watershed areas or to gentle (no more than 1-2°) slopes. In winter they are covered with snow, in contrast to areas with patch formations in the Arctic desert and Arctic tundra.

It has now been established that in polygon-mottled formations there is a specific microclimate, a hydrothermal soil regime, and an assortment of plants and invertebrates; that is, those areas with polygon-mottled formations become elementary natural territorial complexes or topographical facies (biogeocenoses), the smallest morphological units of a district. The material that we have been discussing indicates that the intensity of polygonal-mottled formations and the number of them in the

natural zones and subzones of the Far North have an inversely proportional relationship to the abundance of vegetative mass and the intensity of its growth, which in turn are caused by a complex of physicogeographical conditions. The small phytomass and its negligible growth in the Arctic desert and Arctic tundra correspond to the greatest concentration of polygonal-mottled formations, which here occupy extensive spaces ranging from several to dozens of hectares. Even in these places, however, near settlements in areas fertilized by wastes, the patches and polygons are overgrown with grasses and the processes of frost sorting and patch formation are weakened.

As we move southward (southern tundra, forest tundra, northern taiga), the total phytomass and its growth increase, which means there is an increase in the number of roots reinforcing the soil and neutralizing the processes of ground sorting and patch formation. Simultaneously, the concentration of polygon-mottled formations decreases. For instance, in typical tundra it is now encountered only in the form of small areas ranging in size from 0.5 to 1-2 hectares. In the forest tundra, in rare instances polygon-mottled forms stretch over an area of 1 hectare. Here patches are not seen in large groups; they do not last long and are overgrown quite rapidly. In the northern taiga they are seen even less frequently -- they occur singly or in small groups and are overgrown even more rapidly than in the forest tundra. In the middle, typical taiga there are no patches. In recent years human activity, which more and more often and intensively is disturbing the integrity of the plant cover, has contributed to the advance of polygon-mottled formations into the tundra, forest tundra, and northern taiga.

From what has been said, it follows that the most common factor leading to the formation of polygon-mottled complexes is a small phytomass quantity and retardation of its growth, caused by the extreme natural and (primarily) climatic conditions of the Arctic and Subarctic. Against the background of these very severe climatic conditions and the overmoisturization and poorness of the soil, under the present conditions in the Arctic and the subzone of Arctic tundras, vegetation either absolutely cannot or can ot quickly enough (in the southern Subarctic) cover the denuded mineral soils and shut off the processes of frost sorting of the soil and its loss by splitting, wind erosion, and so forth. As a result, we see the formation of patches, polygons, stone polygons, and other polygenetic forms that are associated by the commonality and interconnectedness of the processes taking place in them. The natures of the causes of plant degradation and the subsequent processes taking place in the exposed ground depend on the physicogeographical conditions in the specific region.

This geographic approach is lacking in a number of works in which the reasons for the formation of polygonal-mottled forms of microrelief are analyzed. Their authors, while quite correctly explaining the formation of polygonal-mottled complexes in specific regions, then try to extend this viewpoint to the entire territory of the Arctic and Subarctic. From this comes the multiplicity of competing hypotheses. In the Arctic and Subarctic, the explanation of the formation of polygonal-mottled complexes must essentially, in each specific case, come down to finding the reasons for the absence, weakening, sparseness, or degradation of the vegetative cover.

Special Features of the Vegetative Ground Cover

The specific nature of the Subarctic's climatic and soil conditions is also reflected in its vegetation. Botanists (A.I. Tolmachev, B.A. Yurtsev, and others) distinguish for this region a special group of so called hypo-Arctic plants that prosper and are widely distributed in the southern tundra, forest tundra, and northern taiga. They include stunted, pygmy, and scrub birches, as well as willows, bilberry, blueberry, whortleberry, voronika [translation unknown], several types of rosemary and other small shrubs, and several kinds of algae, sedge, and cotton grass. Based on botanical features, Yurtsev [29] distinguished a hypo-Arctic belt, to which he assigns the greater part of the subzone of typical mossy lichen tundras and the southern tundras, forest tundra, and northern taiga. He then divides the hypo-Arctic belt into two bands: the hypo-Arctic taiga and the hypo-Arctic tundra. The southern boundary of the hypo-Arctic belt is simultaneously the northern limit of propagation on plakor [possibly sod] of not only connected boreal forests (taiga), but also connecting forests in general; that is, it is actually the boundary of the forest zone as a whole. V.O. Targul'yan [19], in distinguishing cold, humid areas for which a single type of soils -- podbury [translation unknown] -- is characteristic, mentions that the hypo-Arctic belt's southern boundary is simultaneously the most clearcut southern border of the cold, humid areas.

In Yurtsev's opinion, the boundaries of the hypo-Arctic belt coincide with those of the Subarctic, as delineated in the Physicogeographic Atlas of the World (1964).

The following basic groups of surface-layer plants are native to the Subarctic: woody khamefity [translation unknown] -- small shrubs and low bushes that have their regenerative buds in the surface parts of their shoots, which are protected by the snow cover in winter; grassy plants -- primarily perennials; green and sphagnum mosses, and lichens (rootless plants).

The area of limitless dominance of the living form of wood ends in the Subarctic, where the tree is no longer numbered among the plant life forms that prosper. The viable optimum for trees lies to the south of the Subarctic. The range of tree species in the Subarctic is extraordinarily impoverished in comparison with the adjacent sections of the typical (central) taiga. The depression of trees and their scarcity, plus the thinning of tree stands in the forest tundra and northern thin forests results in a more luxuriant development of plants in lower stages: bushes, shrubs, mosses, and lichens; that is, the plants that predominate in the southern and typical tundras.

The evolutionary process -- natural selection, in particular -- in the Subarctic (the hypo-Arctic, according to Yurtsev) is not directed toward the formation of new hypo-Arctic species of trees, but toward the formation of nonarboreal tree species such as dwarf birch, undersized scrub willows, and so forth.

What are the special features of one of the basic grounds found in the Sub rctic -- the woody khamefity; that is, shrubs and low undergrowth? They are undersized and they have small annual shoot growth, their skeletal branches are quite long-lived, and they are subject to being beaten down, after which adventive rooting frequently occurs. Thanks to this, in summer they find a sufficient amount of heat in the surface layer for their growth and development, while in winter they are covered with snow.

The capability of the bushes and undergrowth for growing in very poor soils is their next feature. It is very closely related to their symbiotrophism; that is, the possibility of obtaining deficit nutritive elements through symbiosis with fungi (mycorhizal formations). Since they are capable of extracting the necessary nutritive elements from organic substances through a mycorhiza[1], the hypo-Arctic bushes and undergrowth are quite independent with respect to the degree of fertility of the mineral substrate [29].

The next two groups -- mosses and lichens -- are even more independent of the substrate. These rootless plants can assimilate dust and water from the atmosphere. It is a well known

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[1]Mycorhiza -- a set of root endings of higher plants and fungus mycelia that are in symbiosis; the type of interrelationship between green plants and a mycorhizal fungus, where the fungus receives nonnitrogenous organic matter from the higher plant, while the latter receives mineral salts and nitrogenous matter from organic litter through the former.

fact that lichens settle on rocks, tree trunks, spreading undergrowth, and even pads of moss.

One of this planet's main natural boundaries -- the northern boundary of the forests -- passes through the Subarctic. On the north and south, the forest zone is bordered by subzones in which primarily bushes predominate; more often than not, they are of the spreading type.

The northern boundary of the forests and woody plants is formed by: twisted birch and Siberian spruce in the Kola Subarctic; Siberian spruce and twisted birch, with infrequent stands of Sukachev and Siberian larches, in the Eastern European sector; Siberian larch from the Urals to approximately the Pyasina River; farther east to the Chukotsk Peninsula, the northern forest and thin forest limits are formed by daurskaya [translation unknown] larch.

The author has established that these trees, as well as dwarf birches, bush alder, and cedar stlanik [translation unknown], require approximately the same air and soil temperature for their growth and development. The foliage and needles of these plants open and shoot growth begins at average daily temperatures of 7-8°, although the diurnal temperatures must exceed 10-11° for at least 3-4 hours. If these vitally necessary temperatures are maintained for 4-6 weeks, then normal growth will take place and these plants will bloom and bear fruit[1].

North of the forest boundary (or above this boundary in the mountains) we see a "pressing" of the vitally necessary temperatures toward the Earth's surface, and at the northern boundary of the underbrush tundras they "close" with the Earth's surface. Such a phenomenon is also typical of soil temperatures. The strip adjacent to the northern forest boundary where the temperatures vitally necessary for the growth and development of trees and underbrush is maintained in the surface layer of air is called the belt of relative deforestation of the tundra (Figure 17). Here the trees quite often form small, separate groves. Farther north is the belt of absolute deforestation of the tundra; this is usually mossy-lichen underbrush (that is, typical) and Arctic tundras. In this absolute deforestation belt trees do not grow, because of the absence of the requisite minimum heat; at the same time, in the subzone of

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[1]On the northern and upper forest boundaries the dwarf birches, willows, and other underbrush frequently begin to open their leaves somewhat earlier than the trees, since during the day the air is always warmer at ground level than at treetop level.

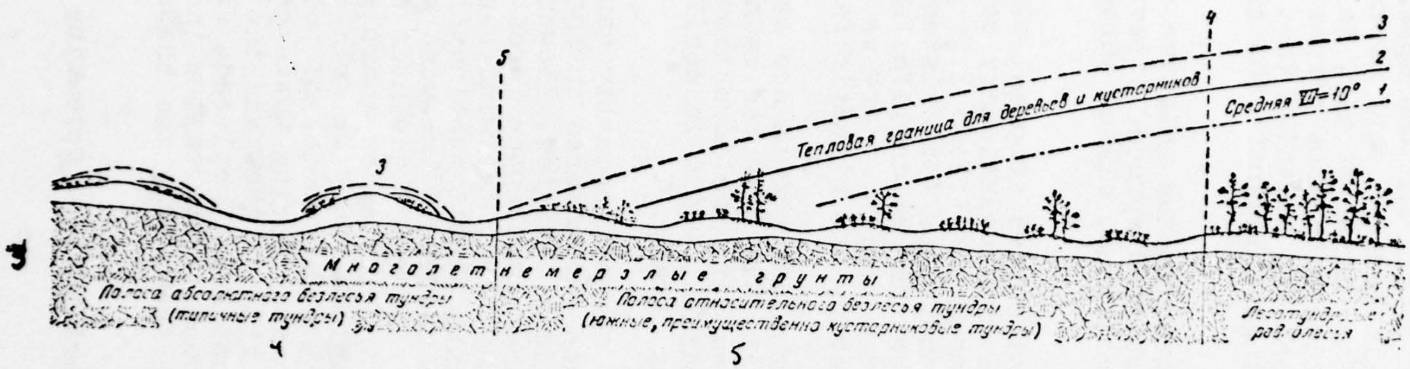

Figure 17. Relationship of belts of relative and absolute deforestation of the tundra: 1. average July isotherm = 10°; 2. thermal boundary for trees and large bushes (corresponds to 30-40 days with diurnal temperature above 10-11° (during a cold summer); 3. the same (warm summer). In the area between 2 (cold summer) and 3 (warm summer), bushes and trees usually do not grow taller than 1.5-2.0 m; 4. northern boundary of thin forest-tundra forests; 5. northern boundary of southern, primarily underbrush, tundras, which almost coincides with the northern boundary of the relative tundra deforestation belt, where the thermal conditions allow trees and large underbrush to grow.

Key:

1. Thermal boundary for trees and bushes
2. July average = 10°
3. Permafrost
4. Absolute tundra deforestation belt (typical tundras)
5. Relative tundra deforestation belt (southern, primarily underbrush tundras)
6. Sparse forest-tundra forests

typical tundra we frequently encounter small areas above which the temperature of the surface layer of air and the upper layers of soil allow some undergrowth (including dwarf birch) to grow. The thinness of the warm surface layer of air, in addition to the strong winds in combination with snow corrasion, result in creeping forms of underbrush and stlaniki that grow close to the ground, and correspondingly eliminate the growth of trees with straight trunks.

Bushy and spreading forms of trees grow in the relative deforestation belt: twisted birch, Siberian spruce, Siberian and daurskaya larches. Under normal conditions, all of these trees grow with straight trunks.

It is now known that the geobotanical series arboreal plant growth → bushy plant growth repeats the evolutionary series of life forms tree → bush. In both cases the tree's life form corresponds to the more favorable conditions for existence. There are many factors that can cause changes in life forms: climatic, edaphic, phytocenotic, and so forth. Here we will dwell on only a few of them -- primarily the climatic factors.

In the Subarctic, the conditions for plant growth are especially unfavorable during the winter. At this time the main growth axis dies, which in leafy species leads to the formation of multitrunk or bushy tree forms or bushes, while in coniferous species it results in low, spreading forms.

Let us discuss how the formation of the ecologically caused[1] spreading form of the Siberian spruce encountered in the European Subarctic takes place (Figure 18). Twisted, flowerlike forms of spruce develop on the northern and upper forest boundaries and in the forest tundra. In winter, the wind-carried snow crystals, which strike the plants almost continually, damage their bark and destroy buds and needles. The wind also stunts the trees physiologically: the rate of winter evaporation from the trees is quite high, and increases sharply during warming (and especially thawing) periods. On the Kola Peninsula, thaws occur quite often during the 8-9 months of polar winter (the influence of the Gulf Stream). During these periods the thin branches and needles have time to thaw and their moisture evaporates more strongly without being replaced, since the plants' roots are in the frozen ground. Evaporation increases sharply when it is windy. The more frequently the thaws occur,

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[1]As is known, there are no hereditarily fixed spreading forms of spruce.

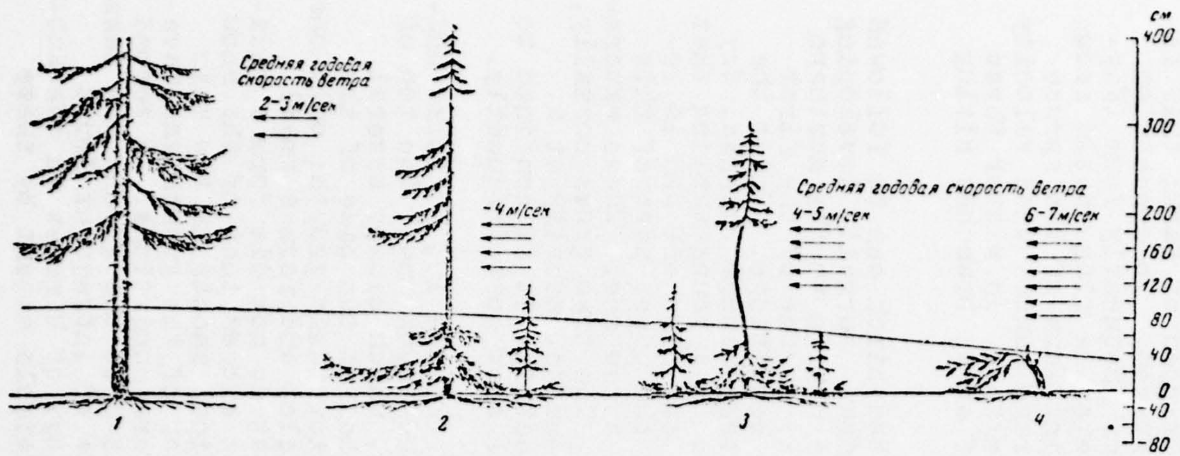

Figure 18. Change in growth forms of Siberian spruce under the influence of environmental conditions: 1. straight-trunk tree (forest zone); 2. flag-shaped and double-top form of spruce. Under the influence of wind, the branches on the windward side have died, as the result of which the flag-shaped crown in the upper part of the tree took shape. The lower part of the crown, which is under the snow, was preserved and grew, forming a sort of second crown with branches stripped of their bark. This is the way a spruce bed of vegetative origin is formed (forest tundra); 3. spruce bed of vegetative origin for which double-crown and spreading spruce trees are typical. The lower part of the crown and the spreading branches are under the snow in winter and are not subjected to wind acaction. The middle part of the trunk, denuded of branches, corresponds to the layer in which the main mass of snow is transported in winter, which mass corrades and destroys the branches. This phenomenon is seen in the relative tundra deforestation belt (underbrush tundra); 4. spreading spruce. Underbrush tundra. Here the heat is full adequate for the growth and development of spruce, but this is prevented by severe wind (6-7 m/sec, with gusts up to 40 m/sec) and frequent thaws. The arrows show average annual wind velocity (given in meters per second); the line -- average snow thickness; on the right -- height scale, in centimeters.

the drier the branches become and the more easily they undergo mechanical wind corrasion. Consequently, the wind's mechanical and physiological effects on the trees are interrelated.

When the upper part of a spruce tree's trunk dies, only the lower branches that are protected by snow during the winter continue to grow. Some of them are stripped of bark; this is how a bed of vegetative underwood is formed. In connection with this process, double-crown spruces frequently form (Figure 18, 2, 3). When the winds are weaker, a flag-shaped crown is formed (Figure 18, 2). The spreading form of the spruce (Figure 18, 4) develops where the average annual wind velocity is 6-7 m/sec, with gusts reaching 40 m/sec. In winter these spruces can live only under a cover of snow; branches rising above the snow will die.

The change in the growth form of twisted birch can be followed in the forest tundra and southern tundra. Normally developing twisted birch trees (Figure 19, 1) are native to the northern forests. A curved trunk (Figure 19, 2) is one of the first signs of some deterioration in growth conditions. Under the influence of strong winds and abrupt temperature changes, dry periods or early frosts, and so forth, on a young sapling that is sensitive to external effects, the top dies off and is replaced by a shoot from a lateral bud; the upper part of this shoot can also die and be replaced by a new one. These external influences have no further effect. The tree grows normally, although the curvature of the trunk remains, usually at a height of from 30-40 to 100-120 cm; that is, it is confined to the level where ice crusts form on the snow most frequently.

A multitrunk tree with a radical bush (Figure 19, 3) forms under more severe conditions than a curved-trunk one. The top of a young tree dies and is not replaced, which causes several shoots to grow from dormant buds located at the base of the trunk. Many of these shoots die or slow their growth; only one or two, more rarely three, shoots develop and form a small multitrunk tree. The other shoots that do not die form a radical bush, the height of which does not exceed that of the snow cover. The capability of forming radical shoots is the main biological reserve for the continuation of the growth and development of defoliated trees under severe conditions. A second possibility is that the branches pressed to the ground can take root. Poor seed regeneration (because of infrequent fruit bearing and a poor germinating capacity) of birches in the Subarctic is compensated for to a considerable extent by these biological features.

Trees with curved or multiple trunks usually grow at the northern and upper boundaries of a forest. The trunks of a

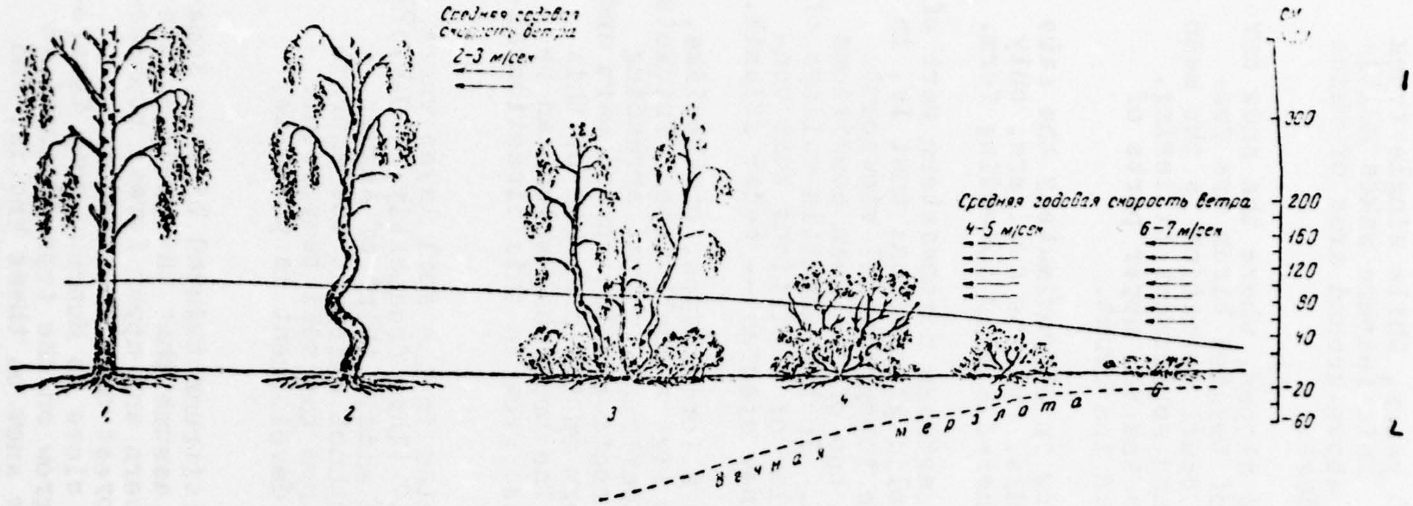

Figure 19. Change in growth form of twisted birch under the influence of environmental conditions: 1. straight-trunk tree (forest zone); 2. curved-trunk birches in forest tundra. The curving of the trunk indicates that the treetop has died many times and been replaced by a shoot from a lateral bud (forest tundra); 3. bushy, multitrunk birch with radical bush (forest tundra, southern tundra); 4. bush (or bushy) form of birch. The double crown is evidence of the strong influence of wind and snow (forest tundra, southern tundra); 5,6. bushy and spreading forms of birch. Because of the long winter and strong winds, branches reaching above the snow level and losing more than 50 percent of their moisture than die (southern tundra, relative tundra deforestation belt).

Key:

1. Average annual wind velocity, ... m/sec.
2. Permafrost

multitrunk twisted birch live 40-60 years, while single-trunk ones live up to 150 years or more. This feature makes multitrunk trees similar to bushes, the above-ground axes of which also survive for only several decades[1].

On convex relief forms and windward slopes, where the snow cover is thin and dense, bushy forms of twisted birch are frequently seen (Figure 19, 4)[2]. Ice crust formation is the main cause of dying of the parent axis and subsequent tillering. One can frequently see severed buds and the upper parts of birch seedling shoots frozen into an ice crust.

Willow, alder, and mountain ash grow in approximately the same forms in the forest tundra and tundra. Of the conifers, only cedar stlanik is represented by a hereditarily spreading form.

Cedar stlanik is widespread in the extreme northeastern part of Asia, which was not subjected to solid glaciation; that is, in a region that is quite old from the topographical viewpoint. Protracted geographic isolation is one of the main conditions for the emergence of a new species. In the mountain valleys of northeastern Asia there was a complex of conditions that contributed to the appearance of the new species -- cedar stlanik.

Cedar stlanik is the name given to a forest-type, or treelike, bush that branches and spreads out like a small tree. Thickets of this plant are seen in large-underbrush tundra, spreading forests, and so forth. Adventive roots growing toward warm and heated sections of the soil can form on the branches of this plant if they lie on the ground. The branches, which can be mistaken for small, spreading trees, grow in this direction also.

The main root mass is usually located in the soil layer where the temperature is no lower than 5° (less frequently, 4.0-4.5°) from the last third of July to the middle third of August. Solid, dense thickets apparently cannot exist at the extreme limit of cedar stlanik's range, since the soil temperature would be below that at which root development is possible.

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[1]This "youth" (40-60 years) of multitrunk twisted birches sometimes misleads investigators, who assume that the predominance of such "young" trees at the northern and upper forest boundaries indicates an advance of the forest onto the tundra.
[2]An interesting fact is that even close to Moscow, near Tatarovo, bushy forms of cottony birch grow on the tops of morainic knolls. In winter there is little snow on these knolls, and their tops are frequently covered with an ice crust.

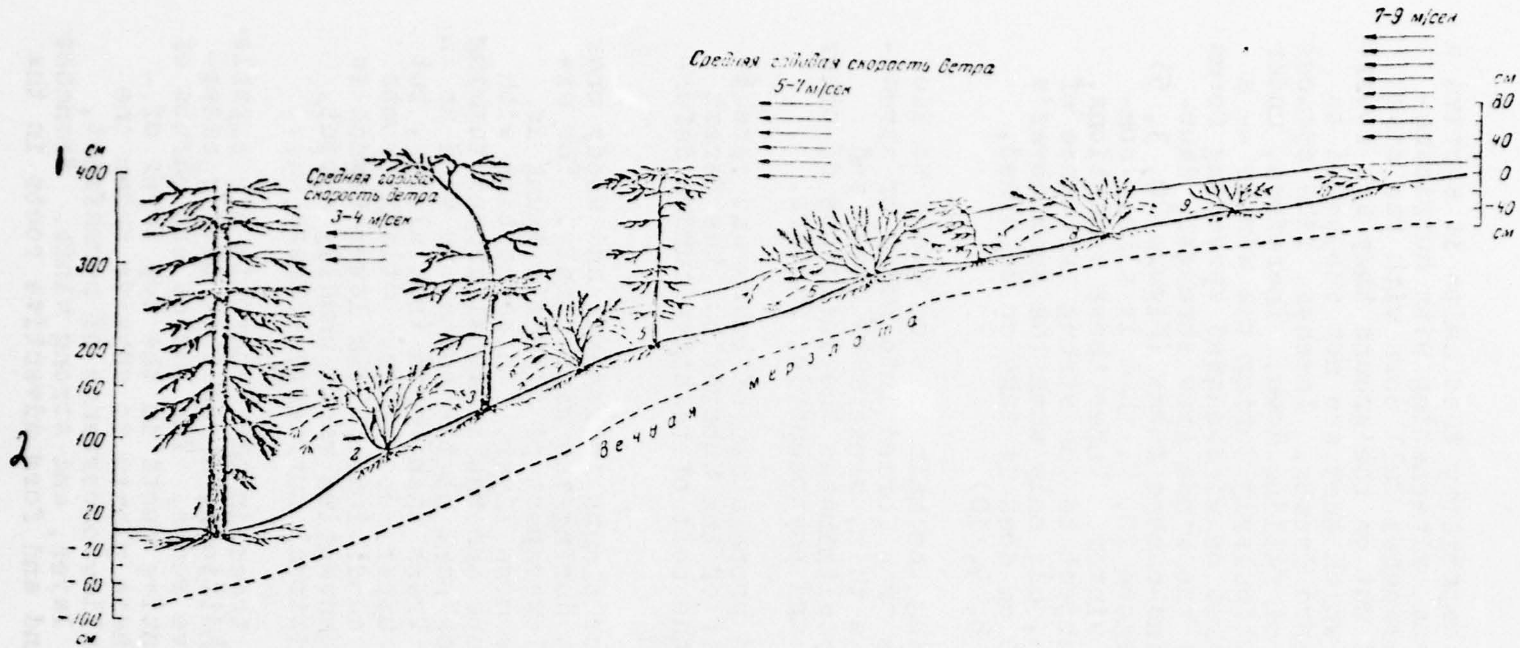

Figure 20. Growth forms of daurskaya larch and cedar stlanik: 1. normally developed larch; 3,5. wind-deformed larch shapes, growing under conditions where the winter lasts 8-9 months (sparse forest-tundra forests on plains and in the mountains); 2,4,6,8. cedar stlanik, the branches of which fall down under the influence of frost and are under the snow in winter; the dotted lines indicate the branches that fall down and are covered by snow in winter; 7. daurskaya larch, which does not have a similar adaptation, acquires a deformed, spreading form (southern underbrush tundra, relative tundra deforestation belt); 9,10. under extreme conditions of existence, with a snow cover not exceeding 20 cm, strong winds (7-9 m/sec), and a long winter (8-9 months), cedar stlanik takes on a depressed, dwarf form. Its height is basically determined by the thickness of the snow. The dotted line underneath indicates the depth of seasonal ground thawing; the solid line above -- the depth of the snow cover; on the left and right -- two scales of numbers for determining plant height, snow cover thickness, and depth of seasonal ground thawing.

Key: 1. Average annual wind velocity, ... m/sec 2. Permafrost

Cedar stlanik has an amazing capability that helps it survive a severe winter with heavy frosts, alternating with hurricane-force winds and thaws: its branches fall down with the onset of the frosts; once flattened out on the ground they are covered with snow, as a result of which they are not subjected to the action of the winds and hard frosts. Larches, like spruces and birches, are not capable of falling down. Therefore, under the influence of winds -- particularly during the winter -- a larch tree (like a spruce) takes on wind-caused spreading forms (Figures 20, 21) or dies. As the winds grow stronger, daurskaya larch first takes on wind-caused forms (Figure 20, 3, 5) and then a spreading form (Figure 20, 7) that is almost completely covered with snow in winter. Under these conditions, cedar stlanik is still not subject to the strong influence of winter winds (Figure 20, 2, 4, 6); only when the snow cover's thickness is reduced to 20-40 cm does it take on deformed, spreading shapes (Figure 20, 8, 9, 10).

Thus, the basic factors causing the main axis of trees to die, as a result of which they are transformed into bushy or spreading forms, in most cases are a thin, dense snow cover and strong winds, which in no way eliminates the influence of other climatic, as well as edaphic and phytocenotic, factors.

The area of the formation and propagation of bushy and spreading forms is the northern half of the Subarctic: the forest tundra and southern tundra (the belt of relative tundra deforestation).

The unfavorable conditions for plants in general and woody ones in particular are not present during the winter only. For example, when mosses grow the lower part of a tree's trunk is more or less submerged in the moss layer. In connection with this the soil temperature drops and the seasonal ground thawing depth decreases. In this case part of the roots can wind up in the frozen, unthawed layer. Trees then begin (not always, but quite frequently) to form an upper root stage. Stlanik roots grow more easily under these conditions. If a lower branch is covered with growing mosses, adventive roots usually sprout, providing the plant with additional nutrients (Figure 22).

When they are young, all the trees in the Subarctic are capable of forming, under extreme conditions, spreading, bushy, creeping growth forms and adventive roots. The bushes and shrubs of the Subarctic also grow adventive roots in the top layer of soil, which enables all of these plants to survive under the very severe conditions of shallow occurrence of permafrost, continual growth of the moss layer, and strong winds. Branches that flatten out on the ground and form adventive roots in the

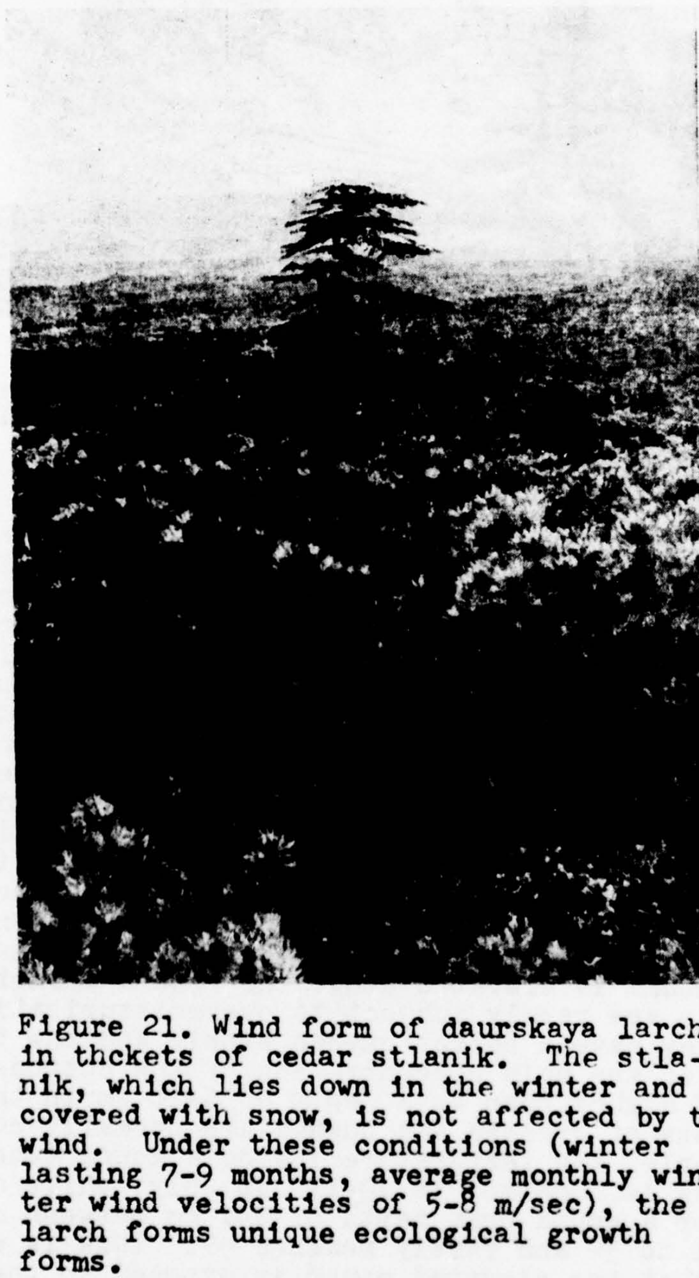

Figure 21. Wind form of daurskaya larch in thckets of cedar stlanik. The stlanik, which lies down in the winter and is covered with snow, is not affected by the wind. Under these conditions (winter lasting 7-9 months, average monthly winter wind velocities of 5-8 m/sec), the larch forms unique ecological growth forms.

topmost layer of soil give these plants the capability of using the warmest layer of air and soil.

Because of the very severe conditions, plants in the Far North do not produce seeds every year. For annuals, the absence of

Figure 22. Growth of moss layer (dark area) in the trunk area of a tree resulted in a situation where the bottom branch was buried by moss, thereby causing the formation of adventive roots.

mature seeds is equivalent to dying. This is why there are so few annuals in the Subarctic. Even under the conditions encountered in the central, typical taiga they total no more than 5 percent of the total number of species growing there, while in the northern part of the Subarctic, in the mossy-lichen and Arctic tundra subzones this figure drops to about 1 percent. Perennials can also multiply by the vegetative method. They do not have to begin again from a seed every season. One of the most widespread perennials in the Subarctic is the herbaceous plant ocreate cotton-grass, which usually forms mounds (Figure 23). In the Asiatic part of the Subarctic, and particularly in the tundra zone, such mounds occupy extensive areas (Figure 24), and to the east of the Lena River they in essence form a subzone of the tundra. The mound's shape is very convenient, since it provides the plant with the best hydrothermal conditions. The mound is elevated above the ground's surface, so that its roots are rarely subject to overmoisturization. Consequently, they have a better oxygen supply and the temperature at the point of the main concentration of the cotton-grass's roots is 5-8° higher than at a depth of 5-10 cm in the ground, where the roots of grasses and bushes are normally concentrated. For example, the temperature inside a mound (where the main root mass is located) is 10-11° in July, while at a depth of 10 cm under a mound or a depth of 5-7 cm between mounds it varies from 1 to 3° and rarely reaches 4°. This is explained by the fact that the elevated mound is exposed to the sun and is additionally heated because of this. New mounds form only through seed regeneration of the cotton-grass, since its vegetative multiplication takes place only inside a mound. The cotton-grass bears fruit quite infrequently, but when a new plant appears, it is usually through branching and the

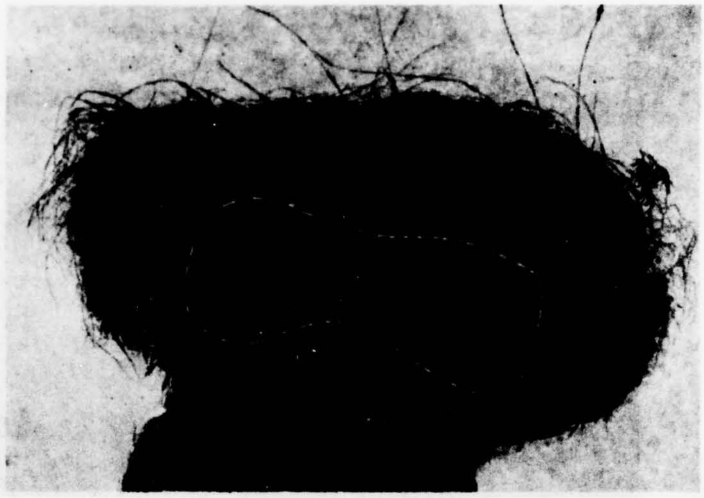

Figure 23. Mound formed by ocreate cotton-grass growing a great number of shoots connected to each other by short rhizomes. The dotted line indicates the area where decomposition of the shoots and rhizomes occurs. Together with the additional solar heating of the mound, this contributes to a slight increase in temperature inside it.

formation of a new individual plant that eventually grows into a mound, while the mounds live for several decades and even up to 100 years or more.

The next adaptive property of high-latitude plants is the abundance of evergreen species: marsh tea, bilberry, ordinary bearberry, Dryadaceae (partridge grass), Alpine arktous [translation unknown], several species of cassiopeium, butterbur (andromeda), lying louzeleriy [translation unknown] and other small bushes that can be covered by the snow. As soon as such plants are freed from the snow, they immediately begin assimilation, which is very important when the summer is short.

The basic reason for the plants' resistance to frosts, which can occur in the Subarctic even during the summer, is their high concentration of cell fluid, thanks to which the plants' freezing temperature is lowered.

The biological productivity of the plants in the Subarctic is low. For instance, according to V.N. Andreyev's data [1], in the Eastern European sector of the North the growth (in the

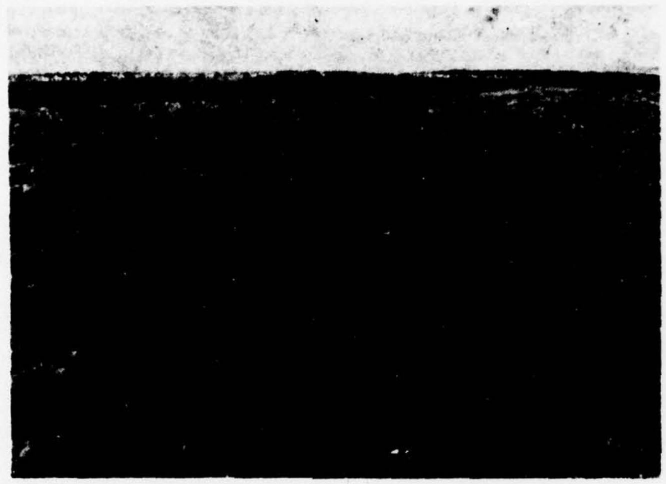

Figure 24. Mounded tundra in peaty-gleyey loamy soils.

numerator) and reserve (in the denominator) of the above-ground phytomass (air-dried state, in quintals per hectare)[1] are as follows: Arctic tundra, 7.0/12.4; typical tundra, 11.4/29.6; southern tundra, 8.7/31.6; forest tundra, 11.0/72.7; thin northern-taiga forests, 11.8/119.7. From these materials it is obvious that the growth of the phytomass from the Arctic tundra to the thin northern-taiga forests increases by 4.8 quintals, while the total phytomass reserve is much greater -- it increases by a factor of almost 10. Such a regularity is also common to other regions of the Subarctic.

These bioclimatic features are of decisive value for soil formation and the fauna of the Subarctic.

The most important common features of the soil-formation factors in the Subarctic are: 1) a heat deficit and excessive atmospheric moisturization; 2) the protracted winter period with air temperatures below zero and universal development of soil freezing and thawing processes; permafrost, which also plays a large role in soil formation in the Subarctic; 3) the predominance of bush-shrub and moss-lichen soil covers with surface distribution of the root biomass and primarily surface onset of shedding; 4) little annual growth and shedding; low capacity and intensity of the biological circulation of substances,

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[1]The air-dried state of plants begins after they are dried in open air at a temperature of 15-25°.

which embraces primarily the upper levels of the mineral stratum. V.O. Targul'yan showed [19] that the bioclimatic conditions for soil formation in the tundra, forest tundra, and northern taiga (cold, humid areas) are in principle monotypical and that the indicators characterizing them change only quantitatively.

For watershed areas in the Subarctic (cold, humid areas), Targul'yan distinguishes two different epitypical groups of soils.

The first group is nongleyey soils with free internal drainage. In them, excess atmospheric moisturization is not realized in the persistent overmoisturization and gleying of the profile. These soils form under conditions of well fragmented watersheds in stony and silt-rock soils where the permafrost level lies rather deep.

The second group consists of gleyey soils with hampered internal drainage. They have developed in loam-clay and layered sandy-loam rocks in which excess atmospheric moisture is realized as persistent overmoisturization and gleying of the entire soil profile and its significant part.

Soil gleying -- this is a soil-forming process that takes place under anaerobic (without access to the oxygen in the air) conditions, with the participation of micro-organisms, the presence of organic matter, and constant or protracted flooding of the individual levels or the entire soil profile.

Soil gleying is accompanied by the conversion of acid compounds into oxides, an increase in density, and a decrease in porosity. The external indicator of soil gleying is specific coloration with dove-colored, azure, and dark-blue tints. A gleyed level is designated by the symbol Gl.

The first group of soils, with free internal drainage, is subdivided into two subgroups.

1. Soils with a brown, morphologically unpodsolized profile are subbrowns. The following profile structure is typical for them: an organoaccumulative horizon (A_0); an illuvial inwash horizon lying under the organoaccumulative one that is reddish-brown or dark and light brown. Below this, there is soil-forming rock (the C horizon). The subbrowns are encountered in all zones and subzones of the Subarctic (cold, humid areas), but are most common in continental regions.

2. Podsolic illuvial-alumo-ferro-humus soils. The profile consists of the following horizons: organoaccumulative horizon

A_0, podsolic outwash horizon A_2, illuvial inwash horizon B, and soil-forming rock. These soils are formed in a subzone of the southern tundra, the forest tundra, and the northern taiga. They do not occur in the Arctic and typical tundra and the coldest sectors of the forest tundra and northern taiga in Yakutiya. The soils in this subgroup have developed in different rocks, but only where they contain bright minerals (quartz, potash-sodium feldspars that are bright or capable of clarifying layered silicates) that are resistant to weathering. Soils with a podsolic profile do not form in the basic quartzfree rocks consisting of dark-colored, unresistant minerals.

The second group, gleyed soils with hampered internal drainage, are also subdivided into two subgroups.

1. Soils with a differentiated gleyed profile. A characteristic of soils in this subgroup is stable gleying in the upper (A_0-A_2gl-A_2Bgl-B_1-B_2-C), middle (A_0-A_2-B_1gl-B_2gl-C), or lower (A_0-A_2-B_1-B_2gl-Gl) sections of the profile, in combination with fragmentation of the profile into eluvial and eluvial-illuvial horizons. The most common members of this subgroup with its differentiated gleyed profile are gley-podsolic and podsolic-gleyed soils of atmospheric moisturization.

2. Soils with a homogeneous gleyed profile, a characteristic of which is persistent overmoisturization and gleying of the entire soil profile. In such soils, the frozen, water-resistant level lies at a depth of 0.4-1.0 m. However, the presence of a frozen horizon impervious to water is not a mandatory condition. These soils form in seasonally frozen rocks, particularly on the Kola Peninsula. The degree of overmoisturization and gleying in the soils of this subgroup can vary quite widely -- from slightly gleyed (Arctic and typical tundra) to heavily gleyed, usually solifluction and thixotropic soils (southern tundra, forest tundra, northern taiga).

Both subgroups of gleyed soils have developed extensively in the Subarctic in clay-loam low-rock or layered sand-loam rocks.

Targul'yan emphasizes that the basic causes of the differences between these groups and subgroups are differences in the mechanical composition of the soil and soil-forming rock and the degree of fragmentation of the watershed territories. Each of these types of soil profiles includes tundra, forest tundra, and northern taiga soil profiles with similar structures. At the same time, a regular dependence on bioclimatic conditions is seen in the dissemination and combination of these types of soil profiles.

Fauna

The severe, protracted winter, the small amount of food available during this time, and the absence of cover where an animal might find shelter during snowstorms and hard frosts -- all of these cause the migration of the overwhelming number of Subarctic animals to more southerly regions. Even the white polar owls and tundra partridge, which winter in the Subarctic, frequently leave the most unfavorable regions and migrate a little southward. The migration of wild reindeer is a particularly majestic sight. The largest herd of wild reindeer, numbering about 350,000, is on the Taymyr Peninsula. In summer they move into the tundra areas, where there is sufficient food for them and the wind drives off the mosquitoes, while in winter they set off for the southern regions of the forest tundra and northern taiga. Wolves usually move with the wild reindeer herds.

Birds are most adaptable to migration. In general, in the Subarctic birds are sharply predominant over the other vertebrate animals: according to calculations made by S.M. Uspenskiy [22], in the Arctic and Subarctic there are more than 90 species of birds and about 20 species of mammals. Their mobility and rapidity of movement enables birds to make fuller use of the short northern summer and the adequate amount of food during this period.

We have already spoken of the fact that the excess of precipitation over evaporation causes greater flooding in the Subarctic than in other zones of Earth. One of the consequences of the huge amount of water in the Subarctic is the prevalence there of birds related to swamps, lakes, and rivers. We will name only a few of them: ducks (whistling teal, eider, kamenushka, moryanka, turpan, shilokhvost', sviyaz', sredniy krokhal', nyrok [translations unknown], and others), geese (white, barnacle, belolobyy, gumennik, piskul'ka [translations unknown]), snipe (ruff, sparrow snipe, common and Asiatic snipe, great snipe, brown-winged plover, kulichok-lopaten', malyy veretennik, garshnep, tules [translations unknown]), loons (red-necked, black-necked, white-billed), gulls (silver, grey, fork-tailed, burgomaster, rosy, polar krachka [translation unknown], and others), cranes (Canadian, sterkh [translation unknown]), swans.

The life of the animals and waterfowl is especially rigidly limited by heat. For example, for the most northern waterfowl, the red-necked loon and the moryanka, the nesting period lasts 60-70 days. This means that if the open-water period on the water areas lasts less than 60 days, it is impossible for a single species of bird to reproduce itself. Waterfowl with a nesting period longer than 80 days usually do not nest in the tundra and forest tundra. Under these conditions fledglings do not have time to grow up, and they die during the period of stable ice on open water; that is, a slight cooling that will extend the ice regime by several days can prove fatal to the life of birds. The open-water period is extended by an insignificant increase in temperature, and waterfowl can move quickly to the north.

Fluctuations in summer temperatures also affect other animals, causing a unique pulsation in their range, including the nesting areal. For example, in normal years the tundra partridge on the Taymyr Peninsula nests in the Arctic and typical (sedge-and-moss) tundra subzones; the white partridge in the typical and southern (underbrush) subzones, as well as the forest tundra. In cold years with a lingering spring, these birds' nesting areals are sharply reduced: the tundra partridge is almost not seen in the Arctic tundra, but concentrates in the sedge-and-moss area, while the white partridge confines itself to the underbrush subzone of the tundra. In such years, broods of fledglings are small -- 2-3 instead of 8-9 -- and the number of nesting pairs is 1-3 per square kilometer instead of 8-10. When spring lingers on for an exceptionally long time, the partridges occupying the nesting sections just do not reproduce (as was the case on the Taymyr Peninsula in 1968).

There was a dramatic situation for the white geese on Vrangel' Island in 1974. In the first third of June, the birds were already sitting on their eggs. On 13 June, however, a blizzard began and lasted 3 days. Part of the birds left the nest, but many remained to warm their eggs. After the blizzard, only the heads of the birds protruded above the snow drifts. Many white geese died this year from the bad weather, cold, hunger, and predators. Not one fledgling hatched. Such years occur frequently in the North. However, when the white geese numbered about 100,000, this was not dangerous for their survival as a species. Now there are only a few thousand of them. Hunting for white geese is forbidden in the Soviet Union, but in the United States where they winter, they are still hunted.

Under the conditions of the short summer, the protracted day enables animals and birds to be especially active for 18-20 hours, which is favorable to more rapid fattening and growth of the young than in southern latitudes with their short day. If the day were shorter, then many birds would not be able to reproduce and raise their fledglings under the conditions of the short polar summer.

Thus, birds -- and other animals -- are far from being able to raise progeny every year. The long, severe winters in the Subarctic also have a negative effect on such large animals as elk, particularly if the snow depth exceeds 80-90 cm. They find it difficult to move through the deep snow in search of food. They get weak, sicken more quickly, and become the prey of predators or simply die from exhaustion.

The severe conditions and shortage of food contributes to the fact that in the Arctic and Subarctic, most of the animals are distinguished by polyphagia. Snow buntings eat Lapland plantain, and insects, and plant seeds. The pomornik [translation unknown] eats fish, mouselike rodents, birds and their eggs, insects, carrion, plant leaves, and berries. The polar fox is also carnivorous. Even reindeer eat not only lichens, but also grasses, bushes, fungi. Because of the shortage of mineral matter in the plants, reindeer eat lemmings, mice, fledglings and bird eggs, and the excrement of some animals.

To a considerable extent, animal interrelationships are determined by the food chain. If these relationships are disrupted for some reason or other, this affects the entire ecosystem. Any ecosystem can be represented as a unique productivity pyramid and energy pyramid. This is frequently called the pyramid number, or Elton's pyramid, after the eminent English ecologist Charles Elton, who substantiated it theoretically [28]. At the base of the pyramid lies the mass of producer plants[1]. The severer the conditions, the less phytomass per unit of area, and vice versa. Above this base (the producer plants) are the herbivorous animals, with considerably less mass. For instance, on typical tundra the growth is 11-12 q/ha, while the above-ground phytomass is approximately 30 q/ha. On the Taymyr Peninsula in summer, there are 135 reindeer per 1,000 ha, and their biomass is 12.1 kg/ha [30]. The mass of lemmings is approximately the same in normal ("unharvested") years. Let us assume that all other herbivorous animals are also about 12 kg/ha. Their total mass is then about 36-40 kg/ha. This is high for the tundra. Somewhat smaller figures are usually cited. On the other hand, however, this is slightly less than one-thirtieth of the growth and less than the total phytomass weight by a factor of 75. This is the second level of the productivity pyramid.

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[1]Producer plants are autotrophic plants capable of living on nonorganic soil matter, water, and air, and creating from them all their own organic matter. All animals (including man), which are heterotrophic organisms, feed on producer plants.

The next level is the predators. One of the most common predators in the Subarctic is the white polar owl. Each pair of owls nests 2-3 km apart and hunts over an area of 13-30 km^2 (1,300-3,000 ha). A family of owls eats 2,000-2,600 lemmings during a summer (according to Uspenskiy's data [22]). The weight of a lemming averages 80 g. The total weight of the lemmings eaten by a family of owls is 160-208 kg; that is, to feed a family of predators (weighing a total of several kilograms) it takes about 200 kg of meat. The owls' biomass per hectare is several grams. If we also take the other predators (birds and mammals) into consideration, this figure apparently rises to several dozen or hundreds of grams per hectare.

Thus, the productivity pyramid in the Subarctic tundras is approximately as follows: above-ground phytomass -- about 3,000 kg/ha; phytomass growth -- 1,100-1,200 kg/ha; herbivorous animal biomass -- about 40 kg/ha. The predators' biomass ranges from several dozen to several hundred grams per hectare. These are very approximate figures, but they give a general idea about the nature of the productivity of Subarctic ecosystems. This is the key to determining the reindeer capacity of pastures[1], as well as the feasibility of fur farms. Actually, predators are raised on fur farms. They are representatives of the highest level of the ecological pyramid, each of which under the natural conditions of the Subarctic requires its own hunting area of several dozen and even hundreds of square kilometers. In such situations, it is always necessary to make exact calculations and be oriented toward cheap, primarily local foods (fish of little value, waste products from reindeer slaughters, and so on). If this is not taken into consideration, then the animals in the cages will either die or it will be necessary to kill elk, feed them canned food, and so on (Syroyechkovskiy [18]).

This rule also makes it possible to calculate the optimum sizes of game preserves in each of the natural zones, including the Subarctic. For any type of animal there is a definite optimum population that insures reproduction and normal functioning of the ecosystem, which is especially necessary for game

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[1]The reindeer capacity of a pasture is determined by the number of reindeer that can feed in a specific area during an established unit of time. Exceeding a pasture's reindeer capacity means that phytomass consumption is greater than its growth; the vegetation is exhausted and the pasture deteriorates. Pasturing a lesser number of reindeer than the natural reindeer capacity leads to incomplete utilization of vegetative food and underproduction in reindeer breeding.

preserves -- the standards of nature. It is a well known fact that in the tundra zone, the same species of predators control considerably larger areas than in the forest zone. For example, in the forest zone sapsan [translation unknown] hawks nest 3-5 km apart, while in the tundra they are 15-20 km apart. This is in favorable years, when there are many birds and other animals. In bad years there are fewer predators per unit of area and the areas that they control get larger. Thus, if all of this is taken into consideration and we assume that 50 pairs of animals is the minimum population to insure reproduction and normal functioning of the ecosystem, we find that in the continental part of the tundra zone, where the animals have nothing to do with the sea, the size of the game preserves must be much larger in comparison with preserves located in more southerly zones (Figure 25). Calculations indicate that in order for tundra game preserves to be self-regulating ecosystems, they must occupy an area of about 10,000 km^2 (or 1 million hectares).

In the forest zone, self-regulation can be achieved in a much smaller area. For example, Isle Royale National Park (United States), the area of which is 550 km^2, is a stable, self-regulating ecosystem in the opinion of investigators[1]. In the park there are several dozen wolves (one wolf per 25-26 km^2), about 1,000 elk, and 2,000 beaver.

Sharp and frequent fluctuations in animal populations are characteristic in the high latitudes. For the forest zone this runs in 10-12 year cycles, while for the forest tundra and tundra zones they are 2-4 year cycles. Cycles of population fluctuations have been seen for 15-20 animal species in the Subarctic (lemmings, hares, partridges, owls, polar foxes, kanyuk [translation unknown], and others). They are manifested particularly graphically in the case of lemmings. Every 3-4 years their number increases to several thousand per hectare (lemming years); between these periods the lemming population decreases sharply. In lemming years, polar foxes have 10-15 pups in a burrow and white owls lay 9-10 eggs. At this time on the tundra there are many shaggy-legged kanyuki, gulls, and pomorniki. In periods when there are few lemmings, fox dens are either empty or there are only two or three pups in them; the white owls also lay few eggs. However, it is not only the foxes and owls that suffer. These predators, in turn, switch over to snipe, ducks, geese, eiders, and partridges, destroying their nests, eating the fledglings and, indeed, the adult birds are

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[1]Durward, A., "Of Fire, Moose, and Wolves," AUDUBON, Vol 76, No 6, 1974.

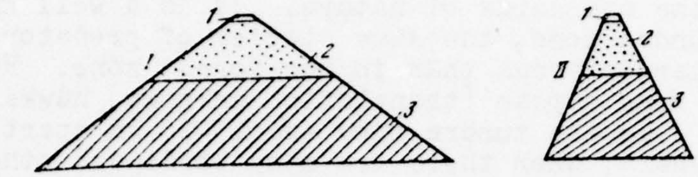

Figure 25. Productivity pyramid, which can serve as a guideline for determining the size of game preserves as self-regulating ecosystems: I. in the tundra zone; II. in the forest zone; 1. predators in the upper part of the pyramid; 2. herbivorous animals; the same biomass in the tundra zone is dispersed over a much greater area than in the forest zone; 3. phytomass; the quantity of it concentrated on 1 hectare in the forest zone is scattered over dozens of hectares in the tundra zone, so the area of game preserves in the tundra must be considerably larger than in the forest zone.

also killed more frequently by predators at this time. In lemming years, procuring organizations obtain greater quantities of eiderdown while, on the contrary, in "poor crop" years they receive very little, since the eiders' nest are heavily destroyed by foxes, white owls, and other predators.

The causes of lemming cycles have not yet been conclusively determined. There is apparently a complex of causes in operation here. For example, although during the time of mass lemming deaths when they reach a large population there is no substantial decrease in vegetative food, this still cannot be rejected as a possible cause. In lemming years, thousands of animals inhabit a single hectare. For an average lemming weight of 80 g, their total mass reaches several quintals; that is, their mass becomes almost equal to the annual plant growth. The protracted existence of such a number of animals is impossible, even if it were to depend on food availability alone. Investigators think stress states, with their typical low content of sugar in the blood, exhaustion, convulsions, and death, play a large role in their dying.

Temperature fluctuations, which have a large influence on the life of animals and the number of abandoned young, and cyclic changes in their populations (more frequent and abrupt than in other zones) -- all of this in combination with other causes draws us an unambiguous picture of the dynamic nature of the Subarctic and its sensitivity to any deviations.

Boundaries of the Subarctic

The material that we have been discussing indicates that nature in the Subarctic is very specific. It is different from nature in the regions adjacent to it. Climatic and soil features explain the greater area (in comparison with other physico-geographic belts) of the lakes and swampy areas in the Subarctic. Here the annual water runoff is at its highest. Another characteristic of the Subarctic zones -- tundra, forest tundra, northern taiga -- is subsurface glaciation with a huge amount of subsurface ice, which causes continuous deformation of the earth's surface and the formation of thermokarst relief forms. The small total phytomass and its small annual growth, the small number of roots binding the soil, the vulnerability of the plants, frequent temperature transitions through 0°, the presence of permafrost -- all of these contribute to the specific zonal microrelief forms: polygonal-mottled formations. Low-fertility soils and an abundance of plants possessing the property of symbiotrophism (the ability of obtaining deficit nutritive elements through the symbiosis of higher plants with fungi-mycorhiza formers), cold soils and rootless plants -- mosses and lichens that have little dependence on soil -- all of these are features of the Subarctic. Another peculiarity is the continuous migration of animals: in summer, large accumulations of birds and animals in the tundra and forest tundra; in winter, the flight of a large part of the birds to the south, beyond the limits of the Subarctic, and the migration of reindeer and other animals onto the northern taiga, on the southern limits of the Subarctic.

Before we start defining the Subarctic's boundaries, let us briefly examine the features of the typical Arctic (or Arctic deserts) and typical taiga. Ye.S. Korotkevich devoted his monograph "Polar Deserts" [10] to this subject, and in it he first summarized the huge amount of material on these little-studied zones in both the northern and southern hemispheres of our planet.

The polar, Arctic deserts -- that is, the Arctic itself -- have a positive or negative radiation balance that averages close to zero as the result of the snow and ice surface's high albedo. Progressive cooling does not take place, however, because of heat advection by air and ocean currents from the lower latitudes. The temperature of the warmest month is negative or close to zero. The cold air cannot hold large amounts of moisture, so its absolute humidity is low -- fractions of a millibar. In connection with this, when there is a slight increase in temperature, a moisture deficit sets in; many regions in the Arctic deserts have a low relative air humidity, reaching 5-10 percent, which is also seen only in hot desert zones. Precipitation is insignificant -- 50-150 mm. Evaporation frequently exceeds precipitation. In low-temperature regions (the warmest month is still below zero), where abundant thawing is excluded and the snow cover does not disappear in summer, glaciers form. These and other features of the Arctic deserts' climate gave Korotkevich grounds for placing them in a special zone distinct from the tundra zone. Summarizing his materials and conclusions on the climate, Korotkevich wrote: "The climate of the polar desert zone is a climate of constant frost, low moisture content, and solid precipitation."

The next difference is that ground (fossil) ice is developed only slightly and to a considerably lesser extent in the Arctic deserts than in the tundra, and as a result of this, "thermokarst does not develop in the polar deserts, for all practical purposes, and cracks contouring polygons frequently do not have glacial wedges" [10].

The landscapes of the Arctic deserts are young, the river network is weakly developed, and the valleys are worked out poorly. Extensive drainless areas are common. There are no swamps. Primitive, skeleton soils containing almost no humus predominate, the surface of which is split by frost clefts. Because of the shortage of moisture, soil gleying is not seen. The moisture regime is characterized by rising flows of solvents, which frequently lead to the accumulation of salts in the upper part of the soil layer. Soil micro-organism activity is seen only from the second half of July to the beginning of August.

The low temperatures and shortage of moisture determine the vegetation of the Arctic deserts. Vascular plants are encountered as individual examples or groups, and do not form phytocenoses -- plant communities with interlocking roots. Nor are mosses the dominant plants, because of the low temperatures and, in particular, the dryness. The most common plants in the Arctic desert zone -- the Arctic proper -- are lichens (scale lichens, in particular), as well as bacteria and algae (primarily blue-green). The few vascular plants have the same features for adaptation against desiccation as plants in the low-latitude deserts: small leaves, lowering, a waxy coating, leathery skins on their leaves. The surface phytomass is larger than the subterranean. All of this also distinguishes the Arctic deserts from the tundra zone, where the subsurface plant mass -- the roots -- is greater than the above-ground mass.

The poor vegetative cover cannot serve as a food base for large or numerous land animals. In the Arctic deserts, therefore, there are no trophically (for purposes of feeding) land-related mammals, few land birds, and no freshwater fish. Here the only animals that can exist are invertebrates, feeding on sparse plant remnants or the few live plants. Fauna that is trophically related to the sea is plentiful (birds, mammals). The biogeocenoses of the Arctic deserts are extremely poor and simple. There is no competition between organisms; there is only consumption of some organisms by others. Predation is weakly developed. In the tundra zone, however, the trophic relationships in the biogeocenoses are considerably more complicated because of the large role (and frequently predominance) in the biomass of vertebrates with different feeding relationships and the abundance and diversity of invertebrates.

We think that the zone of polar Arctic deserts should be regarded as the typical Arctic.

Let us now turn to the main features of nature in typical taiga. Here the radiation balance is 15-30 kcal/cm^2; 70-90 percent of the radiated heat arrives during the summer. The average July temperature is 14-17°. Precipitation is 400-700 mm while evaporation is 250-500 mm, causes an excess of surface water, the shallow occurrence of ground water, widespread swamps, a dense river network and an abundance of water in the rivers, soil erosion conditions, and the formation of typical podsolic soils. In the northern taiga the podsolic process is complicated to a considerable extent by gleying, while in the southern it is mixed with sodding. Frozen-taiga soils form in Siberia, in the presence of permafrost. Erosion develops only when there is artificial reduction of the forests, and thermokarst only in the Eastern Siberian light-con er taiga, which is on permafrost, when there is significant climatic warming or the same artificial reduction of the forests.

These climatic and soil features are responsible for the vegetative cover of the typical taiga. In this area trees find their ecological optimum and form joined stands. A tree, as is known, is the plant life form that is most demanding as to environmental conditions. Shade-enduring and shade-loving plants live under the sloping, joined stands of trees.

The large amount of phytomass and the abundance of ecological niches is responsible for the wealth of fauna. Animals can find shelter under the ground and on its surface, in thickets of bushes and the tops of trees at various heights, in hollows and in loose snow. The taiga provides animals with food (grasses, small bushes, leave, tree and bush branches, buds, sees, needles, berries, fungi, tree bark, and so on) on a year-round basis. Here we find: elk, reindeer, brown bears, squirrels, chipmunks, white hares, mouselike rodents, lynx, wolves, sable, and so on; birds: wood grouse, hazel grouse, crossbill, woodpeckers, cuckoos, shaggy-legged owls, accipitral owls, kedrovka [translation unknown], and so on. In the typical taiga we begin to see reptiles: the common viper, viviparous lizards, the common grass snake; several species of amphibians are encountered. The trophic relationships in the forest ecosystems are very complex, just as the taiga ecosystems (biogeocenoses) themselves are.

Even this very brief list of the features of nature in the typical Arctic (the deserts of the Arctic belt) and the typical taiga in the temperate zone is indicative of the profound difference between them.

Now, let us attempt to define the boundaries of the Subarctic. Drawing boundaries between natural geographic zones is not a simple matter. For this reason these questions are always controversial, and it may be the case that there is not a single natural zone for which scientists would have a unanimous opinion as far as its boundaries are concerned. In this respect, the zones of the Subarctic are no exception: tundra, forest tundra, northern taiga. A brief history of what the Subarctic is and where its boundaries are, is as follows. The author of the first integrated work on the Subarctic, Academician A.A. Grigor'yev, wrote: "The Subarctic belt, which by the nature of its vegetative cover is also called the tundra zone, envelops both the Subarctic and Arctic tundras of geobotanists"[1]. Grigor'yev did not include the forest tundra and northern sparse forest zone in his work "The Subarctic" [5]. However, in Volume 4 of the "Short Geographic Encyclopedia" (KGE), the chief editor of which was A.A. Grigor'yev, in the article "The Subarctic Belt" (KGE, Vol 4, 1964, p 32) it is written that the Subarctic consists of not only the tundra, but also the forest-tundra zone. This viewpoint now divides most investigators of the North. Moreover, as our knowledge about the Far North's natural zone grows, there is a growing trend toward expanding the boundaries of the Subarctic. It has already been mentioned that the hypo-Arctic belt, which is distinguished by botanical features, also includes the northern taiga. Its southern boundaries almost coincide with those of the Subarctic belt as given in the "Physicogeographic Atlas of the World" (1964). The cold, humid areas, distinguished by Targul'yan according to soil features, also include the northern taiga and coincide with the hypo-Arctic belt and the Subarctic. The Subarctic's southern boundary, as established according to botanical and soil

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[1]Grigor'yev, A.A. IZBRANNYYE TEORETICHESKIYE RABOTY [Collected Theoretical Works], Moscow, Izd-vo Mysl', 1970, 255.

features, coincides with the southern boundary of the range of the zonal relief forms known as polygonal-mottled formations, which -- although rarely -- are still seen in the northern taiga. This coincidence of three boundaries cannot be accidental: it is explained by a complex of physicogeographic factors.

Typical zonal vegetative communities (phytocenoses) and soils are those that are located in level watershed areas composed of loams. Such sections are called plakory. The northern boundary of the natural geographic zone is considered to be the line (or even belt) connecting plakor locations in which the soil and vegetative complexes (more accurately, biogeocenoses) typical of the given zone first appear. The zone's southern boundary is the belt where the typical biogeocenoses disapp ar from the plakory.

In the Arctic deserts (the typical Arctic), the species composition of flowering plants is very poor. On the plakory they grow in isolation and do not form phytocenoses; that is, plant communities that would be joined by surface or subsurface (root) parts.

Among the distinguishing features of the polar-desert type of vegetation native to the Arctic, geobotanist V.D. Aleksandrov includes: 1) uniqueness of the structure of the vegetative cover, which forms a thin layer in the form of an incrustation on the substrate's surface that ranges in thickness from several millimeters to 2-3 cm, the base of which consists of sporophytes -- lichens (usually of the scale type), fine mosses, and slimy lichens and algae; the flowering plants are embedded in the layer of sporophytes and usually do not rise above them; 2) complete reduction of multistage activity; 3) absence of a seasonal change in appearance; 4) absolute pre minance of lichens in the living vegetative mass; 5) predominance of above-ground over underground phytomass (the opposite of the ratio in the tundra zone).

Areas devoid of vegetative cover are abundant in the polar desert and frequently predominate. Here, polygonal-mottled formations, stone polygons, and so on are widely disseminated, as we have already seen. As we move to the south, however, the number of flowering plants on the plakory increases, and where there is sufficient heat they form communities on the plakory that have interlocking root systems. The average air temperature in July is 4-6° at a height of 2 m, while during the day it frequently exceeds 10° in the surface layer. This is the northern boundary of the tundra zone, which even Grigor'yev includ d in the Subarctic; that is, it is the boundary between the Arctic and Subarctic (see Figure 26). The tundra zone's southern boundary is located where forest islands begin to be seen and become normal on the plakory. The trees in these forest islands are well spaced, but their roots -- in the topmost soil layer -- occupy a large area and are interconnected. In the forest-tundra zone, the same forest biogeocenoses are seen as in the tundra zone. However, the further south we move, the more rarely will we see on the plakory tundra plant communities, within the boundaries of which the tundra biogeocenoses are contained. Where the tundra phytocenoses finally disappear from the plakory is the southern boundary of the forest tundra and, of course, the northern boundary of the taiga.

It has recently been established that intensified competition among tree roots in the thin, seasonally thawed surface layer in sparse forests leaves little opportunity for the existence of the root systems of other plants. Therefore, this structure enables the tree roots in sparsely forested islands to retain their dominant role and, at the same time, contribute to the maximum intensification of the dominating role of rootlees plants -- mosses and lichens.

Stands of trees in the northern taiga are well spaced, as a result of which the ground and the tree trunks are not completely shaded and are additionally heated by the Sun's rays during the short, cool summer. The sparseness of the stands strengthens the position of light-requiring Subarctic plants in comparison with typical shade-requiring forest plants (pyrole, club mosses, oxalis, maynik, sedmichnik [translations unknown], and some species of ferns). As we move to the south, the taiga phytocenoses become more connected and dense, and the number of Subarctic (hypo-Arctic) plants under their canopy decreases. At the point where closed stands of conifers begin to completely dominate the watersheds, controlling the lower plant stages, is the southern boundary of the northern taiga and the Subarctic. This boundary coincides with the southern boundary of the range of subbrown soils, hypo-Arctic bushes and shrubs, and zonal polygonal-mottled formations. This is the closed-forest boundary of the temperate zone. Here trees find the most favorable conditions for their growth and development.

The material in this section indicates that the differences between the natural zones are primarily bioclimatic. And plant communities are sensitive indicators of these differences. At the same time, the plant communities themselves determine to a considerable extent the nature of soil formation and the quantitative and qualitative composition of the fauna; that is, the boundaries between natural zones must be drawn where there is a change in biogeocenoses. These will be the most accurate and integrated boundaries. No one has doubts about the necessity for drawing boundaries between natural zones and physicogeographic belts. However, boundaries established with a mechanical set of indicators -- latitude, number of days with one temperature or another, type of freezing, radiation balance, and so forth -- are frequently called integrated when they are no such thing. It is necessary to look for integrated indices in nature itself, which allows us to do it. They are the biogeocenoses. The Subarctic can be defined as the natural (physicogeographic) belt with very large daily (more than 30°) and seasonal (more than 90°) temperature fluctuations, the largest water supply and the greatest reserves of subsurface ice, continuous deformation of the ground surface, very sharp seasonal changes in the areals of animals, and constant migration of these animals. This dynamicity and instability of nature are responsible for its extraordinary vulnerability and sensitivity to any deviations and influences, which cause a chain reaction throughout all branches of the ecological system.

Key to Figure 26 (see next page):

1. Boundary between the Arctic and Subarctic -- northern boundary of the tundra zone
2. Northern boundary of the forest tundra and thin forests -- southern boundary of the tundra zone
3. Southern boundary of the forest tundra and thin forests -- northern boundary of the northern-taiga forests
4. Southern boundary of the northern-taiga forests -- southern boundary of the Subarctic
5. July 10° isotherm
6. Belt of relative tundra deforestation; to the north, belt of absolute tundra deforestation
7. Forest islands in the tundra
8. Southern boundary of permafrost
9. Temperature isolines at depth of layer with annual fluctuations
10. Mountain tundras, sparse bald-peak vegetation; on the Taymyr Peninsula -- mountainous Arctic deserts

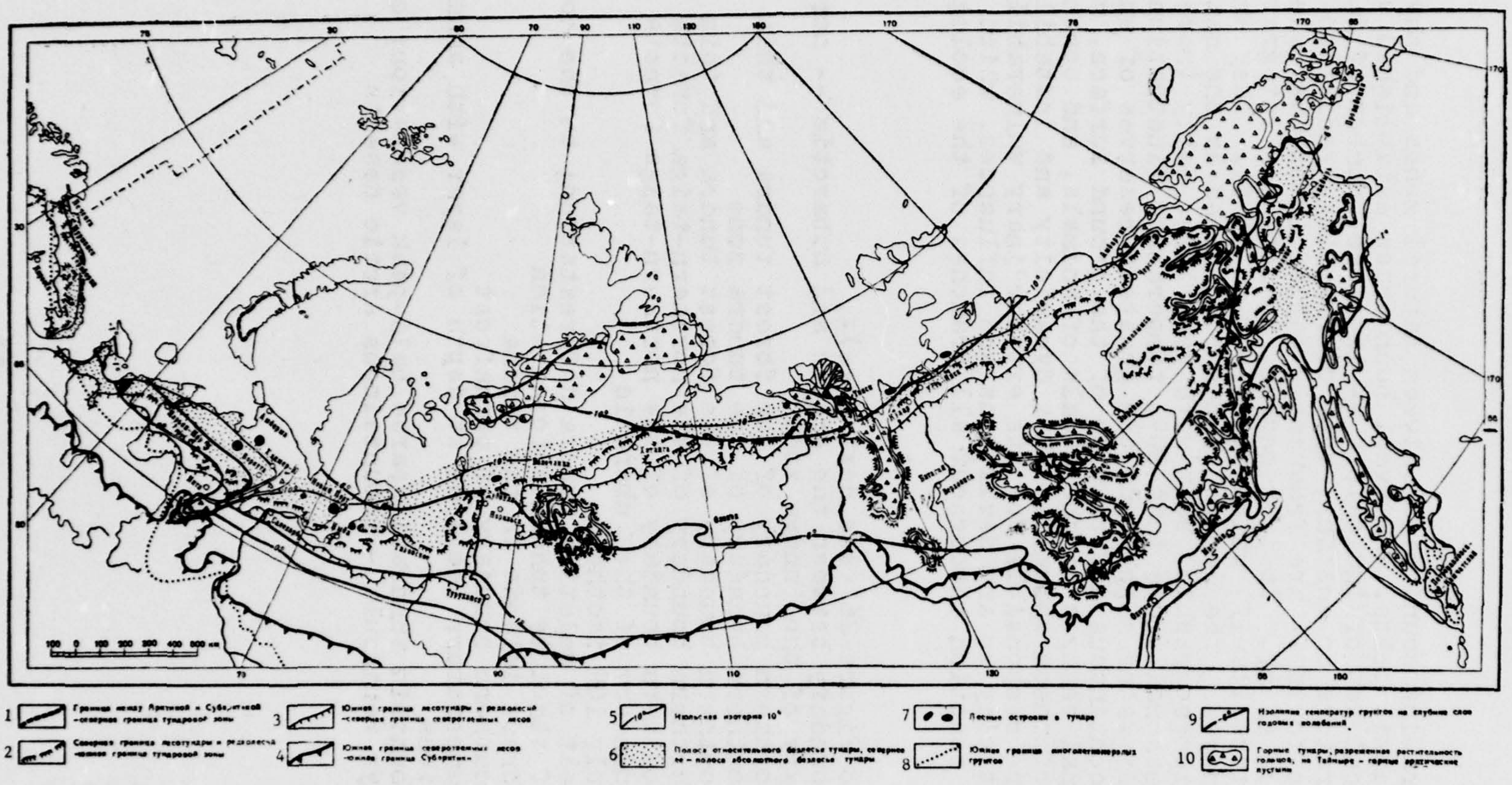

Рис. 26. Субарктика

Figure 26. The Subarctic (key on preceding page).

ECOSYSTEMS OF THE SUBARCTIC

Up until recently, the natural components of the Far North were extremely stable. Nothing, it seemed, could disturb these boundless lands, covered with snow for 7-9 months of the year and armored with ice and permafrost. The very words themselves were hypnotic: "eternal frost," "the white Sphinx," "the country of silence." This is probably why some different terminology became stylish: "the conquest of the North," "the conquest of the Arctic," "the assault on the North." We treated nature like an enemy, forgetting the wise words of Engels: "We will not, however, be too hopeful about our victories over nature. For each such victory she will take her revenge. True, each of these victories has as its first consequences those upon which we counted, but after that there will be completely different and unforeseen consequences that will very often destroy the value of the first ones"[1].

We can now explain how such a contradiction can occur. The large number of components of an ecosystem -- vegetation, soil, air, water, animals, and so on -- are in a very close interrelationship that forms a unified whole -- a natural territorial complex. This complex is very complicated; by changing one of its components, we put all of the others in motion. Some of them react immediately, others after years, decades, and even centuries have passed.

We can explain the behavior of an ecosystem, but we still cannot predict it with 100-percent accuracy, especially after the intrusion of man into it. This applies to all ecosystems. In their ranks, however, the ecosystems of the Subarctic are the least studied and, at the same time, the most unstable and vulnerable ones, so it is more difficult to predict their behavior than that of ecosystems in more southerly zones.

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[1]Marx, K., and Engels, F., SOCH. [Works], Vol 20, 495-496.

In science there are now several terms for naming natural territorial complexes that are regarded as self-developing and self-regulating systems: ecosystems, geosystems, biosystems, and so forth.

The concept "biogeocenosis" was introduced by Academician V.N. Sukachev. This is a section of the Earth's surface where, over a certain period of time, the biocenosis (phytocenosis, zoocenosis, and microbocenosis) and the parts of the atmosphere and lithosphere corresponding to it remain uniform and closely connected to each other by interrelationships and so form, in total, a united, internally interdependent complex [16, p 260].

For example, a pine forest with lichen cover (a pine forest-belomoshnik [translation unknown]) on a sandy hill is a biogeocenosis. It can be regarded as an elementary ecosystem or geosystem. But the same pine forest-belomoshnik on the upper part of the hill is associated with a band of spruces on the lower part of the hill and the swamp in the depression between hills that is crossed by a stream -- this is also a complicated ecosystem (or geosystem) that is interrelated by a flow of matter and energy and is self-developing and (to a certain extent) self-regulating. The drying up of the swamp, for example, can lead to withering of the spruce grove or to other consequences. Cutting down the forest, in turn, will affect the swamp, the ground-water level, and so on.

The term "landscape" is firmly entrenched in our literature, although there are several different interpretations of it. In the first place, a landscape as a natural complex is generally -- independently of its size -- a complexity: mountain, lake, forest, and so on. Secondly, a landscape is an actually existing, specific, unique section of the Earth's surface for which the geological foundation, type of relief, and climate are uniquely identical and different from those in neighboring areas. For example, the Sopkayskiy morainic landscape in the great bend in the Shchuch'ya River on the Yamal Peninsula is an accumulation of morainic hills overgrown with Siberian larch and interhill depressions occupied by lakes and swamps. To the south of the Sopkayskiy morainic landscape, and bordering on it, is the Longot-Yuganskiy landscape with plains, as if it had been scraped smooth by glaciers.

The plains are composed of ancient bedrock and are covered with a thin mantle of sandy and crushed stone soil several dozen centimeters thick. Water stagnates on these plains, turning them into swamps. Therefore there are no forests in the Longot-Uganskiy landscape, although it is farther south than the Sopkayskiy landscape.

Each such landscape consists of small territorial complexes, such as forested hills (in the Sopkayskiy landscape) and inter-hill depressions. In turn, however, a hill-ecosystem -- as we already know -- consists of smaller natural territorial complexes -- landscape facies -- that most scientists identify as a biogeocenosis; that is, an elementary ecosystem.

But no matter how individualistic each landscape may be, it will be possible to associate it to one form or type of landscape, and so on.

Let us turn to an examination of the Subarctic's biogeocenoses and analyze those of them that are located in the upper part of watershed plains and flattened hills. They are called plakor (that is, more typical in contrast to slope or valley) biogeocenoses.

Many plants in the Subarctic, including trees, are located at their climatic limits. Therefore, even small changes occurring as the result of the self-development of biogeocenoses have a substantial effect on the plants and, in particular, the trees.

In order to be able to follow these changes, let us first give brief descriptions of the biogeocenoses by sectors of the Subarctic (for brevity's sake, we will use BGC to mean "biogeocenosis").

Eastern European Sector

The biogeocenoses we are studying are located in the southern underbrush tundra; that is, in the relative tundra deforestation belt, in leveled watershed sections covered by a mantle of loam 2-3 m thick.

BGC-1. Small bush-lichen-moss small-hummock tundras in the northern part of the relative tundra deforestation belt. The temperature of the permafrost at the level of the layer of annual fluctuations (8-10 m) is approximately -1.5°. Summer thawing is 0.5-1.0 m deep. The soil is peaty-gleyey.

BGC-2. Willow-yernikovaya [translation unknown] small-hummock tundras. Permafrost temperature at a depth of 8-10 m is -0.5°. Summer thawing to a depth of 1.0-1.5 m. The soils are tundra, gleyey, podsolized. Spruce in groups or standing alone are frequently encountered in such biogeocenoses, and sometimes clusters of twisted birch.

BGC-3. Willow-yernikovoye small-hummock communities. Located on the boundary between the southern tundra and forest tundra.

Figure 27. Birch community with spruce seedlings in southern underbrush tundra (BGC-3).

They are distinguished from BGC-2 by the mandatory presence of woody plants -- twisted birch and Siberian spruce (Figure 27).

During warming periods, in all biogeocenoses there is an increase in the thickness of the seasonally thawed layer in frozen grounds, which leads to a lowering of the water-resistant (frozen) horizon and is favorable for considerable warming of the upper soil layers, since the part of the heat previously consumed for the evaporation of excess moisture now goes to heat the soil. There is a simultaneous increase in the volume of soil available to the roots; that is, the mineral nutrition of the plants improves.

This improvement in conditions can be followed most graphically on the boundary between the tundra and forest tundra. It is precisely here that birches and spruces appear in the tundra BGC-1's and they are transformed into BGC-2's. In a BGC-2, in turn, there is an increase in the number of young trees, as well as bushes. This promotes a greater accumulation of snow than on the previously unforested tundras, which prevents intensive winter freezing and contributes to the further degradation of the frozen ground under the forest islands. In a BGC-3, therefore, the thawed layer's thickness is no less than 3 m and is usually 4-6 m. Here the frozen ground is not confluent; that is, the winter thawing layer (2.0-2.5 m) does not connect with the upper surface of the permafrost, which is located at a depth of 3 m. This is a sign of degrading frozen ground.

Thus, warming leads to the capture of tundra sections by woody vegetation, which causes further improvement of the microclimate and permafrost degradation; that is, a landscape biogeocenotic succession[1]. The end of a warming period does not lead to the death of such islands, because in the southern tundra -- the relative deforestation belt -- the minimum of heat for the growth and development of trees is available. The soil climate itself has already been determined, to a considerable extent, by the wood and underbrush vegetation. Here trees can change their growth form during cooling periods, but they do not die.

Such a series of birch transformations takes place under the influence of the environment. Straight-trunk birch grows in the forest and forest tundra in places that are shielded from strong winds. When there is an increase in wind force, frequent glazed frosts, spring freezes, and other severe conditions, during its growth process a birch tree is transformed into a multitrunk tree with a radical bush. A further deterioration in conditions leads to the formation of bushy forms of birch. Approximately the same thing happens with spruce. If straight-trunked trees with a normally developed crown change into flag-shaped and double-crown trees, while the lower branches take root and form a spruce bed of vegetative origin, ecologically caused stlaniki result.

When there is an improvement in conditions and routine warming, the existing forest islands expand through new seedlings. Thus, sections under which the soil temperature increases and the permafrost degrades also expand. Simultaneously (during warming), new islands of woody vegetation arise in the unforested tundra. As V.N. Andreyev established, this continuous, unidirectional process has already been going on for at least 500 years and maybe even longer. The abundance of forest islands in the tundra and young thermokarst subsidences is the result of repeated warmings (the most recent one, in the first half of the 20th Century, and earlier ones) that are registered in the relief and vegetative cover because the permafrost in the Eastern European sector of the Subarctic has a high, near-zero temperature and is therefore unstable. Once having

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[1]A succession is a change in vegetation under the influence of external factors or as the result of the activities of the plants themselves. However, since the plants in BGC's are interrelated with soils, microclimate, fauna, and other components, it is more accurate to speak of a change in BGC's than a change in plant communities; that is, of a biogeocenotic (landscape) succession. Academician V.N. Sukachev wrote on biogeocenotic succession in this sense [16, p 239].

retreated under newly formed thermokarst basins and islands of woody vegetation (in which snow accumulates, preventing freezing), permafrost does not recover its former locations under existing climatic conditions, although this does not eliminate (in other situations) freezing and the appearance of permafrost. In particular, in wide (more than 60-100 m) and shallow drained lake basins where a large accumulation of snow is not seen, permafrost can form.

In the first stages after colonization of one section or another by woody vegetation, there occur quite complex processes for establishing equilibrium in the changed natural territorial complex.

Their essence is as follows. The better the conditions become in the section colonized by wood and underbrush vegetation, the more plants converge there. For example, in young spruce-birch communities on plakory along the forest tundra boundary, in a BGC-4 of 1 hectare there are about 2,500 birch trees 4-5 m high with a trunk diameter of 6-15 cm, and 600-650 spruces 5-6 m high with a trunk diameter of 8-18 cm. Young growth is quite abundant: no less than 10,000 spruces 20-100 cm high per hectare and about 6,000 birches that are 30-100 cm high. The moss and peat layer is 12-15 cm thick (living moss, 3-5 cm deep; the rest -- dead moss). In more southerly areas on the taiga and forest tundra boundary in this region, there are only 500-550 spruces 6-8 m tall and 800-850 birches 5-7 m tall for a crown closedness[1] value of 0.2-0.3; that is, significantly fewer trees than in the young communities on the forest tundra's northern boundary.

In a BGC-4 the soil is shaded and its temperature is lower than in underbrush BGC-3's and BGC-2's. At a depth of 20 cm in a BGC-4 in July it is 4-9°; in a BGC-2 or BGC-3 it is 8-12°. Snow lies on the ground longer in a BGC-4 and shortens the growing season; as they grow, many individual plants die from a shortage of nutrients and light and the death of old plants is hastened. This means that the community thins itself out during the development process, and this eventually improves the conditions for existence of the remaining trees: they are well illuminated by the Sun's rays, the soil is heated better, and so on. A new dynamic equilibrium is established in a northern-taiga BGC-4 (Figure 28). Here it is as if a negative feedback mechanism is triggered.

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[1]The closedness of very thick, interconnecting tree tops is considered to be unity (100-percent closedness of the tops). Top closedness of 0.2 means 20 percent, and so forth.

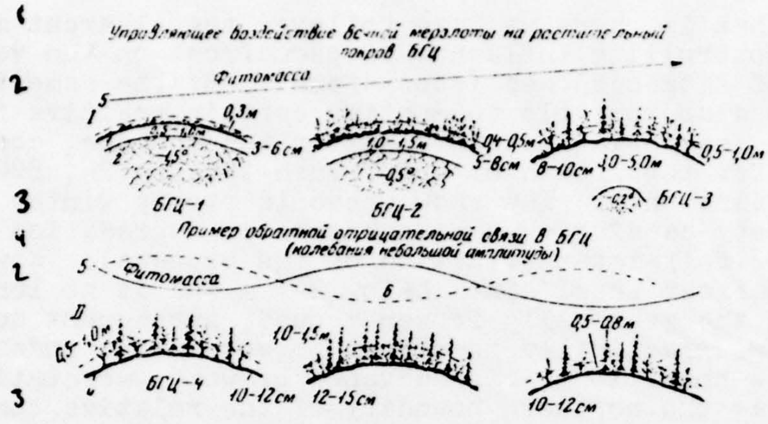

Figure 28. Diagram of development of biogeocenoses in the relative tundra deforestation belt (I) and the forest tundra (II). Thickening of the seasonally thawed layer and an increase in soil temperature result in a change in the following vegetative communities: small bush-lichen-moss (BGC) is replaced by bush (willow-yernikovoye) BGC-2, in place of which forms a sparse spruce-birch forest (BGC-3, 4). 1. seasonally thawed layer; 2. permafrost (the numbers indicate its temperature); 3. snow depth (in meters); 4. thickness of the moss and peat layer (in centimeters); 5. change in phytomass; 6. change in soil temperature at a depth of 20 cm.
Key:

1. Controlling effect of permafrost on vegetative cover of BGC
2. Phytomass
3. BGC-.
4. Example of negative feedback in BGC (fluctuations of small amplitude)

Thus, actually existing biogeocenoses -- small bush-lichen-moss small-hummock tundras (BGC-1), willow-yernikovaya small-hummock tundras in which lone spruces and birch clusters are encountered infrequently (BGC-2), willow-yernikovoye communities with twisted birch and Siberian spruce (BGC-3) -- are simultaneously links in a single chain of self-developing biogeocenoses (ecosystems).

As the permafrost degrades (an increase in soil temperature, thickening of the active layer, and so on), small bush-lichen-moss BGC-1 communities are replaced by small-hummock willow-yernikovoye communities. The phytomass increases.

Further degradation of the permafrost and an increase in soil temperature leads to the formation of BGC-3 spruce-birch communities; that is, here we have followed the clearcut mechanism of the controlling influence of permafrost on the vegetative cover of biogeocenoses (ecosystems). At the same time, however, it is also possible to mention certain positive feedback features: as permafrost degradation takes place, conditions improve for the growth of underbrush (Figure 28, BGC-2, -3), which retains snow. The snow prevents strong winter freezing, thereby causing even more energetic degradation of the permafrost (self-intensification of the process). However, after the permafrost level sinks below 3-5 m and is no longer confluent with the seasonally frozen ground, subsequent degradation of it has practically no effect on vegetation under existing climatic conditions. The advance of woody vegetation can go as far as the northern boundary of the relative tundra deforestation zone; that is, to the northern boundary of the underbrush tundras.

In the Eastern European sector of the Subarctic we also see the directly opposite processes -- degradation of the sparse forests in the forest tundra -- which was noted as long ago as the end of the last century by the well known geobotanist G.I. Tanfil'yev and then recorded by other investigators as well. Tanfil'yev's point of view, in brief, is that in the Timanskaya tundra in connection with the buildup of mosses and subsequent swampiness, permafrost appears where there was none before, its temperature drops, and this eventually leads to the death of the forests and their retreat to the south. Tanfil'yev assumed that this takes place throughout the entire Eurasian North, and not only in the European North.

How do we tie together the factors: on the one hand, the advance of the forests; on the other, their degradation in a number of areas?

The fact of the matter is that different biogeocenoses behave differently. For example, the swamp formation and death of forests about which Tanfil'yev and other investigators wrote is confined to small depressions in the relief -- to areas where slow tectonic subsidence[1] of the site is occurring and contributing to the swamp formation. This settling of the relief in areas where the forest is dying off and a swamp is forming was established only recently.

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[1]Tectonic subsidence of an area is caused by the displacement of matter in the Earth's crust; in this case, by its outflow. The influx of crustal matter in other places causes them to be uplifted.

Figure 29. Public garden consisting of willow plantings in the mine yard in the settlement of Khalmer-Yu. Northern part of the underbrush tundra.

Tanfil'yev correctly noted swamp formation and the death of forests in some sections of the Timanskaya tundra. However, he elevated regularities on the level of a single type of biogeocenosis to the rank of a rule intrinsic to the entire North. Now, when we have much more information on the tundra and the Far North in general, we can make the appropriate corrections. Suffice it to say that the very concepts of "biogeocenosis" and "ecosystem," among others, were not in existence during Tanfil'yev's time.

Knowing the basic regularities and conditions under which the advance of woody vegetation into the tundra can take place, it is possible to develop special agrotechnical methods and create artificial forest plantings in the relative tundra deforestation belt.

Industrial development can also contribute to the movement of woody vegetation into the tundra. This development frequently has a negative effect: trees and entire sparse forests in the forest tundra and forest islands in the tundra are cut down, underbrush and young trees are trampled down, fires cause great harm. However, if the trees and undergrowth are treated carefully, industrial development in this sector can reflect favorably on the existence of trees and large underbrush and their progress into the tundra. It is a known fact that in populated points the air and soil temperatures increase, the permafrost level is lowered, and wind velocity drops. In Vorkuta, for instance, the summer air temperature is 0.6-0.8^{o} higher, and the winter temperature is 1.5-2.0° higher, than at a point 10 km from the city. Here the soil temperature has increased and the upper layer of the permafrost is dropping or the permafrost has entirely disappeared. The wind velocity has decreased by an average of 35-40 percent. All of this is favorable for the creation of woody-underbrush plantings at populated points in the tundra zone. For that matter, it applies to the area around them as well.

The plantings of treelike willows in the mining settlement of Khalmer-Yu (Figure 29) are curious in this respect. The willow trees reach 3-5 m in height. In winter in the yard where they were planted, about 1.5-2.0 m of snow accumulates and protects the tree roots and soil against strong freezing. Dust on the snow causes it to melt rapidly. As a result, the permafrost here has thawed to a depth of 2-3 m, while on the unforested tundra it thaws to 0.8-1.5 m; that is, the industrial development of this region has contributed to permafrost degradation and an increase in temperature in industrial centers, as a result of which favorable conditions have been created for tree plantings in populated points in the tundra zone.

In developing the agricultural technology of plantings, it is necessary to start with the fact that each section is a self-regulating and self-developing ecosystem. By affecting a single component of the ecosystem, we thereby put into motion the entire complicated, interrelated mechanism.

Western Siberian Sector

Development of biogeocenoses in the southern tundra and forest tundra

Marine plains of Pleistocene age and varying degrees of ruggedness are found in the northern part of Western Siberia. The tundra and forest-tundra regions are more rugged than the taiga, especially on the Yamal, Tazovskiy, and Gydanskiy Peninsulas. In the tundra and forest tundra we commonly find sloping- and flat-topped hills and sloping watersheds composed of loams and heavy sandy loams. Each such hill, as well as a watershed and its slopes, we regard as a system of biogeocenoses (elementary ecosystems) combined into a larger ecosystem. Let us first investigate the dynamics of plakor biogeocenoses-ecosystems on the boundary between the tundra and forest tundra in Western Siberia.

BGC-1. Sparse larch forests on level or slightly convex sections on the upper part of the hills and watersheds, which are composed of boulder loams with peaty-gleyed soils (Figure 30).

Figure 30. Sparse larch forest on the upper part of a flat-topped hill.

The trees are 3-6 m tall, crown closedness is 0.2, and the seedling growth is uniform. The following plants are typical of the small bush-grassy stage: willows, wild rosemary, voronika, sedges, cotton-grasses. The moss cover is 4-8 cm thick. Lichens are scarce. Above-ground phytomass is about 50-80 c/ha. The ground thaws to a depth of 50-60 cm, and in July its temperature at a depth of 20 cm is 4-5°. The snow cover is about 100 cm thick.

BGC-2. Dying sparse larch forests with small bush-mossy cover (Figure 31). The mossy-peaty layer is 10-12 cm thick, with live moss in the top 6-7 cm and a half-decomposed mass of organic matter below that. The soils are peaty-gleyed and thaw to a depth of 30-45 cm, with the temperature at a depth of 20 cm being 1-2° in July. There are many stumps -- buried, overgrown with moss, sticking out on the surface.

BGC-3. Mottled tundras in sections analogous as to location; that is, on plakory. The soils under the spots are brown and slightly gleyed; between the spots are strips (40-120 cm wide) with rosemary, blueberry, cloudberry, and dwarf birch. Green mosses and lichens are seen. Under the strips of vegetation, the soils are more gleyed than under the spots. The ground thaws to 60-80 cm. If these sections of mottled tundras are located no more than several hundred meters from larch islands (seed sources), then young, stunted larches are found on the mottled tundras (Figure 32). If they are more than 500-1,000 m away, there are usually no larch trees.

Figure 31. Dying forest island.

Figure 32. Mottled tundra overgrown with Siberian larch. Degradation of the forest island has ended in this section.

BGC-4. Sections analogous as to location and composed of boulder loams. On the surface of these sections there is a large amount of shingle-debris rubbly material that was "frozen out" (ejected as the result of upwarping to the surface) after the disappearance of the sparse larch forests and yernikovoye small bush and moss communities. Tundra soils, slightly gleyed. On the rocks there are crustose lichens and individual specimens of blueberry, foxberry, dwarf birch, Alpine arktous, low fescue. These BGC's are seen in places that are at least 1 km from larch islands and alder thickets.

BGC-5. Analogous sections composed of boulder loams with peaty-gleyed soils; the vegetation is heavily beaten and trampled down.

After analyzing the properties of the elementary ecosystems -- the biogeocenoses -- it is possible to establish that BGC-1 is the basic one, while the others are derived from it.

We have already mentioned that successions are inherent to biogeocenoses, and in this case they take place as the result of the fact that a moss layer grows in a sparse larch forest. Mosses make up 40-70 percent of the above-ground phytomass.

As the mass of the mosses increases, heating and aeration of the soil is made more difficult, its temperature is lowered, and the layer of seasonal thawing gets thinner. Trees and bushes start to die, young growth ceases. The tree and underbrush vegetation becomes sparser, which leads to the sweeping of snow away from such sections. Once denuded of their snowy shield (when its thickness is less than 15-20 cm), the mossy-peaty layer is split by frost clefts. This corresponds to the BGC-2 state. A further increase in dryness and snow corrasion finally destroys the mossy-peaty layer, which is usually no thicker than 15-20 cm. Spots of mineral ground appear. The least amount of phytomass is seen in this state.

As the spots, devoid of any mossy layer, appear, soil heating increases sharply, with its temperature rising to 8-9° and even higher. Conditions are created for the emergence of larch seedlings, and they appear if tree seeds fall on the spots of bare ground. However, as a result of the very severe conditions (strong winds,that blow the snow from the surface, severe winter freezing, sharp soil temperature and moisture fluctuations), the upper part of the larch seedlings die. The living branches are concentrated in the layer near the ground and their height above the surface does not exceed 20-40 cm; that is, they frequently take root, and this leads to the formation of larch beds (Figure 32).

Stlaniki and beds, by retaining snow and moderating the wind's force, create around themselves sections favorable for the appearance of new seedlings. Under the protection of the stlaniki and beds, the new individual specimens reach a somewhat greater height. Their tops do not die. The larches now have the life form of a tree, and not a stlanik. The lower branches of these straight-trunked trees do not spread out across the ground and take root, as is the case with stlaniki. A new stage in the life of the BGC has begun. Eventually the spots are overgrown. A larch island forms.

Tree growth continues on a young larch island -- their height, trunk thickness, and number of branches all increase, as do their mass and the area occupied by their roots. For its vital activity, all of this growing phytomass requires a large quantity of mineral matter, which it (the phytomass) can draw out from the limited volume of the seasonally thawed layer. Moreover, the increase in the phytomass leads to less heating and a reduction in the thickness of this layer. The trees and bushes start to die. And so on -- the cycle repeats itself.

According to our investigations, in the forest-tundra sparse larch forests of Western Siberia there is an annual increase in the layer of loose peat of 1-2 mm; that is, in the southern tundra a mossy-peat layer 15 cm thick probably forms in about 150 years. It is more difficult to determine the period of development from the mottled tundra stage to the stage of the formation of a young, sparse larch forest island. It can be assumed that under favorable conditions and a continuous accumulation of seeds, this segment of time is at least 150-200 years long. Thus, the total duration of a succession from the mottled tundra stage through the larch island and its aging and dying, to a new mottled tundra stage, is apparently 350-500 years.

This regularity can be presented in the form of a curve that graphically demonstrates the change in the soil's temperature and summer thawing as functions of the phytomass per unit of area, above all of the thickness of the mossy-peaty layer (Figure 33). An abundance of plants and their shading of the soil play a substantial role in soil heating, but the greatest -- as research has shown -- is played by the mossy-peaty layer.

The phenomenon we have just described can quality as a cyclic fluctuation of great amplitude with the manifestation of a negative feedback mechanism in the elementary ecosystem (or BGC). Growth of the mossy-peaty layer does not lead to self-intensification of the process (as in tundra depressions and the taiga). It causes the death of many plants and the mossy-peaty layer, as a result of which there is again an improvement in the conditions for the existence of wood and bush plants; that is, it triggers the negative feedback mechanism.

However, if a section on which mottled tundra has formed as the result of a succession is at least 1 kilometer from any larch islands (the seeding source), regeneration of the Siberian larch does not occur. The upper layer of soil is deprived of the branching, dense network of tree and bush roots, and this intensifies the freezing and swelling processes whereby the rubble and shingle material contained in loams and sandy loams

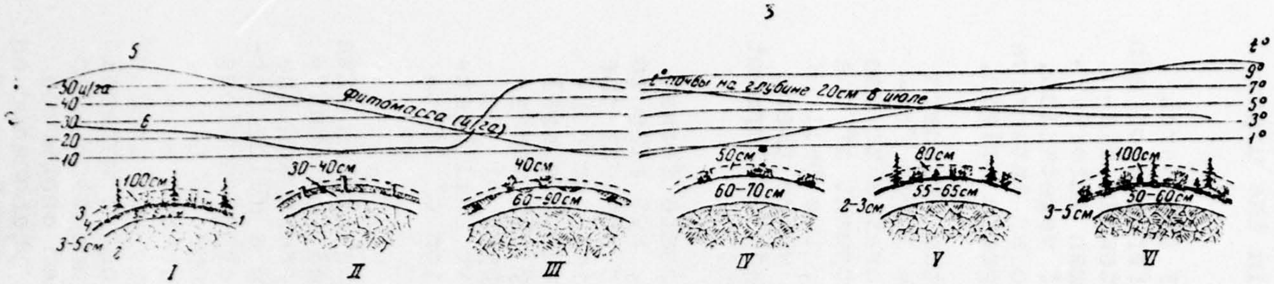

Figure 33. Diagram of development of several biogeocenoses in the southern tundra and forest tundra of Western Siberia: I. initial stage of BGC development -- forest island of Siberian larch; II. as the result of growth of the mossy-peat layer, the woody vegetation dies, mosses predominate, and small bushes and dwarf birch are encountered; III. mottled tundra on the site of the former forest island, with only remnants of stumps and trunks to indicate recent existence of trees; IV. overgrowth of mottled tundra by larch and undergrowth; V. formation of forest island of Siberian larch (takes place only if larch communities -- seed sources -- are nearby); VI. further growth of mossy-peaty layer leads forest island to the stage where new cycle of degradation of woody vegetation in the BGC begins; 1. seasonally thawed layer (in centimeters); 2. permafrost; 3. depth of snow cover (in centimeters); 4. mossy-peaty layer and its thickness (in centimeters); 5. line showing change in phytomass (centers per hectare, in air-dried state); 6. soil temperature at depth of 20 cm in July.

Key:

1. centers per hectare
2. Phytomass (centners per hectare)
3. Temperature (t°) of soil at depth of 20 cm in July

is ejected. The soil's surface is covered with stones and resembles boulder pavement. (Ignorance of these processes frequently leads to an incorrect estimate -- more properly, an overestimate -- of the amount of rubble material in the upper part of the soil.) Thus, a BGC-4 forms.

Considering the scattered nature and remoteness of the larch islands, it can be assumed that without the interference of man in these landscapes, the larch islands would eventually disappear as the result of successions. However, human interference -- overgrazing by reindeer, the dislodging of vegetation, the felling of trees for various needs -- leads to an intensive growth in the number of biogeocenoses of anthropogenic origin.

The material we have presented indicates that in the northern part of Western Siberia, degradation of the sparse larch forests and a retreat of the polar boundary of the forests to the south is taking place as the result of self-development of the ecosystems in an unchanging climate. As a result, the belt of relative tundra deforestation is growing; this is where there is the necessary minimum of heat for the growth and development of trees, although the trees themselves are absent.

Knowing the pattern, it is possible not only to create forest islands in the relative tundra deforestation belt, but also to regulate the vegetation in the ecosystems so as to prevent the death of the trees; that is, there are opportunities for controlling the ecosystem. In order to this, once every several decades it will apparently be necessary to destroy the mossy-peaty layer, maybe by mixing it with the mineral part of the soil. As a result, there will be an improvement in soil heating and aeration, and conditions for the germination of larch seeds will appear.

In view of the fact that a BGC is a self-regulating system with inherent fluctuations, new possibilities are opened for studying the problem of the interrelationship of the forest and the tundra. This approach makes it possible to see in a dying forest island not a general degradation of woody vegetation along the entire northern boundary of the forests, but one of the swings in the large-amplitude fluctuation of a specific ecosystem. In the same way, in the overgrowth of some sections of mottled tundras by larch, it is necessary to see not a general advance of woody vegetation into the tundra in connection with a global improvement in climate (which has not been confirmed by meteorological observations), but to view this phenomenon as one of the stages of ecosystem fluctuation on the boundary of the forest and tundra that involves the manifestation of a feedback mechanism -- both positive and negative.

Figure 34. Section of slope-topped hill-ecosystem. On the upper part of the hill (background) alder bushes 1.5-2.5 m tall retain snow, the depth of which reaches 80-100 cm here, so it takes longer to thaw than on the mossy-peaty tundra (foreground). Snow water flowing downward overmoisturizes the slopes.

The lack of a systematic approach to this question resulted in a situation where the regularities belonging to an elementary ecosystem -- a biogeocenosis -- were elevated to the ranks of rules for a physicogeographic (natural) sector and even for the entire tundra zone.

Up until now we have been studying the dynamics of elementary ecosystems -- biogeocenoses located in the upper parts of watersheds and on large flat-topped hills. Let us now attempt to examine the behavior of more complicated ecosystems consisting not only of plakor biogeocenoses, but including slope biogeocenoses. How, for example, do vegetative communities and and biogeocenoses change in connection with the death of larch islands on the upper part of large hills? Observations show that if there exists a larch island or yernikovyy-alder phytocenosis on the upper part of a hill, then on the lower part of the hill there must be a hummocky moss and cotton-grass community (Figures 34,35). This is explained by the fact that the snow accumulating on the upper part of the hill, which is covered with woody-bushy vegetation, is the source of a great amount of moisture for the slopes' lower parts. Moss and cotton-grass communities usually do not occur on the lower parts of hills.

In connection with this, the process of interaction and the interrelationships among vegetative communities within the

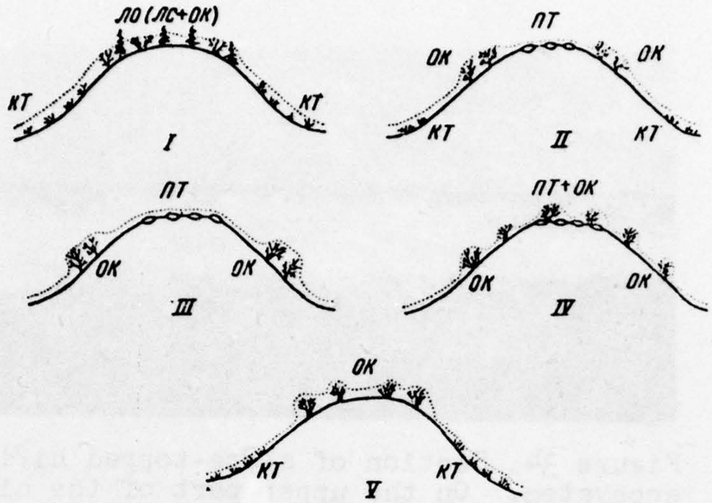

Figure 35. Diagram of interaction and interrelationship among vegetative communities on a well delineated hill in the southern tundra (I-V are sequential stages in the replacement of vegetative communities): I. sparse larch forest with bush alder undergrowth on the upper part of a slope-topped hill; on the lower part of the slopes there are hummocky moss and cotton-grass communities (hummocky tundra -- KT); ЛО -- larch island; ЛС -- Siberian larch; OK -- bush alder; II. the larch island on the upper part of the hill died. Patches of bare ground -- mottled tundras (ПТ) -- appeared. Alder bushes remained only on the upper part of the slopes. Because of the decrease in the snow reserves on the upper part of the hill there was a shrinkage of the sections occupied by the moss and cotton-grass hummocky tundras; III. the mottled tundra section has expanded. Individual alder bushes were displaced to the lower parts of the slopes, the moisturization of which dropped sharply after the disappearance of the woody-bushy vegetation on the upper part of the hill; IV. overgrowth of mottled tundras by bush alder. Increase in the amount of snow on the upper part of the hill leads to increase in moisture on the slopes, preventing the growth of bush alder, which shifts to the upper part of the hill; V. yernikovoye-alder community formed on upper part of hill and retains large amount of snow. This led to regeneration of hummocky moss and cotton-grass communities on lower part of slopes; dotted line -- depth of snow.

limits of hill-ecosystems are presented in the following form. As the woody vegetation on the upper part of the hill or watershed degrades, the amount of snow retained by it decreases. When mottled tundra forms here as the result of succession, the hummocky tundras disappear from the lower part of the slopes and are replaced by sedge-moss-small bush communities. If the upper part of the slope-topped hill again becomes covered with woody-bushy vegetation, then the hummocky tundras reappear on the slopes. More often than not, yernikovoye-alder communities arise on the upper part of the hill, since it is more difficult for larches to re-establish their positions. The appearance of a large-bush community on the upper part leads to the regeneration of the hummocky tundras on the lower part of the slopes. Yernikovoye-alder communities are more stable in comparison with sparse larch forests. The leaf fall prevents the intense growth of mosses and the death of the undergrowth. Therefore, hills, ridges, and watersheds occupied by yernikovoye-alder communities on the upper part and hummocky moss and bush communities on the lower, are more stable and less subject to changes.

Dynamics of biogeocenoses in the northern taiga

Let us now discuss the types of biogeocenoses found in the northern taiga of Western Siberia. We will analyze these actually existing BGC's in order, as links in a long evolutionary chain. At the beginning of this chain there are conifer, frequently lichened (these are usually called belomoshnyy) forests, at the end -- dry, convex peat bogs covered with small bushes and with lichens in the soil cover.

Types of biogeocenoses

BGC-1. Pine-cedar-larch lichened forests. Microrelief -- hills and sinks (residual polygonal). Hummocks rise 0.8-1.0 m above the sinks. Tree diameter at a height of 1.5 m is 25-35 cm. Crown closedness is 0.4-0.6. Tree restoration is normal. Dwarf birch, blueberry, whortleberry, and foxberry are seen in small beds (primarily in the sinks) and individually. In the soil cover there is a mat of lichens, primarily Alpine cladonia. The lichens occupy the upper parts of the mounds and their slopes; in the centers of the sinks there are usually patches of moss. The ground water level is at a depth of 2 m. The soil is podsolic, with clearly expressed A_2 outwash (podsolic) and B (inwash) horizons, and is sandy. In the A_2 horizon there are usually dark bands (at least two or three) -- traces of forest fires. The snow cover's average thickness is 70-90 cm. The grounds are thawed; seasonal freezing is to a depth of 1.5-2.0 m. Soil temperature at a depth of 8-9 m (the level at which seasonal temperature fluctuations have almost no effect) is 1.5-2.0°. In July and the first half of August, the soil temperature at a depth of 20 cm is 8-12°.

These biogeocenoses are usually found in the higher, well drained parts of plains sections; they are surrounded by swampy and stunted forests, swamps, and peat bogs. They are either round, with a diameter of at least 800-1,000 m, or elongated (the width of such a strip is at least 800-1,000 m). Their relative height advantage over the surrounding swamps and peat bogs is no more than 2-3 m. These forests are not confined to hill and sink microrelief. They are also seen in other microreliefs -- it has no effect on the composition of a stand of trees, soils, and ground-water level.

BGC-2. Stunted spruce-larch forests with admixtures of birch, small bushes, and moss; sparsely treed, higher than the swamps surrounding them by about 1.0-1.5 m or even less. Hummocky microrelief. The hummocks are 20-80 cm tall and 40-120 cm in diameter, and are based on a mineral nucleus. Crown closedness is 0.2-0.3. The trees' diameter at a height of 1.5 m ranges from 5-12 (for the birches) to 10-25 (conifers) cm. The trunks and branches of the trees are covered with lichens. Young growth is usually absent or very sparse. There is a moss cover between the hummocks. On the hummocks there are dwarf birch, wild rosemary, whortleberry, voronika, and lichens. During rainy periods, water stands between the hummocks. The closer to a swamp, the longer the water is retained among the hummocks, and the hummocks themselves are taller in such areas (at least 70-80 cm). The soil is peaty-gleyed-podsolic and sandy. The peat layer is 5-12 cm thick, while the snow cover reaches a depth of 70-90 cm. The ground is primarily thawed, although under the largest hummocks (close to a swamp), which are 70-80 cm tall, permafrost lenses 0.5-1.5 m thick are found. These lenses thaw out, but not every summer. Soil temperature at a depth of 8-9 m is 0.2-0.5°. In July and the first half of August, the temperature at a depth of 20 cm is 5-8° in the center of a hummock and 1.5-2.5° between hummocks.

Similar sections with stunted forests and permafrost neogeneses are seen both in the upper parts of a plain (BGC-2a) that stand above the swamps surrounding them by no more than 1.0-1.5 m, and in the form of strips (BGC-2b) outlining the pine-cedar-larch lichened forests (BGC-1). In the first case (2a), they (like a BGC-1) have a round shape, but the diameter of these sections is much less than that of a BGC-1 and usually does not exceed 150-250 m. Hummocky microrelief with permafrost lenses (permafrost neogeneses) are an obligatory component of the BGC-2a and BGC-2b conifer-birch forests.

Figure 36. Hummocky-hillocky swamp with drying trees and permafrost lenses (BGC-4a). Formed on site of stunted coniferous forest (BGC-2a).

BGC-3. Sparse larch-spruce forest with moss cover, located in a depression; crown closedness 0.1-0.2. In the center of the depression the trees stand alone. Trunk diameter is 8-15 cm, and they are twisted and usually bare-topped; there is no young growth. The soils in the center of the depression are peaty bog soils and the thickness of the mossy-peaty layer is 0.3-0.4 m. Buried tree trunks are frequently seen in the peat. At the end of July, the permafrost depth is 0.3-1.1 m. Along the edges of the sink, peaty-gleyed soils are encountered. The mossy-peaty layer here is 0.2 m thick, and below it there is a gleyed level. The permafrost depth here is 0.4-0.7 m. A permafrost lens with outlines that parallel those of the depression, which is becoming a peat bog, lies beneath it and does not thaw during the summer.

Depressions occupied by sparse, moss-covered larch-spruce forests (BGC-3) are usually surrounded by lichened forests with thawed ground (BGC-1), and between them there is a narrow strip (30-40 m) occupied by a conifer-birch forest with hummocky microrelief (BGC-2b).

Now let us describe the biogeocenoses that are transitional from forests to swamps and peat bogs.

BGC-4. Hummocky-hillocky swamps. Among them we see sections both with single trees -- remnants of the forests that existed

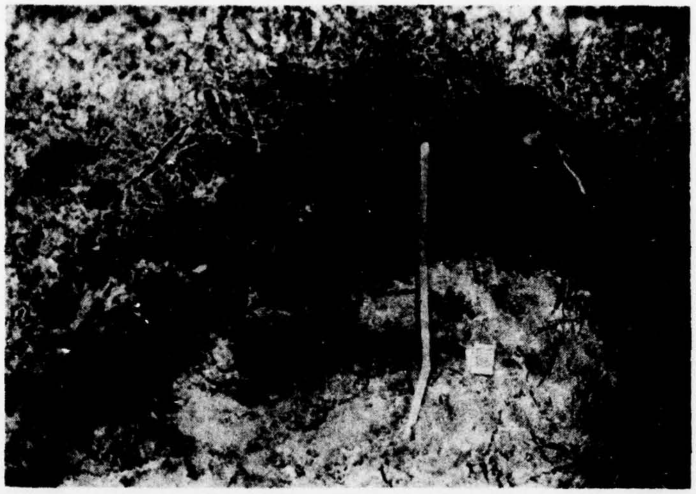

Figure 37. Profile of one of the hummocks in a hummocky-hillocky swamp. In the upper part of the hummock the mossy-peaty layer is about 20 cm thick; along the edges it is 10 cm thick. This means that before the emergence of the hummock with its mineral core, in its place stood a peat mound rising 10 cm above the moss cover surrounding it. It froze more intensively than the surrounding area, which led to swelling and the formation of a hummock with a mineral core.

there at some time (Figure 36) -- and without them. The hummocks' dimensions are from 2 to 7-8 m and they are 0.8-1.5 m tall (Figure 37). Dwarf birch, wild rosemary, butterbur, blueberry, voronika, and cloudberry grow either singly or in beds on the hummocks; lichens are widely developed (primarily Alpine cladonia). The trunks of dead trees are frequently encountered on the hummocks. The interhummock depressions are occupied by moss and sedge vegetation. If a depression is 5-8 m in size, its center is filled with sedge, and close to its edge there are green mosses that in turn are outlined by a band of sphagnum mosses. If the space between the hummocks is no larger than 1-3 m, it is usually filled with peat covered with sphagnum mosses, the surface of which is only 40-60 cm lower than the hummocks. The peat layer on the hummocks is 20-40 cm thick. A hole made in one of these hummocks revealed the following internal structure.

From the surface to a depth of 0.3 m -- a thawed peat mass. From 0.3 m to 0.6 m -- peaty, frozen sand; wood and birch bark remnants are encountered; at a depth of 0.4-0.5 m there are two distinct dark bands (1-3 mm thick) of wood ash (traces of a slash fire). From 0.6 to 1.4 m -- brownish frozen sand with traces of iron and ice interlayers; there are no wood fragments. From 1.4 to 2.7 m -- gray, frozen sand with ice lenses. Deeper than 2.7 m -- thawed ground.

Such a structure for hummocks in hillocky-hummocky swamps is, according to borehole data, typical. The thickness of the frozen layer in them is 2.5-3.0 m, and in the depressions between the hummocks the frozen layer is slightly thicker.

A mossy-peaty thawed layer is seen from the surface to a depth of 0.3 m, while below that to a depth of 0.9 m there is dark- and light-brown frozen peat. Deeper yet there is dark, humic, frozen sand. Thawed sand begins at a depth of 1.7 m. The wider the interhummock depression, the thinner the frozen layer in it is.

In interhummock depressions that are wider than 8-10 m, the frozen layer usually thaws completely in summer.

The size of sections with hillocky-hummocky swamps is no more than 300-400 m; they appear on the site of stunted spruce-larch forests (BGC-2).

We have already said that BGC-1 pine-cedar-larch forests are usually surrounded by a belt of stunted coniferous forests with hummocky microrelief (BGC-2b) that, in turn, is surrounded by hillocky-hummocky swamps. These swamps are located not only in the center of peat bogs, but also surround the stunted coniferous forests and are the next stage of development of BGC-2b; that is, they replace it. We will designate such sections as BGC-4b (Figure 38).

Farther along in our series stands moss-sedge lowland bogs (BGC-5). Let us discuss only those of them that are strips between the forests and peat bogs. They are usually 0.5-0.7 m lower than the forest sections and 0.5-2.0 m lower than the upper surface of the peat bogs. Frozen soil begins at a depth of 0.5-1.0 m and sometimes deeper.

The final form of biogeocenosis (BGC-6) is peat bogs -- hillocky, dry, and frozen beginning at a depth of 0.4-0.6 m. The peat is at least 0.5-1.0 and up to 6-7 m thick. The mounds are peaty, 0.3-0.5 m tall and 0.5-0.8 m in diameter; they are covered with dwarf birch and small bushes (wild rosemary, foxberry,

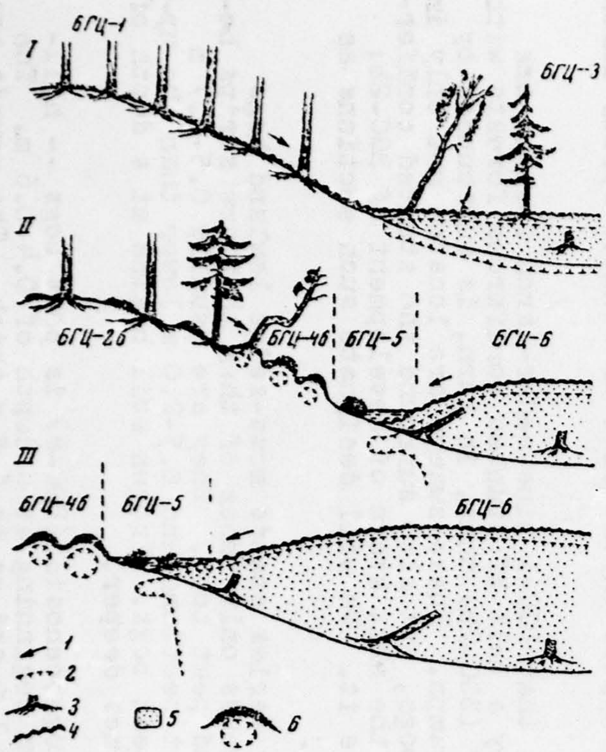

Figure 38. Diagram of swamp formation in lowland and peat bog development: I. growth of mossy-peaty layer leads to deterioration of the soil's hydrothermal and aeration regimes so that tree roots cannot survive; II. in a low area a convex peat bog appears, from the surface of which the snow is blown off, thus contributing to intense freezing of the peat bog and the formation under it of permafrost several dozen meters thick. A depression forms between the peat bog and the forest; water flows into it from both the forest (located on the upper part of a plain) and the peat bog. This results in the formation of an overmoisturized strip on the boundary between the peat bog and the forest -- a moss-sedge swamp (BGC-5) -- that in turn warms and turns into a swamp a belt adjacent to the forest and contributes to the formation in it of a hillocky-hummocky swamp (BGC-4b). From the time that the convex peat bog forms, swamping of the forest adjacent to it intensifies; III. convex, bush-and-lichen, dry, frozen peat bog. Runoff goes in only one direction -- from the peat bog toward the forest. The peat bog's upward growth ceases and it moves sideways, as a result of which the forest swamping and death rate increases sharply, as does the permafrost formation rate; 1. direction of water runoff; 2. permafrost boundary; 3. tree trunks buried in the peat bog; 4. peat mounds; 5. peat bog; 6. swelling hummocks with new permafrost formations.

blueberry, crowberry); between the mounds Alpine cladonia grows. As is the case with lichened forests, anthills are found in the dry peat bogs. They are also subject to fires, because of the abundance of lichens.

In July and the first half of August, the temperature at a depth of 20 cm is 2.0-3.5°; at a depth of 8-10 m it is 1.5-2.5°. Peat thickness is greatest in the center and decreases in the peripheral sections. The same thing happens with the permafrost: it is thickest (several dozen meters) in the center, particularly under hummocks from which the snow has been swept, and decreases to several meters in the peripheral sections, tapering out as contact is made with the forest. A hole made in one of the peat bogs revealed the following structure.

Peat thickness is 3.7 m. The peat is frozen, with fragments of birch trunks and traces of fires. From a depth of 3.7 m there is peaty, frozen sandy loam with ice lenses. The peatiness gradually decreases, disappearing entirely at a depth of 4.5-5.0 m. The frozen sands and sandy loams go deeper, to a depth of 30-50 m. Their temperature at a depth of 8-10 m is -1.5 to -2.0°.

Now let us see how these biogeocenoses change in the northern taiga. Four stages are distinguished in the development of permafrost [2].

In the first two stages, the ground froze as the sea regressed to the north in Western Siberia. The second stage continued until the onset of the Middle Holocene thermal maximum. The third stage coincides with this maximum. At this time there was a partial thawing of the permanently frozen strata from the surface, and their boundary shifted to the north, to a latitude of approximately 67-68°; that is, the limit of freezing from the surface was much farther north than it is now. However, during the period of climatic warming, complete thawing of the frozen strata did not take place. The permafrost thawed only to a depth of 100-150 m, while below this the unthawed permafrost reached a depth of 300-350 m, which is its present level. The fourth stage in the development of the frozen strata began at the end of the climatic maximum and continues today. A characteristic of this period is freezing of the ground from the surface, as a result of which a two-layer permafrost stratum, the boundary of which is shifting to the south, formed and continues to form.

Baulin and his associates [2] think that the fourth stage has lasted for 2,500 years so far. Research done in recent years with the help of the radiocarbon method has established that the sudden transition to cooling in the northern part of Western Siberia took place about 4,500 years ago, or 2,000 years earlier than was previously believed to be the case (N.A. Khotinskiy, 1972). Thus, swamp formation and the growth of peat bogs, resulting in the formation of permafrost and the simultaneous degradation of forests, has been taking place in the northern taiga for about 4,500 years.

Swamp formation begins (and began) in low-lying areas (Figures 38, 39). A good illustration of this process is the modern sparse, moss-covered larch-spruce forests (BGC-3) that are located in depressions. The relative settling of the modern depressions is 1-2 m, and they are located on the upper parts of plains. Deeper and lower basins have already become peat-filled or are completing that stage of this process at the present time.

As the mossy-peaty layer grows, heat exchange between the atmosphere and the ground is altered and seasonal freezing exceeds summer thawing. Permafrost lenses form under this layer. At first they are quite thin -- 10-30 cm. As the peat layer thickens, however, the trees and bushes die and the snow is swept from such sections, which leads to even more intensive freezing.

As time passes, a convex frozen peat bog forms in the depression and water starts to flow out of it. Alongside the peat bog (and outlining it) an overmoisturized swampy strip (BGC-5) forms and receives water from both the forest and the peat bog. In this overmoisturized strip -- a moss-sedge swamp -- the mossy-peaty layer grows at a very high rate. Not only does the moss grow upward, but moss mounds and pads form along the outer side, invading the forest.

These moss mounds and pads freeze more intensively than the sections between them. Under a moss mound (or pad), a permafrost layer grows, as if piercing the thawed layer. Moisture migrates toward the freezing front from the surrounding thawed, overmoisturized ground, then freezes, which leads to swelling of the moss pillow (mound) and its transformation into a hummock with a mineral core. The frozen ground thaws in summer; under the overmoisturization conditions, the voids left by the melted ice lenses are filled with soil flowing in from the sides. This means that if a permafrost lens thaws completely, the hummock is still preserved. Further growth of a hummock with a mineral core depends largely on an abundance of moisture, without which it is impossible for it to swell up. The most moisture is available near a moss-sedge swamp with areas of open water. Biogeocenoses with the largest hummocks -- up

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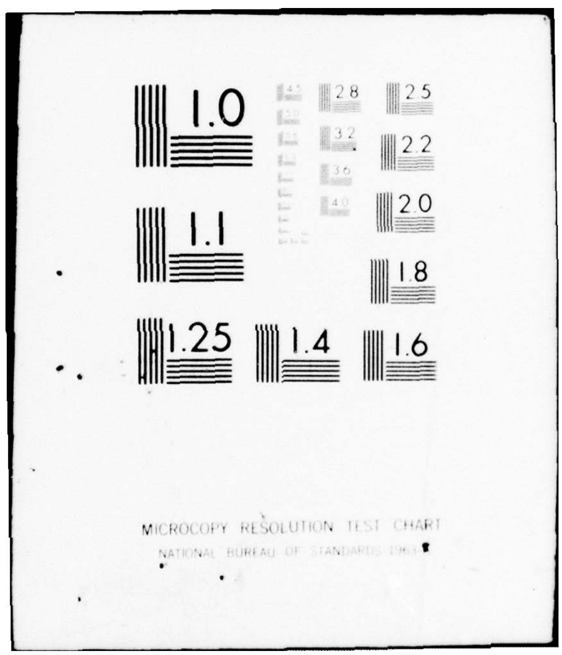
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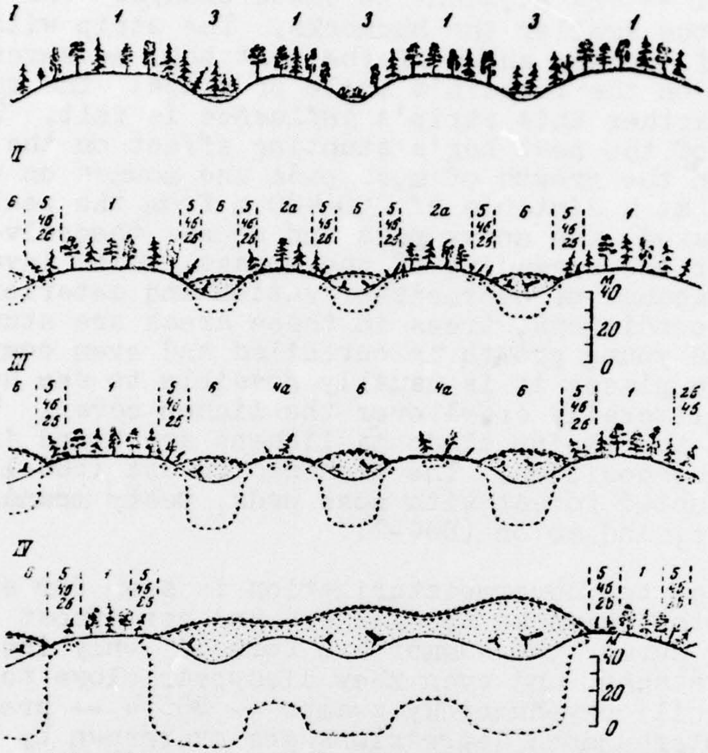

Figure 39. Diagram of forest degradation and peat bog and permafrost growth in the northern taiga of Western Siberia: I. forests until the end of the postglacial Middle Holocene thermal maximum. Normal, unstunted groves of trees predominated, in combination with wet and swampy depressions; II. in the more severe climate that set in after the thermal maximum, swamping of the depressions led to the formation of permafrost and the death of the forests; III. formation of convex peat bogs from which water flowed, accelerating swamp formation in the forests surrounding them. Simultaneous sharp increase in the area and thickness of the permafrost; IV. by the present time, many formerly isolated peat bogs have run together into continuous peat bog masses occupying up to 60-70 percent of the northern taiga in Western Siberia. The forests that at one time covered a large part of this territory are now represented by isolated islands, located on the upper parts of the plain, that are condemned to die; the numbers above the drawings designate BGC's; the scale on the right shows altitude above sea level.

to 1.5-2.0 m tall -- are adjacent to these swamps. The farther from the swamp, the smaller the hummocks. The strip with hummocky microrelief, moving ahead of the peat bog, measures 200-400 m, depending on the terrain's angle of slope: the greater the slope, the farther this strip's influence is felt. Thus, the first signs of the peat bog's stunting effect on the forest are manifested in the growth of moss pads and mounds on overmoisturized soil at a distance of 200-400 m from the peat bog. Once having appeared, the mossy pads and mounds themselves now become nuclei for the spreading of the mosses, which invade adjacent areas. Because of overmoisturization and deterioration of the aeration conditions, trees in these areas are stunted more severely and young growth is curtailed and even completely halted. In these places it is usually possible to see how the sphagnum mosses literally crawl over the lichen cover. Under the moss mounds, the Alpine cladonia lichens are found in various stages of decomposition. The lichened forest (BGC-1) is replaced by a stunted forest with moss pads, peaty mounds, hummocky microrelief, and so on (BGC-2).

Closer to the peat bog, overmoisturization is seen for even longer periods, the hummocks are larger, and permafrost lenses that do not thaw during the summer are formed. Only individual stunted trees are seen, and even they disappear close to the peat bog. Here hillocky-hummocky swamps -- BGC-4 -- predominate. As the interhummock depressions are overgrown by the moss, the hillocky-hummocky swamp is transformed into a peat bog. At first the peat layer is thin, but with time it thickens to several meters and the ground under freezes to a depth of several dozen meters. This transformation results in the appearance of a hillocky-hummocky swamp (BGC-4) on the location of a stunted coniferous forest with hummocky microrelief (BGC-2). As the peat bog grows and expands, the strip that it is converting into a swamp, with moss mounds and hummocky microrelief, moves toward the forest; that is, biogeocenoses with hummocky microrelief in front of the peat bog are outposts of the advancing swamp and indicative of the imminent death of the forest.

As time passes the small, individual peat bogs coalesce into large ones stretching for dozens of kilometers. Simultaneously, the islands of permafrost also run together into massifs of permanently frozen ground with boundaries advancing to the south (Figure 40). The forested area shrinks steadily.

Change in the components of the environment

We have seen how the growth of a moss cover, with subsequent formation of a mossy-peaty layer and swamp formation, leads to

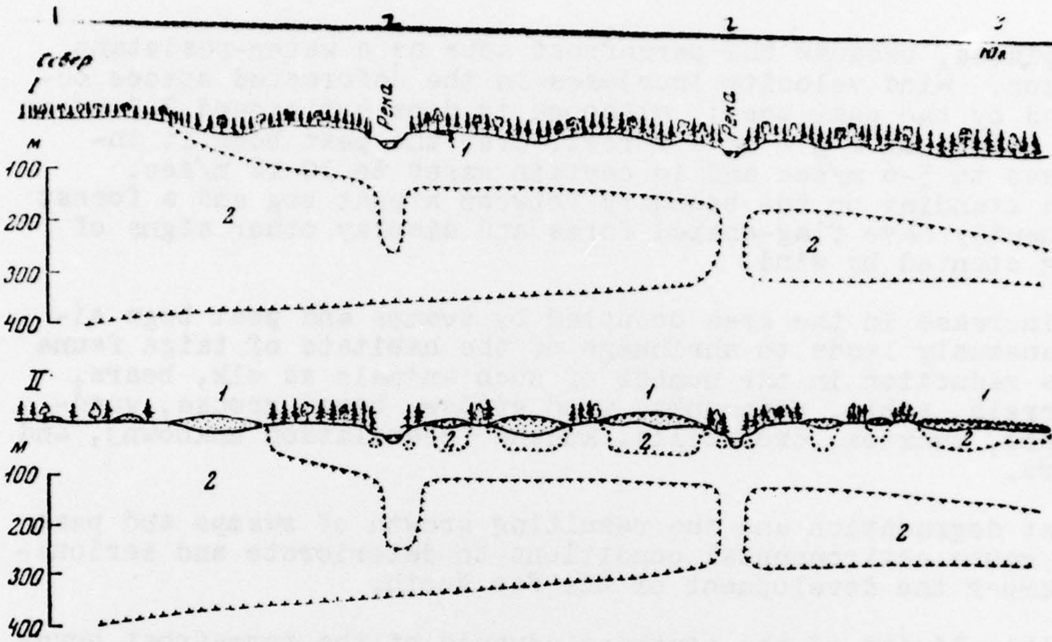

Figure 40. Diagram of formation of two-layer permafrost in the northern taiga of Western Siberia: I. location of permafrost by the end of the Middle Holocene thermal maximum. A large part of the territory is covered with forests. The frozen ground thawed to a depth of 100-150 m; II. present location. A large part of the territory is covered with peat bogs and swamps. An upper layer of permafrost has formed. To the north, the upper and lower layers have already joined; 1. peat bogs and swamps; 2. permafrost.
Key:
1. North 2. River 3. South

a two-sided result. First, to deterioration of the conditions for the existence of trees: soil temperature drops; the filling of the soil pores with water has a deleterious effect on aeration; tree regeneration ceases in the mossy-peaty layer; tree decay and disease intensifies, accelerating their death. All of this results in degradation of the forests. Secondly, to a change in heat exchange between the soil and atmosphere, as a result of which seasonal freezing exceeds seasonal thawing under the invariable climatic conditions, which causes the onset of the formation of small permafrost lenses and then (after the death of the trees and an abrupt thinning and reduction in density of the snow cover) the formation of a permafrost stratum several dozen meters thick, which also accelerates the degradation of the forests. After peat bogs appear (with permafrost under them) there is a sharp increase in the territory's swampiness, because the permafrost acts as a water-resistant horizon. Wind velocity increases in the deforested spaces occupied by the peat bogs: although it does not exceed 2-3 m/sec at a height of 2-3 m in a forest, over the peat bogs it increases to 5-6 m/sec and in certain cases to 10-12 m/sec. Trees standing on the boundary between a peat bog and a forest frequently have flag-shaped forms and display other signs of being stunted by wind.

The increase in the area occupied by swamps and peat bogs simultaneously leads to shrinkage of the habitats of taiga fauna and a reduction in the number of such animals as elk, bears, squirrels, sable, chipmunks, wood grouse, hazel grouse, woodpeckers, cuckoos, crossbills, kuksha [translation unknown], and others.

Forest degradation and the resulting growth of swamps and peat bogs cause environmental conditions to deteriorate and seriously hamper the development of the Far North.

Possible limits of the southern advance of the permafrost boundary

Theoretical calculations made by V.P. Chernyad'yev [25] showed that the southern boundary of potential permafrost development lies 400-450 km to the south of the present boundary of frozen ground found in peat bogs. Such freezing at several hundred kilometers to the south could take place under the present climatic and temperature conditions if there is a change in heat exchange between the soil and the atmosphere, which process is regulated by the moss (or, more accurately, vegetative) and snow covers. We have already seen how this control is exercised under natural conditions. The southern boundary of the possible advance of the permarfrost stratum lies 400-450 km from the present boundary. In the potential freezing zone, extensive permafrost development is excluded only under conditions of fragmented relief, where good drainage prevents intensive swamp formation, while the small peat bogs are isolated and, as a result of the ruggedness of the relief and the large ground slope angles, cannot grow sideways and merge. Here permafrost can develop only if the forests are felled by man, after which the snow will be swept away from these sections and winter freezing will intensify. Chernyad'yev also reveals the boundary of probable permafrost thawing. It lies 580-620 km to the north of the present southern permafrost boundary. Such thawing could also occur under present climatic conditions. In order to achieve this it would be necessary to remove the moss cover and regulate the accumulation of snow, which is impossible without woody-bushy vegetation being present.

Other calculations led us to the same conclusion: inside a belt 300-500 km wide that is adjacent to the southern permafrost boundary, systematic removal of the peat or its mineralization and the simultaneous accumulation of snow at least 1 m deep can result in the thawing of a 10-m thick frozen layer in 10-20 years. It is a known fact that when the moss cover is removed, the soil temperature at a depth of 20 cm increases by 11-15° in summer, while a snow cover 20 cm thick warms the soil by 2-3°; when it is 60-70 cm thick, the warming is 6-7°.

Such are the scales and possible results in the case of a change in heat exchange between the soil and the atmosphere, and they can be achieved by controlling the moss and snow covers.

Causes of swamp formation and forest degradation in Western Siberia

Some investigators relate swamp formation and the death of forests to climatic cooling, assuming that during warming periods permafrost degradation is seen, while during cooling periods permafrost appears and grows as the temperature drops. It is indisputable that climatic fluctuations -- cooling in particular -- affect the dynamics of swamp and permafrost formation. However, we cannot ascribe the leading role to them. Mosses possess sufficiently aggressive qualities under certain physicogeographic conditions, which happen to be those present in Western Siberia: cool summer, excess of precipitation over evaporation, poor drainage as the result of the plains-type relief, and so on. The mosses' ecological range is great, and warming by 1.0-1.5° -- which took place from the beginning of this century to approximately 1950 -- hardly had a negative effect on their growth. Possibly, it was even the opposite. On the other hand, growth of the moss cover in the northern taiga of Western Siberia always leads to an increase of freezing over thawing and eventually to the formation of permafrost. In this region the thicknesses of the moss and mossy-peaty layers and the peat bogs are extremely variegated -- from several centimeters (the moss layer) to several meters (peat bogs). Permafrost also has an extremely variable thickness -- from several dozen centimeters to several dozen meters. We have already seen that there is a clearcut genetic relationship between biogeocenoses with variable moss and peat bog thickness and the irregular thickness of permafrost strata. All of this indicates that the processes of moss growth, swamp formation, peat bog formation, and permafrost formation are unidirectional and continuous, although they are possibly retarded under unfavorable conditions. The very fact that there is a distance of 1,000 km from the southern boundary of potential permafrost formation to the southern boundary of its possible thawing indicates that insignificant temperature deviations over the course of several decades cannot exert a decisive influence on permafrost degradation or regeneration under taiga conditions.

A knowledge of these processes is necessary, particularly at the present time, so that they can be taken into consideration during the development of Western Siberia's taiga regions and the planning of economic activities.

From the explanation that has been given it is obvious that forest degradation and the environmental deterioration that accompanies it in the northern part of Western Siberia are caused not by general climatic factors upon which man can have no effect, but by local factors. The main role here is played by self-development of the mosses. It causes peat bogs to expand, with the subsequent appearance and expansion (in area and thickness) of permafrost. The appearance of water-resistant frozen ground, in turn, leads to the intensification of swamp formation, and so on. In this case we see self-intensification of processes, the overall result of which is the expansion of peat bogs with permafrost and the death of forests.

At the present time, it is fully possible to stop the swamp formation processes and the death of forests. The founder of geocryology, M.I. Sumgin, long ago pointed out the need for controlling soil freezing and thawing with the help of agrotechnical methods [17]. P.I. Koloskov [8,9] devked out the basic principles for controlling heat exchange between the soil and the atmosphere. Their essence is that by changing the vegetative soil cover, it is possible to achieve an increase in the influx of heat during the summer and a decrease in heat losses during the winter. The removal of mosses from the soil surface results in an increase in its summer temperature of 10-15°. The simplest method of destroying (or, more accurately, mineralizing) the mosses is the introduction of lime. Liming simultaneously neutralizes soil acids and is favorable to the development of micro-organisms that decompose the plant remnants. The possibility that in some cases it might be advisable to remove the mosses by burning has not been ruled out.

It has also been established that a loose snow cover inhibits soil cooling and freezing: a snow layer 60-70 cm thick warms the soil by 6-7°. The simplest method of snow accumulation is with the help of trees and bushes. Blackening of the snow in spring accelerates its disappearance by 2-3 weeks, which would contribute to an increase in the heat inflow during the spring-summer period.

It is also necessary to consider the fact that pumping oil out of the Earth usually leads to settling of the surface. Under the conditions present in Western Siberia, this can intensify swamp formation. Experience shows that injecting water into the voids formed after the oil is pumped out prevents soil subsidence. If we allow for the overmoisturization of the soil and abundance of water in this region, then its elimination will retard the swamp formation processes.

The exploitation of the peat deposits can be doubly profitable: it will produce organic raw materials, and permafrost degradation will begin in sections from which the peat is removed. In time, forest plantings can be made, which will then combine with the unforested grassy-bushy sections.

This is a brief list of the possible measures that can retard swamp formation and the death of forests and the general deterioration of environmental conditions. In order to do this, of course, we will need new research, the formulation of experiments, and the development of scientific-organizational measures.

Eastern Siberian Sector

The next sector, in an example of which we will examine the dynamics of Subarctic ecosystems, is the tundra and forest tundra of Eastern Siberia between the Indigirka and Omoloy Rivers. Here we commonly see plains composed of lacustrin-alluvial loams with an abundance of subsurface vein ice that are occupied by hummocky tundra moss and cotton-grass communities, to the south of which there are sparse larch forests. Observations show that as we move to the south, from the zone of moss and cotton-grass hummocky tundras into the sparse forests, the areas occupied by the hummocky communities decrease. In the southern tundra they occupy not only plakor sites, but slopes as well. Tongues and islands of hummocky tundras are wedged into the sparse larch forests. Where the mounds of sheathed cotton-grass cover a large part of the soil surface, larches are either completely absent or only single trees are seen.

Field investigations showed that such a distribution of vegetative communities is a record of definite stages in the continuous, centuries-long change of Subarctic ecosystems and biogeocenoses in Eastern Siberia. These changes take place in the following manner.

Each new mound is formed only through seed regeneration of the sheathed cotton-grass. From young cotton-grass, which consists of a mother shoot and several small leaves, there begin to sprout daughter root-rosette shoots from which an individual plant forms. The plant gets larger, occupying an ever greater area, and in time becomes convex. The accumulation of organic matter causes the formation of rhizomes, which carry the tillering zones to the mound's surface. The mound expands, reaching 20-30 cm in height and 30-40 cm in diameter. The foot of the mound is covered with moss, while the upper parts of the mounds interlock. Soil temperature decreases. Although the loamy soils under the mossy-bushy cover thaw to a depth of 55-65 cm at the end of July (the July temperature at a depth of 20 cm is 3.5-4.5°), under the hummocky communities thawing does not exceed 30-35 cm (the soil temperature at a depth of 20 cm is 1.8-2.2°). These mounds live for a long time -- usually several decades, frequently 100 years or longer. Once having appeared, cotton-grass does not abandon the occupied territory, but expands into a mound and seeds the surrounding area, where new mounds appear, the upper parts of which become interlocked after several decades. An abundance of sheathed cotton-grass mounds results in a situation where the cotton-grass produces many more seeds than the daurskaya larch, so the former's capability of capturing new territories is better than the latter's.

Thus, the hummocky communities advance to the south, taking over ever more new sections from the sparse larch forests. As the area occupied by hummocks increases, the conditions for larch growth and development deteriorate, the soil temperature drops, the depth of thawing decreases, trees age, and young growth is curtailed and then ceases entirely. The sparse larch forest is fragmented and transformed, in essence, into tundra with lone trees. Although individual larch seedlings appear against the background of hummocky tundras, they can no longer change the direction of the natural processes' dynamics in the ecosystems (Figure 41). These trees are not bases for the reforestation and dispersion of daurskaya larch.

In the region under discussion, moss and cotton-grass hummocky communities are the most stable ones. The parameters of ecosystems-biogeocenoses with hummocky communities regenerate themselves more quickly than those of the unstable communities with sparse larch forests.

Let us remember that the tree is the life form with the most rigorous demands for environmental conditions. Under the conditions found in the tundra and forest tundra it does not find its ecological optimum. Here trees live at their ecological limits, so even insignificant changes in the environment push their parameters to critical values, causing the death of trees. These environmental changes are caused by the self-development of components of the ecosystems, so in order to explain the

Figure 41. Moss and cotton-grass hummocky tundra with lone larch trees. Larch seedlings and young growth are not seen in this section, although there are many half-decayed, covered trunks and stumps, which indicates that 150-250 years ago this site was covered with sparse larch forests.

degradation of the forest cenoses at their northern limits and the retreat of the forests' polar boundary we must look for external causes (changes in climate, permafrost, and so forth).

Far Eastern Sector

In this sector of the Subarctic, cedar stlanik occupies large expanses and is the edifier (main) plant in many phytocenoses. As has already been mentioned, cedar stlanik is also called a treelike, woody bush and a branching, spreading tree.

In Eastern Siberia, daurskaya larch forms the northern forest boundary. Here the cedar stlanik grows 100-300 km away from the larches; that is, its boundary lies more to the southa, although in the Far Eastern sector of the Subarctic -- in the Anadyrskaya Lowland, in particular -- larch grows farther south than cedar stlanik. This is primarily because of the different physicogeographic conditions in these two adjacent sectors of the Subarctic and the ecological peculiarities of these two plants. Let us examine these peculiarities.

For a comparison of climatic features, let us take Ust'-Yansk (71° N. Lat.) and Nizhnekolymsk (68°30' N. Lat.), located in the forest tundra of Eastern Siberia on the northern forest boundary, and the city of Anadyr' (64°50' N. Lat.) and Ugol'naya Creek (about 63° N. Lat.), which are located in hummocky tundras in the relative tundra deforestation belt. Winter temperatures at the points named in Eastern Siberia are 10-18° lower than at Anadyr' and Ugol'naya. In the coastal regions of the Chukotsk Peninsula and the Anadyrskaya Lowland there are frequent winter warm spells during which the temperature can reach 3-4°. The summer temperatures at all four points are quite similar: the average July temperature is about 10.5° at Ust'-Yansk, 11.5° at Nizhnekolymsk, and 10.5° at Anadyr' and Ugol'naya; in August it is 8.5-8.6° at the points in Eastern Siberia and 9.6 and 9.4°, respectively, at Anadyr' and Ugol'naya; that is, somewhat higher than in Eastern Siberia. The number of days with an average 24-hour temperature above 10° is 30-35 at Ust'-Yansk, Anadyr', and Ugol'naya.

Thus, the winter temperatures in Eastern Siberia are considerably lower than in the extreme northeast of Asia, while the summer ones are about the same, and the absence of daurskaya larch in the relative tundra deforestation belt in Asia is explained by something other than air temperature. In the relative tundra deforestation regions of northeastern Asia, the average July temperature is 10-12°, and days with a temperature of 10° and higher number 35-45.

Observations show that the soil temperature in the 20-cm layer and the depth of summer thawing in Eastern Siberia (on the northern forest boundary) and extreme northeastern Asia are approximately the same, and even higher on the hills in the Anadyrskaya tundra. This means that soil temperature also does not inhibit the growth of daurskaya larch in the relative deforestation belt of the Far Eastern Subarctic.

A further comparison of climatic factors indicates that these two regions differ not only in their winter temperatures, but also in wind conditions. The average annual wind velocity at the points in Eastern Siberia is 2.9-3.5 m/sec, with it being somewhat higher in summer than in winter. At Anadyr' and Ugol'naya the average annual wind velocity reaches 6.7-7.0 m/sec. In winter it is considerably higher than in summer: the average winter value reaches 9.5-10.0 m/sec, with maximums exceeding 40 m/sec.

Now let us see how the climatic conditions affect plant distribution. In order to do this, we turn to the ecological peculiarities of daurskaya larch and cedar stlanik. Daurskaya larch is the only tree that needs so little heat for its growth and development: a total of 25-30 days with the temperature above

10°, with an average air temperature of 6.2° in June, 10.7° in July, and 8.5° in August (Ust'-Yansk). Average soil thawing depth is 40-45 cm, and its summer temperature at a depth of 20 cm is 2-4°.

Investigations have determined that cedar stlanik grows in warmer soils: the temperature in the root-inhabited layer in places where cedar stlanik grows is no lower than 4-5°; that is, for its growth and development it requires a somewhat higher temperature (especially in the soil) that daurskaya larch. This is why cedar stlanik grows to the south of daurskaya larch in Eastern Siberia. But why, then, does it grow farther to the north and east than daurskaya larch on the Chukotsk Peninsula and in Magadanskaya Oblast? What is even more curious is that wind velocity increases in the northerly and easterly directions.

As it turns out, cedar stlanik has adapted magnificently to winter conditions with strong winds and warm spells: with the onset of frost, its branches lie down and are covered with snow. For cedar stlanik, the strong winter winds that stunt growth both physiologically and mechanically have practically no effect. After the appearance of many works devoted to the causes of the lodging of cedar stlanik, this question was answered satisfactorily in a monograph by G.E. Grosset [6]. Grosset's experiments showed that the wood in cedar stlanik branches is differentiated into upper (tractive) and lower (knotting) layers. When it is chilled, the knotting (lower) layer contracts strongly in the longitudinal direction and more weakly in the radial direction than the tractive (upper) layer. The result of this difference is that when frosts set in, the branches bend downward and the stlanik clings to the earth. Freezing of the water in the wood begins at a temperature close to zero. A significant part of the water freezes. As the temperature continues to drop, for each degree of decrease there is a smaller and smaller amount of water that freezes. The movements of the stlanik's branches have the same damping nature.

In connection with this, there is another interesting feature of cedar stlanik that helps it survive under such severe conditions -- the ability of the lodging branches to form adventive roots. They form best of all when the stlanik does not grow in solid, dense thickets, but in beds, between which there are open, well warmed sections. As we move toward the polar and upper boundaries of woody vegetation, cedar stlanik thickets become thinner because of the drop in temperature and the decrease in the seasonally thawed layer's thickness, the separation between them increases, and the size of the beds decreases.

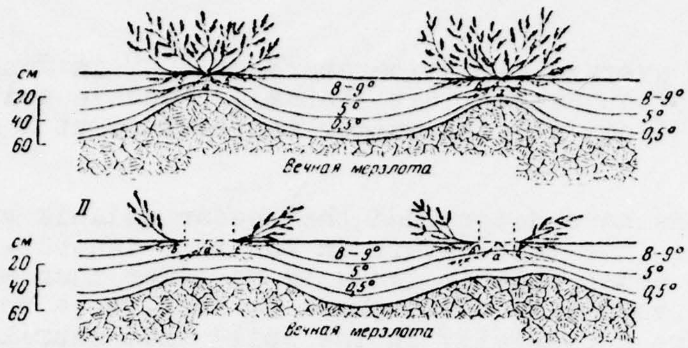

Figure 42. Diagram of transformation of cedar stlanik bush into several independent and individual branches: I. under the stlanik bush the permafrost is closer to the surface (and the soil temperature is lower) than in illuminated sections where there are no bushes. Clinging to the ground, the stlanik's branches put out adventive roots that grow toward the heared side; II. as time passes, the primary root system and the basal part of the cedar stlanik die, while the branches are transformed into cloned, fruit-bearing individuals. A cedar stlanik's root system is always located in a heated surface layer where the temperature is no lower than 4.0-5.0°.
Key:
1. Permafrost

Separate beds grow at the northern limit of cedar stlanik's range. In the central shaded part of the bed the soil temperature is usually lower, and the primary concentration of fallen needles is also here. The growing organic layer hinders the heating and thawing of the soil. The thickness of the seasonally thawed layer in the central part of a bed decreases to 20-25 cm and the soil temperature drops sharply. It becomes impossible for cedar stlanik roots to exist here. The branches of the cedar stlanik, which are capable of putting out adventive roots, grow toward the side of the heated and warmed section. In time, both the roots and the basal part of the plant die in the central part of the bed and the branches, which have taken root and transferred to their own root nutrition system, become independent cloned plants that are not connected to each other (Figure 42). The bed-island deteriorates, disintegrating into individual branch-plants. The central part of the former bed, now denuded of plants (that is, of a certain amount of thermal resistance), heats up better; the thickness of the seasonally thawed layer increases. In such a section, therefore, a bed of cedar stlanik eventually reappears.

Thus, the presence of permafrost and the comparatively shallow summer thawing of the soil (40-80 cm) dictate the bed-island distribution of cedar stlanik at the northern and upper limits of its range. On the other hand, by interacting with the vegetation these same factors cause continuous movement of the cedar stlanik beds in the ecosystems of the Far Eastern sector of the Subarctic. The role of permafrost in this process is usually underestimated.

From what has been said, it is obvious that it is impossible for solid, dense thickets of cedar stlanik to exist at the extreme limit of its range, because the soil temperature under them would be lower than the minimum temperature at which root growth and development can take place. For these same reasons, at its temperature limit in the north and northeast, cedar stlanik does not grow in soils with a heavy mechanical composition (clays, loams), although in more southerly regions they are seen in heavy soils. The absence of cedar stlanik thickets in negative relief forms in the Far North is explained by the low temperature of the overmoisturized soil.

Larch, which does not have similar adaptive abilities, takes on stunted, dwarf forms or dies completely under the influence of winds -- particularly in winter (snow transfer by the wind causes mechanical corrosion, while warm spells result in an abrupt loss of moisture that cannot be replaced from the frozen ground). Larch forests begin to be encountered only at 250-300 km from the sea, in intermontane basins and mountain valleys, where the wind velocity drops sharply (the average annual velocity does not exceed 4 m/sec) and warm spells are not seen during the winter. The Maynskiy larch region, which is surrounded on all sides by mountains, lies closest to the sea -- 250 km from the Anadyr' estuary. Here larches predominate, with cedar stlanik underbrush. In this intermontane basin, larches grow up the slopes to an altitude of 150-250 m above sea level; the cedar stlanik belt goes higher, and highest of all is a mountain tundra belt (the mountains are 800-1,200 m high). On the mountains' outer slopes, which are turned toward the sea, larches do not grow. Here, cedar stlanik thickets rule. The other larch regions are located even farther from the sea -- they are also protected by mountains and are under more nearly continental conditions than the Maynskiy larch region.

Man's Effect on Tundra Ecosystems

In recent years, people have ever more frequently written and talked about the reduction of lichen cenoses in the tundra and the decrease in reindeer pasturage. Man is the cause of these phenomena. The number of expeditions in the tundra continues to grow -- geological, geographic, topographic -- as do the different types of transportation and the amount of drilling rigs and other technical equipment. The network of populated points is getting denser and they are connected by roads that are getting wider, so that tractors and cross-country vehicles are always breaking up new strips of tundra vegetation during the summer period.

There are now more than 2.5 million households and about 600,000 wild reindeer in the Subarctic. They have a great effect on vegetative communities and on the tundra ecosystems as a whole: they eat plants and pull them up, pack or loosen the soil (depending on the time of year and the soil's mechanical composition), fertilize the soil with excrement. A. Shrenk, who traveled through the Eastern European tundras in 1837, wrote with alarm on the catastrophic degradation of reindeer pastures: "Considering all of these circumstances (overgrazing by the reindeer and, as a result, exhaustion of the pastures -- author's note), it is very easy for anyone to understand how the numberless herds of reindeer on the tundra, in some three decades, could destroy to such a degree such an immense expanse of earth as the Bol'shezemel'skaya tundra, and why there are grounds to begin fearing for the future existence of the people who live here, since it is closely related to the reindeer's existence"[1].

In 1908-1909, the biologist and veterinarian S.V. Kertselli roamed the Bol'shezemel'skaya tundra with the reindeer herdsmen. His job was to discover the causes of reindeer murrain and determine the possibilities for colonizing the tundra. He also wrote about the exhaustion of pastures and the dying of reindeer in conjunction with this phenomenon.

At this time, scientists had already begun to say that the lichens in the overgrazed pastures recover very slowly. Since this was the case, maybe it would be possible to plant them in grasses. A.V. Zhuravskiy, an enthusiast for the development of the Far North, assumed that after the destruction of lichens, the intensive growth of grasses would begin on the tundra; that is, natural meadow formation would occur. However, it may be that Zhuravskiy overrated this process, because Kertselli answered him, quite reasonably: "Assertions that meadows might appear

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[1]Shrenk, A., PUTESHESTVIYE K SEVERO-VOSTOKU YEVROPEYSKOY ROSSII CHEREZ TUNDRY SAMOYEDOV K SEVERNYM URAL'SKIM GORAM, PREDPRINYATOYE V 1837 GODU [Journey to the Northeast of European Russia Through the Tundra of the Samoyeds to the Northern Ural Mountains, Undertaken in 1837], St. Petersburg, 1855, p 501.

where reindeer have pulled up the moss are nothing more than the fruits of a fantasy. Between Adz'vaya and Rogovaya no less than 15,000-20,000 reindeer pass each year in both directions, but the meadows here are unnoticeable, despite the many years that the reindeer have spent pulling up the moss. In actuality, the conversion of tundra into meadow is a very, very difficult thing to achieve"[1]. Further, Kertselli estimated the cost of transforming a desyatina (1.09 ha) of tundra land into meadow, and calculated how much manure and mineral fertilizer would be needed. He may have been right: the creation of meadows in place of tundra vegetative communities is a very laborious thing.

However, the overgrazing of lichen pastures and the reduction of lichen reserves is taking place throughout the entire Far North, and not only in the Eastern European Subarctic.

Captain Billings, who landed in Mechingmenskaya Gulf in 1791, subsequently wrote about medium-sized mountains covered with white moss; that is, with lichens[2]. At the present time, there are few sections on the Chukotsk Peninsula with lichen covers. The area occupied by them does not exceed 1-3 percent. This is explained by the intensive overgrazing of reindeer for many decades.

In order that pastures not be overgrazed, it is necessary to observe certain rules: reindeer cannot stay in one area for a long time, especially when there is no snow on the ground. Otherwise the vegetation will not be eaten up so much as it is beaten down, and a mud puddle that takes a long time to be overgrown can often form in this area. It is necessary to drive the reindeer from some pastures to others systematically, according to a previously worked out plan; that is, pasture rotation must be practiced.

Although meadows do not form on the site of overgrazed pastures, there is still some increase in the quantity of grasses in such areas. Lichens actually grow very slowly -- several millimeters a year. Bushes -- dwarf birch, willows -- also grow slowly, but somewhat more rapidly than lichens. Moreover, for centuries the reindeer herdsmen have used them for fuel. All

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1Kertselli, S.V., PO BOL'SHEZEMEL'SKOY TUNDRE S KOCHEVNIKAMI [On the Bol'shezemel'skaya Tundra With the Nomads], Arkhangel'sk, 1911, p 75.
2see SEVER DAL'NEGO VOSTOKA [The Northern Part of the Far East], Moscow, Izd-vo Nauka, 1970, p 288.

investigators, beginning with A. Shrenk, have written about this. In addition, bush willows are willingly eaten by reindeer.

Observations in the tundra and conversation with herdsmen indicate that every year up to several dozen kilograms of bushes are stripped from a hectare of tundra area; that is, from one to several dozen percent of their total mass. Of course, intensive overgrazing by reindeer, the pulling up and destruction of lichens and bushes, the use of dwarf birch for fuel -- all of this cannot help but affect the tundra biogeocenoses.

In an untouched tundra phytocenosis consisting of mosses lying in a thick mat on the ground surface, as well as small shrubs, bushes, and lichens, it is difficult for grasses (cereals, in particular) to get established and even more difficult for them to survive, because they have almost none of those adaptations that the named groups of plants do. The bushes and shrubs are symbiotrophic; that is, they are capable of extracting mineral matter from the mossy-organic layer through a mycorhiza, and lodging and adventive rooting help tundra plants exist under the severe conditions encountered in the Subarctic. Under cold soil and permafrost conditions, even the mosses' and lichens' lack of roots is an advantage in their competitive struggle with grasses.

But here the bushes and shrubs, mosses and lichens are destroyed. There are no competitors, and then the grasses occupy the almost bare sections. And although the grasses grow sparsely and their mass is small, in the percentage sense there are more grasses than other plants. This is what scientists call meadow formation, or the grassing of the tundra. If such sections remain at rest, however, in a few years the mosses will begin to recover their positions. The expanding moss cover hinders soil warming more and more, its thawing decreases, and the amount of moisture in it increases. Conditions for the existence of grasses deteriorate. Hypo-Arctic bushes possessing symbiotrophism appear -- dwarf willows, birch. Grasses -- and cereals, in particular -- are more demanding of natural conditions and are usually devoid of such adaptations, so they begin to die.

In most cases, however, it does not happen that the tundra lies quiet. Here reindeer graze, frequently without observance of the rules of pasture rotation about which we have already spoken and exceeding the established reindeer capacity.

Having once triggered an ecosystem, we thereby open the way for chain reactions in it. In addition to changes in the vegetative soil cover and relief, of which we have already spoken, the fauna changes also. The number of lemmings in such beaten down sections decreases. They are the basic food of the tundra predators, and this cannot help but have an effect on the latter. The reindeer also change. For instance, on the Chukotsk Peninsula, where the area occupied by lichens has been reduced to 1-3 percent, a new strain of reindeer has appeared -- the khargin [translation unknown], which can feed on grasses and do without lichen (reindeer moss) foods. This animal has shorter legs than the usual reindeer and a more massive body that is capable of rapid fattening. Kharginy herds at pasture cluster close together, which helps them break up the hard tundra snow that is packed because of warm spells and strong winds, and get the green feed (grasses, evergreen shrubs) from under the snow. Thus, the reindeer as a part of a Subarctic ecosystem has changed along with this ecosystem.

Equilibrium is always maintained between the vegetative cover and the reindeer population. In pre-Revolutionary years, judging by the descriptions of A. Shrenk (1855), S.V. Kertselli (1911), and other investigators, this equilibrium was maintained automatically: if the number of reindeer exceeded the food reserve, the pastures were beaten down and the reindeer started to die off from disease. As a result, the load on the pastures was reduced and the vegetative cover recuperated. In our time, the elements have been replaced by intelligent regulation: the introduction of pasture rotation and timely shifting of the reindeer, the fencing of pastures, the shaping of specific herd populations and structure, and so on. These rules are not always observed, so the beating down of the pastures and meadow formation and grassing continue.

With the increased numbers of industrial centers in the Subarctic, the growth in population, and the necessity of creating a local subsistence base, there arises the question of not only preserving the reindeer pastures, but of extending the areas on which green fodder for livestock can be raised. In connection with this there appears the problem of creating meadows and cultivated pastures in interfluvial areas (Figure 43).

But what must be done to create meadows in tundras, where mosses and lichens force out the grasses eventually, since phytocenotically the grasses are weaker than these plants?

With the help of agrotechnical methods -- multiple disking, plowing -- the tundra's primary vegetative cover is destroyed. Soil acidity is then reduced by liming and fertilizers are added. Grasses are sowed in the improved soils. It is necessary to plant artificial meadows with tree and bush windbreaks. They also distribute the snow evenly and protect the soil from

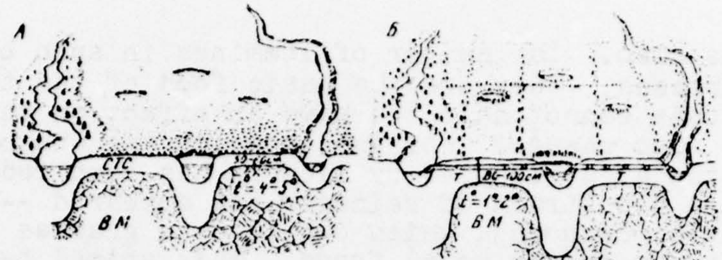

Figure 43. Plan for possible tundra transformation: A. complex tundra ecosystem, including simpler ecosystems: two rivers (the valley of one of them is covered with a sparse larch forest); interfluvial expanse occupied by hummocky cotton-grass vegetative community on peaty-gleyed loam soils; thermokarst lakes. Seasonally thawed snow (CTC) on the plakor does not exceed 50-60 cm. Permafrost (BM) temperature -- 4-5°. The ecosystem is located in the relative tundra deforestation belt of Western Siberia; B. agroecosystem that can be created on the site of an original tundra ecosystem. The soil can be drained by laying drainage pipes (T). As a result, conditions will be created for a further rise in soil temperature and an increase in the seasonally thawed layer, which in turn will contribute to improving the plants' mineral nutrition -- both the grasses and the trees in the windbreaks. The fauna will be enriched with forest animals.

severe freezing. The grasses are protected against perishing under the snow, since the windbreaks prevent deep snowdrifts. Sprinkling the snow with peat dust or soot (mulching) accelerates its disappearance and intensifies soil heating.

There is some available experience in the creation of sown meadows in the tundra[1]. Fertilizers improve the positions of grasses in the competitive struggle with shrubs and mosses (Figure 44). For instance, elevated sections in tundras are usually covered with grasses. The fact of the matter is that these small hills are used by polar owls as observation posts; here the owls and other predators eat their prey. Arctic foxes dig their burrows in such elevated locations. The constant soil fertilization with food remains and excrement results in

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[1]Khantimer, I.S., SEL'SKOKHOZYAYSTVENNOYE OSVOYENIYE TUNDRY [Agricultural Development of the Tundra], Leningrad-Moscow, Izd-vo Nauka, 1974.

Figure 44. Grasses appear in a section that is continually fertilized (in this case, by excrement and food remains under an eagle's nest).

the formation of grassy swale. Specially formulated experiments in which the tundra soils were fertilized with nitrogen, phosphorus, and potassium produced the same results: in a section covered with mosses and lichens, the quantity of grasses increased after a few years, and after 7-8 years the grasses finally pushed out their rivals.

Thus, the development of the Subarctic and the forms of effects on its ecosystems that are related to this unambiguously raise the question of the creation of controllable agroecosystems. Much has already been done in this direction, but they are only the first steps.

Experience has shown that any transformation with preservation of the ecosystems' optimum parameters is more difficult or even impossible without woody vegetation -- trees, groves, windbreaks. They soften the climate and moderate its extremes, improve the area, and so on. The restoration of forests and sparse forests is considerably more difficult than maintaining them by creating optimum forest conditions, because if the woody vegetation is destroyed, radical changes occur in ecosystems. Therefore, the preservation of the Subarctic's forests and the prevention of the degradation of their northern boundaries is one of the most unpostponable problems of our time.

The forest boundary is one of nature's main borders: climatic, botanical, soil, zoological, and so forth. This means that on both sides of the forest boundary there are substantial changes in wind force, snow thickness and density, depth of soil freezing and thawing, soil temperature and the nature of soil formation, and habitation conditions for lower-stage plants and animals. The forest boundary, like the needle of a complicated and complex automatic recorder, reflects the actually existing conditions of the surrounding environment. When the boundary changes (by retreating, say), environmental conditions are also altered. The wind force increases in the deforested territories, the snow is redistributed (it is swept off the elevated sections and accumulates in the depressed ones), the soil freezes more severely and its temperature drops in areas from which the snow was swept. The intensity of the appearance of polygonal-mottled formations (soil splitting, swelling, "freezing out," and so on) increases. The soil in snowless sections starts to freeze to a greater depth than it thaws, which leads to a lowering of the permafrost's temperature (hardening of the permafrost) or the formation of permafrost if there was none. Swamp formation increases, as does the intensity of thermokarst processes, and the daily fluctuations in air and soil temperature become sharper. Conditions for the existence of animals deteriorate and the forest animals migrate from the deforested areas. Thus, the changes that take place in the natural situation are huge ones. The mechanism of interrelationship and intercausality in an ecosystem is manifested in full measure in such cases.

It is impossible to understand the dynamics of woody vegetation on its northern boundaries if we attempt to do so only on the basis of the natural processes occurring in the ecosystems and do not take human activity into consideration. Man, as research has shown, appeared in the Far North several thousand years ago. His activities have become increasingly more intense. The trees at their northern boundaries are the main factor that has suffered from this. Even A.F. Middendorf, who who traveled through northern Siberia in 1842-1845, wrote: "The more mercilessly the forest's primeval defenses are destroyed, the more doubtful the regeneration of forest vegetation becomes. Population reproduction in the far north can easily outstrip forest reproduction"[1]. In our time, this is no longer an assumption for the regions of the Subarctic, but reality.

Let us examine the effect of man on the sparse northern forests, using as our example the regions in northern Yakutiya that are located more than 1,500 km to the east of those places in central Siberia where Middendorf worked.

A.L. Birkengof conducted research on an expedition into the basin of the Indigirka River in the 1920's [3]. He found large numbers of burned and logged areas in the sparse forests. Along with attempts to preserve the forests as the habitat of commercially valuable wild animals, people were deliberately felling the forests in order to obtain meadow lands with a good stand of grass. On the basis of this, Birkengof arrived at the conclusion that the northern forest boundary on the Indigirka had, in the recent past, undoubtedly extended farther to the north than it did at that time. The following observations made by Birkengof are rather curious, and have not lost their value even today. At the time when kolkhozes were organized on the Indigirka, the number of snares (traps for polar foxes) belonging to the inhabitants of the village of Russkoye Ust'ye alone exceeded 10,000. If we assume that the number of trees per hectare in sparse larch forests is 200 (possibly somewhat more or fewer) and that one snare requires one tree, then it turns out to be the case that in order to construct this number of snares, no less than 50 hectares of sparse forest were cut down. This total was arrived at for only one settlement and one tree per snare. There are many villages, however, and in addition to snares, wood is used for fires, tent poles, sledges, and making karbasy [translation unknown] and small boats; for each of them no less than three trees are needed.

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[1]Middendorf, A.F., PUTESHESTVIYE NA SEVER I VOSTOK SIBIRI [Journey to the North and East of Siberia], St. Petersburg, 1867, Part 1, Section 4, p 559.

The need for wood -- which means its consumption -- is no less at the present time. On the contrary, it has increased in connection with the increase in population. For example, Ye.K. Tsoy notes [24] that no less than 50,000 m^3 of firewood is stored up every year in the sparse forest-tundra forests on the lower reaches of the Kolyma River. In 1965, about 40,000 m^3 of firewood was stored up in the settlements of Cherskiy and Zelenyy Mys. Tsoy writes that although previously a considerable part of the firewood was gathered from the sites of forest fires, today green masses on the left bank of the Kolyma are being cut down. And, as wood disappears in the vicinity of the villages, the cutters move farther and farther afield in the interfluve. As a result, the area of unforested tundra territory is growing. Firewood is already being gathered at distances of 60-70 km from Cherskiy and Zelenyy Mys.

On the lower reaches of the Kolyma the trees are 4-8 m tall and have an average diameter of 8-13 cm (16-24 cm maximum), so that for a figure of 100-300 trees per hectare, the total wood supply is 6-20 m^3 per hectare. If we assume a stock of firewood totaling 50,000 m^3, this means that 2,500-8,300 hectares of territory are deforested on the lower reaches of the Kolyma every year. The picture is approximately the same on the lower reaches of the Alazeya, Indigirka, Yana, and Omoloy.

However, frequent and essentially systematic burning destroys considerably more sparsely forested area every year than cutting does. Many investigators have written about this.

From the end of June to the middle of August there is usually dry weather in Yakutiya, which contributes to the appearance of fires. At this time there are sufficient sparks from cross-country vehicles and unextinguished cigarettes, in addition to which the cotton-grass forming mounds and lichens sometimes ignite spontaneously. The increase in the number of expeditions contributes to the increase in fires. As a result of the huge quantity of underground vein ice, subsidences that increase swampiness usually appear on the site of fires, and ground swelling is frequently seen. On sections where a sparse larch forest burned, tundras that have been given the name pyrogenic appear. They are stable and the sparse larch forests usually do not recover in them (Figure 45) because of the sharp change in the soil's hydrothermal regime. The abundance of moisture in loamy soils, which increases after the death of the trees, leads to a lowering of their temperature; the next summer the cold, moisture-saturated soil thaws to a depth that is 10-15 cm less than usual. At the same time, the soil aeration conditions deteriorate.

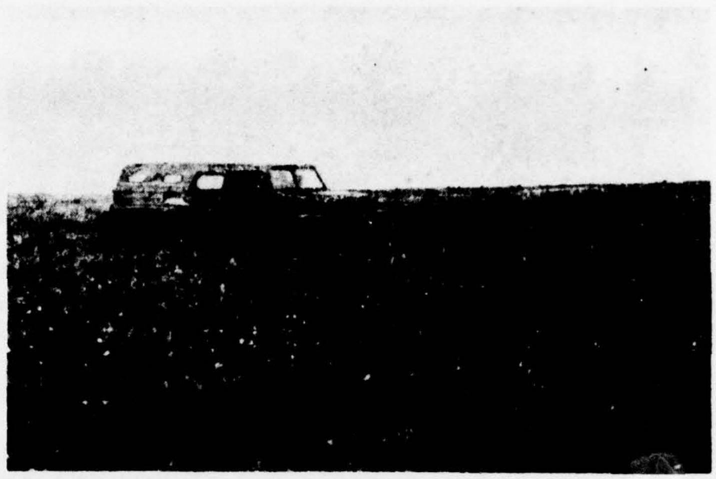

Figure 45. Pyrogenic tundra formed as the result of a fire that occurred several decades ago in a sparse forest-tundra larch forest.

The sparse larch forest islands that remain after fires and cutting are surrounded by tundra and are usually doomed.

After a fire, the changes that occur can go in several different directions, which are governed to a considerable extent by the amount of underground ice that is present. The most dangerous of them takes place when there is a fire on a section made up of loams with a large number of subterranean ice veins (Figure 46). In these cases, after the fire intensive thawing of the underground ice and surface subsidence (or even caving) sets in. On the site of abrupt subsidences, hollows under the ice veins and even little hills outlined by these ice veins are clearly visible. The ecosystem that was previously present is completely destroyed: it cannot regenerate itself.

One of the causes of poor young growth on the northern boundary of the sparse forest-tundra forests is fires, which lead to an increase in soil moisture, the elevation of the permafrost level, and a reduction in the soil temperature.

From aerial photographs, pyrogenic tundras can no longer be distinguished from primary, climatically caused tundras after several decades have passed since a fire. In the pyrogenic tundra belt we usually encounter charred stumps both on the soil surface and under a thin layer of moss. The area occupied by anthropogenic tundras -- pyrogenic and those that form after

Figure 46. Larch forest in loamy ground containing 30-40 percent underground ice veins, after a fire. As a result of the change in heat exchange between the atmosphere and the soil, intensive thawing of the permafrost and ice veins has begun, causing surface subsidence. The thermokarst depression that has formed is 4-6 m deep.

cutting -- is rapidly expanding around populated points located on the northern forest boundary (Ust'ya-Yansk, Kazach'ye, Khayyr, Kular, Andryushkino, Ozhogino, and others). If a resolute struggle against fires is not begun, the deterioration of the physicogeographic conditions in the catastrophically expanding areas of anthropogenic tundras will continue.

Another reason for the anthropogenic tundras' stability is the continually increasing distance between them and seed sources. Therefore, tundra areas in the relative deforestation belt, in which trees can exist, are doomed to remain unforested until man ceases to be occupied with transforming them.

As we have already said, the relative tundra deforestation belt is basically the southern tundra, where there are 30-40 days a year when the diurnal temperature exceeds 10-11°. This number of warm days is sufficient for the growth and development of trees. The relative deforestation belt formed as the result of natural processes (which were described in preceding sections -- from Western Siberia to the Far East) and human activities.

At the present time, the relative tundra deforestation belt in Eastern Siberia amounts to about 60,000-70,000 km^2. Here the climatic conditions permit the existence of sparse larch forests; they were here, but died out because of man's activities and natural processes. Self-regeneration of the sparse forests is impossible; however, even if it were probable, it would take several centuries. At the same time, larch planting and seeding with the help of specially developed agrotechnical methods is fully possible here in the relative tundra deforestation belt.

Within the borders of the Soviet Union, the total area of the relative deforestation belt is 470,000-500,000 km^2. Forestation operations on this territory would change the nature of the Subarctic substantially.

Thus, the relative tundra deforestation belt is an arena for future agricultural and forest reclamation work. The southern part of the Subarctic -- the forest tundra and northern taiga -- is an area that requires careful preservation and thoughtful utilization of the natural resources. Otherwise, deforested areas similar to the tundra will form here quite rapidly, at a speed proportional to the rate of development. The Subarctic's southern boundary should be the nort ern boundary of commercial forest cutting.

In the northern taiga, where trees do not find their ecological optimum, continuous commercial cutting should be banned. Forest regeneration after cutting is difficult even in the typical and southern taiga, while in the northern taiga it is maximally complicated and frequently simply does not take place. Finally, solid forest cutting in the Subarctic is simply economically unprofitable because of the small reserve of forests and the poor quality of the wood. It is a well known fact that Murmanskaya Oblast is located in the warmest and most favorable (from the viewpoint of physicogeographic conditions) sector of the Subarctic, but here also -- in the opinion of economists -- "The result of the systematic excess of planned clearing and an inadequate volume of reforestation projects is that the oblast's forest raw material resources are exhausted, and the cessation of logging operations is being contemplated; therefore, forest raw materials cannot be a positive factor in the future development of the oblast's productive forces"[1].

In the eastern sectors of the Subarctic, where more severe climatic conditions are encountered, the situation can be even more complicated when solid cutting takes place.

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[1]Freydin, I.L., PROBLEMY SEVERA [Problems of the North], Moscow, Izd-vo Nauka, No 16, 1976, p 109.

In the decree "On Establishing Protective Belts in the Northern Part of the Pre-Tundra Forests"[1], which was issued by the RSFSR Council of Ministers on 16 May 1959, it is pointed out that the primary group of protective forests consists of sparse forest-tundra forests in a belt 30-150 km wide. Commercial forest cutting is prohibited in the belt. But trees, as we have already said, do not prosper not only in the forest tundra, but also in many regions of the northern taiga. Here trees grow slowly and regenerate poorly. Therefore, it is necessary to assign all the Subarctic forests -- including the sparse northern taiga ones -- to the group of protected forests where commercial cutting is banned. These forests generate large quantities of oxygen, purify the air, and transform the cold air masses coming down from the north; that is, this zone is of great importance for regulating the climate, so its deforestation must not be allowed.

As is known, pollution of the atmosphere with dust (and smoke, as a result of industrial development) sharply reduces its transparency, as well as the amount of illumination and ultraviolet radiation received. This dustiness is especially undesirable in the Subarctic because of the lowness of the Sun, as a result of which its rays travel a longer path through the lower layers of the atmosphere. Considering the small amount of ultraviolet radiation[2] received in the Subarctic, it should not be permitted that it be reduced. Because of the long, severe winters with dark nights and the short, cold summer, industrial and administrative buildings and residences are heated considerably and continually, except for an occasional break during the summer. Therefore, more waste products are produced per unit of industrial and residential area than in the southern regions. At the same time, the consequences of atmospheric pollution are considerably sharper in the Subarctic than in more southerly regions, while the possibility of self-cleaning of the atmosphere is less than in any other zone because of the briefness of the growing season, the small amount of phytomass, and the small number of sunny days.

Polluted air has a deleterious effect on the health of both men and animals. It has a negative effect on the durability of materials. For instance, when air humidity is high and when fogs are present (and both of these phenomena are quite common in the Subarctic), sulfur dioxide can enter a reaction with the

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[1]SBORNIK ZAKONODATEL'NYKH AKTOV. OKHRANA PRIRODY [Collected Legislative Acts: Nature Conservation], Moscow, Yurizdat, 1961, p 90.

[2]Normal functioning of the organism requires ultraviolet radiation.

water and form sulfuric acid vapors. These vapors are not only dangerous for men, animals, and plants, they also corrode steel. Under the same conditions (high humidity), carbon dioxide enters into a reaction with water and forms carbonic acid, which attacks limestone and other materials. At low temperatures (-20 or -30°), many grades of steel that are used for standard machine building lose their strength and fail under even small loads. The more corroded the steel parts are, the faster they fail.

As is known, green plants -- trees, in particular -- can purify air. Under Subarctic conditions, however, the phytomass is small and there are frequently no trees. The growing season is short -- 3-6 weeks. Rain,(especially torrential thundershowers) can also clean the atmosphere. However, there is little precipitation in the Subarctic -- 250-400 mm per year. A large part of it falls as snow and freezing rain that is at times indistinguishable from fog. These rains cannot purify the atmosphere. Moreover, when the air is polluted with smoke and dust, fog can accelerate the appearance of suffocating smog, which has already been observed repeatedly in London and other cities in Western Europe and North America.

The capacity of the atmospheric air in the Subarctic for self-purification is very low.

This situation is also correct with regards to surface water in the Subarctic. It is formed by the melting of snow and the falling of rain, so it is weakly mineralized and contains a large amount of organic matter (which gives it its brownish color), for the oxidation of which much oxygen is consumed. Even without this, however, the waters of the rivers and lakes in the Subarctic are poorly oxygen-saturated, particularly in winter. The longer the period of stable ice on open water lasts, the worse the quality of the water, because it cannot be enriched with oxygen at this time. The small amount of oxygen is the primary cause of the deaths of fish in the rivers and lakes of the Subarctic. As long ago as 1877, I.S. Polyakov wrote: "Throughout the lower reaches of the Ob', the water begins to turn red in winter; it then has an unpleasant taste and releases bubbles. The water 'dies' earliest of all in Obdorsk (Salekhard -- author's note) and Poluy, where even the ice yields water that is unpleasantly bitter to the taste. In winter, therefore, the citizens of Obdorsk get their ice from the Ob' at a distance of several kilometers from the village"[1].

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[1]Drachev, S.M., BOR'BA S ZAGRYAZNENIYEM REK, OZER I VODOKHRANILISHCH PROMYSHLENNYMI I BYTOVYMI STOKAMI [The Struggle Against

This was almost 100 years ago, before drainage water was disposed of into the Ob'.

Thus, because of the specific bioclimatic features of the Subarctic, the surface water in this region is worse than the water of the temperate zone, especially in winter.

It is a known fact that it is dangerous to pollute the water of rivers and lakes; under the conditions present in the Subarctic, it is doubly dangerous. In summer the open water flow is in contact with the air, is enriched with oxygen,and acted upon by the Sun, so it purifies itself. When it is under ice for 7-9 months of the year, however, water quality deteriorates by itself, because of the lack of oxygen; river and lake water undergoes an acid reaction and its pH drops below 6.5, where 7.0 is normal. Of itself, this results in the death of fish. In addition, if industrial and domestic wastes are allowed to flow into a river and oxygen is additionally consumed for their oxidation, the situation becomes catastrophic, especially in winter. In the temperate zone, river water can purify itself over a stretch of 200-300 km; under the conditions in the Far North, with the protracted period of stable ice on open water, even 1,500-2,000 km is sometimes not enough, as observations have shown[1].

In the northern taiga, as we have already said, precipitation exceeds evaporation, and so in places where there is no permafrost (Murmanskaya Oblast, the southern part of Arkhangel'skaya Oblast and the Komi ASSR), the ground water level is about 2 m below the surface. Forests, as is known, cause a large amount of water to evaporate, so if they are cut down in such areas, the result is frequently swamping.

Many roads are being built in Murmanskaya Oblast. Sand and shingle material is needed for roadbed fill, and it is obtained from quarries. Many of these quarries have already been filled with water (Figure 47). It is possible that the increase in the number of these manmade ponds in Murmanskaya Oblast will result in the draining of surrounding areas and the death of forests.

Some investigators recommend that urban drainage water be used to irrigate agricultural fields. First, this improves the economics of irrigation agriculture; second, soil is the most

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Pollution of Rivers, Lakes, and Reservoirs by Industrial and Domestic Drainage], Moscow, Izd-vo Nauka, 1964, p 30.

[2]Ibid.

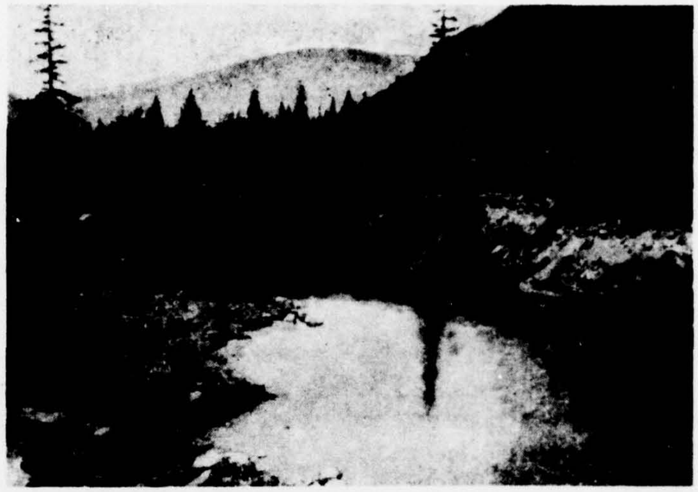

Figure 47. In the northern taiga zone, almost every depression more than 2 m deep reaches the ground water level. As a result of this, ditches and quarries are transformed into ponds.

efficient means of rendering drainage water harmless. These recommendations are valid, but only for the southerly zones. In the Subarctic the soil layer is thin (30-150 cm) and very cold; at a depth of 20 cm, its temperature rarely exceeds 5-10°, even in July. The normal summer soil temperature at this depth is 2-4°. As I recall, the soil temperature near Moscow is 18-20° at this time. The speed of chemical reactions, as is known, depends on the temperature (van't Hoff's law). Moreover, the permafrost layers that are at a depth of 50-100 cm in summer act as a water-resistant horizon. In the Subarctic, the almost complete absence of drainage infiltration into the soil leads to river pollution through the surface layer considerably more than is the case in the temperate zone, where there is no permafrost. Therefore, in the Subarctic drainage water can be used in permafrost areas only as fertilizer and then in very limited quantities, for the disinfecting capacity of the seasonally thawed, thin, frozen soil is itself extremely limited.

It is a known fact that sulfur dioxide, ammonia, fluorine compounds, and the vapors of asphalt, resins, and some acids have a negative effect on trees, bushes, lichens, and mosses. These substances are products of the incomplete combustion of gasoline and oils and industrial dust in general, which contains chemically active substances. Lichens, and particularly the bushy ones that serve as reindeer fodder, are very sensitive to air pollution.

In decreasing order of sensitivity to atmospheric pollution, trees and bushes are arranged in the following manner: spruce, pine, fir, larch, alder, willow, birch. When planting northern roads with trees, therefore, emphasis should be placed on larch varieties, which, incidentally, also cause dust to settle better than the conifers.

Finnish investigators have mentioned that in recent years there has been a sharp increase in the number of galls[1] on willow trees along streets and highways. They relate this primarily to the increased air pollution along roads under the conditions of the North. Thus, the facts indicate that vegetation is an accurate and sensitive indicator of changes in the surrounding environment.

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[1]Galls are abnormal growths of plant tissue, or unusual "tumors," caused by plant damage and parasitic insects, as well as fungi and bacteria.

CONCLUSION

The Subarctic -- this is a region that includes the tundra, forest tundra, and northern taiga. Huge mineral raw material reserves are concentrated here, and the rate of their development will increase. Our knowledge of nature in this region is proportional to the degree of industrial development and growing at about the same rate. For example, in Academician A.A. Grigor'yev's classic book, "The Subarctic," in which he basically correlated materials gathered during the prewar and early postwar years, he speaks of permafrost as a factor that consolidates loose soil and hinders the formation of gullies. Industrial development has shown that the actual situation is somewhat different. The gully growth rate depends on the degree of disruption of the vegetative soil cover and the quantity of underground ice that is present. The relief around industrial centers is different now from what it was 20-30 years ago. The environs of such points abound in gullies and depressions. In connection with this there has arisen the problem of the necessity of developing measures so that the transformation of the relief will not be an elemental process hindering the development itself. This problem cannot be set aside, since in the Subarctic there will soon be no places where cross-country vehicles and tractors have not gone. At the same time, in the path of almost any tracked vehicle there appear gullies, depressions, and other disruptions of the relief. In addition, gullies grow quickly in the Subarctic -- 15-20 m per year.

It is precisely this instability of the ground complex, leading to a change in the relief, that is the most typical feature of the Subarctic.

Nature in the Subarctic, as a unique resonator, is capable of intensifying all effects: a small pit is transformed into a lake or cave-in, a trench -- into a gully. Small (several tenths of a degree) but protracted secular reductions in temperature will lead to glaciation; first to small, nuclear glaciers, then to large ones. As a result, large climatic changes occur, such as those that occurred in the high latitudes in the course of the Earth's geological history, while in the low latitudes the temperature has always been almost the same. Normal temperature fluctuations (2-, 3-, and 11-year cycles, and so on), while almost unnoticeable in nature in the southern zones, lead to intensive thawing and thermokarst processes -- that is, a change in relief -- in the Subarctic. However, once a thermokarst lake has formed, it expands and evelops according to its own rules, changing the parameters of the surrounding environment. The water surface absorbs more heat than a ground surface covered with plants, which leads to the formation of taliks and the crumbling of shore lines; fish appear in the lake and waterfowl begin to nest nearby. This continuous and extraordinarily intensive variability of nature is particularly graphic when modern large-scale maps are compared with maps 20-25 years old. In areas where there was tundra, lakes have appeared; in the path of a cross-country vehicle that passed between two rivers there is now a unique canal with crumbling banks.

The analysis of nature in the Subarctic, using biogeocenotic and ecosystem methods, revealed the extraordinary vulnerability and delicacy of this area's ecosystems.

For example, the tendency that trees have to expand their own areals in the Eastern European Subarctic has been explained and is even now explained by some investigators as being due to a centuries-long, planetary climatic warming. However, extended meteorological observations refute this thesis and indicate a uniform climate with constant small fluctuations. As it turns out, because of the instability of the high-temperature, close-to-zero stratum of the ground in the Eastern European Subarctic, slight warming results in the capture of tundra sections located on the polar boundary of the sparse forests by woody vegetation. Woody vegetation hinders winter freezing by accumulating snow on the sections captured by it. The seasonally thawed layer thickens, which leads to an improvement in not only the thermal and water regimes, but also mineral nutrition. This contributes to the preservation of trees even when the warming period ends, and causes a continuous expansion of the area occupied by the woody vegetation, so that a self-regulating ecosystem develops. Thus, we again encounter the property of the unique resonator, which manifests itself because of the sensitivity and instability of nature in the Subarctic: small temperature fluctuations have a great effect.

Under the conditions present in Siberia, insignificant but cumulative changes in the soil environment caused by the growth of mosses and cotton-grass mounds lead to a steady cooling of the soil and shrinkage of the seasonally thawed layer, which means they lead to deterioration of the woody plants' mineral nutrition and their death; that is, to an eventual retreat of the sparse forests' northern boundary. In order to explain the degradation of the forests in this region it is not necessary to refer to climatic factors on a planetary scale (cooling of the climate, a change in the angle of tilt of the Earth's axis). However, such attempts have been made in the works of some investigators.

Because of their instability and vulnerability, the ecosystems of the Subarctic are capable of bearing only small additional loads that are dozens of times smaller than ecosystems in the more southerly natural zones can handle. For example, about 1,300 domesticated reindeer were transported from the Chukotsk Peninsula to Alaska, for the first time, at the end of the last century. By the beginning of the 1930's, their number had increased to 1.0-1.5 million. In only a few decades the reindeer had exhausted their Subarctic pastures, and the herds were quickly and catastrophically reduced. By the end of the 1940's there were no more than 25,000-28,000 reindeer in Alaska.

In the Soviet Subarctic in the 1930's there were about 1.4 million domesticated reindeer. At the present time there are about 2.5 million of them, plus more than 600,000 wild ones. The possible further growth in their numbers is: 400,000 in the tundra and forest tundra and 400,000-500,000 in the northern taiga[1]. It is possible that more precise calculations and allowing for the exhaustion of the pastures can substantially reduce these figures. In order to preserve this reindeer population -- to say nothing of increasing it -- it is necessary that the mass of vegetative fodder in the pastures not be reduced.

Sowing the tundra in grass, along with the creation of a forest belt, will increase the reindeer capacity and expand the deficit pastures (with shelter from the wind), and reduce the growth of thermokarst, gullies, swellings, and so on.

However, controlling the Subarctic agroecosystems is a considerably more complicated affair than it is for the same ecosystems in more southerly areas. Vegetation that is too thick, for example, weakens soil warming, which results in a decrease in the depth of the seasonally thawed layer. This means that

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[1]Andreyev, V.N., Golosov, I.M., and Preobrazhenskiy, B.V., SEVERNYYE OLENI [Reindeer], Krasnoyarsk, 1972.

the plants' mineral nutrition deteriorates, since the volume of soil from which the nutritive substances come is reduced. When the plants occur more sparsely, their roots do not bind and strengthen the soil as well, and this leads to "freeze-out" of rocks and the formation of hummocks, the plant growth conditions deteriorate, and working a field becomes more difficult.

Here is an example of the complexity involved in controlling the Subarctic's agroecosystems. Summer in Yakutiya is quite warm, and dry periods are common. Therefore, here we see the frequent use of irrigation in fields where agricultural crops are growing. During the first year of overhead irrigation the depth of the seasonally thawed layer increases, because of the influx of additional heat with the water. Because of the irrigation, every year the moisture content of the seasonally thawed layer's lower horizon increases, which means that the amount of heat consumed to warm it increases. Eventually, the seasonally thawed layer shrinks, while the soil temperature drops and its moisture content increases. As a result, a field that was suffering from dryness is turned into a swamp. In these irrigated sections salinization frequently occurs because of the fact that a so called "sweating" regime is established: the moisture evaporates, leaving salts on the soil surface.

It is possible that in the future we will create agroecosystems that are saturated with self-regulating instruments utilizing the free energy of the wind and permafrost. It is a well known fact that summer cooling in the Subarctic is primarily caused by intrusions of cold Arctic air accompanied by winds. It is apparently possible to create wind-powered power plants that would heat water and force it through pipes to heat the soil when the Arctic winds grow stronger.

The vulnerability of nature in the Subarctic and its ability to react strongly to all influences and intensify them have become known during the process of developing this region; that is, in the last few decades. Industrial development of the Subarctic will continue at increasing rates. Therefore, the future fate of nature in this area is entirely in the hands of man.

BIBLIOGRAPHY

1. Andreyev, V.N., "Features of the Zonal Distribution of the Surface Phytomass in the Eastern European North," BOTAN. ZHURNAL [Botanical Journal], No 10, 1966.

2. Baulin, V.V., Belopukhova, Ye.B., Dubikov, G.I., and Shmelev, L.M., GEOKRIOLOGICHESKIYE USLOVIYA ZAPADNO-SIBIRSKOY NIZMENNOSTI [Geocryological Conditions in the Western Siberian Depression], Moscow, Izd-vo Nauka, 1967.

3. Birkengof, A.L., POTOMKI ZEMLEPROKHODTSEV [Descendants of the Nomads], Moscow, Izd-vo Mysl', 1972.

4. Budyko, M.I., KLIMAT I ZHIZN' [Climate and Life], Leningrad, Izd-vo Gidrometeoizdat, 1971.

5. Grigor'yev, A.A., SUBARKTIKA (OPYT KHARAKTERISTIKI OSNOVNYKH TIPOV GEOGRAFICHESKOY SREDY). IZBR. TEORETICHESKIYE RABOTY [The Subarctic -- an Attempt to Describe the Basic Types of Geographic Environment: Collected Theoretical Works], Moscow, Izd-vo Mysl', 1970.

6. Grosset, G.E., KEDROVYY STLANIK [Cedar Stlanik], Moscow, Izd-vo MOIP [Moscow Society of Naturalists], No 12, 1959.

7. Dylis, N.V., STRUKTURA LESNOGO BIOGEOTSENOZA (KOMAROVSKIYE CHTENIYA, XXI) [Structure of the Forest Biogeocenosis (Komarov Lectures, XXI)], Moscow, Izd-vo Nauka, 1969.

8. Koloskov, P.I., "On the Question of Thermal Improvement in Areas of Permafrost and Deep Winter Freezing of the Soil," VECHNAYA MERZLOTA [Permafrost, Collection of Works], Moscow, Materials of the KYePS [Permanent Commission for the Study of Natural Productive Forces of the USSR at the USSR Academy of Sciences], Izd-vo AN SSSR [USSR Academy of Sciences], No 80, 1930.

9. Koloskov, P.I., "On the Causes and Consequences of Ground-Ice Melting in Central Yakutiya," ISSLEDOVANIYA VECHNOY MERZLOTY V YAKUTII [Permafrost Investigations in Yakutiya, Collection of Works], Moscow, Izd-vo AN SSSR, No 2, 1950.

10. Korotkevich, Ye.S., POLYARNYYE PUSTYNI [Polar Deserts], Leningrad, Izd-vo Gidrometeoizdat, 1972.

11. Kryuchkov, V.V., KRAYNIY SEVER: PROBLEMY RATSIONAL'NOGO ISPOL'ZOVANII PRIRODNYKH RESURSOV [The Far North: Problems in the Rational Utilization of Natural Resources], Moscow, Izd-vo Mysl', 1973.

12. Middendorf, A.F., PUTESHESTVIYE NA SEVER I VOSTOK SIBIRI [Journey to the North and East of Siberia], St. Petersburg, Part 1, Section 4, 1867.

13. Popov, A.I., MERZLOTNYYE YAVLENIYA V ZEMNOY KORE (KRIOLITOLOGIYA) [Permafrost Phenomena in the Earth's Crust (Cryolithology)], Moscow, Izd-vo MGU [Moscow State University], 1967.

14. Rubinshteyn, Ye.S., and Polozova, L.G., SOVREMENNOYE IZMENENIYE KLIMATA [The Modern Change in Climate], Leningrad, Izd-vo Gidrometeoizdat, 1966.

15. Sochava, V.B., and Gorodkov, B.N., ARKTICHESKIYE PUSTYNI I TUNDRY. RASTITEL'NYY POKROV SSSR. (POYASNITEL'NYY TEKST K GEOBOTAN. KARTE SSSR) [Arctic Deserts and Tundras; Vegetative Cover of the USSR (Explanatory Text for the Geobotanical Map of the USSR)], Moscow-Leningrad, Izd-vo AN SSSR, 1956.

16. Sukachev, V.N., IZBRANNYYE TRUDY. T. I. (OSNOVY LESNOY TIPOLOGII I BIOGEOTSENOLOGIYA) [Selected Works, Vol I (Principles of Forest Typology and Biogeocenology)], Moscow, Izd-vo Nauka, 1972.

17. Sumgin, M.I., "On the Question of the Prospects for Studying Permafrost in Yakutiya," TRUDY KOMITETA PO VECHNOY MERZLOTY [Works of the Committee on Permafrost], Moscow, Izd-vo AN SSSR, Vol 9, 1940.

18. Syroyechkovskiy, Ye.Ye., BIOLOGICHESKIYE RESURSY SIBIRSKOGO SEVERA [Biological Resources of the Siberian North], Moscow, Izd-vo Nauka, 1974.

19. Targul'yan, V.O., POCHVOOBRAZOVANIYE I VYVETRIVANIYE V KHOLODNYKH GUMIDNYKH OBLASTYAKH [Soil Formation and Weathering in Cold, Humid Areas], Moscow, Izd-vo Nauka, 1971.

20. Tikhomirov, B.A., VZAIMOSVYAZI ZHIVOTNOGO MIRA I RASTITEL'-NOGO POKROVA TUNDRY [Interrelationships of the Tundra's Fauna and Vegetative Cover], Moscow, Izd-vo AN SSSR, 1959.

21. Tyrtikov, A.P., VLIYANIYE RASTITEL'NOGO POKROVA NA PROMER-ZANIYE I PROTAIVANIYE GRUNTOV [The Effect of Vegetative Cover on Ground Freezing and Thawing], Moscow, Izd-vo MGU, 1969.

22. Uspenskiy, S.M., ZHIZN' V VYSOKIKH SHIROTAKH [Life in High Latitudes], Moscow, Izd-vo Mysl', 1969.

23. FIZIKO-GEOGRAFICHESKIY ATLAS MIRA [Physicogeographic Atlas of the World], Moscow, Izd-vo Nauka, 1964.

24. Tsoy, Ye.K., "On Rational Forest Utilization by Consumers on the Lower Reaches of the Kolyma and Cessation of the Use of Wood Fuel," OKHRANA PRIRODY YAKUTII [Conservation in Yakutiya, Collection of Works], Irkutsk, 1971.

25. Chernyad'yev, V.P., "Research in the Dynamics of Seasonal and Permanent Freezing Under the Conditions Encountered in Western Siberia," TRUDY PNIIIS [Works of the Industrial and Scientific Research Institute for Engineering Surveys in Construction], Moscow, Vol 2, 1970.

26. Shvetsov, P.F., MERZLYYE SLOI ZEMNYYE [Frozen Earth Layers], Moscow, Izd-vo AN SSSR, 1963.

27. Shvetsov, P.F., "The Role of Two- and Three-Year Increases in Soil Temperature in the Development of Modern Thermokarst and Cryogenic Slope Processes in the Far North," SOVREMENNYYE VOPROSY REGIONAL'NOY I INZHENERNOY GEOKRIOLOGII [Contemporary Questions in Regional and Engineering Geocryology, Collection of Works], Moscow, Izd-vo Nauka, 1964.

28. Elton, Ch., EKOLOGIYA ZHIVOTNYKH [Animal Ecology], Moscow-Leningrad, Izd-vo Biomedgiz, 1934.

29. Yurtsev, B.A., GIPOARKTICHESKIY BOTANIKO-GEOGRAFICHESKIY POYAS I PROISKHOZHDENIYE YEGO FLORY (KOMAROVSKIYE CHTENIYA, XIX) [The Hypo-Arctic Botanic-Geographic Belt and the Origin of Its Flora (Komarov Lectures, XIX)], Moscow-Leningrad, Izd-vo Nauka, 1966.

30. Yakushkin, G.D., Pavlov, B.M., Zyryanov, V.A., and Kuksov, V.A., "On the Biological Productivity of the Dominant Types of Commercial Animals in the Taymyr Tundra Zone," MATERIALY VSESOYUZNOY NAUCHN.-PROIZVODSTV. KONFERENTSII VNIIZHP [Materials of the All-Union Scientific-Production Conference of the All-Union Scientific Research Institute of Animal Raw Materials and Furs], Kirov, Part 2, 1969.