Microbiological activity in the soils of pingos and thermokarst depressions in the south of the Vitim Plateau (Transbaikalia, Eastern Siberia)

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Abstract. The intensity of microbiological processes in soils of pingos and thermokarst depressions in the south of the Vitim Plateau was studied. The number of dominant groups of microorganisms (Fungi; Bacteria, and Actinomycetes as a separate group) in Haplic Chernozems (Stagnic, Turbic) and Calcaric Gleyic Phaeozems were identified. Carbon accumulation in microbial biomass in soils of pingos and thermokarst depressions varies considerably in comparison with background soils. Bacterial microflora has been proven to prevail in soils under the study. The maximum indicators of actinomycete and fungal mycelium were found in the soils of thermokarst depressions. Microbiological activity for all studied parameters is higher in Calcaric Gleyic Phaeozems.

1. Introduction

In recent decades, one of the key factors in the functioning of cryogenic ecosystems has been global warming [1], in particular, there is an increase in the thickness of the active layer, an increase in temperature, and a reduction in the spread and confluence of permafrost [2], activation of thermokarst in some regions [3]. The melting of ice contained in the soil is accompanied by changes in the day surface and the development of dangerous permafrost processes: heaving of soil and thermokarst, which leads to changes in soil properties [4, 5]. Strengthening the spatial heterogeneity leaves an imprint on the quantitative and qualitative composition of the microbiota.

On the permafrost territory of the southern part of the Vitim Plateau, a hummocky-depression microrelief is widespread; the beginning of its formation is attributed to the Sartan time [6]. With the warming of the climate, permafrost began to degrade, pseudomorphs arose, then transformed into depressions, which were filled with water for a long time. On other landfills pingos arose as a result of the bulging of the soil and the collapse of their sides. R V Desyatkin [7] believes that pingos are elements of thermokarst landforms, and their formation was associated with the freezing of water-saturated thawed layers under disappearing lakes.

The extreme environment of cryogenic ecosystems determines the peculiar composition and structure of the microbe community, increase the vulnerability of the microbiota, while at the same time contributing to their adaptability to changes in conditions. Microbial biomass, activity, and diversity of the microbial community are indicators of changes in the soil environment [8, 9]. Biological processes in them take place during a short growing season against the background of permafrost.
The cryogenic nature of soils leaves an imprint on the structure of microbial complexes, determines their dynamics and activity, thereby determining the specificity of the process of transformation of substances. The work was aimed to study the microbial community in the soils of pingos and thermokarst depressions in the south of the Vitim Plateau. The significance of the study lies in obtaining new data on the microbiocenosis of cryogenic landforms and identifying the direction and intensity of microbiological processes.

2. Objects and Methods

The study area was located in the Yeravninskaya depression in the south of the Vitim Plateau, where permafrost reaches a maximum thickness of 120-130 m, averaging 80-85 m [10]. The upper permafrost boundary occurs at a depth of 1.5-3.0 m from the day surface, and in some places – at a depth of less than 1 m.

The climate of the Yeravninskaya depression is sharply continental [11]. Cold, thin-snowed, and long winter is followed by late windy and dry springs. Summer is hot and short. According to the data of the Sosnovo-Ozersk meteorological station, which is located in the study area, the average annual air temperature is $-4.1^\circ C$, with the mean temperature of the warmest month (July) $+17.1^\circ C$ and the lowest (January) is $25.4^\circ C$. The sum of biologically active temperatures is 1,330°C.

The vegetation of the study area is variable. Cryophytic relatively well-moisturized steppe communities in combination with cryophytic wet meadows and larch and birch coppices are typical in the area. Accounting for aboveground, underground, and total phytomass showed that the biological productivity of the herbage from the pingos was 2.08 kg/m² and was on a par with the background variant – 2.05, but significantly lower compared to those of depressions – 2.50 kg/m² [12]. Deluvial carbonate loamy sediments and layered lacustrine sediments represent the parent rocks.

The soils of pingos and thermokarst depressions were the objects of the research. A detailed description of the soil morphology and soil classification was presented earlier [13]. There are Haplic Chernozems (Stagnic, Turbic) within the pingos area and Calcaric Gleyic Phaeozems in thermokarst depressions. Gleyic Chernozems in the surrounding areas were taken as background soils. The sites with pronounced cryogenic phenomena were selected as experimental plots. Test site location and soil types are given in table 1. Soil profiles in the pingos area ($n = 3$) and thermokarst depressions ($n = 3$) were studied throughout the depth of the seasonally thawed layer (STL). Soil samples were taken with a step of 10 cm to a depth of 80 cm in thermokarst depressions and up to 100 cm in pingos. In 2008 STL thickness in Gleyic Chernozem reached 285 cm [14]. The current study provides the data on soil microbial community up to 50 cm in depth.

The intensity of microbiological activity was determined by the carbon content of the microbial biomass, the number of microorganisms, and the dominant groups of microbial communities. The number of microorganisms in soils was determined under the microscope by counting bacteria in the soil samples taking into account the adsorbed cells [15]. The cells were pre-desorbed on a UZDN–1 ultrasonic disperser. When counting the cells of soil bacteria and mycelium of actinomycetes, the preparations were stained with an aqueous solution of the “acridine orange”, and the “calcofluor white” was used to stain the mycelium and fungal spores. The work was carried out in the laboratory of Soil Biochemistry of the Institute of General and Experimental Biology SB RAS on a luminescent microscope “Micromed 3 LUM”, the carbon of the microbial biomass ($C_{mb}$) was determined by the rehydration method [16].

Background Gleyic Chernozem is characterized by a small thickness of the humus-accumulative horizon and a medium loamy texture. The organic carbon content ($C_{org}$) in the upper horizon is average (table 2). The amount of absorbed bases in the upper humus horizon is high. The soil reaction in the upper part of the profile is slightly acidic ($pH$ 6.52) and close to neutral ($pH$ 7.15), in the lower part, it is alkaline ($pH$ up to 8.36).
Table 1. Test site location and soil types.

| Site                        | Location, elevation          | Soil type                                              |
|-----------------------------|-----------------------------|--------------------------------------------------------|
| Pingos                      | 52°32'18.4” N; 111°27'19.3” E; h 954 m | Haplic Chernozems (Stagnic, Turbic)                   |
|                             | 52°32'17.9” N; 111°27'19.3” E; h 955 m | Haplic Chernozems (Stagnic, Turbic)                   |
|                             | 52°32'16.8” N; 111°27'18.4” E; h 952 m | Haplic Chernozems (Stagnic, Turbic)                   |
| Thermokarst depressions     | 52°32'19.4” N; 111°27'18.8” E; h 951 m | Calcaric Gleyic Phaeozems                             |
|                             | 52°32'09.2” N; 111°27'25.03” E; h 945 m | Calcaric Gleyic Phaeozems                             |
|                             | 52°32'13.2” N; 111°27'24.58” E; h 948 m | Calcaric Gleyic Phaeozems                             |

Haplic Chernozem (Stagnic, Turbic) and Calcaric Gleyic Phaeozem differ from background soils in terms of microbiological parameters. The soil reaction in thermokarst depressions is alkaline (pH 8.02-8.40), in pingos – slightly alkaline (7.71-7.81). The soils in pingos are of sandy loamy and light loamy texture, in thermokarst depressions – light loamy within the layer of 0-30 cm, medium loamy in the 30-50 cm layer. The maximum content of organic carbon was marked in the top layer of Calcaric Gleyic Phaeozems of thermokarst depressions (17.56%) (table 2).

Table 2. Some physical and chemical parameters of soils (n = 3).

| Soil type, site                   | Depth, cm | pHw   | C_{org}, % | C_{ab}, mg/100 g | Particles <0.01 mm, % |
|-----------------------------------|-----------|-------|------------|------------------|-----------------------|
| Haplic Chernozems (Stagnic, Turbic), pingos | 0-10      | 7.71±0.66 a | 11.10±2.69 | 83.70±9.30 | 12.4±9.9 |
|                                   | 7.50 b    | 24.2 | 11.11      |                  | 79.3                  |
|                                   | 10-20     | 7.35±0.31 | 6.38±1.88 | 78.61±6.01 | 19.9±12.8 |
|                                   | 4.18      | 29.48 | 7.65       |                  | 64.7                  |
|                                   | 20-30     | 7.65±0.57 | 7.97±1.51 | 39.52±8.48 | 22.7±9.7 |
|                                   | 7.38      | 19.01 | 21.47      |                  | 42.6                  |
|                                   | 30-40     | 7.75±0.60 | 6.00±2.08 | 23.05±7.15 | 19.7±7.6 |
|                                   | 7.75      | 34.68 | 31.03      |                  | 38.7                  |
|                                   | 40-50     | 7.81±0.63 | 1.64±0.38 | 16.5±5.16 | 20.1±8.4 |
|                                   | 8.11      | 23.41 | 31.21      |                  | 41.9                  |
| Calcaric Gleyic Phaeozems, thermokarst depressions | 0-10      | 8.02±0.09 | 17.56±2.26 | 178.1±32.30 | 23.6±14.7 |
|                                   | 1.06      | 12.87 | 18.14      |                  | 62.4                  |
|                                   | 10-20     | 8.05±0.06 | 15.85±0.55 | 120.85±10.45 | 21.6±12.5 |
|                                   | 0.68      | 3.44  | 8.65       |                  | 37.8                  |
|                                   | 20-30     | 8.26±0.12 | 4.96±0.65 | 28.4±0.80 | 28.6±14.6 |
|                                   | 1.43      | 13.11 | 2.32       |                  | 30.9                  |
|                                   | 30-40     | 8.40±0.02 | 1.39±0.09 | 26.95±6.95 | 34.3±4.9 |
|                                   | 0.18      | 6.47  | 25.79      |                  | 14.21                 |
|                                   | 40-50     | 0.84±0.07 | 1.39±0.01 | 17.87±3.70 | 33.5±3.4 |
|                                   | 1.19      | 0.72  | 29.31      |                  | 10.3                  |
| Gleyic Chernozem, Background soils | 0-10      | 6.52±0.25 | 7.54±0.35 | 144.22±25.44 | 42.5±7.83 |
|                                   | 3.83      | 4.37  | 17.64      |                  | 18.41                 |
|                                   | 10-20     | 7.15±0.24 | 5.66±2.10 | 131.69±22.41 | 42.10±8.1 |
|                                   | 3.36      | 37.03 | 17.02      |                  | 19.26                 |
|                                   | 20-30     | 7.81±0.22 | 0.83±0.31 | 25.41±4.63 | 39.5±1.32 |
|                                   | 2.82      | 37.49 | 18.23      |                  | 3.35                  |
|                                   | 30-40     | 8.26±0.13 | 0.42±0.02 | 21.47±2.76 | 40.77±1.66 |
|                                   | 1.63      | 4.76  | 12.86      |                  | 4.08                  |
|                                   | 40-50     | 8.36±0.31 | 0.46±0.03 | 13.8±1.67 | 36.77±6.93 |
|                                   | 3.71      | 6.69  | 12.10      |                  | 18.84                 |

a – average value; b – coefficient of variation, %
3. Results and Discussion

3.1. Carbon microbial biomass (Cmb)

The average content of Cmb in the upper soil layer of Haplic Chernozems (Stagnic, Turbic) is 83.70±9.30 mg/100 g of the soil (V = 11.1%) (table 2). The maximum microbial mass carbon was found in Calcaric Gleyic Phaeozems at a depth of 0-10 cm (178.1±32.30 mg/100 g), which is explained by the abundance of rhizosphere microflora and high content of Corg. The average Cmb value in the upper soil layer of background soils is 144.22±25.44 (V = 17.64%). The profile distribution of Cmb is uneven. There is a tendency towards a decrease in microbial carbon with depth.

Despite the higher carbon content, the accumulation of Cmb in Haplic Chernozems is less as compared to background soil. Presumably, there is carbon in a stable form unavailable for microbiota.

Coefficients of variation are evident that the set of data is homogeneous and significant. Microbial biomass carbon data are of a close correlation with organic carbon (r = 0.73-0.99).

3.2. Microbiocenosis structure in soils

The uneven distribution of biogenic elements (C, H, O, N), organic matter, and environmental factors caused the fluctuation in the number of bacteria along the profiles (figure 1). As a rule, soil microorganisms are confined to the upper humified and well-warmed horizons, but their amount in the 0-10 cm layer of Haplic Chernozems (Stagnic, Turbic) is low and increases down the profile. That is connected with rapid drying up of the top layer of soils on pingos, and microorganism activity was ceased here during dry periods. The number of bacteria in Calcaric Gleyic Phaeozems reached about 1.5 billion/g of dry soil.

![Figure 1. The number of bacteria in the soils of pingos and thermokarst depressions: 1 – Haplic Chernozems (Stagnic, Turbic) (n = 3); 2 – Calcaric Gleyic Phaeozems (n = 3).](image)

Distinct feature of the microbial population of the studied soils is its differentiation across the profile. The maximum value is found in the layer of 10-20 cm in soils of thermokarst depressions, and it decreases down the profile. There is the inverse pattern in Haplic Chernozems (Stagnic, Turbic), where the value increases down the profile. The structure and distribution along the depth of soil microbial communities are significantly affected by soil moisture and organic matter ability. Data obtained closely connected with the Corg content (r = 0.60-0.90).

The soil is a heterogeneous microzonal system containing both favourable and unfavourable microsites for microorganisms. The mycelial forms (Fungi and Actinomycetes) are able to proliferate through the soil due to the apical growth that allows them to overcome unfavourable microsites and
occupy effectively the soil space [17]. Actinomycetes evolutionarily have a richer enzymatic apparatus, a high level of adaptation, and are found in various types of soils. There are both aerobes, and anaerobes among them. The number of actinomycetes characterizing the processes of organic matter mineralization in the upper part of pingos’ soils was found to be 0.004 m/g of dry soil. At a depth of 40-50 cm, the value is halved (figure 2). In Calcaric Gleyic Phaeozems, the value reaches 0.014 m/g. The length of actinomycetes mycelium positively correlated with $C_{org}$ ($r = 0.51-0.52$).

![Figure 2. Mycelium of actinomycetes in the soils of pingos and thermokarst depressions: 1– Haplic Chernozems (Stagnic, Turbic) ($n = 3$); 2 – Calcaric Gleyic Phaeozems ($n = 3$).](image)

Differences in the intra-profile distribution of actinomycete mycelium are explained by the fact that they more intensively decompose many substances at high pH values. Besides, carbonate-containing horizons are their typical habitats [18]. The largest amount of actinomycetes occurred in soils rich in plant residues [12] since they largely participate in mineralization processes. In our study, such soils were confined to thermokarst depressions.

![Figure 3. Mycelium of fungi in the soils of pingos and thermokarst depressions: 1 – Haplic Chernozems (Stagnic, Turbic) ($n = 3$); 2 – Calcaric Gleyic Phaeozems ($n = 3$).](image)
Soils are known to contain a very large supply of fungal spores mainly dormant. Fungi were found throughout the entire depth of Haplic Chernozems (Stagnic, Turbic) in an amount of 0.0008-0.012 m/g of soil (figure 3) with biomass of mycelium of 0.12-0.35 × 10⁻⁶ g. Mycelium of actinomycetes in Calcaric Gleyic Phaeozems is 0.006-0.01 m/g.

The distribution of fungi along the soil profile has a general tendency – a decrease with the layers of 10-20 and 20-30 cm with further increasing. The maximum content of fungi was found in the depth of 40-50 cm in Haplic Chernozems (Stagnic, Turbic).

The number of fungi varied widely in the soils of the pingos due to more active degradation of organic compounds at low pH values. In Haplic Chernozems pH values are lower than in Calcaric Gleyic Phaeozems (table 2). A sharp increase in the number of fungi in the lower part of the soil profile is possibly related to the high resistance of fungi and water regime peculiarities. In the lower soil layers, fungi survive and continue to destruct the plant’s organic matter. During periods of temporary excessive moisture in soils of thermokarst depressions, the development of fungi can be suppressed to some extent [19].

Calcaric Gleyic Phaeozem soils of thermokarst depressions are a more optimal environment for microorganisms due to better conditions for moisture and nutrient supply.

4. Conclusion

The studied soils differ in the content of microbial biomass, the ratio of different groups of microorganisms (bacteria, fungi, and actinomycetes), and their distribution. In the course of the study, it was reliably determined that the microbiological activity in Calcaric Gleyic Phaeozems was higher than in Haplic Chernozems (Stagnic, Turbic). The low level of energy supply, deep freezing of the soil profile, and significant drying in the spring-summer period negatively affected the microbiota activity in pingos soil.

Bacterial microbiota dominated in soils under the study. Actinomycete and fungal mycelium were uneven along the soil profiles. The intra-profile heterogeneity in the soil microbe distribution indicated that the soil as habitat was significantly differentiated along the profile. Microbiological parameters correlated with Corg content.

Acknowledgments

The field studies were performed within the framework of the state assignment of the Institute of General and Experimental Biology SB RAS No. 121030100228-4; laboratory work was supported by RFBR grant No. 16-04-01297.

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