BIOLOGICAL PROPERTIES OF SOIL AND GROUND WATERS

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Summary

Biological properties of soil water are related to the universal role of water in living organisms, which acts as solvent for nutritive reserves and intercellular metabolite pool and as chemical reagent in hydrolysis and condensation reactions. For definiteness, we assume that the *biological properties of soil waters* include their physical (*Physical Properties of Soil and Ground Waters*) and chemical (*Chemical Properties*) properties, when the latter are considered as factors in the ecological niche of a specific organism. The niche is a multidimensional space (hypervolume), where the environmental conditions are suitable for the existence of some populations. This approach in principle allows analyzing the structural and functional peculiarities of the biota depending on the ranges of the preset factors and predicting the events in natural habitats.

The properties of soil water largely determine the functioning regime of the soil biota as a sustainable natural system, which ensures the turnover of elements and the conservation of parameters of the global ecosystem. Depending on the level of soil water availability, these processes are realized by different organisms, and the decomposition rate of soil organic matter varies significantly. Soil moisture is an essential factor controlling the functions of soil biota in the supply of plants with the main growth resources and the self-purification of the environment from anthropogenic contamination.

The biological properties of subsurface (subsoil, ground) water are the features and qualities of this chemical compound that it acquires due to biotic components. The latter include the living population of subsurface water, the products of its metabolism and

decomposition, and compounds resulting from the impact of metabolites on the surrounding mountain rocks and passing into the soluble forms. The concentration of organic substances in subsurface waters varies between few tenths and 20 mg/l, with significant fluctuations in the qualitative composition depending on the soil type.
The subsurface water population is composed by microorganisms, mainly (from 95 to 99%) prokaryotes (aerobic and anaerobic hemoheterotrophic bacteria, including spore-forming ones, actinomycetes, and cyanobacteria), and some eucaryotes (microscopic fungi, amoebas, and flagellates, protozoa). Their abundance, composition, distribution, and physiological features depend on the occurrence depth of subsurface water and its geochemical features. Microorganisms (subsurface microbiota) of subsurface waters and impregnated rocks compose the major part of the subsurface biosphere. The solution of some hydrobiological problems in subsoil conditions and deep lithospheric horizons requires studies at different levels, from the molecular, cellular, and organism levels to the population and biocenotic ones.

The metabolic activity of bacteria in the aerobic, mixed, and anaerobic zones of the subsurface biosphere can result in the formation of gaseous (CH_4, H_2, NO, N_2O, and N_2) and some other (S^{2-}, S^0, Fe^{2+}, and Mn^{4+}) products. Therefore, subsurface microbiota is an essential biotic factor, which actively affects the migration, accumulation, and redistribution of ore substance, gaseous products, and water in the subsoil and deep-seated layers of the lithosphere and, hence, the sustainable existence of the biogeosystem.

1. Introduction

The functioning of soil biota largely depends on the availability of water and its parameters, including pH, redox potential, and concentration of resources and metabolites. These are the key parameters for the ecological niche of any organism that determine the range conditions, for which the specific organism is adapted. Therefore, water belongs to the main factors determining the functioning of soil biota.

These are soil organisms that are responsible for the decomposition of organic matter, which was produced in the terrestrial ecosystem during the photosynthesis, and supply plants with available resources. They also play an important role in the formation of stable soil aggregates, and larger organisms (primarily earthworms, ants, and termites) contribute to the processes of pore formation and water movement in the soil. The functioning of soil biota determines the level of soil fertility, and the possibility of biota management on the basis of soil moisture control is of interest in terms of sustainable development. It can be even said that soil biota is an ideal example of a system ensuring sustainable functioning of undisturbed ecosystems during long time periods. The essential role of soil biota is related to the organization of cycles of elements (C, N, P, etc.), which makes it possible to repeatedly use the limited amount of each resource, as if to impart the properties of infinite quantity to a finite one.

Bacteria, fungi, and their predators, including protozoa, nematodes, ticks, earthworms, and other organisms, ensure the decomposition of organic matter. Organic matter of natural origin includes the products of photosynthesis (fallen leaves and exudates of plant roots). The main role of soil biota is related to the mineralization of organic matter and the retention of nutrients within the ecosystem. Biota supplies the plants with mineral resources, which are formed during the mineralization of organic matter. The resources that are not consumed by plants and can be removed from the ecosystem by surface or soil waters are immobilized by soil biota and temporarily conserved in its biomass. The latter process is called the immobilization of resources. During the subsequent natural processes of the partial extinction of biota (death and predator activity), these resources return to the environment. In undisturbed ecosystems, mineralization and immobilization processes are closely related to the growth of plants, which ensures sustainable development of the ecosystem.

The biodiversity of soil biota is not yet well understood. The modern genotypic methods confirm that specialists still do not know the major part of soil microorganisms. The mass of biota, including bacteria, fungi, and algae, attains several tons per hectare in fertile soils. To a first approximation, fungi are predominant by biomass in the surface soil samples. The bacterial biomass is comparable by the order of magnitude with the fungal biomass, and the other components, including soil fauna specimens, are less significant. At the same time, the biomass parameters themselves give no indication to the functional role of separate specimens of soil biota. It is not excluded that the estimation of the active surface, through which the interaction between cells and the environment proceeds, is more founded in this case. Taking into account the active surface, bacteria are functional dominants. It is also evident that bacteria perform essential digestive functions in the organisms of soil animals. In some cases, it can be supposed that the level of soil fertility increases when the functional significance of bacteria exceeds that of fungi.

Some soil bacteria and fungi cooperate with plants using specific mechanisms. An example can be provided by specific microorganisms, phytopathogens, which cause plant diseases. Bacteria fixing the atmospheric nitrogen on the roots and in tissues of plants are undoubtedly useful. It is known that nitrogen is one of the main factors limiting the yield of plants. Therefore, the capacity of soil biota specimens for supplying the plants with nitrogen is of great practical interest, as well as the interaction between plants and some nonpathogenic fungi, which form peculiar structures (so-called mycorrhiza) on the roots. The significance of a prevalent mycorrhiza species is determined by the fact that the fungus allows the plant to absorb hardly available phosphates more efficiently.

V.I. Vernadsky already wrote about the existence and significance of "living matter" in the subsurface biogeosphere down to a depth of 3–4 km. However, only studies performed recently at the new theoretical and instrumental level in some world laboratories, allowed one to reveal the following:

- the subsurface biosphere, represented by microorganisms, exists to depths below 6000 m and inhabits subsurface waters, various fluids, and mountain rocks. The available water and the stratum temperature depending on the occurrence depth are the environmental factors limiting its activity. Other necessary and limiting factors of subsurface biosphere functioning are the dynamics of habitat, which determines the possibility of substance exchange with the environment and utilization or migration of metabolites, and the presence of substrates for the energetic and structural metabolism in microbial cells;

- the real functioning of microorganisms in deep lithospheric layers is characterized by an extremely low rate of metabolism; however, bacteria have a high potential metabolic capacity, which can be activated, when the ecological situation changes. The geochemical activity in the subsurface microcosm is of global scale, because microorganisms actively participate in the formation of the gas composition of terrestrial atmosphere, chemical composition of subsurface water, recent processes of mineral formation, and metamorphism of lithospheric rocks.

The study of the oxidative metabolic capacity of subsurface microbiota and bacterial production of gases (methane, hydrogen sulfide, carbon dioxide, and nitrogen and its gaseous compounds) is of special importance for predicting various changes in the deep lithosphere, including those related to nuclear waste disposal, as well as bioremediation of contaminated subsurface water.

Difficulties of microbiological studies in the subsurface biosphere are caused by both technical and theoretical problems. Technical problems are related to the almost stable contamination of deep-seated horizons during the boring, which is accompanied by qualitative and quantitative transformations of microbocenosis, including change or activation of its vital functions. This can result in some adverse consequences related to the functioning of natural and introduced microbiota. Theoretical problems are caused by the lack of fundamental methodological basics of subsurface biosphere studies, particularly, those based on scientific holes. Therefore, international scientific programs such as The Deep Subsurface Science Program (DSSP) and The Natural and Accelerated Program in Bioremediation Research (NABIR) were developed. These programs finance the theoretical studies related to the survival of microbial life under extreme conditions and problems of life origin, as well as the applied investigations, including the study of subsurface microbiota for the purposes of remediation and biotechnological processes.

2. Soil Water as a Condition for the Existence of Soil Biota

2.1. Estimation of Water Demand

The estimation of soil and sediment moistening is frequently based on the volume and mass moisture contents; however, these parameters inadequately characterize the biological properties of water in natural habitats. It is known that water can exist in the natural environment in different states, from hygroscopic moisture strongly adsorbed on soil particles to gravitation water freely moving in large pores under the effect of gravity. A more rigorous estimation of water availability to organisms requires the thermodynamic approach.

In particular, it is more informative to determine the moisture potential as the amount of thermodynamic work required for an organism to extract water. The ranges of water potential for organisms are most frequently given in bars. Among other thermodynamic parameters, water activity, the ratio of the water vapor pressure in the system studied to that over pure water, is also used frequently. The wide use of thermodynamic approach, which permits the integral description of water regime in soils and sediments, their biota, and land soil cover, is only beginning.

It was found that the need for water and tolerance to its deficiency differ significantly among soil biota specimens. Water activity in the natural environment is primarily determined by the adsorption of water molecules on the surface of solid substrates (the matrix component) and the interaction between the water molecules and solutes (the osmotic component). In order that water enters the cell, the concentration of low-molecular substances and ions in the cell should be higher than that in the environment.

An optimal value of moisture potential (water activity) exists for the growth of every organism. When the real conditions are not optimal for this factor, the organism should expend a part of its energy for osmoregulation with the increased load of transport systems and the synthesis of low-molecular osmoprotectors. Under osmotic stress, the growth rate is reduced, and the population biomass decreases. In ecological terms, osmotic effects are of interest for the examination of inhabitants in soils and sediments with the high salt content.

Special terms are used for describing the capability of different organisms to exist under the reduced water activity. In particular, microbiologists roughly determine the particular ecological niche (by water availability) as follows. Organisms capable of growing at an extremely high concentration of salts in the environment are called halophils. Osmophils are organisms that can grow under the high concentration of sugar in the environment. Xerophils are organisms accommodated to the existence in dry habitats.

Organisms in soils generally develop in capillaries filled with water solution or in thin films rather than in a large volume of liquid. The thickness of films and capillaries is essential for microbial activity. Even thick capillaries are frequently filled with air, and film water is present only on the surface of their walls. Microorganisms are practically not developed in thin films. From some data, organic matter in capillaries <1 mm in diameter is unavailable to microorganisms. A good development of microorganisms is observed in water films 10 mm thick and thicker. Along with the large adsorbing surface, the distribution and diffusion of resources and metabolites affect microorganisms in capillaries and films. It was noted that the cell sizes decrease, when the cells are developed in thin water films. The development of cells in soil capillaries is apparently the main reason for the lower size of cells in the soils as compared to those in nutritive media.

Other conditions, including the so-called pH effect, should be taken into consideration for the development of microorganisms in the soil. The value of pH at the interface between the negatively charged adsorbent and the liquid differs from the solution pH by 0.5–2 units. As a result, the optimal pH value for adsorbed cells is displaced toward the alkaline reaction, when the pH of the liquid phase is considered. Both hydrogen ions and various substances composing redox systems are concentrated at the interface between an adsorbent and soil solution. In this microenvironment, microbial cells can create relatively suitable conditions in terms of pH and redox potential. There are strong grounds to believe that the propagation rate and growth energy of cells in the films of soil water differ from the analogous parameters of populations developed in a large volume of liquid.

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Biographical Sketches

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