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The Role of Microbial Communities in Soil Formation and Soil Ecosystem Health

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Abstract—The concept of the microbial community (MC) current at the time of writing, its structure, and the theories that reflect and generalize the progress in MC research are considered. Contemporary knowledge is used as the basis to discuss the role and functions of microbial communities in the emergence and maintenance of what is traditionally referred to by the brief and capacious term "soil", even though soil is essentially a product of the interaction of diverse biological communities and materials, and is a substance of infinite complexity and diversity, which can be regarded as an ecosystem; namely, the soil ecosystem (SE). A novel concept of soil health (SH), which integrates current knowledge of MCs and their functions, and can be used to understand their role in the soil ecosystem, is discussed. Methods for assessment of soil health parameters are briefly presented.

Keywords: microbial community, concepts, soil, soil ecosystem, soil health

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INTRODUCTION

The experimental and theoretical material accumulated in experimental microbiology, microbial ecology, and soil sciences by the first quarter of the 21st century "calls upon" experts to further ponder the material and search for obvious and hidden relationships for further synergistic expansion of the knowledge of nature. This applies primarily to knowledge of the structure of the microbial community (MC). Generalization of progress in MC research and knowledge of MC functioning with conceptualization of disparate facts and long-term consequences in the capabilities of MCs stimulated the expansion of knowledge of the role and abilities of MCs in the soil ecosystem, the most complex of terrestrial ecosystems. Soil health, a new category in the characterization of soil ecosystems (SEs), has emerged. The need for approaches fundamental in content but simple and accessible in use becomes evident as further research on SEs is considered. All this requires the researcher and consumer to be dynamic, critical, and integrative in time.

The aim of this communication is to summarize achievements in the understanding of the structure of microbial communities, the reciprocal influences of these achievements on other areas of microbial ecology, such as the microbial community of the soil ecosystem, and the emergence of soil health as a new category used to characterize soil ecosystems (soils).

1. THE MICROBIAL COMMUNITY; ON THE EMERGENCE OF THE MC CONCEPT

The study and understanding of the properties, capacities, and distinctive features of microorganisms take place at the microorganism population level only, that is, multiple identical unicellular organisms not visible to the "naked" eye, whereas only the ultrastructure of an individual cell can be studied at the level of an individual organism. The microorganisms form a multitude of different populations in nature. It is logical to expect certain populations to influence others, and interactions between populations are manifested as diverse conspicuous and inconspicuous processes. Terms for these interactions, such as competition, antagonism, neutralism, cooperation, synergism, syntrophy, and others, have already been proposed. It is completely logical to expect spatial and temporal changes in the quantities and/or quality of the populations. The term "community" is used to denote the existence of multiple populations at a specific place during a specific time interval. The term "community" reflects the "plurality of multiple" communities in its content. This was apparently the reason for this term to be established in biological science. Thus, the term "microbial community" can be used for a certain combination of multiple species of unicellular organisms that form populations not visible to the naked eye.

The concept of a microbial community (MC) is the key to ecology of microorganisms. The content of the MC concept and the representation of MC structure define the strategy and tactics of relevant research and, of course, the application of the knowledge. The "microbial community" term has synonyms that reflect cognitive aspirations related to the essence of the object: they include "association", "consortium", "microbiota", and even "microbial assemblage" (Zvyagintsev, 1987, Zvyagintsev et al., 1999; Dobrovol'skaya, 2002; Kotelevtsev, 2019). The other existing terms, probably proposed earlier in history, have been constructed in order to denote and reflect the multiplicity of diverse populations that coexist in the world of living beings. For example, the term "consortium" is reminiscent of the concept of society, which reflects the sphere of social interaction specifically of human beings. The term cenosis and its more specific modifications, such as phytocenosis, microbocenosis, biocenosis, biogeocenosis, and others, were proposed in order to distinguish a community with social interactions from communities of living organisms—in other words, living matter.

1.1. Assessment of the MC Content and the MC Characteristics

The term community will be used below, since it is the least ambiguous and accepted by the scientists internationally. The concepts on the essence of a microbial community and the possible trophic, functional, spatial, taxonomic, or other structure of a community or communities developed along with the research methods and knowledge, primarily those related to the trophic diversity of microorganisms. Essentially the entire arsenal of biological and physicochemical methods is used for studying MCs. The objective of the present communication is limited to the microbial community (more specifically, a community of bacteria and micromycetes), and the following MC definition will be used: "A microbial community should be represented as a certain combination of taxonomically different, but functionally interacting microorganism populations that that exist for a certain time in an appropriate place. The components of an MC can be strongly interconnected, also at the physical level, or weakly interconnected, and an MC can be highly specialized or poorly specialized" (Semenov, 1991; Semenov, 2005; Semenov, 2010; Semenov, 2011). What is the objective of acquiring knowledge on MC structure, especially for each distinct community of microorganisms and in each ecotope that is of interest for a researcher or practical worker (even though this is definitely not feasible)? The thing is, a more objective and accurate concept of MC structure has better explanatory and prognostic characteristics (functions!) and thus increases the probability of correct decisions being made in environmental and industrial biotechnology. Let us note that the above definition of MC implies that the MC is dynamic, that is, it can change in time and space. Knowledge of the functional composition and the diversity of components and their amounts in the MC is important along with the dynamic character. The taxonomic composition is at a still lower level of importance, because the process is of primary importance at the macroscopic level. This is demonstrated by the biogeochemical methods being a very important complex of methods in research on microorganism ecology. These methods use physicochemical assays to identify the product of a process implemented by microorganisms (communities!) at the macroscopic level and thus characterize these microorganisms or communities. For example, a distinct smell of hydrogen sulfide is indicative of an intensive sulfate reduction process at a certain site.

1.2. The Evolution of Ideas on MC Structure and Microbial Community Structure Characterized through Trophic Grouping

Interest in studies of the key structure, that is, the trophic structure of microbial communities that dwell in geochemically "moderate" ecological niches decreased at the very end of the 20th century and the first decades of the 21st century, essentially due to because of the absolute dominance of molecular methods of microorganism identification. Interest in the study of trophic interactions in the anaerobic MCs, especially in niches of anthropogenic origin (Zavarzin and Bonch-Osmolovskaya, 1981; Nozhevnikova, 1987, 1991; Zavarzin, 1990a; Zumstein et al., 2000; Hofman-Bang et al., 2003) and the niches with extreme characteristics in the case of natural niches (Zavarzin et al., 1993, 1999; Zavarzin, 2004), persisted. Moreover, the taxonomic features of MCs and the molecular biological composition of their components are studied at present, instead of the physiological and biochemical aspects (Kirk et al., 2004; Hug, 2018). However, the understanding and management of MCs requires knowledge of the number, functions and activity of organisms, rather than solely the electrophoretic DNA bands used to draw extensive conclusions on the potential of MCs, but with poor actual results. Knowledge of the physiological composition of MCs is of primary importance for successful in-depth study and for the use of MCs, whereas the taxonomic (molecular biological) characteristics are secondary to it (Hug, 2018).

Several periods can be formally distinguished in the research on MCs. One of them is the period when the existence of enormous numbers of microorganisms was realized. The period when the diversity of their functional capabilities and evolutionary flexibility became apparent was summarized by Beyerink's phrase "everything is everywhere, and Nature selects". Progress in physicochemical research methods (microscopy, chromatography, electrochemistry, electropho-

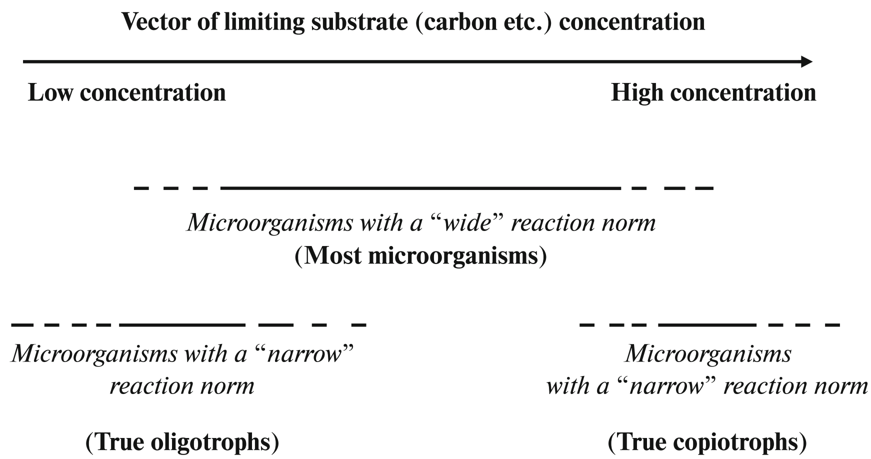

Fig. 1. Grouping of microbes in a microbial community scheme. A symmetric-asymmetric structure with the different partially overlapping trophic groups.

resis, and others) was instrumental for this period. The possibility of microorganism detection in ecotopes and ecological niches with very scarce resources, and even purely inorganic media, in addition to media rich in organic matter, became apparent.

"Models" of MC structure help to understand and reveal the infinite depth of MC content. Let us name the best-known examples of representation of the microbial community structure based on trophic grouping without an in-depth chronological analysis of the development of concepts of microbial community structure.

Each organism has its own boundaries of existence, and the properties and characteristics of the organism are reflected in distinct physiological characteristics and constants. Since such terms as oligotrophic (OB) and copiotrophic microorganisms or bacteria (CB) will be used below, it seems appropriate to recall the definitions of these groups (Semenov, 1991). OBs are organisms that have evolutionarily adapted to existence in habitats characterized by low concentrations of available organic substrate and energy fluxes of low intensity. They possess highly efficient systems for the absorption of organic and inorganic substances, which can be present at nanomolar and even picomolar concentrations in the niches. At the same time, oligotrophs can also develop in natural or artificial (laboratory) environments rich in organic substances, with limitations characteristic for each specific organism. However, the isolation and characterization of oligotrophs can only be accomplished on extremely poor, but qualitatively complete media, since these are the only conditions for the manifestation of the oligotrophs' competitive advantages (Semenov, 1991, 2005). Copiotrophic bacteria have opposite characteristics, and the definition given by J. Poindexter (1981) is accepted for them.

Comparative analysis of some kinetic characteristics of CB and OB growth, such as affinity of the microorganisms' transport systems for the substrate (K_s for growth kinetics and K_M for the kinetics of substrate transport), m (the magnitude of the maintenance energy), and the distinct presence or absence of "bottlenecks" (rate-limiting stages) in the metabolism of a microorganism allows trophic (physiological) grouping of microorganisms to be identified. The respiratory chain is, most likely, the "bottleneck", or rate-limiting stage in oligotroph metabolism (Semenov, 1991).

The use of kinetic characteristics of growth to distinguish between OB and CB with the concentration and types of substrates consumed taken into account led to the conclusion that the entire diversity of heterotrophic microorganisms can be represented as a certain continuum, with microorganisms with extremely high parameter values grouped at one "end", and those with low values, at the other "end" .

The overwhelming majority of microorganisms has been long known to have similar and moderate characteristics (Stanier et al., 1979, Zavarzin, 1990b; Hug, 2018). The division of the entire diversity of microorganisms into copiotrophs and oligotrophs does not fully characterize the essence of the microbial world, and even the use of the *r–K* continuum concept does not solve the problem. An MC scheme based on the "norm of reaction" concept is proposed to solve the problem of the rigid categorical character of the structural division. As known from general genetics, the "norm of reaction" reflects the morphophysiological variability of the organism in the case of an unchanging genotype. The microorganisms are divided into three unequal groups in the scheme proposed, and the MC is represented as a symmetric-asymmetric vector structure that reflects the continuum of forms, populations, and communities (Fig. 1) (Semenov, 1991). The two extreme groups are represented by organisms with a "narrow norm of reaction" with regard to the concentration and type of substrates used, on the one

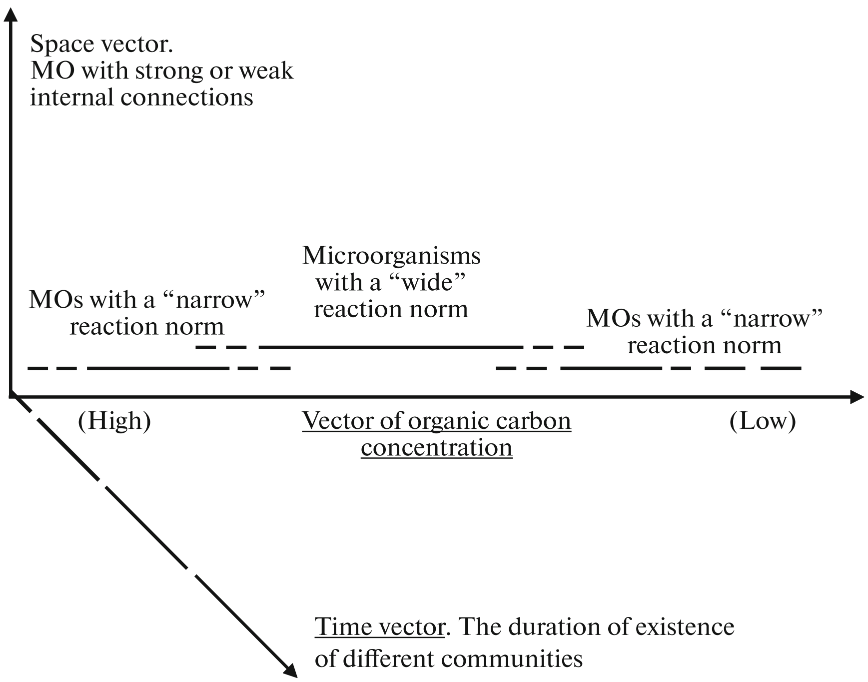

Fig. 2. A three-dimensional representation of a microbial community structure.

hand, and the variation ranges of the physiological characteristics (K_M, m, and V_{resp}), on the other. The properties of these groups correspond to those of the true copiotrophs and true oligotrophs. The third group with a "wide norm of reaction" includes the majority of known heterotrophic microorganisms (majority) and occupies a position between the groups with a "narrow norm of reaction" (Hug, 2018). Since the MC exists in time and space, it is more reasonable to depict the MC structure as a three-dimensional scheme, so that the spatiotemporal characteristics and trophic grouping inside the MC are taken into account (Fig. 2).

The present dynamic concept does not refute the previous representations (Table 1), but rather incorporates or expands them. The concept of MC trophic structure proposed has explanatory and prognostic properties. For example, the concept explains why fewer microorganisms grow on very rich or very poor organic media as compared to the "diluted" ones: the thing is, both microorganisms with a "wide norm of reaction" and some of those with a "narrow norm of reaction" grow on the dilute media. The concept explains why the bacteria isolated as oligotrophic are often taxonomically assigned to the typical "copiotrophic" taxa, such as *Pseudomonas* and *Spirillum,* and even *Escherichia* and *Bacillus* (Fry, 1990). Indeed, the bacteria with a "wide norm of reaction" are concentrated in these genera. As follows from the scheme of MC structure proposed, the number of true oligotrophs or copiotrophs is relatively small (they constitute a minority), whereas the majority of microorganisms possess moderate characteristics. Industrially important microorganisms should be sought, first of all, among microorganisms with a "wide norm of reaction", whereas microorganisms with a "narrow norm of reaction" will prevail in ecological niches with extreme characteristics.

The properties and characteristics of heterotrophic organisms (chemo-organo-heterotrophs) were used to develop the MC model proposed. The position of autotrophic microorganisms, which do not require organic carbon compounds to function and cannot control the concentration of the carbon source essential for them (CO_2), in this MC model becomes an issue in this case. However, the "position" of this MC component, or even an entire autotrophic (chemolithic-autotrophic) community, in the symmetric-asymmetric structure proposed can be quite realistically determined. It suffices to recall that autotrophic habitats are oligotrophic or even extremely oligotrophic habitats with regard to C_{org} content, some autotrophs are capable of mixotrophy, and competition and selection among autotrophs are as real as those among heterotrophs.

1.3. Generalizations in MC Research; the Laws and Concepts of MCs

The generalizing provisions in the knowledge on MC functions and properties that have been accumulated by now should be termed 'laws' to reflect their significance, even though most of them are currently termed 'concepts'. Concepts in biology, microbiology,

Table 1. Examples of division into trophic groups in microbial community structures

Groups	Distinguishing features	Author of the concept
—Two groups: autochthonic and zymogenic	Growth rate and substrate structure	Vinogradskii, 1952
—14 groups, including hydro lytics and dispersion microflora (dissipatrophs)	Growth rate, exohydrolase production capacity, substrate type and concentration	Zavarzin, 1970; 1976; 1995
—Heterotrophs divided into copiotrophs and oligotrophs	Concentration, substrate type and growth kinetics	Poindexter, 1981
—4 groups: autochthonic, zymogenic, oligotrophic and lithotrophic	Growth rate, substrate type and concentration	Mishustin, 1982
—*r*–*K* continuum	Growth rate and substrate concentration	Gerson and Chet, 1981
—3 groups: oligotrophs, stenoheterotrophs and euryheterotrophs	Substrate concentration	Horowitz et al., 1983
—3 groups: copiotrophs, hydrolytics, and oligotrophs	Substrate type and concentration, hydrolase production capacity	Guzev and Ivanov, 1986
—“autochthones” divided into 3 groups: hydrolytic, “patient”, and oligotrophic	Exoenzyme production capacity, substrate structure and growth rate	Gordienko, 1990

and microbial ecology have the same role and significance as legislation does in the human society. The more precise and detailed the laws and concepts are and the more carefully a consumer follows them, the better a consumer is “insured” from failures in biotechnological ecology. The more accurate the proposed MC structure, the more profound its predictive properties (functions), which are the fundamental goal of research on communities.

Below we consider the laws and concepts already known and recognized regardless of the time of their appearance and their subordination. The analysis will be restricted to the concepts related to MCs, since, for example, the concept of a species is used in other research areas beside microbial ecology. Let us note that the concept of the microbial community (Zavarzin, 1970; Semenov, 1991), the main object of this communication, is, of course, the first concept addressed.

The best known and most significant biological laws and concepts are as follows. The exponential growth capacity characteristic of all kinds of populations (and communities) (1), self-restriction (limiting or inhibition) of the growth (2), and the wave-like dynamics of the populations’ existence (that follows from limiting or inhibition) (3). These three laws are objective for all living organisms, including microorganisms. P.V. Turchin (2002) realistically compared their significance to that of the first three laws of dynamics in general physics. Apparently, these three laws should be reinforced by the “observation” of the “norm of reaction” of an organism limiting the adaptive capacity of this organism to environmental conditions.

The concept of MC being an evolving unit of ecosystems, in addition to being the main functional unit (Zavarzin, 1990a), and the concept of the evolution of microorganism development within the community and through the community are gaining recognition. The concept of microorganism evolution in and through the community, together with the “concept of symbiosis” and succession, orient the theoretician and practitioner towards a systematic approach to achieving the result. The use of sustainable microbial communities is a way to control natural microbiological processes.

The concept that a process and its role in an ecosystem depends on the number and activity of microorganisms participating in the process is highly meaningful; in other words, a process is significant and detectable if the microorganisms that implement it are numerous and active (Zavarzin, 1989). This concept is reminiscent of the philosophical law of the transition of quantitative changes into qualitative ones. The detection of several cells of a certain saprotrophic microorganism in a certain habitat does not demonstrate the importance of a process, even though the same process implemented by a large number of these microorganisms can be important. The “quorum sensing” phenomenon, which is actively harnessed in scientific publications, is simply a manifestation of the concept formulated above.

The food chain and the “food pyramid” concept is universal. It is complemented by the concept of “relationship” of large and small organisms. The essence of the latter concept is as follows: the larger organisms exploit and sometimes directly consume the smaller ones, whereas the very small organisms often parasitize the larger ones. This concept is apparently true for general ecology and biology as a whole, rather than solely for microbial ecology. The concept of “symbiosis”, or the coexistence of all organisms, is probably an extension of the concept named above.

The law of succession is the next law, which is closely connected with the previous ones and can be regarded as a continuation of them. According to this law, very strong disturbances or changes in the environment disturb (destroy) the coexistence and some organisms (species) are replaced by others; this phenomenon is called succession. This phenomenon is not infrequent in the practical functioning of sewage treatment plants or other technological processes based on the use of natural and, even more commonly, artificially created MCs.

In addition to these general ecological concepts, several more specific concepts, which can be termed pedo-microbiological, are known. Zvyagintsev (1987) was apparently the first to discuss some of these concepts (Zvyagintsev et al., 1999). The essence of the concept of the microbial pool and the redundancy of this pool in the soil compared to the availability of a nutrient resource is as follows: the viable part of the microbial biota is "excessive" compared to the mass of available nutrients, and therefore, most of the microorganisms in the soil are not provided with nutrition and are in a state of starvation, and therefore, in a physiological survival state (dormant, anabiotic, and even viable-noncultivable). It is especially important to take this concept into account when microorganisms are introduced into the natural ecosystem with any pragmatic goals.

There is a concept of functional interchangeability, functional parallelism, or functional duplication among microorganisms. It is known that the same function, for example, cellulose decomposition, can be fulfilled by bacteria, actinomycetes, and fungi, that is, prokaryotes and eukaryotes. Parallelism and backing-up of functions are diverse and observed in the local processes along with the global ones, such as cellulose degradation, fermentation, or oxidation of substances. The suppression, and even more so the complete removal of any individual functional group, causes an increase in the number and activity of the functional substitute, often quite an undesirable one.

The concept of soil (viewed as the microorganism habitat) microzonality, along with the concept of redundancy of the soil's microbial pool, reminds us that, for example, an introduced organism will be viable if it dwells in the microzones, on the one hand, and if the substrate is also delivered to the microzones, on the other hand.

The *r*–*K*-continuum concept in microbial ecology reflects the continuous and discrete character of the organisms' characteristics and diversity. The concept of oligotrophy explains the importance and meaning of the emergence and existence of oligotrophic ecosystems as a mechanism for creating and maintaining healthy ecosystems (including soils, of course).

The concept of regulation of the natural MC activity states that a change in MC activity in nature is largely due to a change in the community composition related to succession, rather than to a change in the activity of the dominant MC components (Semenov, 2005).

The concept of "disturbing effects and wave-like development of microbial populations (MPs) and MCs" is a continuation and development of the (third) law of general ecology that concerns wave-like population dynamics. However, the predator-prey interactions are generally regarded as the underlying reason of wave-like dynamics in general ecology, whereas the substrate-consumer interaction plays the corresponding role and underlies the alternation of MP and MC growth and extinction phases in microorganism ecology. The role of predation (grazing) in the wave-like development of MPs and MCs is less important. The internal and external disturbing effects that constantly arise in nature are the driving forces of the wave-like MP and MC dynamics. The MP and MC dynamics is wave-like both in time and in space. The concept of disturbing effects and wave-like dynamics of MCs served as the basis for developing a method for the assessment of the health of soil, composts, and other solid substrates (Semenov, 2005; Van Bruggen, Semenov, et al., 2006; Semenov, Van Bruggen, et al., 2009, 2011b).

The concept of disturbing effects and wave-like development of MPs and MCs is associated with the concept of microorganism turnover or the microbial cycle (Semenov, 2005, Semenov et al., 2010). Microorganism turnover or the microbial cycle is the process of constant movements (transitions) of individual cells, MPs, and MCs through basic natural environments, such as soil or water, plants, animals, excrement and/or excreta of animals and plants, and soil or water again. The microbial cycle concept complements the idea of MC structure, reflects MC flexibility, succession, the ability to adapt, and selection of the fittest, and connects the disturbing effects to the wave-like development of MPs and MCs. The microbial cycle, viewed as the movement of MPs and MCs along the food chain with the formation of a cycle and a "network", is one of the natural sources and permanently operating mechanisms of disturbing effects on MCs. The practical aspect of the microbial cycle concept is the rationale for revising the traditional epidemiological concepts of reservoirs, sources, habitats, and carriers of pathogens.

Thus, the dynamic, vector, symmetric-asymmetric MC structure with a trophic basis that reflects the continuum of forms, populations, and communities and a complex of laws and concepts create an objective basis for understanding and using the mechanisms that underlie MC functioning in both natural and anthropogenic ecological niches. Such knowledge of MCs determines the reasonable expectations of results of the planned processes and, additionally, enables the assessment of risks related to unpredictable phenomena.

2. THE SOIL ECOSYSTEM

The soil is the research object of different scientific disciplines that address the different aspects, often with identical or similar methods, but in order to achieve different objectives and fulfill different tasks. Therefore, different definitions have been proposed for an object traditionally termed the soil. An evolutionary-phylogenetic approach that largely relies on physicochemical concepts and operates on a global scale still predominates when the term soil is defined. Modern knowledge obliges us to consider the entity called soil as a multiphase ecosystem with its biodiversity and globally significant and already conspicuous anthropogenic impacts (Semenov and Semenova, 2018). Let us note that a clear, unambiguous definition of soil does not yet exist.

2.1. On the Problem of Soil Emergence and Soil Formation

In a scientific discussion of the soil-forming process, references are made to descriptions developed by V.V. Dokuchaev, P.A. Kostychev., V.I. Vernadsky, T.V. Aristovskaya, V.A. Kovda, G.V. Dobrovolsky, and others. At the same time, **the significance of the weathering processes of the parent a rock of the planet is noted,** the process of populating the surfaces of crystalline rocks of the planet with chemolithoautotrophic (anaerobic?) bacteria is mentioned. Chemical and physical destruction of rocks by microorganisms that transformed the rocks into organomineral substrate suitable for colonization by higher vegetation and associated fauna, leading to the formation of initial primitive soils, is discussed (Dobrovolskii et al., 2011, pp. 7–15). Of course, such reconstructions cannot include essential details of processes, for which there are no answers yet. Therefore, such reconstructions remain quite fantastic. For example, life on Earth is supposed to have emerged about 3.8 billion years ago. Life is a self-developing cyclic system (a "perpetual motion machine"), which necessarily includes death. Therefore, we can also talk about the accumulation of dead organic matter. At least part of such a substance should be converted into a substance, which constitutes at least a part of the organic components of the modern soils, within a relatively short time period due to autolysis and external influences. However, it is necessary to note that a clear and unambiguous definition of soil has not yet been given.

The definition of soil in the official "Soils. Terms and Definitions" GOST (State Standard) 27593-88 document (http://docs.cntd.ru/document/1200007341) is as follows: soil is an "An independent natural-historical organomineral natural body that arose on the surface of the earth as a result of prolonged exposure to biotic, abiotic and anthropogenic factors, consisting of solid mineral and organic particles, water and air and having specific genetic and morphological characteristics, properties that create the corresponding growth and development of plants conditions". Even a superficial analysis of this definition reveals the presence of substantial controversy. The soil as a system, an ecosystem, definitely appeared billions of years earlier than the anthropogenic factors (that is, human factors) did, since humans (*Homo sapiens*?) emerged 2 million years ago at the earliest. The term "body" that creates the conditions for plant growth and development is used in the definition, and this implies that the "body" appeared first and created the conditions for growth and development of plants. How was the organic part of this "body" formed then? Of course, the reconstruction of events involved in the emergence of soil billions of years ago should raise many questions.

The microbial community was considered in the previous section, and the trophic characteristics were put forward as the main, integrating feature of MC structure. The trophic characteristics pertain to nutrition and consumption. Bacteria (prokaryotes), fungi (eukaryotes), and micromycetes are osmotrophs. Holozoic nutrition first appears in certain unicellular protozoans. Hydrolysis (destruction) of a solid or liquid polymeric substance is required for osmotrophic nutrition. Microorganisms that have hydrolytic capacity (hydrolytic enzymes, exoenzymes) were termed hydrolytics. Hydrolytic capacity is not characteristic of all organisms, especially as far as bacteria are concerned; on the contrary, only a minority of these organisms possesses such capacity. The fungi that possess hydrolytic capacity apparently form a majority.

If massive death of bacteria occurs within a short time interval under appropriate conditions, nonhydrolyzable organic matter that does not disappear without trace will persist. Modern knowledge substantiates the opinion that no substances on planet Earth are immune to the hydrolytic-synthetic activity of microorganisms, but the depth and rate of manifestation of this effect vary considerably. However, synthesis (creation) processes still prevail, even after the microorganisms gained the ability to hydrolyze organic polymers of the dead tissue (and, subsequently, those of living tissue, in a process termed pathogenesis), and some polymers, especially heteropolymers, such as lignin, keratin, chitin, wax, and especially kerogenes, still remain hard to decompose. As a result, the organic matter accumulates and the substance called humus is formed (Semenov and Kogut, 2015). Many thousands of articles and many books in the field of science related to soil studies are published annually in the world, but the purpose of this review is not to consider all these publications, but to briefly present the concept of the soil ecosystem (soil) from the point of view of modern, primarily microbiological, knowledge.

2.2. The Contemporary Definition of Soil

A modern understanding and, therefore, the definition of soil should focus on its biological origin and the biodynamic essence of the concept of soil. The parameter termed soil health is clear and legitimate only if this understanding of soil is accepted. A "holistic" approach to soil as a product of prolonged mutual assimilation-dissimilation activity of microorganisms and plants in the dominant mineral-organic substance is proposed. The modern SE (soil) is an organomineral natural product created and maintained in accordance with the local climatic regimen by continuous microbe–plant interactions in the inorganic substance, which was quantitatively dominant at the initial stage. The product includes the biota, its residues and metabolites, and biophilic elements. The biological and physicochemical processes, namely, the biogeochemical cycles of elements and microorganism cycles, occur in this product. The product has significant buffering properties with regard to a variety of stressors, provides nutrients to plants and various soil biota, and serves as a source and sink of biodiversity. It is exactly the biological component of SE that performs the functions of environment formation and maintenance, which include production, preservation, and maintenance of the biotic diversity in the active state. This is why such biological and environmental characteristics as soil health and, possibly, soil pathology, are legitimate and applicable for a normal SE, that is, a stable one that functions autonomously. Self-reproducibility, self-sustainability, and dynamism should be especially emphasized among the many characteristics of the capabilities of the biological component of the soil (Semenov and Semenova, 2018).

As already mentioned, the microbial community as an active component of the soil, on the one hand, can hydrolyze part of the organic polymers into the simplest components, and, on the other hand, transform them into polymers that are more inert or less prone to assimilation, this leading to the formation and accumulation of the organic SE component. It is quite obvious that higher organisms would only survive for an evolutionarily short time period on a planet devoid of microorganisms, whereas the microorganisms, especially prokaryotes, can survive indefinitely in the absence of higher organisms. Thus, the emergence, formation, accumulation, and maintenance of soil is a continuous, dynamic, but not uniform, multidirectional biological (life-associated) process, and the formation of a product termed soil is impossible in the absence of this process. This is confirmed by the presence of a substrate, but not soil, on the neighboring planets, where there is no life (O'Neill et al., 1986; Barrios, 2007; Semenov and Semenova, 2018).

3. SOIL ECOSYSTEM (SOIL) HEALTH AS A NEW CHARACTERISTIC OF SOIL

The introduction of soil health as a new category and characteristic of the soil ecosystem is the reaction of the scientific community and society to changes in the state of the ecosphere and the quality of plant products in the first place, which indirectly affected the quality of products derived from animal farming. The scientific community was not satisfied with traditional soil characteristics, such as soil quality, fertility, and others. The situation was especially aggravated as the land users moved to organic farming, where the biological characteristics and parameters of SE assessment acquired decisive importance as compared to the traditional physicochemical categories. The introduction of the new category of soil health became necessary (Doran et al., 1996; Van Bruggen and Semenov, 2000). The goals and tasks necessary for solving this scientific and applied problem were constructed and methods for the initial characterization of soil health with regard to a range of parameters were proposed within a relatively short historical period (Semenov et al., 2011a, Semenov et al., 2011b). Since the first definitions of soil health did not differ from the definitions of soil quality, we proposed a comprehensive definition of soil health (Semenov et al., 2011b; Semenov and Sokolov, 2016; Semenov and Semenova, 2018).

Thus, "soil health" is a biological category that reflects the state of activity dynamics of the biotic component in the organomineral complex of the soil; this biological category is characterized by adequate activity of biotic processes (synthesis and hydrolysis) that corresponds to the natural climatic zone, their resistance to disturbing influences (biotic and abiotic stressors), and the "closedness (self-sufficiency)" of biophilic element and microorganism cycles. The healthy soil of agrocenoses is also characterized by the conformity of its quality to standard indicators and adequate fertility (for a specific climatic zone) (Semenov et al., 2011b; Semenov and Semenova, 2018). This definition of soil health is applicable to any soil (with the exception of anomalous soil) and does not contradict the substantive essence of traditional characteristics, but rather integrates their content, since the indicators of the dynamics of the biotic component's activity are interrelated with both the physicochemical parameters of the soil and the actual soil fertility.

3.1. Health of the Soil Ecosystem and the Methods for Parameter Assessment

The concept "of disturbing effects (DE) and wave-like dynamics of the MP and MC" that we formulated previously (Semenov et al., 2011a, b) helped to overcome difficulties related to the problem of method development for soil health assessment. The quantitative parameter can be calculated after the wave-like dynamics of the MC is characterized. For this, the values of peak width (period) at half-maximum (amplitude) for the highest peaks in the control (healthy) and tested soils are compared after DE (the introduction of glucose) (Semenov et al., 2011a, b; Semenov and Semenova, 2018; http://bankpatentov.ru/node/62779). The fulfillment of the following four principles is obligatory for this method and the subsequent ones: (1) the soil studied should be compared to the selected "healthy" (conditionally standard or conventionally healthy) soil of the same genesis and landscape; (2) native, that is, freshly collected, soil samples should be used; (3) the stressor must be the same for the samples being compared; and (4) dynamic observations and assessments should be conducted.

The method is named assessment of the heterotrophic parameter of soil health, because a glucose solution is proposed for use as the "stressor" (Semenov et al., 2011; Semenov and Sokolov, 2016). The dynamics of the rate (V) of CO_2 emission by soils is assessed daily during up to 5 days and the parameters are calculated (Semenov et al., 2011b).

CONCLUSIONS

The physiological parameters that can be used for objective trophic grouping of microorganisms include: (a) the values of K_s and/or K_M substrate constants; (b) m, the energy consumption for the maintenance needs; and (c) the presence and location of "bottlenecks" in a microorganism's metabolism. The "norm of reaction" of a community's components expressed, on the one hand, as the concentration and chemical complexity of the substrates, and, on the other hand, as the variation range of the physiological and biochemical constants listed above, is a continuous-discrete integral characteristic of the trophic structure of a microbial community. That is why microbiologists believe that soil should be considered as a biological system in the modern science. It is exactly the biological component that forms and ensures the functioning of this complex system, and therefore such biological characteristics as soil health and soil "pathology", soil immunity, and soil therapy are legitimate and applicable. Soil health, a new SE characteristic, includes soil quality and soil fertility, the parameters that have not been systemically integrated yet, despite being undoubtedly necessary and substantial. The quality and fertility of a healthy soil ecosystem are undoubtedly high. Theoretical development and practical implementation of the soil health concept is a substantial scientific advancement in soil ecology at present.

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