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Entropy and dynamics of soil-plant system

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Abstract. We used information theory methods to analyze the process of primary soil formation in a model soil-plant system with the permanent cultivation of plants under controlled conditions. When studying the dynamics of the diversity of the microbiotic complex, the organic matter formed and the distribution of macro- and microelements in plant organs, the 'entropy of information' source was used as their quantitative characteristic. We found that both production and expenditure of entropy simultaneously occurred in the model soil-plant system.

Keywords: soil-plat system, model, microbiotic complex, organic matter

INTRODUCTION

The integrity and interrelation of natural objects and phenomena underlie the formation of the entire diversity of soils with inherent information content (Dobrovol'skii and Nikitin, 1990). When studying the information function of soils, information theory methods permit the quantitative estimation of the relative diversity of structures, of the multitude of elements and monitoring of changes of these structures with time. This approach seems to be very useful for the analysis of the evolution of diversity measures in the case of the physical modeling of primary soil formation reproduced in a model soil-plant complex with permanent intense cultivation of plants in a regulated agroecosystem (RAES). In this study, we searched for certain quantitative relationships of the degree of diversity of the soil-plant systems in a RAES and analyzed its effects on plant functions.

In requirements of global negative technogenic action on processes in agro-ecosystem and a degradation of connatural medium searching of trajectories of perfecting existing and mining of in essence new technologies providing year-round production high-quality vegetative food stuffs. The knowledge of fundamental legitimacies of transformation of granulouse rocks and other materials is extremely important for its solution in like soil bodies as a result of exhibiting primary soil formation to activity of assemblages of rootlets of plants with attendant biota in intensive year-round cultivation of plant communities in requirements adjustable to the agro-ecosystem. Thus the particular dynamic combination physical, hydrophysical, the physicochemical and biotics properties formed like soil substantially is determined with efficiency and reliability of technological processes of manufacture of vegetative production.

The purpose of this study was the quantitative description of the response of the root media (RM) plant system to complex evolutionary processes occurring in it in the course of long-term cultivation of higher plants (23 vegetation cycles of wheat and tomato in RAES; during 7.5 years) in a one-crop system for 11 vegetations, subsequent crop rotation, and the accompanying changes in the relative contents of micro- and macroelements in plant organs. These changes allow the researchers to obtain information on the redistribution of chemical elements in plants and the variation of diversity measures in the course of primary soil formation and the evolution of the RM-plant system under controlled conditions.

It was established experimentally that considerable changes in physical, chemical, and biogenic characteristics of root-inhabited media (RMs) based on granite crushed stone and other mineral materials occur in the case of long-term year-round cultivation of plants (wheat and tomato) in RAESs. The element composition of plant matter, as well as the biochemical compositions of organic matter, formed in RMs and the accompanying microbiotic complex also

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*Corresponding author's e-mail: ivl@agrophys.spb.su changes (Ermakov, 1999; Ermakov *et al.*, 2000). It has been noted that these changes in the RM-plant system have much in common with the evolutionary processes involved in primary soil formation under natural conditions, with coarse mineral RMs being subjected to intense biogenic erosion in RAESs. The accumulation of the fine fraction, which readily interacts with elements of nutrient solutions and metabolites of soil microorganisms, is accompanied by the formation of certain secondary minerals. The results of the studies performed may serve as a basis for the physical modeling and mathematical simulation of the processes involved in primary soil formation in the RM-plant system that occur for long periods of time under natural conditions and are drastically accelerated in RAESs.

The exact use of these legitimacies is a methodological basis for making ecologically harmonized systems of intensive cultivation of plants in a proof soil and express greenhouse buildings for year-round, high quality production.

MATERIALS AND METHODS

On originally abiogenous initial granite breakstone during 23 vegetations – all year-round – grew spring wheat Siete Ceros and an 'Apple of love' of the variety 'Ottava-60' in lighting vegetative installation at bilateral regulation of a water relationships of roots. Applied nutrient solution Knopp, used lighting devices on the basis of sodium valves high pressure sodium lamp with a solid-state heat-sink light filter. Intensity of a radiant stream made 100 ± 10 W m^{-2} in range of PAR. Duration of light period was 16 h per day.

After the terminal of each vegetation deleted roots first and second-order and RM subjected composting in flow 20–30 days. After odd vegetations we explored a composition of the organic matter which had collected in granite rubble. Organic matter is submitted by root oddments in varying degrees of decomposition, products of a metabolism of plants and microorganisms. On the basis of examination of the biochemical composition of the organic matter formed in granite rubble at intensive cultivation of plants the procedure designed by Alexandrova (1980) was fixed.

Humic substances extracted a solution of pyrophosphate of sodium at pH 13. Deposition of humic acids effected method of Tyurin (1937) with the spectrometric terminal 8, nitrogen on Kjeldahl (in micro variant), carboxyl groups by means of a method of direct potentiometric titration. Absorbancy of humic acids in visible range of a spectrum measured on the spectrophotometer SF - 14. Chemical composition of plants was determined on a roentgen fluorescent analyzer A-30.

Microbiologic examinations of granite rubble carried out after the terminal of each odd vegetation of plants. The censuring and examination of physiological bunches of microorganisms carried out on the procedures accepted in soil microbiology (Egorov, 1983).

RESULTS AND DISCUSSION

We studied the pattern of the relative redistribution and formation of the relative diversity of chemical elements (Ca, K, P, S, Na, Si, Al, Fe, Mg, and Cl) in the course of the evolution of the RM-plant system that played an important role in the mineral nutrition of plants. Simultaneously, we monitored the dynamics of the changes in the biochemical composition of the formation of organic matter, including cellulose, hemicellulose, alkaline-soluble and alcohol-benzene fractions, and nonhydrolyzed residue, as well as the amount of its water-soluble part in the nutrient solution. In addition, we analyzed the dynamics of the species composition and the amount of microorganisms (bacteria consuming mineral nitrogen, bacteria consuming organic nitrogen, spore-forming bacteria, cellulose-fermenting bacteria, fungi, and actinomycetes) in RMs. The biogenic accumulation of chemical elements observed in this case is specific with respect to the mechanisms and results related to the initial stages of the transformation of RMs into soil.

A number of fundamental studies (Vernadskii, 1922; Kovda, 1956; Il'in 1985) dealt with the problem of the close relationship between the element composition of plants and the soils on which they grow under natural conditions. At the same time, the biogenic accumulation of chemical elements in the initial stages of primary soil formation in the case of intense year-round plant cultivation under conditions of the physical modeling of soil-plant systems in RAESs has been insufficiently studied. However, this problem is very interesting from both the theoretical and the practical point of view.

The results of our studies demonstrated that the dynamics of changes in these components of the RM-plant system is not chaotic or random. Instead, it is strictly determined and governed by evolutionary relationships. In this study, we attempted to systematize the experimental data on the formation of a biogeocenosis in an RAES in terms of a unified theory applicable to all components of the plant-soil system. In the course of soil formation, the plants and the biota accompanying them are closely related to the environment. This relationship is expressed in the form of material, energy, and information connections (Dobrovolskii and Nikitin, 1990). Therefore, the information approach seems promising in this case. As a quantitative estimation of the dynamics of change in the RM -plant system, Shannon's entropy of information source of a finite ensemble of events $\left(H = -\sum_{i=1}^{n} p_i \log_2 p_i \right)$ may be used. This value characterizes the diversity of the system's states under additional conditions $0 \le p_i \le 1$ and $\sum_{i=1}^{n} p_i = 1$, where n is the number of events-charters of the sequence of states that determine the space of their possible discrete values and p_i is the probability that the ith event character will occur (the measure of the definiteness of the event realization). The p_i values are determined from the experimental data on the percentage content of average composition of the biotic complex and the element compositions of plant organs and the soil organic matter. H is a generally accepted measure of the information that is obtained when a given state of a complex multi-component system (here, an RM-plant system) is realized. After each vegetation, for each variant of experience, in each subsystem the content a components of subsystems, a fraction (in percentage) were experimentally defined and varied from vegetation to vegetation. This allows the time dynamics of the relative diversity of subsystems to be traced.

The entropy of information source and statistical entropy are proportional to each other; therefore, the function H also serves as a measure of the diversity or structural organization of the system. The maximum H corresponds to the minimum orderliness of the system. If the system transits into the stationary state, its entropy reaches the extreme value, with the growth of entropy being compensated for by a flow of negentropy. By the structural diversity of the system, only the system of interrelations between elements is usually meant. As a measure of the degree of organization, the redundancy is usually used: $D = 1 - H/H_{\max}$, where $H_{\max} = \log_2 n$, i.e., the entropy of equally probable set of n events. If the redundancy of the source is zero, then the messages formed by it are optimal in terms of the maximum information carried. According to Quastler (1956), the diversity and stability of a system are interrelated, and the stability of the system may be expressed in terms of its complexity, i.e., the information function H (Zalzberg, 1966). According to Odum (1971), a developing biocenosis, in a general case, tends towards a higher orderliness. The diversity of characters and ratios between them are decisive for the quantitative characteristics of evolutionary processes (Shmal'gausen, 1968).

The direction of evolution is mainly determined by the state of the environment. Therefore, let us first consider the dynamics of the relative contents of the components of the organic matter and the biotic complex of the RM. Figure 1 shows the behavior of function D for organic matter and the biotic complex of the RM in the case of cultivation of wheat (curves 1 and 2) and tomato (curves 3 and 4). For a given moment of time, the entropy is calculated from the specific components of the organic matter and biotic complex, the sum of which is normalized to unity. Variants 2 and 4 served as a control; in variants 1 and 3, we used complex acid-alkaline regeneration of the RM in order to free it of excessive organic matter. This method was developed by us earlier (Ermakov, 1999). The biochemical composition of organic matter and relative diversity of the biota vary with time. Humus substances are known to accelerate leaching of chemical elements from minerals and promote formation of a trophic medium favorable for plants.

As seen from Fig. 1, the complexity of the biochemical composition of organic matter monotonically increased (which suggests destructive processes) until the 11th vegetation and then flattened out, reaching equilibrium (D = min or H = max). The maximum redundancy of diversity measures means the lowest degree of organization and, hence, maximum disorder. Note that, in this case, the restrictions (Shmal'gausen, 1968) to the variants of the system's development are absent, i.e., the minimum D perhaps corresponds to the maximum probability of the realization of evolutionary processes. As a result, the system is unstable and tends to change. Therefore, we may assume that function D determines the vector of the evolutionary process. During the first 11 vegetations (Fig. 1), the dynamics of change of organic matter and the biotic community corresponds to the evolution of a thermodynamically open inanimate system; after the 11th vegetation, the evolution followed the dynamics of an open living system and tends towards higher orderliness. Thus, the processes occurring in the organic and biotic subsystems may be arbitrarily subdivided into two types: on the one hand, the entropy is maximized, which may last a long time; on the other hand, the interaction between the subsystem and its environment leads to restriction of the maximization of the entropy function. For example, the biota subsystem evolves towards adaptation of the subsystem to the environment by means of interaction with this subsystem.

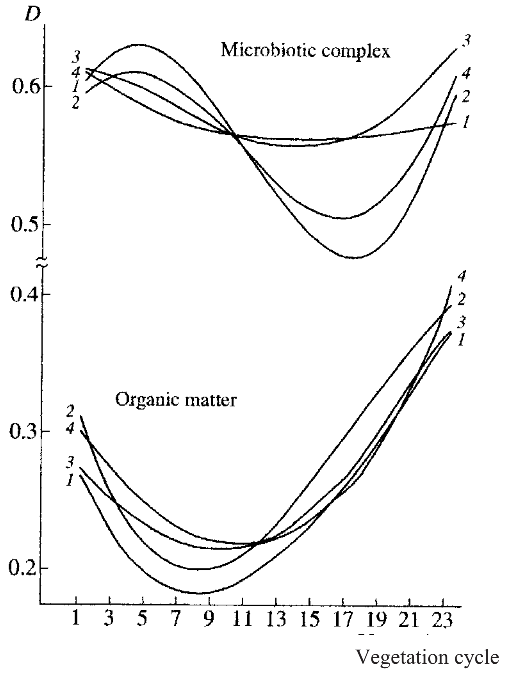

Fig. 1. Dynamics of the redundancy function D for the micro-biotic complex and organic matter. Curves 1–4 correspond to the respective experimental variants (see the text for more explanation).

By the 11th vegetation of both wheat and tomato monocultures, we experimentally observed a decrease in elements of the organic matter accumulated earlier and its humification in the course of microbial synthesis, which led to transformation of RMs into soil bodies. After the 11th vegetation, we rotated the crops. This caused immediate changes in the relative diversity of the biochemical composition of organic matter, which began to monotonically decrease. Destruction or disruption of the structure of the distribution of the elements of organic matter gave way to organization and order. Apparently, the system's negentropy increased. This agrees with the notation (Brillyen, 1962) that negentropy and information are transformed in a living system in the form of consecutive links: negentropy-entropy-negentropy. Simultaneously, the complexity of the composition of the biotic complex also changed; it was at its maximum in the fifth vegetation in the control variants. The use of complex acid-alkaline regeneration of RMs noticeable smoothed function *D* describing the dynamics of the biotic complex for both wheat and tomato plants. The same qualitative pattern of the behavior of temporal dependences of function *D* was observed in both cases, irrespective of plant species.

We additionally studied the effect of the content of organic matter on the diversity measure of the biotic complex. For this purpose, we used the technique of composting plant-root remains in keramzit. Function *D* proved to decrease and finally flatten as the duration of composting (i.e., decrease in the amount of organic matter), the relative measure of the diversity of the biotic complex changed from minimum in the original state to maximum by the end of composting (60 days). This is confirmed by the data shown in Fig. 1, where the lower content of organic matter (the variant with regeneration) corresponds to lower values of *D* until the moment of crop rotation. Therefore, the mutual organization (*D*) of the components of the biotic complex decreased with time, which was accompanied by a monotonic decrease in the diversity of organic matter. This was apparently related to the formation of humic acids and utilization of the organic matter by biota in the course of its vital activity.

The transition of the dynamic system into another state was apparently caused by the instability of the previous state relative to the next and was related to the final transformation of the dynamic system into a static system. Crop rotation may be regarded as an intervention into the dynamics of the natural processes in plants growing in monoculture, which changes the unstable equilibrium state itself. For example, instead of the plateau that was expected for all parameters of the model soil-plant complex after the 11th vegetation, function *D* gradually returned to its initial values. In term of evolutionary theory, crop rotation actually leads to the violation of the principle of the 'directness and irreversibility' of the evolutionary processes (Zalzberg, 1966; Shmal'gausen, 1968). Apparently, information is produced, accumulated, eliminated, and transmitted in the evolutionary model studied as in natural dynamic systems. Here, we are dealing with the well-known notion on the value or indispensability of information (Vol'kenshtein, 1986). The decrease in entropy function *H* during the evolution of the system indicates that the indispensability of information increases in biological processes. The information value changed after the 11th vegetation, which led to a simultaneous decrease of the function *H* (or decrease of *D*) for the complexity measures of the composition of the organic matter.

Regarding the complexity measure of organic matter, note that complex acid-alkaline regeneration of RMs accelerates its change with time from vegetation to vegetation: $\left|dD_{org.matt.} / dt\right|_{regener.} < \left|dD_{org.matt.} / dt\right|_{contr}$. Crop rotation promoted structurization of the biotic community and composition of organic matter in the RM, which increased the productivity of both the tomato and the wheat. In the course of evolution (until the 12th vegetation), the measures of orderliness of both biotic complex and organic matter decreased, and the destructive processes began to dominate. Crop rotation prevented negative processes and returned the system into the stable state. Figure 2 shows the changes in the chemical element composition of the roots and,

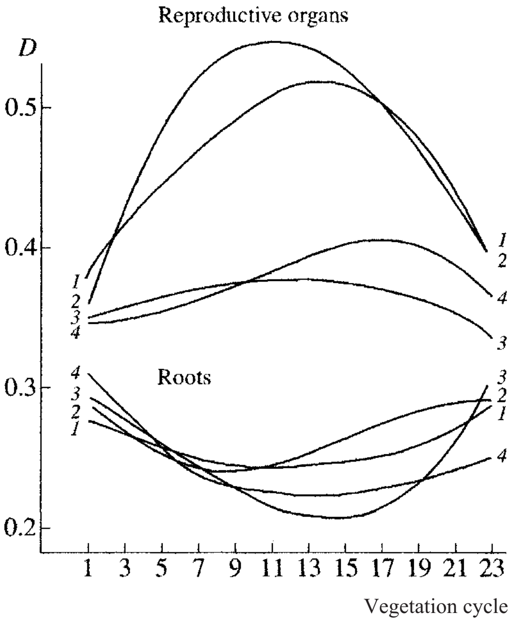

Fig. 2. Dynamics of the redundancy function *D* for chemical elements. Explanations as in Fig. 1.

correspondingly, the reproductive organs of the tomato and wheat during the evolution of the RM-plant system. Despite the generally accepted view that vital activity is accompanied by a decrease in entropy, we found that function H increased (D decreased) in the roots of both plants, whereas the information function increased in the reproductive organs until crop rotation; function D being systematically lower for the roots than for the reproductive organs. The RM regeneration somewhat smoothed the dynamics of integral function D but did not affect its behavior qualitatively, the D value being systematically lower for the roots than for the reproductive organs. The entropy production for the chemical-element composition of the roots was positive ($P = dH_{roots}/dt>0$) until about the 11th vegetation. This inequality is characteristic of irreversible thermodynamic processes in open systems. Conversely, the entropy production for the measures of diversity of chemical elements in the reproductive organs was negative ($P<0$), which is typical of evolutionary processes (Shmal'gausen, 1968). Apparently, the evolution of the RM-plant system is accompanied by simultaneous processes of organization and destruction in living organisms, and the accumulation of information gives way to its expenditure.

We also studied changes in the diversity of the chemical element composition of cucumber plants. In this case, function D was lower for the roots than for fruits: $D_{roots} = 0.184 < D_{reprod} = 0.404$. Apparently, the chemical elements taken up by the plant are heterogeneously distributed in it, depending on the physiological role of each element, the specificity of biochemical processes in different organs, and ion concentrations in the nutrient medium.

We also studied the effect of the content of organic matter on function D, which describes the relative diversity of the chemical element composition of all plant organs (reproductive organs, leaves, stems, and roots). We found that an increase in the amount of organic matter in the RM causes an increase in D. For the cucumber, function D_1 (organic RM)=0.331 > D_2 (granite crushed stone) = 0.298 > D_3 (regenerated granite crushed stone)=0.28. The chemical-element composition of the tomato exhibits a similar tendency (as calculated from earlier data (Ermakov and Medvedeva, 1985)): D_1 (10 ml of organic matter are added to the solution) = 0.346 > D_2 (control) = 0.325 > D_3 (80 mg g^{-1} potassium metasilicate are added to the nutrient solution)= 0.317. The data obtained in this study yields the following sequence of values (in order of decreasing organic-matter content): D_1 (control) = 0.323 > D_2 (RM regeneration between vegetations) = 0.317 > D_3 (RM regeneration between and during vegetations) = 0.31. In other words, the effect of the organicmatter content on the diversity measure of the element composition of plants follows a general pattern and does not depend on the plant species; in all cases, the following inequality is true: D (roots) < D (reproductive organs) < 0.

CONCLUSIONS

Thus, the results of our study demonstrate that, in contrast to closed non-equilibrium systems, in which the entropy monotonically increases in the course of evolution and tends to a constant value, the diversity measures of open systems cyclically change with time. The data obtained indicates not only the exceptional complexity of the diversity of chemical elements in plants in the course of primary soil formation in a model soil-plant system, but also the importance of their relative diversity. Both self-organizing and destructive processes occur in the RM-plant system, with both biotic complex and soil organic matter being involved in these processes. External factors, such as the content of organic matter in the soil, do not affect the qualitative pattern of this relationship but change the quantitative parameters of the behavior of diversity measures. From the initial state to the 11th vegetation of the plants, RMs (granite crushed stone and other materials) are transformed from hydrolytically basic into hydrolytically acidic due to their interaction with higher plants and the accompanying biota; the organic matter formed also participates in this process. Finally, this affects the productivity of plants grown on an evolving soil-like medium. This study opens new fields of research, which may be of considerable practical importance.

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