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The Principles of Regulation of Ecosystem Functions

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Abstract—Ecosystem is perceived as an information-control system that performs the metabolic function in regularly changing environmental conditions. The mechanisms of its functioning with emphasis on soil-forming processes have been simulated in the *Ecotron* experimental facility.

INTRODUCTION

One of the most important and unique features of an ecosystem is its high resilience toward natural and human-induced stresses. Though the resilience capacity of ecosystems is a well-known phenomenon, its particular mechanisms have yet to be studied. Until now, there is no clear notion of the mechanisms of ecosystem stability, resources of this stability in different biological zones, and opportunities to artificially increase ecosystem resilience to various anthropogenic impacts. Meanwhile, this knowledge is already demanded by the practice. We need a profoundly substantiated theory on the management of resilience of natural, agricultural, and urbanized ecosystems toward negative natural and human-induced factors. Without such a theory, it is difficult to avoid errors in the organization of a system of rational nature management and environmental security. A serious challenge for the nearest future is the creation of an autonomously functioning ecosystem as a means of survival for a large group of people in conditions of prolonged space flights or space settlements.

Several years ago, researchers from a number of institutes of the Pushchino scientific center of the Russian Academy of Sciences made an attempt to conduct an experimental study of the mechanisms of ecosystem resilience and the possibility of controlling ecosystem functioning in conditions of external impacts.

Ecosystem resilience can be defined as its ability to preserve its natural state, diagnostic characteristics, and features under the influence of external impacts. In our study, we attempted to solve the following tasks:

(1) To develop a concept of ecosystem as an information-control system that executes the metabolism function in a regularly changing environment;

(2) To describe the mechanism of the main ecosystem function (metabolism) in the form of a mathematical model of this process; and

(3) To construct an experimental installation *Ecotron* aimed at simulation of ecosystem functioning in controlled and regulated environment.

ECOSYSTEM AS AN INFORMATION-CONTROL SYSTEM

A concept of ecosystem as an information-control system was elaborated under the initiative of V.A. Kovda [1] and tested in the course of the international experiment "Ubsu-Nur" under the guidance of V.V. Bugrovskii [2]. This stage of work took a long period of time (1980–1995). It was very difficult to put away the habitual conceptions of the natural sciences and to master the methodology and terminology of technical sciences. This was a transition from the study of ecosystem structure to the study of ecosystem functions, which can be compared in its meaning with the transition from anatomy to physiology of organisms [3, 4].

The major difficulty of this transition was in the fact that, traditionally, all ecosystem components and all environmental factors had been studied separately, by relatively independent branches of science (botany, zoology, microbiology, soil science, geology, meteorology, and hydrology). Therefore, characteristics of each component were considered to be unique and were measured by different methods in different units and assessed by different criteria. This became a large obstacle in the process of integration of separate components into a single and integrated ecosystem. We had to search for some common platform that would allow us to consider all the components as a functional unity and demonstrate their specific roles in the main ecosys-

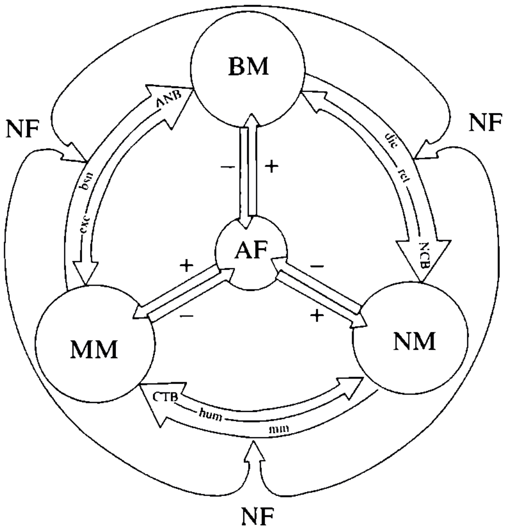

Fig. 1. Structural–functional scheme of an ecosystem. Designations: BM, biomass; NM, necromass; MM, mineral mass; NF, natural factors; AF, anthropogenic factors; ANB, anabolism; NCB, necrobolism; CTB, catabolism; bsn, biosynthesis; exc, excreta; die, dying off; ret, return of assimilates; min, mineralization; hum, humification.

tem function, the metabolism. In this work, some results of the long-term studies are briefly stated with an accent on the solution of the third task from those indicated above.

The scheme (Fig. 1) reflects our idea about an ecosystem structure, mechanisms of its functioning, and its interrelationship with environmental factors. Many processes, terms, and mechanisms are well known in general and molecular biology and are widely used at the cell and organism levels. Our task was to apply them at the ecosystem level. In doing so, we took into account the fundamental difference between the organization levels of an ecosystem and those of an organism. The main difference is in the fact that when external conditions are altered, an organism tends to preserve its structure by means of changing its functions, while an ecosystem tends to preserve its functions at the expense of structural changes.

According to the concept of ecosystem as an information-control system (Fig. 1), its structure consists of three main blocks: biomass, necromass, and mineral mass. In turn, biomass consists of phytomass, zoomass, and microbial mass. Necromass consists of fresh falloff, litter, and humus. Mineral mass is represented by gases, various mineral salts, and colloids.

The main function of any ecosystem is the process of matter and energy exchange. This process is referred to as metabolism in biology. Metabolism is the way to renew and preserve the mass of living matter by means of interaction between two opposite processes: anabolism and catabolism. In an ecosystem, the function of anabolism or assimilation of elementary mineral substances into complex organic compounds is implemented by a phytocenosis, a community of autotrophic organisms. The function of catabolism, or dissimilation of complex organic compounds into elementary mineral substances, is performed by a pedocenosis, a community of heterotrophic organisms dwelling in the soil.

It should be taken into account that anabolism should not be identified with the organic matter synthesis, as the former also includes respiration processes. In turn, catabolism is not restricted to the organic matter decomposition; in fact, it comprises two complementary processes, i.e., the destruction (mineralization) and secondary synthesis of soil humus (humification).

In addition to anabolism and catabolism, it is reasonable to distinguish the process of necrobolism, or a natural genetically programmed process of the completion of the life cycle of al living creatures. In general and molecular biology, this process is referred to as "apoptosis."

Within an ecosystem, necrobolism fulfills an important buffer function that allows harmonious interaction between anabolism and catabolism upon the fluctuations in external conditions. Like anabolism and catabolism, necrobolism should not be restricted to an extinction process, as it consists of two opposite and complementary processes: extinction (necrosis) and return of useful resources (decomposition products) into reserve organs and tissues (the translocation process).

In general, the process of ecosystem functioning represents a consequent transformation of biomass into necromass, necromass into mineral mass, and mineral mass into biomass again with the help of anabolism, necrobolism, and catabolism. The diversity of organisms with different life cycles (from several days to several centuries) forms a multilayered, cyclic, and unidirectional system of continuous and irreversible metabolic process, the main function of an ecosystem.

This process, as well as all particular processes taking place in an ecosystem functioning, is regulated by various environmental factors that are usually classified into natural, anthropogenic, and compound natural–anthropogenic factors. The most important natural factors are light, heat, and moisture. The main anthropogenic factors are the removal, input, and transformation of matter in every structural block of an ecosystem. Human-induced changes in lighting, heating, and moistening, as well as natural removal, input, and transformation of an ecosystem matter (related to natural trophic relations, natural catastrophes, and other unusual phenomena) can be attributed to a group of compound factors.

Natural factors, even their extreme values, are unable to change drastically an ecosystem structure; for these changes, there should be a significant alteration in the proportion between the rates of opposite ecosystem processes. Changes in environmental conditions induce certain transformation in the character of ecosystem functioning; then, the changed functions transform an old structure into a new one that is better adapted to new environmental conditions. The new structure allows better functioning of the ecosystem under the modified environment. To restoration of the previous state of an ecosystem after the restoration of previous environmental conditions can take place within relatively short successions, sometimes, even without considerable changes in the species composition of the biotic component of this ecosystem, via a certain redistribution of spaces occupied by the existing species.

Anthropogenic factors are able to change sharply an ecosystem structure, because they directly influence the mass of major ecosystem constituents via their input, removal, or transformation. Thus, the influence of anthropogenic factors can be compared to that of natural disasters, whose consequences can only be compensated for by a long-term succession of living organisms accompanied by considerable changes in their species composition. One of the examples is the overgrowing of cutover patches and burnt sites in forest ecosystems, or overgrowing of fallow lands.

EXPERIMENTAL

To study the mechanism of ecosystem functioning, it is necessary to have an experimental basis that would enable us to investigate all parts of this mechanism in their dynamics and control the results of mathematical modeling of an ecosystem as an integral formation. Field investigations of real ecosystems are very costly. In addition, the inseparable relationships between ecosystem components do not allow us to control and regulate them independently and assess the role of each component in the general process of metabolism.

In this paper, we discuss the results of simulation of ecosystem functioning in the Ecotron experimental facility. The Ecotron is a tool to study the mechanisms of ecosystem functioning with the opportunity to control these mechanisms. The scheme of this experimental facility is shown in Fig. 2. It is designed in such a way that it provides the possibility to (a) maintain ambient conditions suitable for the most natural functioning of an artificial ecosystem as a whole and each of its components, (b) control every component of this ecosystem (via certain external inputs), and (c) obtain information about the state of the ecosystem as a whole and its particular components, including their response to control measures.

The controlled parameters of ecosystem functioning are as follows:

(a) continuous control of carbon dioxide concentration in the gaseous phase with the help of a continuous-flow infrared CO_2 analyzer (*11*);

(b) potentiometric measuring of pH and Eh conditions in the upper soil horizons (*10*);

(c) sampling and further chemical analysis of lysimetric water (*4*);

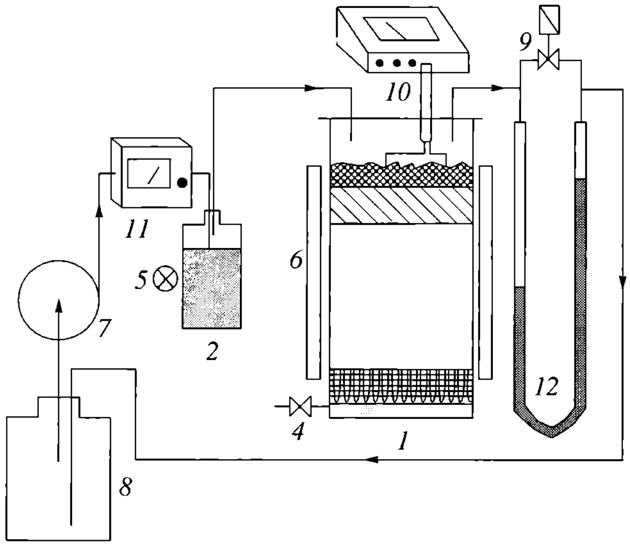

Fig. 2. Principal scheme of the Ecotron experimental installation. Designations: (*1*) Ecotron, (*2*) Phytotron, (*3*) direction of air flow, (*4*) outlet for lysimetric water sampling, (*5*) lighting, (*6*) thermal regulator, (*7*) air compressor, (*8*) buffering vessel, (*9*) electromagnetic valve, (*10*) potentiometer, (*11*) infrared CO_2 analyzer, and (*12*) manometer.

(d) regulation of the total air pressure in the installation with the help of a water manometer (not shown in the scheme); and

(e) regular control of the total chemical composition of the gaseous phase.

After the end of the experiment, the Ecotron installation was opened, and the solid phase of the Pedotron block was analyzed in detail using the methods of meso- and micromorphology, physical chemistry, and mineralogy.

One of the tasks of the experiment was to quantitatively estimate the degree of the influence of natural and anthropogenic factors on the mechanism of ecosystem functioning with the help of the Ecotron facility. We considered light, heat, and moisture as the main natural factors; anthropogenic factors included chemical substances additionally introduced into the soil, water, and air of the artificial ecosystem in the forms of phytomass, fertilizers, or pollutants.

It is known that natural ecosystems differ from one another by the capacity and intensity of the biological cycle of substances (metabolism) and by the resilience of the metabolic function to the influence of natural and anthropogenic factors. Thus, an experimental installation should have the capacity to conduct experiments with ecosystems that differ in the composition of their structural elements. The installation should also provide ecosystem functioning in a wide range of hydrothermic conditions. In our experiments, these requirements were realized via the use of several modifications of the Pedotron block of the experimental facility and the diversity of hydrothermal regimes of functioning.

Table 1. The composition of the artificial soil profile in the Pedotron experimental facility

Horizon	Mass, g	Thickness, cm
Litter	280	11
Litter + loam (1 : 1 by volume)	1960	5
Loam	11965	16.5
Sand	2170	2.5

Figure 2 demonstrates the scheme of the Ecotron installation imitating the metabolic function of an ecosystem, including anabolism and catabolism. Anabolism is imitated by the functional unit called Phytotron; and catabolism, by the functional unit called Pedotron. The interaction between the functional blocks is performed through the gaseous phase that imitates the atmosphere of an ecosystem. In the course of anabolism, Phytotron absorbs CO_2 and evolves O_2; vice versa, Pedotron absorbs O_2 and evolves CO_2. Separate functioning of these two blocks makes it possible to study the mechanisms regulating the regimes of oxygen and carbon dioxide in the entire system. The volume of gas-filled space in the installation was determined by labeling with krypton (50 ml) and was equal to 30 l.

Phytotron represents a container (20 l) with the water culture of chlorella seaweed (*Chlorella* sp. K IPPAS C-1 from the collection of the Institute of Photosynthesis, Russian Academy of Sciences in Pushchino). The regulation of anabolism intensity is achieved via controlling the number of Phytotron containers in the system and via the control over the conditions of their lighting.

The Pedotron facility is a glass container of 25 cm in diameter and 50 cm in height filled with natural soil material to form a shortened artificial soil profile with a total thickness of about 35 cm. Initially, this profile consisted of the following horizons: AO, material from the litter layer of natural soil, with a thickness about 10 cm; A, a mixture of the litter and parent material (loam) in a 1 : 1 volumetric ratio; and C, parent material (loam) underlain by sand for better filtration.

To activate biological processes implementing catabolism, a suspension from top horizons of the natural gray forest soil was introduced onto the surface of the artificial soil profile together with the earthworm culture. The regulation of catabolism was realized by means of changing the hydrothermic regime of the soil. The soil water content was maintained at the level of field capacity, whereas soil temperature was changed according to a certain program and supported for one or two weeks at constant levels of 15, 25, and 35°C.

The entire installation was hermetically isolated from the environment and put into a thermostatically controlled climatic chamber. The variable parameters of the modeled environment were temperature, illumination, and the amount of fresh plant-litter input. A thermoregulating circuit (*6*) was made for the Pedotron block. It was independent from the temperature in the climatic chamber and allowed to decrease soil temperature by 10°C relative to the "air" temperature.

Gas flow (30 l/min) created by a compressor (*7*) goes through a continuously agitated container (*2*) with chlorella (the Phytotron block) and comes into the soil (*1*) (the Pedotron block). The principle of extensional aeration was used in the soil block to prevent the development of anaerobic conditions. For this purpose, an electromagnetic valve (*9*) was closed every 20 min and overpressure (20–25 mm Hg) was created in the container with the soil. The overpressure was controlled by a water manometer (*12*). When the valve (*9*) was open, the gas flow came to the compressor's input through a buffer vessel (*8*).

RESULTS AND DISCUSSION

Table 1 presents data on the initial soil composition. The initial chemical composition of parent rock and plant litter was fixed as a reference point before the experiment. When the soil material was put into the container, it was wetted with distilled water up to the total water capacity. Then, with the help of an outlet (*4*), gravitational water was removed from the system and subjected to hydrochemical analysis to determine the content of anions and cations. This procedure was repeated after each hydrothermic cycle of the experiment (change of temperature regimes).

Catabolism process proceeds in the Pedotron block owing to vital activity of soil microflora and fauna. In the course of this process, some part of the organic mass becomes mineralized to elementary salts that enter liquid and solid phases of the system and gases (mainly, CO_2) that enter the gaseous phase. Some part of the HCO_3 contained in the parent material is also evolved into the gaseous phase. However, the largest part of plant litter is subjected to partial decomposition and transformation into humic substances. The results of our experiments are presented below in accordance with the phase composition of the substances taking part in the metabolisms.

Gaseous Phase

The regulation of the composition of the gaseous phase in the system was implemented via adding containers with chlorella, changing the Phytotron illumination, and heating or cooling the Pedotron block.

The introduction of two liters of chlorella into the system decreased the rate of growth of the CO_2 concentration from 4.0 to 2.7% per day, while the rate of a decrease in the O_2 concentration changed from 4.4 to 3.1% per day. The addition of four more one-liter containers with chlorella caused an even more significant decrease in the considered rates of gas concentration changes (1.96% per day for CO_2 and 2.53% per day for O_2).

In all the experiments, parallel measurements of carbon dioxide and oxygen concentrations were conducted; the rate of a decrease in the O_2 concentration was always a little higher than the rate of a rise in the CO_2 concentration. This phenomenon can be explained by the fact that the consumption of oxygen was not only due to microbial respiration. At the same time, some part of the produced CO_2 could be bound in soil carbonates and bicarbonates. The latter is indirectly confirmed by the growth of the total alkalinity (sum of HCO_3 and CO_3 ions) by two times in the upper part of the loam. Later on, when the chlorella volume was decreased to 4.5 l, the rates of carbon dioxide formation changed within the limits of 1.4–2.1% per day.

The cooling of the Pedotron to 10°C under the chlorella volume of 9 l resulted in a stable (1% per day) decrease in the CO_2 concentration from 12.5 to 2% with a corresponding growth of the O_2 concentration up to 31%. Usually, aerobic microbial oxidation of herb litter causes a decrease in the oxygen concentration and an increase in the carbon dioxide concentration in the gaseous phase. The molar ratio of produced CO_2 to consumed O_2 is a key parameter characterizing soil ecosystem (soil respiration quotient, RQ). In the case of cellulose oxidation to CO_2, the RQ is equal to 1.0, because cellulose is an easily decomposable substance. When a part of oxygen is spent on hydrolysis of organic products or their oxidation to organic acids and the formation of microbial biomass, the RQ is less than 1.0. Table 2 presents the results of RQ measurements in dependence on the oxygen consumption in the Ecotron upon different hydrothermic regimes. At a high concentration of oxygen in the gaseous phase (28–20%), the RQ was within the limits of 0.14–0.4; when the O_2 content became less than 9%, the RQ grew and reached 0.6–0.7.

A possible reason for the RQ growth under low oxygen concentrations in the gaseous phase is the formation of partly oxidized products, e.g., organic acids that, being added to the soil, decrease the soil pH and enhance the emission of CO_2 at the expense of changes in the carbonate–bicarbonate soil pool.

This process may have a principally important significance in regulating the carbon cycle in a closed system containing not only the heterotrophic consumers of the organic matter but also the phototrophic producers of oxygen as a result of CO_2 utilization in the course of photosynthesis.

The Phytotron is the second functional element in the model installation. Oxygen enters the atmosphere of the installation as a result of photosynthetic consumption of CO_2 from the gaseous phase by the green seaweed culture (chlorella). The oxygen concentration in the gaseous phase of the system can be regulated by the volume of seaweed culture, illuminance, nutritional conditions, etc.

Table 2. Changes in the soil respiration quotient as dependent on the soil temperature and oxygen consumption by microflora

T, °C	N_2, %	O_2, %	Ar, %	CO_2, %	RQ
15	78.8	17.7	1.2	2.3	0.7
25	81.7	15.6	1.1	1.6	0.27
	82.4	14.4	1.2	2.0	0.28
	83.0	12.6	1.2	3.2	0.35
	83.3	3.3	1.07	12.3	0.65
	77.6	1.6	1.02	19.8	1.03
	82.2	15.3	1.09	1.3	0.14
35	82.9	14.7	1.11	1.2	0.2
	83.4	9.4	1.1	6.1	0.47
	82.0	9.1	1.1	7.8	0.62
	89.5	6.2	1.16	3.14	0.21

It is known that 1 mole of O_2 is produced in the course of photosynthesis from 1 mole of consumed CO_2. So, when the RQ is low, the biological activity of the soil system lowers down; the system can achieve the state of anaerobiosis because of the more active oxygen consumption by heterotrophs in comparison with oxygen formation by phototrophs.

To estimate ecosystem functioning, it is important to have information about the nature of carbon dioxide and oxygen in the gaseous phase. The use of isotopic characteristics of carbon and oxygen makes it possible to solve this problem.

The isotopic composition of carbon in soil carbonates constituted –15‰; in herb litter, –27.9‰; in the CO_2 of the gaseous phase (during the stage of active litter oxidation), –30‰; and in the seaweed biomass, –38.9‰. These data demonstrate that the formation of metabolic carbon dioxide under the analyzed conditions was mainly caused by the microbial oxidation of plant litter. The contribution of carbon dioxide generated as a result of the destruction of soil carbonates was insignificant.

Measurements of the isotopic composition of oxygen in the Ecotron gaseous phase demonstrated that it is impoverished by 70‰ in comparison with the atmospheric oxygen. While interpreting these data, we took into account the fact that isotopic composition of oxygen in the water used by phototrophs was –24‰. The expected kinetic isotopic effect at the stage of water involvement into the photolysis reaction is estimated to be equal to –54‰. Therefore, the maximum impoverishment of photosynthetic oxygen in comparison with atmospheric oxygen is estimated to be equal to –78‰. The fact that the real content of O in the oxygen was –70‰ is indicative of the partial consumption of generated oxygen by heterotrophs, which can cause the

Table 3. Changes in the composition of lysimetric water at different stages of the Pedotron experiment (from May 19, 1995 to May 20, 1996). The content of ions is given in meq/l; the solid residue after water evaporation (SR), in g/l

Date	pH	SR	HCO_3	Cl	SO_4	Ca	Mg	K	Na	Sum of cations	Sum of anions
June 1995	6.30	0.05	0.28	0.10	0.10	0.3	0.2	0.02	0.08	0.6	0.4
Oct. 1995	7.85	0.95	12.01	4.10	0.75	15.4	2.2	0.12	1.34	19.1	17.0
Jan. 1996	7.80	0.32	1.65	1.93	0.28	4.2	0.9	0.02	0.28	5.4	3.9
Mar. 1996	7.45	0.87	0.40	4.32	1.37	8.2	2.0	0.22	0.49	10.9	6.1
May 1996	7.70	0.33	1.44	1.56	0.56	3.6	0.4	0.06	0.24	4.3	3.6

Table 4. Changes in the composition of lysimetric water at different stages of the Ecotron experiment (from February 4 to October 30, 1997). The content of ions is given in meq/l; the solid residue after water evaporation (SR), in g/l

Date and sample no.	pH	SR	HCO_3	Cl	SO_4	Ca	Mg	K	Na	Sum of cations	Sum of anions
1	2	3	4	5	6	7	8	9	10	11	12
Feb. 4, 6-I	5.50	7.59	54.0	5.0	1.27	62.0	13.0	0.11	1.17	76.28	60.27
Feb. 5, 6-II	5.30	2.26	16.0	1.2	0.39	9.0	9.0	1.41	0.23	19.64	17.59
Feb. 7, 6-III	5.50	5.00	34.0	1.8	0.66	36.0	10.0	2.88	9.41	49.29	36.46
Feb. 20, 7-I	5.90	9.76	55.0	3.4	1.03	96.0	8.0	0.70	1.19	105.89	59.70
Feb. 20. 7-II	5.70	1.47	4.9	3.0	0.18	9.4	2.7	1.38	0.10	13.48	8.13
Feb. 20, 7-III	6.95	6.57	42.0	3.2	1.08	59.0	11.0	1.12	0.64	71.76	46.28
Mar. 20, 8-I	7.70	8.24	58.0	2.8	0.13	88.0	7.0	0.43	0.64	96.27	60.93
Mar. 27, 8-II	6.65	1.98	10.0	2.0	0.26	14.7	3.1	1.42	0.23	19.45	12.26
May 16, 9-I	8.35	0.92	6.60	3.4	0.11	2.2	8.2	0.33	0.60	11.33	10.51
May 16, 9-II	7.10	0.35	1.32	0.8	0.03	1.5	0.6	0.26	0.04	2.46	2.15
May 16, 9-III	7.90	1.17	7.48	2.5	0.04	7.9	2.3	0.41	0.17	10.74	10.04
Oct. 30, 10-I	8.00	0.62	2.95	3.9	0.93	5.7	1.7	0.11	0.40	7.91	7.73
Oct. 30, 10-II	7.90	0.12	3.90	1.5	0.24	5.1	0.5	0.10	0.15	5.80	5.60

enrichment of the remaining part of oxygen in O (kinetic isotopic effect).

Liquid Phase

Control of lysimetric water composition as the system's response to changes in external factors (temperature and humidity) was implemented according to the following scheme.

After each change of hydrothermic regimes, the sampling of accumulated lysimetric water (samples N-I) was implemented. Then, the entire profile was washed with distilled water, and the sampling of lysimetric water was performed again in 1 h after the washing (samples N-II). A day after, samples N-III were taken. After that, a portion of litter was added (until the initial thickness of the litter horizon was restored) and a new cycle was started.

Table 3 illustrates changes in the ionic composition of lysimetric waters at different stages of the experiment that lasted exactly a year and implied changes in the soil temperature regime. The assessment of changes in the chemical composition of lysimetric waters can be made via comparing all collected data with the results of water analysis after the first washing (a month after the beginning of the experiment). The most significant deviations were registered in lysimetric waters taken in October 1995. The total content of dissolved substances (mainly, soluble salts) in the water increased from 0.05 to 0.95 g/l (the weight of solid residue after water evaporation), which means the transition from fresh to salt waters. The most pronounced increase was observed in the concentration of bicarbonates (from 0.2 to 12.1 meq/l).

All sampling series (N-I, N-II, N-III) demonstrate an increase in concentration of all ions in the water extract from artificial soil (lysimetric water) after the soil washing with distilled water.

As seen from Table 4, the composition of lysimetric waters changed many times during the year of the Ecotron experiment. The most significant changes took place during the first two months of the Ecotron functioning. In this period, the reaction of lysimetric waters changed from acid to alkaline (from pH 5.5 to pH 8.4), the concentration of bicarbonate anions varied within the limits of 54–58 meq/l, and the concentration of calcium cations varied from 62 to 96 meq/l. After that, the concentration of calcium decreased by a factor of 10. A high concentration of ions in lysimetric waters was registered mainly in N-I samples after prolonged accumulation of gravitational water in the tray. Waters of N-III samples, collected a day after washing of the Pedotron profile, were characterized by a somewhat lower content of ions. The minimal quantity of mineral elements was registered in waters of N-II samples taken immediately after the profile washing. The total content of dissolved substances in these waters was two to four times lower than that in N-I samples; concentrations of HCO_3, Ca, and Na ions were five to ten times lower. On the contrary, the K ion concentration was two to four times higher.

In natural ecosystems, mineral elements eliminated in the process of necromass destruction are utilized almost completely within an ecosystem. A part of mineral substances are absorbed by vegetation and participate in photosynthesis of the new biomass. Another part fix free radicals formed in the process of necromass destruction and thus participate in the process of secondary synthesis of soil humus. Only a third small part of mineral elements, not absorbed by plants and not participating in the synthesis of humus and secondary soil minerals, can be washed out of the soil profile.

Thus, the suggested scheme of the Ecotron installation simulated the microbial oxidation of the phytomass. This allowed us to solve a number of theoretical, methodological, and practical problems related to the functioning of natural ecosystems and control and regulate the metabolic process and its components (anabolism and catabolism) at all stages of their development in a wide range of environmental factors. For the purposes of full-scale experimental installation, it is necessary to close the cycle of water migration of substances, which was open in the described system. For this purpose, chlorella has to be replaced by the community of autotrophic organisms (phytocenosis) dwelling on an hydroponics of lysimetric waters of the Pedotron.

Solid Phase

The local mantle loam used in the artificial soil of the Pedotron block is characterized by a high content of smectites, which gives us an opportunity to trace the influence of environmental factors (heat and water) on the soil component. It was assumed that soil response to external influence could be estimated via measuring the properties of soil adsorption complex and registering changes in the montmorillonite structure (taking into account that this mineral is relatively labile and can be transformed in soil conditions).

The Pedotron functioning regime corresponded to the conditions of a subtropical or humid steppe climate. In nature, these conditions favor the residual accumulation of hydromica in the upper soil horizons; the accumulation of clay fraction owing to physical disintegration of silt particles also takes place. The process of montmorillonite destruction to elementary oxides is also possible.

Mineralogical composition of loam taken as soil-forming rock was studied by the method of X-ray diffractometry on a DRON-3 installation (CuK radiation, Ni filter) under the scanning (5 sec) regime. The clay fraction (<2 μm) for the analysis was obtained by decantation of the suspension obtained after preliminary mechanical rubbing of the soil paste. Clay films were prepared on glasses (25 × 25 mm). Mg- and K-saturated forms, as well as the forms saturated with ethylene glycol and calcined at 350 and 550°C were studied. The determination of loci with negative charge in the smectite lattice (necessary for the identification of montmorillonite and beidellite) was performed using the Green-Kelly test (Li-test). Quantitative estimation of the ratio between the main groups of clay minerals was conducted according to the Biscaye method [12].

Two types of feldspars (anorthite and microcline) and mica are recognized in the loam in addition to quartz. The clay fraction includes dioctahedral mica (45%), smectite (40%), and kaolinite (15%); chlorite, quartz, anorthite, and microcline are registered in this fraction in trace amounts. The smectitic phase is represented by a mixture of high-charge beidellite and low-charge montmorillonite, with the prevalence of the latter mineral.

There are data on the active process of destruction and transformation of smectites in conditions of steppe pedogenesis; the degradation of mineral structures takes place in the entire soil profile, while the aggradational transformation of minerals is registered mainly in the upper horizon [5]. The proportion between these two processes, together with the destruction and mechanical migration of minerals, dictates distribution patterns of particular minerals in the soil profiles.

Taking into account the applied functioning regimes of the experimental installation (existence of periodic moistening and drying stages and high temperatures) and specific mineralogical features of the loam (the presence of high-charge smectite and K-containing micas and microcline), it is possible to suggest that the aggradational transformation of smectite (illitization) should take place. Additional information necessary to confirm this suggestion and determine experimentally the direction of transformation of other mineralogical phases can be obtained after opening of the Pedotron container.

Mineral components are a conservative part of soil. This is the soil memory, reflecting stages of its development under the changing environmental conditions. The state of mineral soil mass is a fundamental soil property that controls soil genesis and influences physicochemical properties and fertility of soils.

However, the mechanisms of this influence, as well as the processes of formation, natural evolution, and anthropogenic transformation of mineral components, are not studied well enough to perceive the results of the evolution (natural and anthropogenic) of soils and ecosystem as a whole. On one hand, this is explained by the low rate of mineral transformation processes; on the other hand, the methodological basis of soil mineral studies in relation to the entire ecosystem functioning is insufficiently developed. A set of instrumental method was used by us to study soil mineral compounds: X-ray diffractometry, Mössbauer spectroscopy, and magnetic measurements (magnetic susceptibility and thermomagnetic investigations).

There are many studies that show the importance of iron transformation in many soil processes. The ability of this element to change its valence and solubility in dependence on physicochemical conditions is of particular interest for the researchers. Extensive data have been accumulated on the behavior of iron compounds in soils and rocks of different bioclimatic zones [6–11, 13].

In particular, it is demonstrated that the state of iron compounds is syngenetic to soil-forming processes. Iron plays an active role in soil-geochemical processes, which makes it possible to use this element as an indicator of soil-geochemistry conditions and their changes under the impact of various natural and anthropogenic factors [6, 7]. The Fe^{2+}/Fe^{3+} ratio in soils reflects the intensity of soil weathering processes and depends not only on the current state of environmental factors but also on the character of long-term evolution of soils and the environment.

The first experiments with the Pedotron installation showed the growth of Fe^{2+} percentage (% of the total iron) in the structure of soil silicates: from 7.5% in the initial loam to 9.3–10.6% after a year of the experiment. The total content (%) of iron in silicate minerals also increased, as well as the magnetic susceptibility of the soil.

The obtained data about mineral transformation processes in the Pedotron installation have a preliminary character. Further accumulation of factual experimental data is required to elaborate a system of indicators of the state of mineral soil components and the character of their transformation under natural and anthropogenic evolution of soils.

In the course of the Pedotron experiment, the water-physical properties of the loam changed significantly: the dispersion factor decreased from 23 to 17%, and the hydraulic conductivity increased from 0.28 to 0.43 mm/min. These changes attest to some structuring of the soil material filling the Pedotron container; in many aspects, this material became closer to the mineral material from C horizon of the natural gray forest soil.

Considerable changes took place in the organic matter composition both in the surface litter layer and inside the mineral soil profile. The soil acquired a darker (coal-like) color and somewhat decreased in its volume, i.e., it became more compact. As seen under a microscope, the largest part of plant remains on the soil surface preserved their initial structure but became black (as if charred). In the layer filled with a mixture of organic material and mineral soil mass, the organic remains were transformed more considerably; most of them lost the initial structure. Charred organic detritus were interspersed in the mineral soil mass without visible signs of interaction between the organic and mineral soil constituents. Separate fragments of brownish homogeneous material resembling the cutans in natural soil profiles could be detected. Several loci with distinct accumulation of iron oxides on the surface of mineral particles were also registered.

CONCLUSION

This work can be considered a preliminary stage of the creation of an experimental basis for fundamental investigations into the mechanisms of ecosystem functioning, its response to external influences, and its resilience toward natural and anthropogenic stresses. The knowledge of "ecosystem physiology" is necessary to solve actual tasks of rational nature management and environmental protection. On the basis of this knowledge, a more informative system for environmental monitoring and rehabilitation of disturbed ecosystems can be suggested. Moreover, this knowledge is necessary for the creation of autonomous life-support systems necessary for long-term space flights and space settlements.

Our experiment demonstrated that separate studies of the major functions of an ecosystem—anabolism and catabolism—are very promising. However, the system closure only with respect to the gaseous phase is insufficient. It is also necessary to close the system of the liquid phase. In addition, it is necessary to find appropriate methods for the control of the soil solid phase immediately in the course of the experiment and not only after its end, when the installation is open. The application of fresh plant litter in addition to natural organic matter produced by the Phytotron block can be preserved in future experiments as a very efficient tool to regulate ecosystem processes with short characteristic response time.

The problem of studying the mechanisms of ecosystem functioning is tightly connected with the problem of sustainable nature management. From our point of view, this is one of the top-priority fundamental problems of modern ecology. This problem can be also referred to as the "Physiology of Ecosystems and Metabolism in the Biosphere." To solve it, we should concentrate dispersed forces and resources on the priority direction and create modern methodology of experimental ecosystem studies together with further development of the technical basis necessary for these studies.

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