World Journal of Agricultural Research, 2013, Vol. 1, No. 1, 18-24
Available online at http://pubs.sciepub.com/wjar/1/1/5

DOI:10.12691/wjar-1-1-5

Dynamics of the Information Exchange and the Causal-and-Effect Relationships in Plants under Controlled Conditions

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Received January 24, 2013; Revised April 14, 2013; Accepted April 25, 2013

Abstract Information theory methods were used to process extensive test data on the content of chemical elements in wheat and tomato plant organs obtained during their year-round and intensive cultivation on initially abiogenic mineral crushed stone (granite and zeolite). The directions of information flows related to redistribution chemical elements (*Ca, K, P, S, Na, Si, Al, Fe, Zn, Mn, Mg,* and *Cl*) between plant organs were revealed. Cause-and-effect relations in the dynamics of heterogeneity of chemical elements in plant organs under condition of primary soil formation were established. It is demonstrated that the total state of the chemical elements that determined by the integral indicator – information function – is differentiated for various plant organs. A cause-and-effect relation between the composition of organic matter of the root-inhabited environment and the elemental chemical composition of plant organs (root, stem, leaf and fruit, grain) is established by the method of information theory.

Keywords: *abiogenic mineral substrate, cause-and-effect relation, chemical elements, information flow, information function, intensive cultivation, mineral Crushed stone, multicomponent systems, organic matter pedogenesis, primary soil formation*

1. Introduction

The present work is aimed at revealing thorough knowledge in the root-inhabited environment (RIE) – plant system during primary soil formation under conditions long and intensive cultivation on initial abiogenic mineral medium (granite crushed stone, zeolite) in a controlled agroecosystem. The basis of this work is the results of a complex experiment. The details of the experiment reported repeatedly in our studies [1,2,3]. The purpose of this study was quantitative description of the RIEs – plants system to complex evolutionary processes occurring in it in the course of long-term cultivation of higher plants (23 growth periods of wheat and tomato in a controlled agroecosystem (CAES)), and the accompanying changes in the relative contents (% of ash) of micro- and macroelements in plant organs. These changes allow the researchers to obtain information on redistribution of chemical elements in plants and variation of diversity measures in the course of primary soil formation and the evolution of the RIEs – plant system under controlled conditions. Experimentally we established that considerable change in physical, chemical, and biogenic characteristics of RIEs based on granite crushed stone occur in the case of long-term year-round cultivation of plants (spring wheat and tomato) in CAESs. The chemical elements composition of plants, as well as the biochemical composition of the organic matter formed in RIEs and the accompanying microbiotic complex also changes [2]. These changes in the RIEs-plant system have much in common with evolutionary processes involved in primary soil formation under natural conditions, with coarse mineral RIEs being subjected to intense biogenic erosion in CAESs.

The close interrelation between the chemical elements composition of plants and type of soils was indicated long ago by Vernadsky [4], who repeatedly called the attention of investigators to the unknown role of the specific relationships of elements in the composition of living matter during its active effect on mineral substrate. Transformation of the mineral component of rocks, in Polynov’s opinion [5], is the factor which introduces the progressive element into pedogenesis. Long-term and year-round operation of the mineral substrate leads to the fact that there are processes similar or analogous to the natural soil-forming processes. An important phase in this microevolutionary process is the formation of a group of organic components of a different nature, which in many respects determines the main chemical, physicochemical, and biological properties of RIEs. They cause a response of plants which leads to a change in their production potential and chemical elements composition of plants.

According to the experimental information of our investigations, biological communities forming in mineral RIEs and participating in transformation of originally abiogenic rocks are characterized by a considerably higher density of living matter per unit specific surface than natural soils and thereby actively take part in pedogenesis. The density of living matter in mineral RIEs can be judged on the basic that the number, for example, of bacteria and fungi in soil and mineral substrate are equal in size, whereas the specific surface of granite crushed stone is one or two orders lower than in soil (chernozem). In this connection, the initially abiogenic mineral rocks under the effect of plants and accompanying microorganisms are subjected to intense biogenic, physicochemical weathering. They are transformed into soil-like bodies on which directly depends a change in the elemental chemical composition of plants.

In this work we analyzed the dynamics of content chemical elements of the ash in tomato and spring wheat plant organs to reveal the information flows between multicomponent organic matter in RIEs and elemental chemical composition of plant roots. We used an information approach, the methods of which allow a quantitative determination of cause-and-effect interrelations between events as well as the primary direction of information flows between multicomponent systems.

2. Materials and Methods

On initial originally abiogenic granite crushed stone during the course of 23 life cycles we cultivated year-round spring wheat variety Siete Cerros in one experiment and tomato variety Ottawa-60 in another in a pot lighting installation by the small-volume aggregate hydroponics method with two-way regulation of the water regime of the roots and use of Knop's nutrient solution. Water losses due to evaporation from the surface of the RIEs and transpiration of the plants were replenished by adding an equivalent amount of solution or water to the tanks. The solution was corrected at this time. We used luminaries based on DNaT-400 sodium lamps with a solid-state heat-absorbing filter. The intensity of the radiant flux corresponded to 100 ± 10W/m^2 in the photosynthetic active radiation region. The photo-period was 16h/day with growth length of 75 days. After each growth period of the plants, first- and second-order roots were removed, the RIEs was composted for 20 - 30 days.

After each growth period, we studied the biochemical composition of organic matter, which included cellulose, hemicelluloses, water- and alkali-soluble and alcohol-benzene fractions, and nonhydrolyzable residues. At the end of growth periods plant samples were taken for analyze the chemical elemental composition of the plants. Preparation of the plant samples, determination of dry matter and percent of ash content in the plant organs were done by the methods [6]. The elemental composition of plant ash was analyzed on the A-30 X-ray fluorescence analyzer. We investigated the ash composition of plant roots, leaves, stems and reproductive organs (fruits, grain) for the content of chemical elements: *Ca, K, P, S, Na, Si, Al, Fe, Zn, Mn, Mg,* and *Cl.* Experimental details are set out in [1,2]. To manage plant productivity, the experimental design included a change of crops: after 12th growth period on the mineral substrate on which wheat had been grown, tomato began to be grown, and vice versa, and green manure crops were grown instead of tomato and wheat for 18th, 20th and 22nd growth periods. The results of comprehensive experimental investigations of intensive and long-term cultivation of higher plants on an originally abiogenic granulated mineral substrate showed that under conditions of the CAES, intense biogenic and physicochemical weathering of minerals accompanied by a change in the content of chemical elements in plant occurs.

Such processes of the mineral RIEs transformation simulate in a number of ways the evolutionary processes occurring at the initial stages of pedogenesis under natural conditions. The most important consequence of this is a multiple in the activity of biochemical processes of exogenous transformation of the mineral RIEs into bioinert bodies. The accumulation and change in the species and numerical composition of the microbiotic assemblage and formation of multicomponent organic matter accompany processes of transformation of the abiogenic mineral RIEs into soil-like bodies. Transformation of minerals is fostered by acids and bases forming as a result of the activity of microorganisms, leading in turn to the formation of chelates [7]. Already by the 15th growth period, carbon content in the RIEs increased compared to the first growth period by about threefold. The biochemical composition of organic matter changed simultaneously: the proportion of nonhydrolyzable residues and alcohol-benzene and alkali-soluble and the content of cellulose and hemicelluloses in RIEs decreased. Subsequent transformation of organic matter gives rise to the transformation of humus-like components with properties analogous to humic acids of young soil [8]. As is known [9], organic matter interacting with minerals, participates in destruction of rock, promoting extraction of chemical elements from them, and also forms labile compounds with them. Processes of mechanical transformation of the mineral substrate are accompanied by a decrease in the proportion of coarse particles and considerable increase in the proportion of fine granules. Transformation of RIEs leads to a substantial change in the trophic environment and noticeable variation of the elemental chemical composition of plants from one growth period to the next.

3. Results and Discussion

In the present investigation, we are devoting attention to a factor frequently mentioned in the scientific literature but little studied – the exchange of information between interacting multicomponent systems. It is known that a quantitative measure of the content of information in a multicomponent systems consisting of objects belonging to the same set is determined by the Shannon information function [10,11]. The information theory method, using as dynamic indexes conditional entropy and unconditional probabilities (i.e., the probability of occurrence of event *X* depends on the occurrence of event *Y*), makes it possible to unambiguously indicate the direction of cause-and-effect relations or principal direction of information flows in interacting multicomponent subsystems. This approach allows us to get the quantitative characteristic of information exchange between systems.

In information theory, the cause-and-effect relation, or information transmitted from system *X* which is defined by components $\{x_1(t), x_2(t), \ldots, x_n(t)\}$ to system *Y* which is defined by components $\{y_1(t), y_2(t), \ldots, y_m(t)\}$, is determined by initial uncertainty of event *X* or by an a priori measure of information of source *X* at discrete time *t*.

For a discrete set of objects information function (*a priory*) is determined in *nat* (or *nit*) units in the following way:

$$H(X;t) = -\sum_{i=1}^{n} p(x_i;t)\ln p(x_i;t) \qquad (1)$$

For conditional (*a posteriori*) information function we use the following equation:

$$H(X|Y;t) = -\sum_{i=1}^{n}\sum_{j=1}^{m} p(x_i, y_j;t)\ln p(x_i, y_j;t) = -\sum_{j=1}^{m} p(y_j;t)\sum_{i=1}^{n} p(x_i|y_j;t)\ln p(x_i|y_j;t) \qquad (2)$$

where $p(x_i, y_j;t)$ is the compatible of event x_i of source *X* and event y_j of the data acceptor *Y*; $p(x_i|y_j;t)$ is the conditional probability (proportion), i.e., the probability of the *i*th value of event *X* under condition of the y_j realization; *n* and *m* are the number of realization levels. Function $H(X;t)$ is an integral index of the multicomponent system state at time *t*. The values of $p(x_i;t)$ determine the share holding of the *i*th element in the entire elements set (e.g., its percentage content or relative content of organic matter fractions of the RIEs) at time *t*, i.e., $p(x_i;t)$ assigns the number of realizations or possible outcomes, under additional conditions: $0 \le p(x_i,t) \le 1$ and $\sum_{i=1}^{n} p(x_i,t) = 1$; *n* is the discrete number of objects (discriminates) of the set which determine the space of possible values $p(x_i,t)$ at time *t*. Factor of time is the number of the growth period.

Actually, to calculate the specific numbers of $p(x_i;t)$, we use Kolmogorov's combinatorial approach [12] for a set of *n* elements entering this ensemble with proportion $p(x_i;t)$. Function $H(X;t)$ is used for a quantitative determination of the measure of organization or diversity (heterogeneity) of multicomponent systems. The values of $p(x_i;t)$ are calculated from the data on the content of organic matter components in RIEs and chemical elements composition of plant organs for each growth period. We analyzed the temporal variations of function $H(X;t)$ for multicomponent systems at discrete times that correspond growth period ending: *t* = *T*, 2*T*, …, 23*T*, where *T* is the duration of one growth period.

Conditional information function $H(X|Y;t)$ reflects the dependence of the results of event *X* on occurring event *Y*. Obviously, conditional informational function is less than or equal to the unconditional function: $0 \le H(X|Y;t) \le H(X;t)$. Using the results [13], we introduce the definition of causality:

$$\gamma(t) = I(X|Y;t)/I(Y|X;t) \qquad (3)$$

where $I(Y|X;t) = H(Y|X;t)/H(Y;t)$ is the independence of event *Y* from event *X*; $I(X|Y;t) = H(X|Y;t)/H(X;t)$ is the independence of event *X* from event *Y*. If the value $\gamma(t) = 1$, then *Y* does not depend on *X*. If the value $\gamma(t) < 1$, then event *X* is the cause and event *Y* is the effect. When $\gamma(t) > 1$, event *Y* does not depend on event *X*.

An analysis of the experimental results showed that information functions characterizing the dynamics of chemical elements block in tissues of plant organs obey a strict rule under conditions of pedogenesis, lie in a strictly defined region of values, and don't overlap one another. The following sequence of inequalities for the information function was obtained for the ash elemental composition of plant tissues (Figure 1 and Figure 2):

$$H(\text{roots}) > H(\text{leaves}) > H(\text{stems}) > H(\text{fruits, grain}).$$

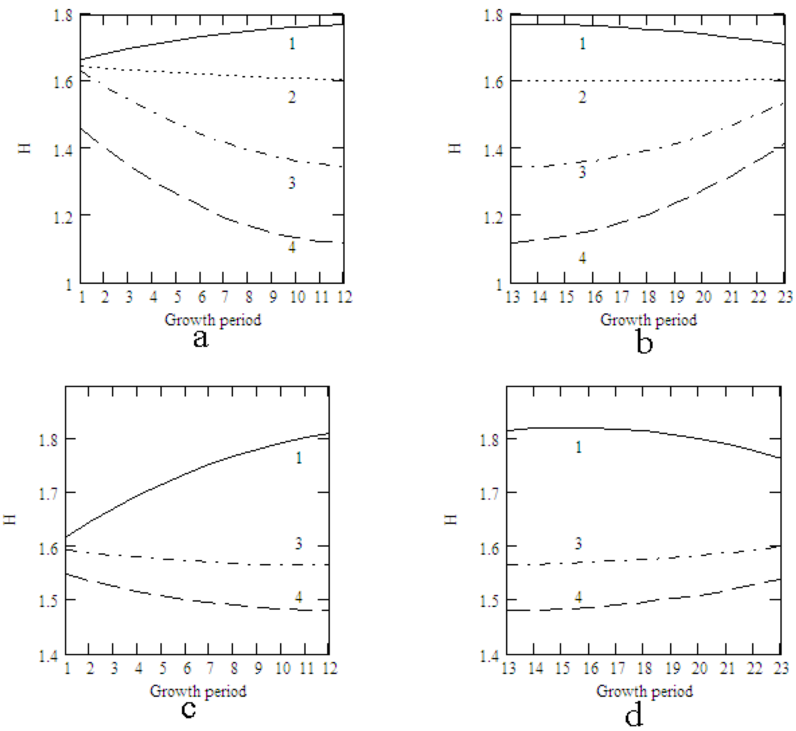

Figure 1. Comparative dynamics (trends) of information function *H*(*t*) of elemental chemical composition (% of ash). (a) and (b) tomato plants; (c) and (d) wheat plants.- roots (1), leaves (2), – stems (3),.— reproductive organs (4). Plants cultivated on crushed stone granite.

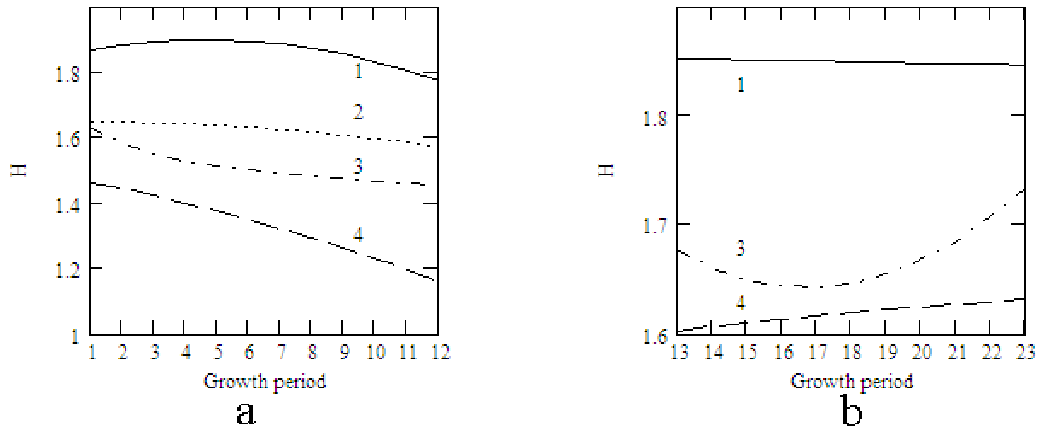

Figure 2. Comparative dynamics (trends) of information function $H(t)$ of elemental chemical composition (% of ash).(a) tomato grown in the original zeolite until 12th of growth period and (b) wheat is grown on the zeolite after tomato. —— roots (1), · · · leaves (2), – · – · – stems (3), — — reproductive organs (4). The content of chemical elements in the leaves of wheat was not investigated.

Actually, the information function reflects not only the quantitative saturation of tissues by chemical elements but also their qualitative combined state. This sequence of inequalities for the ash composition is kept regardless of the botanical species of the cultivated plant, RIEs (granite crushed stone, zeolite) being used, and indicates the nonidentity of the combined state of chemical elements in various plant organs. During evolutionary pedogenesis, the sequence of inequalities for information entropy is a function of time, and does not depend on the duration of exploitation of the RIEs.

Regarding events *X* and *Y* as random processes having a statistically probabilistic character and using the parameter $\gamma(t)$ as a quantitative measure of the cause-and-effect we can reveal the direction of the interrelation between the relative content of chemical elements in plant organs and estimate the quantitative measure of this interrelation. While as $\gamma(t)$ = 0, the relation between events is extremely irreversible and the causal relations (or information exchange) between *X* and *Y* are rigorously determined, i.e., event *X* is the cause of event *Y*. While as $\gamma(t)$ = 1, processes *X* and *Y* depend equally on each other, i.e., cause-and-effect relations (or resulting information flows) are missing. The region of normal causality between events *X* and *Y* is determined by inequalities: $\gamma(t) < 1$, $\beta(t) < 1$, $\alpha(t) < 1$ (Figure 3) and the region of reversed causality by the inequalities: $\gamma(t) > 1$, $\beta(t) > 1$, $\alpha(t) > 1$, where $\alpha(t) = H(Y;t)/H(X;t)$ is unconditional asymmetry; $\beta(t) = H(Y \mid X;t)/H(X \mid Y;t)$ is conditional asymmetry of processes *X* and *Y*. The information approach makes it possible not only to establish the time dependences of causal relations between processes but also to estimate their asymmetry quantitatively.

Figure 3 shows the time trend dependence $\alpha(t)$, $\beta(t)$, and $\gamma(t)$ establishing cause-and-effect relations between the dynamics of heterogeneity of the elemental chemical composition in tomato and wheat plant roots and fruits and grains. It is seen from Figure 3 that the conditions of normal causality are satisfied for tomato and wheat plants, i.e., the change in structural heterogeneity of the elemental chemical composition in roots (*X*) is the cause of the change in content structuredness in reproductive organs (*Y*).

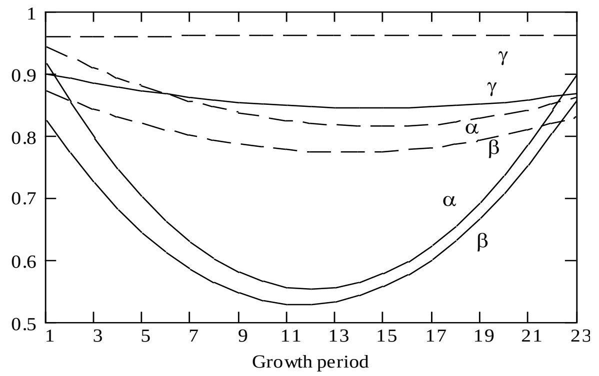

Figure 3. Parameters $\alpha(t)$, $\beta(t)$,and $\gamma(t)$ of normal cause-and-effect relation of the elemental chemical composition in roots (*X*) and reproductive organs (*Y*).─ tomato,─ wheat. Granite crushed rock.

The dependence $\gamma(t)$ not only offers the possibility tracing the change in the causal relation with time but also enables revealing the effect of the crop rotation after 12th growth period.

The lower $\gamma(t)$ with respect to the horizontal line ($\gamma(t)$ = 1), the stronger the causal relation between dynamics processes *X*(*t*) and *Y*(*t*). It is seen Figure 4 that parameter $\gamma(t)$ changes noticeably with time, i.e., during microevolution of primary pedogenesis in the RIE – plant system relative distribution of chemical elements between plant organs increases with increasing number of growth periods. However, crop rotation reduces the causal relationship. These dependences are kept also for wheat but they are more intensively for tomato plants.

The information approach establishes a causal relation (the directions of information flows) between the distribution of chemical elements in plant organs in the following direction: leaves (*X*) → fruits (*Y*), which doesn't contradict the known procedure of foliar fertilization of plants. At the same time, as is seen from Figure 4, a cause-and-effect relation roots (*X*) → stems (*Y*) is absent. The general character of the dynamics of the cause-and-effect relation roots → fruits and leaves → fruits for tomato plants cultivated on zeolite during 12 growth periods remains the same as when growing plants on granite debris; however, in a quantitative respect this relation is strengthened.

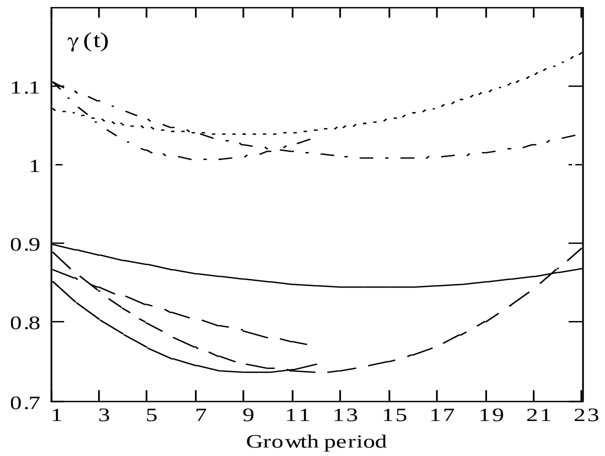

Figure 4. Cause-and-effect relations $\gamma(t)$ between change of heterogeneity of elemental chemical contents in individual tomato plant organs. Interrelation diversity change: - - - roots (X) ← stems (Y); — · — roots (X) ← leaves (Y); ——— roots (X) → fruits (Y); — — — leaves (X) → fruits (Y). The arrows indicate the direction of information flows. Tomatoes cultivated on zeolite until 12th growth period.

According to the capacity theorem in a communication systems [10], the upper limit of the rate of information reception from the source X to the recipient Y is determined by the relation [13]:

$$\sup C_{X\to Y}(t) = R(Y\,|\,X;t)\,/\,H(Y;t) \qquad (4)$$

where $R(Y\,|\,X;t) = H(Y;t) - H(Y\,|\,X;t)$ is the information capacity.

The communication channel is any natural or artificial system in which an initial X and final Y state can be distinguished. Taking into account that the lower limit of information transition is related to the rate by the relation $\inf S_{X\to Y}(t) = (\sup C_{X\to Y}(t))^{-1}$, we obtain: $\inf S_{X\to Y}(t) = d(1 - I(Y\,|\,X;t))^{-1}$ and accordingly for the reverse transition $\inf S_{Y\to X}(t) = d(1 - I(X\,|\,Y;t))^{-1}$. The final difference $\Delta S(t) = \inf S_{X\to Y}(t) - \inf S_{Y\to X}(t)$ determines the direction of information diffusion, i.e., if $\Delta S(t) > 0$, transmission of information from X to Y occurs; if $\Delta S(t) < 0$ transmission of information in the opposite direction $Y \to X$ occurs. After certain transformation of these equations, we obtain the relation for the information diffusion rate:

$$C(t) = \frac{[(\gamma - I(Y\,|\,X;t))(1 - I(Y\,|\,X;t))]}{[\delta t \cdot I(Y\,|\,X;t)(1-\gamma)]} \qquad (5)$$

where $\delta t > 0$ is the characteristic transmission time. Since the inequalities $\gamma(t) > I(Y\,|\,X;t)$, and $0 \le I(Y\,|\,X;t) \le 1$, the sign of the quantity $C(t)$ is determined by the difference in the denominator of the last equation. Figure 5 shows the dynamics $C(t)$ of the change in direction of transfer information about heterogeneity of the set of chemical elements in plants: roots – reproductive organs, roots – stems for wheat and tomato plants. In the first case, information is directed from the plant roots to the fruits and grains, whereas in the second case, mainly from the stems to the roots.

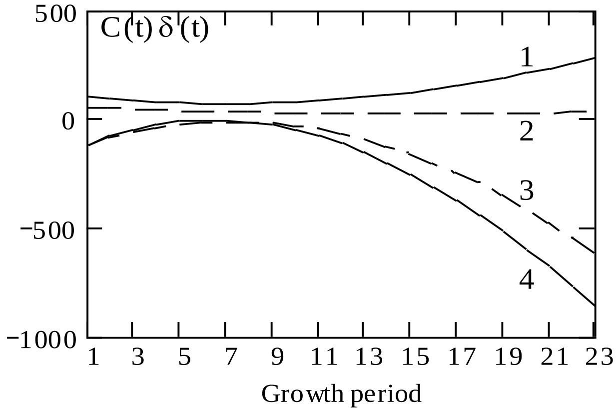

Figure 5. Dynamics of information transmission about structuredness (diversity) of the elemental chemical contents in plant organs: 1, 2 – roots (X) → reproductive organs (Y); 3, 4 – roots (X) ← stems (Y); ——— wheat; — — — tomato. The arrows indicate the direction of information flows.

The uniqueness of the elemental content of plant content under pedogenic conditions manifests itself especially upon comparing it with compositions of the original and transformed mineral substrate. Plants not only control their own total state of chemical elements in accordance with the required elemental content of various tissues but also during primary pedogenesis purposefully act on the mineral RIEs, transforming its elemental composition in accordance with that needed by the plant. We will give the values of the information function (under tomato) of the mineral RIE: the original broken granite (state 1), melkozem after 15 growth periods (state 2), washout from the surface of mineral granules after 15 growth periods (state 3), the chemical composition of organic - mineral film on the surface of mineral granules after 15 growth periods (state 4), the chemical composition of organic-mineral film on the surface of mineral granules after 23 growth periods (state 5), washout from the surface of mineral granules after 23 growth periods (state 6), the chemical composition of the melkozem surface after 23 growth periods (state 7), chemical composition of the sediment in the nutrient solution after 23 growth periods (state 8):

$$H(\text{roots}) = 1.72 \ge H(8) = 1.71 > H(7) = 1.48 \ge H(6) = 1.47 > H(5) = 1.42 > H(4) = 1.18 > H(3) = 1.15 > H(2) = 1.00 > H(1) > 0.95\,nat \qquad (6)$$

An analogous sequence of the inequalities occurs also for wheat. From sequence of inequalities (6) follows that the longer exploited mineral substrate, the closer mineral substrate to the structuring of the chemical elements in the roots of plants. In accordance with inequalities (6) the information content of multicomponent systems is increased from the first state to the ninth state, and their diversity is reduced. Increase the information content of the object is always associated with a decrease in its diversity.

During lengthy, intenseive, and continuous exploitation of a mineral substrate under CAES conditions, in it develop processes analogous to natural pedogenic ones related to the transformation of abiogenic rocks into biogenic soil-like bodies, formation of biochemically multicomponent organic matter in RIEs, and development of a multispecies microbiotic community.

Figure 6 shows the dynamics of information functions $H(t)$ of total organic matter forming in RIEs and state of multicomponent elemental chemical composition of tomato plant roots. Statistics relationship will be the follows: correlation coefficient is $R^2 = 0.94$, Fisher's test is $F = 144.8 >> F^{(cr)}_{1,10;0.05} = 5.0$; t = 12.03 > $t^{(cr)}_{0.95} = 1.81$ is the Student's test for correlation coefficient. For quantitative determination of the mutual correspondence in the positions of the maxima and minima of $dH(t)$ given in Figure 6(b), we used the statistical method of signs conjugation by using a 2×2 contingency tables [14]. The statistic of their relation for oscillatory processes having an alternative variation was established by means of the coefficient of association: $\Phi = 0.66$; test $\chi^2 = 5.2 > \chi^{2(cr)}_{0.05;1} = 3.8$. The given statistical conjugation characteristics of these multicomponent systems indicate mutual correspondence of their dynamics. Temporal variations of multicomponent systems occur are correlated, and a statistically reliable high measure of correspondence is noted for small amplitudes of $dH(t)$ oscillations about the trend.

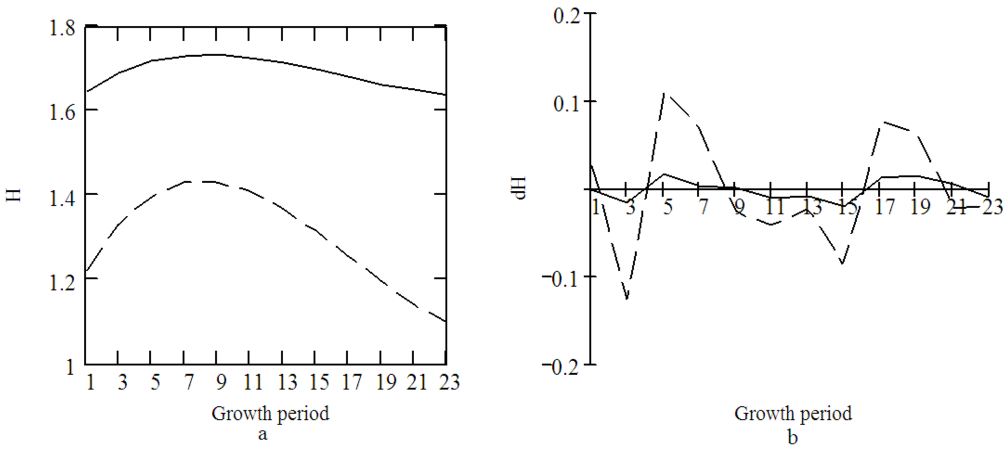

Figure 6. Comparison of information functions for trends (a) and oscillations (b) about the trend of the chemical elements content of tomato roots and organic matter forming in the mineral RIEs. —— chemical elements content; — — — organic matter.

The observed oscillatory processes with a small amplitude are characterized short-time reorganization against the background of the general evolutionary dynamics of the multicomponent systems. It follows from Figure 7 that parameter $\gamma(t) < 1$ and, consequently, information flows for tomato and wheat plants are directed from organic matter to the elemental chemical composition of the plant roots. Thus, during long-term, multiple growth-period cultivation of plants on mineral RIEs under controlled conditions, organic matter of the RIEs has a cause-and-effect relation with variation of the elemental chemical composition in the plant roots and fruits. This relation is more expressed for tomato plants than for the spring wheat ($\gamma_{wheat}(t) > \gamma_{tomato}(t)$).

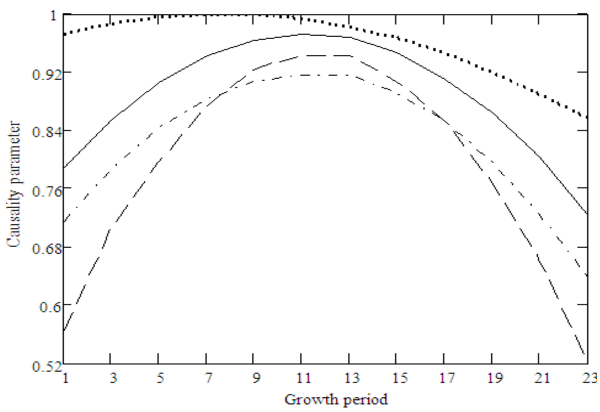

Figure 7. Dynamics (trend) of the causality parameter $\gamma(t)$ between the elemental chemical composition of roots and fruits and grains and multicomponent composition of organic matter forming in the mineral RIEs: —— tomato roots, - - - wheat roots; — — fruits, – ·– · grains.

It is important to note that the information approach allows, on the one hand, to allocate the significance of the controlling factor (change of crops after 12 growth period) and, on the other hand, quantitatively to characterize the effect of species difference on cause-and-effect relation.

As the duration of exploitation of the mineral RIEs and its saturation with organic matter increases the cause-and-effect relation between organic matter and elemental chemical composition of plants weakens. However, rotation of the crops being cultivated leads to strengthening of the cause-and-effect relation. It is known that crop rotation improve the quality of organic matter of RIEs.

The results of the comprehensive experiments allowed obtaining fundamentally new knowledge about progresses of micro-evolutionary primary soil formation related to information exchange between multicomponent interacting systems. As a result of the investigations cause-and-effect relations in the dynamics of redistribution of a set of chemical elements between plant organs during primary pedogenesis were established for the first time. During intensive cultivation of tomato and wheat plants on an initially abiogenic RIEs, and increase of heterogeneity of chemical element contents in root system leads to a decrease of heterogeneity in the plant reproductive organs and vice versa. At the same time, a change in the relative content of chemical elements in plant roots does not have a causal relation to the change in heterogeneity in plant stems. The proposed information approach applied to an analysis of mutual distributions of chemical elements content between plant organs also makes it possible to indicate the direction of information flows in plants and makes the quantitative estimation of information flows.

Earlier [3] information approach was used for interpreting results of plants productivity dynamics. It has been found that dynamics of plant productivity was bound up with information flows between systems organic matter and microbiotic community formed in RIEs. By indirection the information flows also take into account the diversity of multicomponent systems. The causal relation between the state of organic matter forming in the mineral RIEs and state of the microbiotic community is not only of scientific interest but also of practical importance. Thus, information exchange in biological and soil systems become the same reality as the exchange by matter and energy.

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