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Evolutionary Dynamics of Intercoupling of the Chemical Elements in Plants and Primary Soil-Forming Processes

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Abstract We present the results of a comprehensive long-term experiment on intensive cultivation of wheat and tomato plants to initially abiogenous mineral substrate. The experiment simulates the primary processes of soil formation. For the first time is established dynamic synergistic and antagonistic interrelations between the chemical elements (Si, Al, Fe, Mg, Ca, K, P, S, Cl, Na, Mn, Zn) in various plant tissues (roots, fruits, grain, stems, leaves) under condition of primary soil formation. We have identified the dynamics of accumulation and differentiation of collective state of the chemical elements in different plant tissues by the methods of information theory.

Keywords: Chemical Elements; Dynamics; Synergism; Antagonism; Information Function; Soil Formation; Mineral Substrates

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1. Introduction

The first stage of the evolutionary soil formation is expressed as a mechanical destruction of parent rock, and its biochemical processing. Moreover, these processes take place simultaneously and in close synchronous interaction[1,2]. Destruction of mineral substrates associated with the activities of microorganisms[3], vital activity of the root systems of plants, blue-green algae, which are capable of destroying kaolin silicates[4]. The most important consequence of this is multiple increased activity of the chemical processes of exogenous transformation of the minerals, which are accompanied by destruction of rock, the formation of soil-like bodies. At that the chemical elements of root medium pass into cation-anion labile state and become available to plants. The consequence of these processes are variations in the content of the chemical elements in plants.

Study of the mineral composition of plants engaged V.I. Vernadsky[1], who pointed out the close relationship between the elemental composition of living organisms and the composition of the Earth's crust. Significant contribution to the research of substance cycle and the elucidation of its role in soil formation processes made B.B. Polynov[2], V.A. Kovda[5], G.Ya. Rinkis[6], V.B. Il'in[7], C. Barber[8], A. Kabata-Pendias et al.[9], as well as many other scientists. As is known, the elemental chemical composition of a living substance is significantly different from the composition of rocks. On the one hand this compels the plants, to look for ways of self-sufficiency necessary number of elements, and on the other hand to adapt to the characteristics of the geochemical environment. This adaptive response is due to the existence of the interrelationships in the distribution of chemical elements in the tissues of plants i.e., their synergism or antagonism. The phenomenon of synergism and antagonism between chemical elements in the process vital activity of plants has been discussed repeatedly in the literature[6,9].

One of the central problems of modern agricultural production is to provide high quality of products with optimal chemical composition of plants. In this regard, great importance have the fundamental knowledge about the content of the chemical elements in plant tissues under conditions of intensive interaction of plant roots with the medium. Synergism and antagonism of the chemical elements in plants is fundamentally important for the development of plants. Uptake of mineral elements by plants is interconnected. Significant reduction or excessive content of any of the chemical elements in plant nutrition has an effect on relations with contents of other elements, thereby changing the ratio between them in the plant tissues. The consequence of this is the deterioration of plant development, which is accompanied by a decrease in their productivity. This paper presents the results of an intensive, continuously working and long-term experimental study of the dynamics of the associate intake of chemical macro- and micronutrients by various organs of plants under condition of primary soil formation. Cultivation of plants is carried out under controlled conditions.

2. Materials And Methods

An important part of a comprehensive multi-year experiment was to study the dynamics of content of chemical elements in various plant tissues of plants of spring wheat (cultivar Siete Cerros) and tomato (cultivar

Ottava-60). The experiment also involved a study of the dynamics of the emerging organic matter, as well as to study the dynamics of the biotic community. Cultivation of plants we carried out continuously and year-round at initial abiogenous inert mineral substrate (crushed granite, zeolite). Growing plants was carried out in a lighting installation by the method of low-capacity agregate hydroponics. We did not change nutrient solution of Knop during each plant vegetation period. The loss of the water by evaporation from the of the mineral substrate surface and owing to transpiration we realized by addition of equivalent amount of solution or water. Simultaneously, we performed the correction of solution. In the experiment, we used lighting devices based on sodium lamps DNaT-400 with a solid heat-absorbing filter. The intensity of the radiant flux was 100 ± 10 W/m^2 in the PAR region, the length of the light period was 16 h/day, and the growth period length was 75 days. Restricted volume of vegetative installation creates conditions for the powerful impact of the root systems of plants, the organic matter forming into mineral substrate, microflora and their metabolic products on the mineral substrate. This, in turn, leads to the transformation of the mineral substrate and the formation of soil-like bodies[10]. That is the nutrition of plants takes place in a complex - not only of Knop solution, but also due to the weathering of mineral substrates, as well as due to the accumulation and transformation of organic substances.

We grew spring wheat and tomato plants on granite rubble in the course of 23 uninterrupted vegetation periods. Additionally, we performed an experiment on growing tomato plants at a zeolite for 12 continuous vegetation periods. After twelve vegetation period we started cultivate spring wheat instead of tomato on the same zeolite. We continued this experiment until the 23rd of vegetation period. After each vegetation period was carried out analysis of ash composition and the percentage of content of the chemical elements Si, Al, Fe, Mg, Ca, K, P, S, Cl, Na, Mn, Zn in plant tissues (roots, stems, leaves, fruits, grains). Elemental analysis of the chemical composition of the plants ash was carried out by using X-ray fluorescent analyzer A-30.

One of the possible technological methods to regulate the processes associated with the processes of the primary soil formation is acid-base complex regeneration of mineral substrate, is proposed in the work[11]. Regeneration removes some quantity of the emerging organic matter from surface of mineral substrate, thereby changing the dynamics of the trophic conditions of the root inhabited medium. We found that process of intensive use initially inert mineral substrate is accompanied by a progressive accumulation of organic matter in the root inhabited medium, which contains in its composition physiologically active organic compounds. Simultaneously, there is a process forming of a multicomponent micro biotic community. It is known the organic substance is a good adsorbent for anions and cations. Organic matter improves buffering of root medium, reduces the concentration of salts in the soil solution. Formation of organic matter leads to a change in the acidic mode of root medium, the redox potential, numerical and species composition of microorganisms. This, ultimately, may change the terms of weathering minerals. This leads to variations in the chemical composition of the plant tissues. That is why in the experiment we used acid-base complex regeneration of mineral substrate and also its modified version of complex regeneration. In the modified variant, we performed simultaneous regeneration of mineral substrate and growing plants (regeneration no.2). Regeneration effectively removes part of physiologically active components of organic matter which forming in root medium. Acid-base regeneration is represent the processing of mineral substrate by using acid solution (0.01n H_2SO_4). Then, we were carried out flushing water the substrate and processing by alkaline solution of 0.05n KOH concentration (regeneration no.1). Finally, the substrate was washed with water. For a zeolite we performed only check experiment.

Experience on granite rubble, we performed for each crop in three variants: the check experiment and subject to the control factor (acid-base complex regeneration of mineral substrate in two versions – regenerations 1 and 2). We explored the experience of the following variantes: variant 1 (tomato) and variant 4 (spring wheat). In these variants, after each the vegetation period we removed the roots of the first and second orders. Next, we made composting of the mineral substrate for 20-30 days, and then we performed the complex acid-alkaline handling (regeneration no.1). For variants 2 (tomato) and 5 (wheat), we performed additionally thrice acid-alkaline handling of the substrate with the living roots of vegetative plants (regeneration no.2): in phase of flowering and during fruit set for tomato; for wheat - in phase of the output in tube, and at the flowering stage and grain filling. Check experiments are the variant 3 (tomato) and the variant 6 (wheat), in which we carried out only removing of roots and have executed composting substrate.

In addition, we performed change of crops for the 12th vegetation period. On the mineral substrate where we grown tomato plants (wheat), we began to grow wheat (tomato plants). In addition for all variants, in the 18th vegetation period we cultivated peas only, and in the vegetations 20th and 22th we cultivated the green manure. This is due to the fact that we have found in mineral substrate after exploitation the accumulation of fungi, including phytopathogenic fungi. Obviously, this leads to adverse conditions of plant life support. Details of the experiment are summarized in the monograph[12].

3. Results and Discussion

We carried out comprehensive and year-round experimental study, throughout continuous and long-term cultivation of spring wheat plants and tomato on initially abiogenous granular mineral substrate. This experiment demonstrated that under the controlled conditions take place intense physico-chemical weathering of minerals. Using of the adjustable agroecosystems as a physical model of agro- and ecosystems can significantly accelerate natural the soil formation processes due to the vigorous activity of higher plants, micro biota and rapidly forming of the organic matter in the root inhabited medium. Such process concerned with the transformation of mineral substrate simulates by a number of signs the evolutionary processes at the initial stages of soil formation under natural conditions. The most important consequence of these processes is the multiple increase activity biochemical processes of exogenous transformation of rocks into soil-like body, the formation of fine fractions of mineral substrate[10,13,14]. The experimental data on the elemental chemical composition of plant tissues (percent of ash) for the first time allowed to quantitatively analyze the dynamics of the interconnectedness of the relative content of the chemical elements in various plant tissues under conditions of evolutionary formation of primary soil. In our experiments the factor of time is the number of vegetation periods.

Table 1. Synergism and antagonism relative abundances of the chemical elements in plant tissues of tomato (first column) and wheat (second column).

	Ca	Mg	S	P	Cl	K	Na	Mn	Zn	Fe	Si
Mg	– – + – + × +										
S	– – + + + × +	– + + + – + –									
P	– – + – – – +	+ – + – × + +	× × × – – + +								
Cl	× + + – – × ×	× + + × + × ×	× + × – – × –	× – + + × – –							
K	– – – + – × –	× – – – × – –	× – – – – + –	× – – – × – –	– – – – + – –						
Na	+ × × × + + +	+ + – – × – +	– – + – + – –	× × – × – – +	+ + – + – – +	– – + + – × –					
Mn	+ + – – + × +	– – – – + + +	× – – – – + –	– × – + + × ×	– – × + + + +	× × + – × – –	– – × × – – +				
Zn	× + + × × × +	× × + – + + ×	× – + × – + ×	× + + – + + ×	– – × × + – ×	× – – × + – –	– × × × – × ×	+ + – × + + +			
Fe	+ + – + × – +	+ + – + + × –	– – – + – + –	× – – – + + +	+ + – – + – –	– × + × + – –	+ – × – – × ×	× + + – + × +	– × – – + + +		
Si	+ + × × × – +	– – – – + + ×	× – – – – + –	– – – – + + +	× × × + × – –	– – + + – × –	+ – + × + + +	+ – × × + × ×	– × – – + + +	+ + + + × + +	
Al	+ + + + + – +	+ + × + + + –	× – + + – + –	– – – – × × –	× × – – × + +	– – × × – + ×	× – + × × + +	+ – – – + × ×	– × × – + – +	+ + + + – + +	+ + + + + × ×

*) The first line - the roots, the second - tomato fruit or grain of wheat, and the third - the leaves, the fourth – stems. For wheat leaves experiment was not performed. Note: + synergetic elements, ─ antagonistic elements, × relationship was not found.

Table 1 summarizes the synergistic and antagonistic dynamic relationships for the chemical elements (Si, Al, Fe, Mg, Ca, K, P, S, Cl, Na, Mn, Zn) in the various tissues of the tomato plant and spring wheat. We analyzed the dynamic relationships between all macro- and micronutrients of this set of the chemical elements. We have determined of such relationships more than 460. We shall dwell in more detail on some paired interrelationships of the chemical elements. This is caused either by an insufficient knowledge about behavior of the chemical elements in plants, or by the complexity and ambiguity of their pair interrelations. We have found that the direction of the dynamics of antagonistic or synergistic relationships between some pairs of the chemical elements in different parts of plants may be different. We shall demonstrate this on the example of the dynamics of the interdependence of the silicon content and potassium in roots and reproductive organs. As is well known, potassium refers to the chemical elements most required for plants. Its role in plants is multifunctional. As for silicon, the recently[15] significantly increased interest in clarifying its role in the vital activity of the plant as a factor in boosting crop yields. Silicon has a stimulating effect on the development of the root system, increases the surface area of the leaves, he has a positive effect on the growth rate of plants, their dry weight, on the resistance of plants to stress. The silicon content in plants is comparable with the content of macronutrients. According to V.I.Vernadsky silicon can be attributed to the group of biophiles. Assimilable form of silicon replenished by the weathering minerals, decomposition of plant residues and organic matter transformation. However, in the literature there are not practically data of the interconnectivity of the silicon content with the content of other elements in plants.

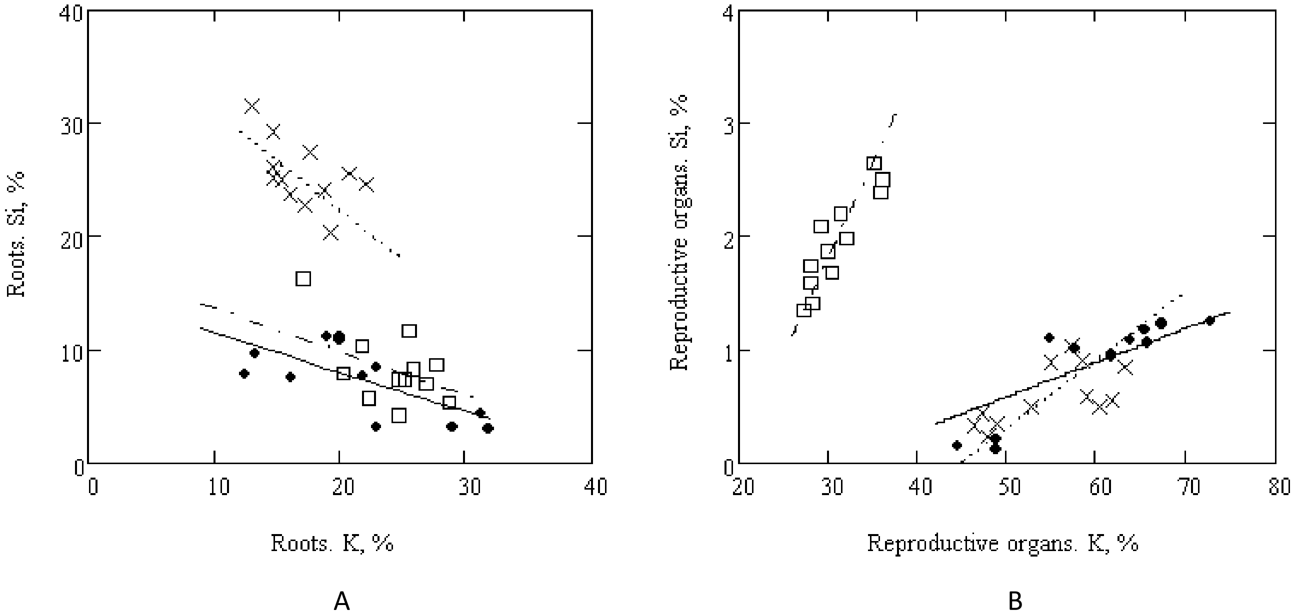


Figure 1. Antagonism of potassium and silicon contents (percent of ash) in the roots (A) and synergism in the fruits and grains (B). Crushed granite. Check experiment. ● - tomato, trend —— ; □ - wheat, trend – · – ·. Zeolite: ✕ - tomato, trend - - - . Here and below: for crushed granite we give data just for the odd vegetation periods; for zeolite we give results of an experiment for vegetation periods from the first to the twelfth.

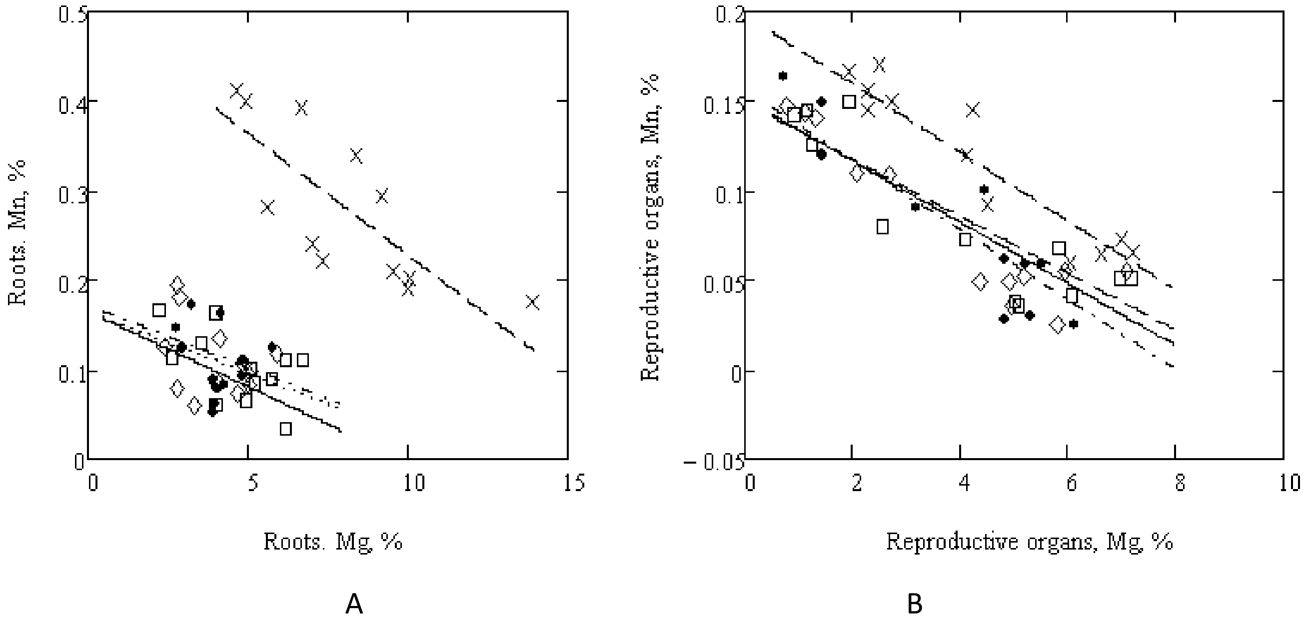
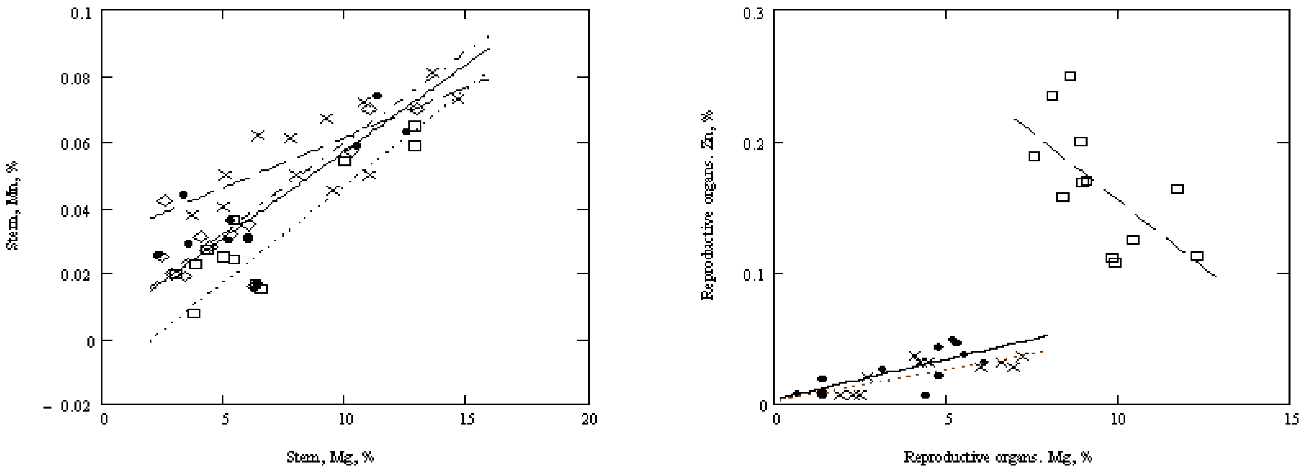


Figure 2. Antagonism of magnesium and manganese (percent of ash) in the root tissues (A) and the fruits (B) of tomato. Granite rubble. ● – check experiment, trend —— ; ◊ - variant 1, trend – · – ·; □ - variant 2, trend - - - -. Zeolite : ✕ - tomato, trend – – .

We have found that when grown plants on the granite rubble the influence of silicon on the content of other chemical elements in different plant organs may has a distinct direction. For example, in the roots of tomato plants and wheat interconnection between contents chemical elements Si and K is the antagonist (Figure 1A), whereas in the fruit, this interconnection has reverse trend that is a synergistic (Figure 1B). Growing tomato on the zeolite qualitatively retains the interconnection between the dynamics of the elements Si and K, but leads to a significant quantitative differences compared with the granite rubble.

Using zeolite as a substrate increases the intensity of synergic interconnection (angle of linear trend higher than for crushed granite). In addition, for the same potassium content in the roots the silicon content in the roots increased approximately three times in compared with granite rubble. Apparently, on the accumulation of the chemical elements affect distinction in the intensity of weathering processes for crushed granite and zeolite. Such complex dynamic behavior is typical of some other chemical elements (Table 1). This underlines the ambiguity of their interaction in various plant tissues. Relatively little information is available in the literature on the relationship between manganese and magnesium (on V.M. Goldschmidt's classification they belong to the group of biophiles[16]), both the interaction between themselves and with other chemical elements in plants. Especially, since there is no data on the dynamics of differential content of the elements in different tissues of plants. Figure 2 shows the dynamics of the interconnection of the weight content of the chemical elements Mg and Mn in roots and tomato fruits on throughout the entire variants of the experiment. Antagonism remains faithful between these chemical elements throughout the experiment, both for the roots, and for fruits. Analysis of experimental results showed that the effect of the control factor (acid-base complex regeneration) on the interconnection of the contents of the elements Mn and Mg in the root tissues of plants is statistically insignificant. We shall compare the dispersions. Using the criterion of Fisher for variants 2 and 3 (Figure 2A) we obtained the value which smaller of the standard value: $F = (S_2/S_3)^2 = 1.06 < F^{cr}_{12,12;0.95} = 2.7$. Consequently, the influence of complex regeneration of mineral substrates on the abundances of these chemical elements in plants can not be considered effective. This conclusion is valid for all investigated pair interactions of the chemical elements in all plant tissues. We found that the distinction between the versions with regeneration and without regeneration is statistically nonsignificant. This may mean that under condition of evolutionary of soil formation[12] replenish nutrients for plants through decomposition of plant residues and organic matter transformation is less important than due to weathering and destruction of minerals. At the same time the cultivation of tomato plants on zeolite (from the first to the twelfth vegetation periods) resulted in statistically significant distinction compared with the results obtained for the crushed granite. However, the angle of inclination of the linear trends for zeolite and crushed granite approximately the same (Figures 2A and 2B). That is, there are close qualitative resemblance of dynamics processes of accumulation of Mg and Mn in the roots of plants, both wheat and tomato. Moreover, this dynamic stored both crushed granite and zeolite. However, for plants grown on zeolite the saturation of plant tissues by manganese higher than when plants grown on a granite crushed stone. Ambiguity of the mutual influence of these elements are emphasized also by the fact that in contrast to plant tissues of roots and fruits we found an inverse dynamic interrelation (synergism) both manganese and magnesium in the stems (Figure 3A) and in the leaves (Table 1). This result does not confirm the opinion that Mg, and the chemical elements Ca and P (Table 1) are the major antagonists in respect of the absorption of other chemical elements. From our experimental data it follows that depending on the whereabouts of the chemical elements in plants the ions Mg, Ca, P may be both antagonists and synergists. For the most of pair interactions of the chemical elements found dynamic interconnections of the chemical elements which have qualitatively identical temporal trends both for wheat, and for tomato plants. However, we note that for some pairs of the chemical elements has great importance the botanical distinction of the plants. This underscores the complexity of the relationships and the ambiguity of interconnections of the relative contents these elements in plants.



A B

Figure 3. A. Synergism of magnesium and manganese (percent of ash) in the tissues of tomato stems. Granite rubble. ● – check experiment, trend —— ; ◊ - variant 1, trend – · – ·; □ - variant 2, trend - - - -. Zeolite: ✕ - tomato, trend – – . B. The interrelations of zinc and magnesium (percent of ash) in the tissues of the fruits of tomato and grains of wheat. Crushed granite: ● - tomato, check experiment, trend ——, □ - wheat, check experiment, trend – – . Zeolite: ✕ - tomato, trend - - - -.

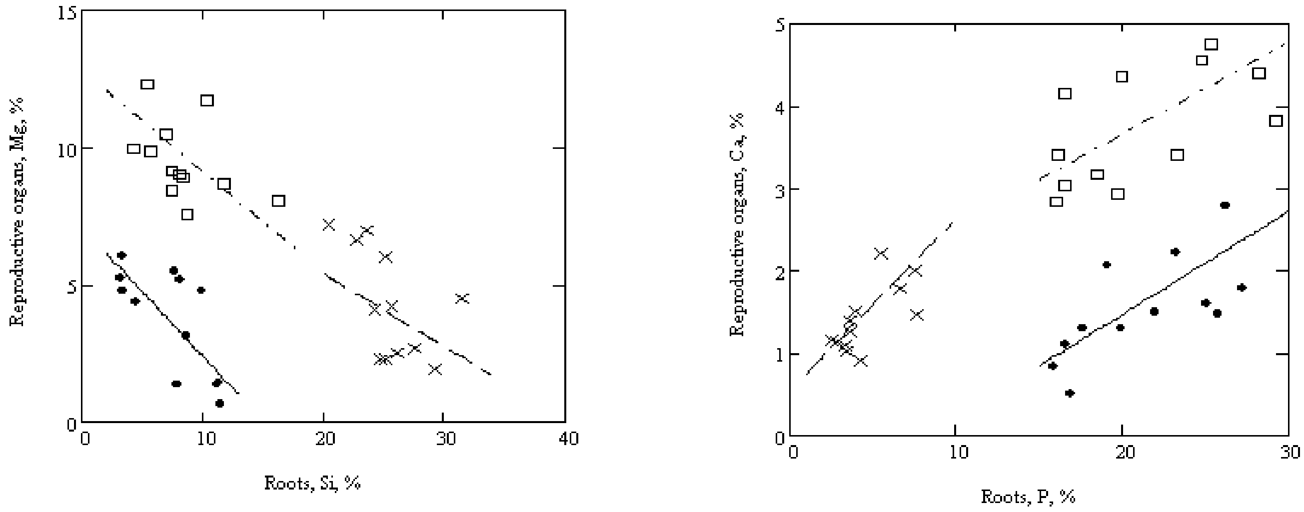
We shall demonstrate this with an example of mutual influence of zinc and magnesium in tomato fruits and wheat grains. As is well known, the excess Zn in plants upsets the metabolism, retards the growth and development of plants, reducing their productivity. Figure 3B demonstrates that in tomato fruits magnesium relative content has a synergistic interrelation with zinc whereas for grain of wheat this interrelation has the opposite direction (antagonistic). The nature of these specific distinctions of plants is kept for all variants of the experiment. This interrelation does not depend on the type of mineral substrate, of action of control factor and number of the vegetation periods. We observed a similar distinction for some other elements (see Table 1), for example, for the interrelation of phosphorus relative content and calcium. In the tissues of tomato fruits interrelation is synergetic between these elements, whereas for wheat grain this interrelation is antagonistic. At the same time for plant stems the interrelation changes the direction for these elements. For tomato this interrelation becomes antagonistic, whereas for wheat stems exists synergistic interrelation (Table 1). Table 1 includes paired dynamical interrelations among all the chemical elements in the following tissues of plants: roots, fruits, grains, leaves and stems. However, the experimental data on the dynamics of the chemical elements also allow to trace the dynamic relationship between the relative content of the chemical elements in different plant organs and, above all, between the content in the roots and the content in the fruits of tomato and grains of wheat (Table 2).

Table 2. Synergism and antagonism relative abundances of chemical elements in plant root tissues and tomato fruits and grains of wheat *).

Reproductive organs	Roots											
	Ca	Mg	S	P	Cl	K	Na	Mn	Zn	Fe	Si	Al
Mg	+ +	+ –	– –	+ +	× –	+ +	+ –	– +	× +	+ –	– –	× ×
S	× ×	+ –	× ×	+ +	× –	× +	× –	– +	× +	× ×	× ×	× –
P	× +	× +	× ×	× –	+ +	× ×	+ –	× +	× ×	+ +	× +	+ +
Cl	+ +	× +	– +	+ –	+ +	– +	+ –	– ×	× ×	× +	× +	+ +
K	× –	– +	× +	– +	× –	× ×	– ×	+ ×	× ×	– –	× ×	– –
Na	× –	× +	× ×	– –	– +	× ×	– +	× –	× –	– –	× ×	– –
Mn	+ –	– –	× ×	– –	× ×	× ×	× –	+ –	× –	× ×	+ –	× ×
Zn	+ –	+ +	× ×	+ +	× –	× ×	× –	× ×	× ×	+ –	– ×	× –
Fe	– ×	– –	× ×	– ×	– ×	+ ×	– –	× ×	× +	– –	× ×	– –
Si	– –	+ –	+ +	+ +	– –	+ ×	– ×	× ×	× ×	– –	– –	– –
Al	– ×	+ –	× ×	+ +	× –	+ +	– ×	× ×	× –	– ×	– +	– –
Ca	× –	+ ×	× ×	+ +	× –	× –	+ +	– ×	× ×	× ×	– –	× –

*) The first line - tomato grown on granite rubble, second row - wheat grown on granite rubble.

The identification of such relationships between the chemical elements opens the possibility of developing methods of controlling the relative chemical composition in plants and in particular in the reproductive organs. This is important for the purposes obtaining of programmed harmonious vegetable food throughout the chemical elements composition. For example, we have found that increasing silicon content in the tissues of the plant roots is accompanied by decrease of the relative content of magnesium in grain of wheat and tomato fruits (Figure 4). This antagonism is retained for the entire observation period and does not depend on the type of mineral substrate, botanical species of plants, the number of vegetation periods. When growing plants on granite rubble the range of variation of the silicon content in the roots of wheat and tomato lies approximately at the same range of values. At the same times for tomato that we grown on a zeolite, this range is much larger and the saturation by magnesium of fruits occurs at a higher relative content of silicon in the roots than in the case of crushed granite. Other dynamics demonstrates the accumulation of phosphorus in the plant roots, which is accompanied by an increase in the relative content of calcium in the tomato fruit and wheat grain (Figure 4B). In this situation the influence of the type of mineral substrate on the content of the chemical elements is essential too, although the qualitative dynamic interrelations are persisted. Figures 4A and 4B are almost reflection symmetric. Increasing the content of phosphorus in the roots leads to increase of calcium content in the fruit of tomato and wheat grains. The calcium content of tomato fruits in three times higher than that in plant roots. The silicon relative content in the roots of plants in ten times greater than in the reproductive organs. These relations between chemical elements do not depend on the mineral substrate, botanical species of plants, number of vegetation periods, and the method of regeneration that we used.



A B

Figure 4. A. Antagonism of magnesium and silicon in the tissues of the reproductive organs and roots, respectively. Granite rubble. ● - tomato, check experiment; trend —— ; □ - wheat, check experiment; trend– · – ·. Zeolite: × - tomato, trend – –. B. Synergism of calcium and phosphorus in the tissues of the reproductive organs and roots, respectively. Granite rubble. ● - tomato, check experiment; trend —— ; □ - wheat, check experiment ; trend – · – ·. Zeolite: × - tomato, trend – – .

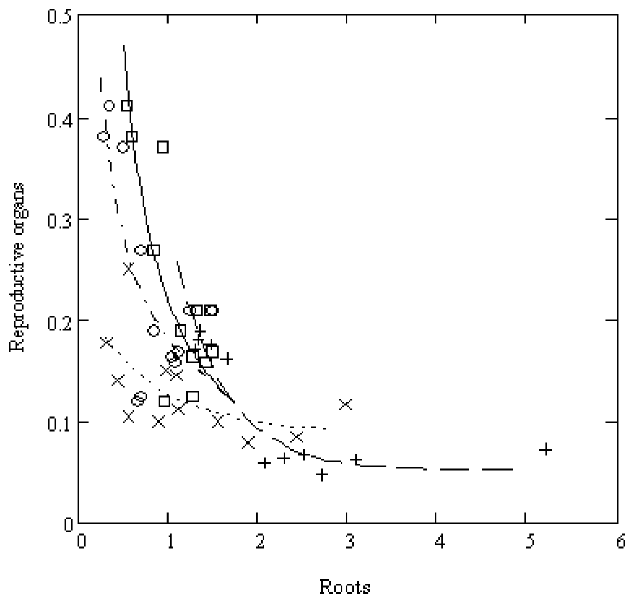


Figure 5. Antagonism of the chemical elements in the roots and reproductive organs. Granite rubble. Interrelations: roots - wheat grains. Zn(roots) – Fe(grain) – □ experimental values, —— trend ; Zn(roots) – Al(grein) – ○ experimental values, — · — trend; Mn(roots) – Na(grein); × experimental values, · · · – trend. Zeolite. Interrelations: roots – tomato fruits. Mn(roots) – Na(fruits); + experimental values , – – – trends.

When growing plants on granite rubble the changes in the silicon content in the roots of wheat and tomato lies approximately in the same range of values. At the same time for tomato that grown on a zeolite, this range is markedly different. Saturation of fruits by magnesium occurs at a higher relative content of silicon in the roots than using crushed granite. As shown by our study, we observed synergistic and antagonistic mutual influence of the chemical elements in plant tissues that are not always rectilinear. For example, Figure 5 shows the interdependences of zinc and manganese in grains wheat and tomato fruits depending on the content of iron, aluminum and sodium in plant roots. When in plant roots high content of the chemical elements, a change in their relative content is reflected weakly on change in the relative abundances of the chemical elements in the reproductive organs. At the same time, in the region with low contents of elements in plant roots small changes result to relatively large changes in the relative content of the chemical elements in the reproductive organs.

We have revealed synergistic and antagonistic the associations of the chemical elements in different plant organs that are determined apparently by genetic properties of the plants. At the same time dynamic quantitative relationships originate from due mainly by the geochemical conditions of the root medium. Verification of the influence of the control factor (regeneration) testify that the content of organic matter in mineral substrates has no statistically significant effect on synergistic and antagonistic relationship of chemical elements in plant organs.

4. Applications of the Information Approach to the Analysis of Dynamics of the Chemical Elements in Plants

As is well known, balance and harmony of the general composition of the chemical elements in living organisms are the main condition for their normal growth and development. Study of the biogeocenose always had the fundamental scientific interest, and now has of great practical importance in connection with the environmental problems of the environment. An important direction of solving this problem should recognize attempts to introduce magnitudes (or descriptors) characterizing multicomponent system as a whole. In this regard, it should be emphasized that for the plants is important not only paired relationships between the chemical elements, but also the dynamics of the additive effect (cooperative effect) chemical elements when synergistic and antagonistic relationships are not presented explicitly. V.I. Vernadsky repeatedly drawn attention to the unknown role of specific relations for cooperative composition of the mineral chemical elements in different parts of living matter[1]. We have established previously[17-19] that organizational composition of the chemical elements in various plant tissues has causal-and-effect relation, and between collective states of the chemical elements in different organs of plants exist directed information exchange. Therefore, us it was important identify the evolutionary dynamics of the collective contents of chemical elements in various plant tissues. In addition, we wanted to determine how strongly influences choice of the mineral substrate and action of the control factor on the dynamics of the collective state of chemical elements. We performed the analysis of the dynamics of the collective state of the chemical elements in plants tissues by using the methods of information theory. Information approach aims to obtain a holistic view of the phenomena and processes, based on the knowledge of the structure of interconnected multicomponent systems. At that, quantitative indicators of their measures of organization are the conditional and unconditional information functions[18,20,21]. Information function is an integral indicator of organization multicomponent dynamic system and characterizes its structuredness, heterogeneity and information content. Magnitude of information theory is that it allow us to get a new non-trivial knowledge on the interrelated dynamics of multicomponent systems. Unconditional information function of K.Shannon[22] for a finite discrete set of n - events (specifier) can be written in the following form: $H(t) = -\sum_{i=1}^{n} p_i(t) \ln p_i(t)$. Value of $p_i(t)$ determines share of i-th element in the entire set of the set of the chemical elements, i.e., $p_i(t)$ is the normalized number of realizations, or the number of outcomes. Such an approach to the implementation of the individual components of the chemical element composition is similar to B.B. Polynov's method[2], which specifies the content of the chemical elements in the ash by weight. For each vegetation period t = 1, 2, ...,23 values $p_i(t)$ are determined from experiment and they satisfy the following requirements: $0 \le p_i(t) \le 1$, $\sum_{i=1}^{n} p_i(t) = 1$. Obviously, the set of observations of $p_i(t)$ form a time series. Practically, to calculate of specific amounts of pi(t), in this paper we use the combinatorial method of A.N. Kolmogorov[23]. We found a statistically significant differential the sequence of values of information function for aggregate chemical elemental composition for tissues of different organs of wheat and tomato plants. So, for example, for tomato (mineral substrate - crushed granite), numerical sequence for the values of H, will be the next: H(root) = 1.72 > H(leaf) = 1.62 > H(stem) = 1.50 > H(fruit) = 1.31 *nat*. Sequence of inequalities we were obtained by averaging both over all the options of experiences and the entire observation period. It is important to emphasize that the deterministic and non-random sequences of dynamic inequalities are persisted for the information function throughout the long-term experiment, both the tomato plants and the wheat plants. Sequence of inequalities does not depend on the mineral substrate that we used (Figure 6), although the relative content of chemical elements in plant tissues may differ significantly from one vegetation period to other vegetation period due to changes in trophic conditions of root medium[24].

We can assumed that the existence of differentiated sequence for the information function is a quantitative measure of the vital level reflection of diversity and information content of chemical elements in different tissues of plant. Figure 6 shows that the information content of the collective state of the chemical elements in plant roots is the maximum, and the same time in fruits of tomato and in grains of wheat is minimal. The content of information in the leaves, stems and reproductive organs is reduced visibly as the number of vegetation periods increases. Furthermore, the heterogeneity of the relative content of elements in the reproductive organs have maximal value and minimal value of heterogeneity in the roots that is most chaotic. When the values of p_i minimally different from each other, then this corresponds to maximizing of the information function H. That is, it corresponds to an increase of disorder or increase of the structural homogeneity (over gravimetric composition of ash) the multicomponent system. Until the twelfth vegetation period the dynamics of structuring of the chemical elements composition of leaves, stems and reproductive organs does not change its direction. We performed a crop rotation in the twelfth growing season. After crop rotation the dynamics of the information function changes its direction (Figure 6). At what, long-term operation of the mineral substrate (up to twelfth vegetation) increases the heterogeneity of the elemental content in plant organs (leaves, stems, reproductive organs). At the same time, the structural heterogeneity of the gravimetric composition of chemical elements of the roots is decreased from previous vegetation period up to the next vegetation period. Thus, the gravimetric composition of chemical elements of plant tissues in the roots, leaves, stems, fruits and grains, we can determine how corresponding to different levels of their structural organization, which does not depend on the choice of mineral substrate and botanical plant species. As statistical analysis has shown, the effect of acid-base regeneration does not lead to statistically significant distinction between the values of H for different variants of experiences. Table 3 shows the values of the information function for all variants of the experiment. We obtained these values after averaging over the entire observation time. We have added in this table also the results of an independent experiment by growing of cucumber plants (variety Gribovskyi-2) during one vegetation period on the mineral and organic substrates. Here we present also the results that were obtained by the cultivation of tomato on a porous polyethylene film under regulated conditions[25]. Sequence of inequalities for the information function remains valid in these experiments: H(root) > H(leaf) > H(stem) > H(fruit) *nat*.

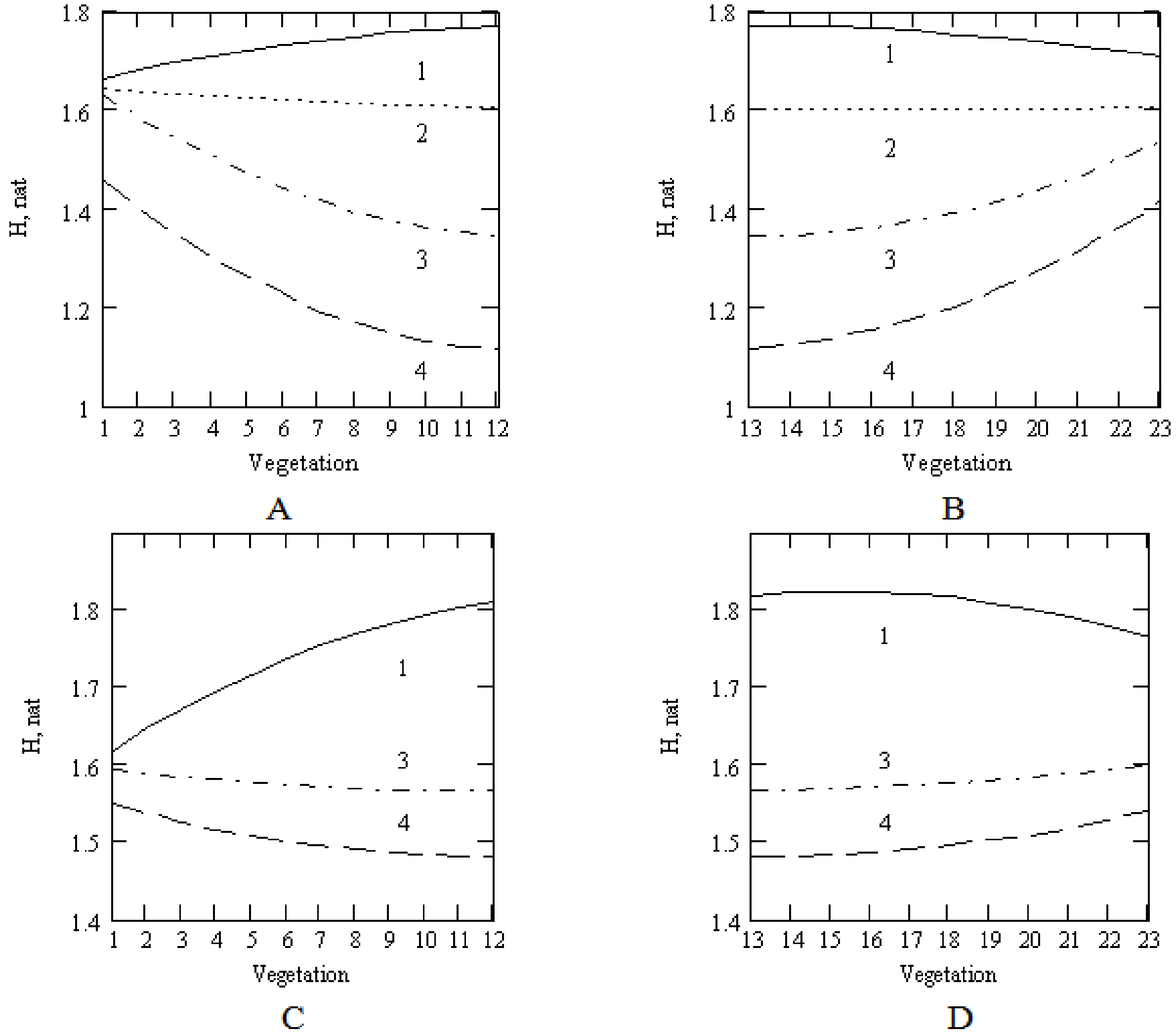


Figure 6. (A-D). Comparative dynamics (trend) of information function $H(t)$ of the mineral composition for the tissues of roots, fruits (grain), stems and leaves. (A) and (B) – tomato grown on granite rubble (check experiment); **(**C) and (D) – wheat grown on granite rubble (test experiment). Content of chemical elements in the leaves of wheat we have not explored. —— roots (1), · · · leaves (2), – · – · – stems (3), — — reproductive organs (fruits, grains) (4).

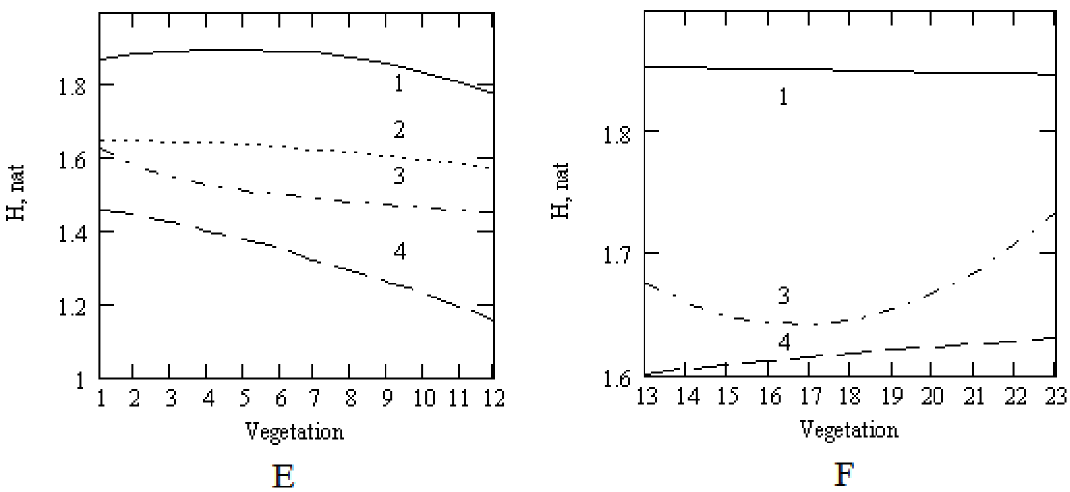


Figure 6. (E, F). Comparative dynamics (trend) of information function $H(t)$ of the mineral composition of the tissues of roots, fruits (grain), stems and leaves. (E) – tomatoes were grown on the original zeolite until twelve vegetation period; (F) – wheat grown after tomato on zeolite until twenty third vegetation period. We have not investigated the content of chemical elements in the leaves of wheat. —— roots (1), · · · leaves (2), – · – · – stems (3), — — reproductive organs (fruits, grains) (4).

Table 3. Summary table of mean values of the information function (in units *nat*).

Variant	Roots	Leafs	Stems	Fruits, grains
Tomato. Granite rubble				
1	1.74±0.02	1.63±0.02	1.50±0.05	1.32±0.06
2	1.71±0.03	1.62±0.02	1.50±0.04	1.34±0.03
3	1.72±0.02	1.61±0.01	1.49±0.05	1.28±0.06
Wheat Granite rubble				
4	1.73±0.04	-	1.58±0.05	1.53±0.03
5	1.75±0.04	-	1.54±0.05	1.51±0.03
6	1.70±0.04	-	1.56±0.05	1.51±0.02
Tomato. Zeolite				
Check experiment	1.87±0.07	1.60±0.02	1.52±0.05	1.32±0.04
Cucumber				
Organic substrate - peat, sawdust, straw	1.67±0.04	-	-	1.29±0.03
Granite rubble	1.88±0.03	-	-	1.37±0.03
Regenerated granite rubble	1.94±0.03	-	-	1.29±0.03
Tomato. Substrate – porous polyethylene film				
Experience – 1[*)]	1.69±0.04	1.49±0.03	1.46±0.03	1.18±0.02
Experience – 2[**)]	1.39±0.03	-	-	1.15±0.02
Check experiment	1.50±0.03	1.48±0.03	1.48±0.03	1.10±0.02

[*)] In nutrient solution added 80 mg/l metasilicate. [**)] In nutrient solution added 10 mL /L ADPP (aerobic decomposition products of plants).

The originality of the multicomponent chemical composition of plants become apparent also when we compare of the starting chemical composition of the mineral substrate with the substrate transformed as a result of prolonged use. Absorption of the mineral elements by plants occurs in another proportions than these elements are in the starting mineral substrates. From our experiment evident that the plants are not only able to control their collective composition of chemical elements, but the plants through the root system of goal-seeking exert influence upon mineral substrate and transform its chemical composition. For example, the surface layers of particles of crushed granite depleted by oxides Al_2O_3, MgO, K_2O and enriched in silica. Values of the information function (conditions – check experiment, tomato) for mineral substrate are follow: for the chemical composition of the of the initial granite rubble (we denote this state as 1); for the chemical composition of wash-out surface rubble after fifteen vegetation periods (we denote this state as 2); for the chemical composition of organic-mineral film on the surface of the granite crushed stone (we denote this state as 3); after twenty third vegetation periods, for the chemical composition of wash-out surface granite crushed stone after twenty third vegetation periods (we denote this state as 4); for the chemical composition of the surface of melkozem after twenty third vegetation periods (we denote this state as 5). The sequence of inequalities will be following: H(roots) = 1.72 > H_5 = 1.51 > H_4 = 1.44 > H_3 = 1.41 > H_2 = 1.18 > H_1 = 0.93 *nat*. In calculating the sequence of functions H_1, H_2, ..., H_5, we used the same set of chemical elements which were used in the analysis of the plant tissues. From this sequence of inequalities implies that the longer is exploited the mineral substrate then the more substrate become transformed. Not far from the roots the structuredness of the transformed mineral substrate very close the structuredness of the chemical elements in the root system of plants. The similar sequence of inequalities have place for wheat plants.

This result confirms the conclusion of V.I.Vernadsky[1] concerning the active geochemical role of the vital activity of plants in primary soil formation. Under the influence of the plant root system, as well as formed organic matter and the biotic community the evolution of chemical content of the mineral substrate is realized in the direction from structured chemical composition (relative content of elements) of mineral substrate to more chaotic state.

5. Conclusion

We got new factual data on the dynamics of accumulation and the interrelationships of chemical elements in the tissues of various organs of tomato plants and spring wheat under the conditions of long-term exploitation of plants on initially inert mineral substrate. Practically the experiment simulates the evolutionary processes of primary soil formation in the nature. The observed synergistic and antagonistic associations (qualitative interrelation) of the chemical elements in the various organs of plants apparently are defined by genetic properties of the plant, whereas the quantitative dynamic dependence conditioned by geochemical environment of root system.

At the same time the verification influence of the control factor showed that the content of organic matter in the root inhabited medium, as a possible source of plant nutrition, has no statistically significant effect both at elemental composition of plant tissues and the interrelation between the chemical elements. Performed studies reflect a number of important features of the interaction of plants with inert mineral matter and allow us to obtain non-trivial patterns that are associated with the deterministic dynamics of chemical elements in plant tissues. The results of this work demonstrate that in the process of intensive exploitation of mineral substrates various plant organs of wheat and tomato saturated of the chemical elements in such a way that the information content about their collective states definitely are differing for different organs of plants. This differentiation is not only maintained throughout the experiment, but with increasing number of vegetation periods differentiation increases (until 12th vegetation period). After crop rotation of grown plants the dynamic process changes direction.

Content of the chemical elements in plant tissues varies in a complicated manner. For example, the dynamics of synergism of the chemical elements in some organs may be contrasted the antagonism in other organs and leads to a statistically significant quantitative changes in the content of interrelated chemical elements in plant. Nevertheless, the cumulative state of the chemical elements in the tissues of various organs subordinates of the deterministic sequence of inequalities that persist under conditions of evolutionary transformation of mineral substrates and do not depend on the choice of the mineral substrate.

Such studies are of practical importance, aimed at sustainable land use and development of techniques for a balanced mineral nutrition of plants. These studies offer the prospect of purposeful formation of elemental chemical content in plants for environmental safety and high quality of agricultural products with optimal elemental composition, which is important in terms of man-caused pollution and intensive chemicalixation used in agriculture.

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