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Interrelation of Chemical Elements Content in Plants under Conditions of Primary Soil Formation

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It is presented the results of a long-term and intensive experiment, which models the processes of primary soil formation under controlled agro-ecosystems. The influence of mineral substrate transformation is analyzed on the content of chemical elements in plants tomato, and wheat. For the first time have been established dynamic synergistic and antagonistic interrelations between the chemical elements in a various bodies of the plant (roots, reproductive bodies, stems, and leaves). Using methods of the theory of information was revealed dynamics of collective state of chemical elements in the plants. It is shown that the collective states of the chemical elements which defined by the information function is strictly differentiated for different plant bodies, and have hierarchic order. We analyzed the following chemical elements *Si*, *Al*, *Fe*, *Mg*, *Ca*, *K*, *P*, *S*, *Cl*, *Na*, *Mn*, *Zn*.

Keywords: Chemical Elements, Dynamics, Synergism, Antagonism, Information Function, Hierarchic Order, Soil Formation, Mineral Substratum

Introduction

The problem of accumulation of chemical elements and their relationships to each other in plants has been paid much attention. A series of fundamental studies (Vernadskii, 1922; Polynov, 1956; Aristovskaya, 1980) dealt with the problem of the close association between the chemical elements composition of plants and the soils. In this paper first analyzes the dynamics of chemical elements in plants under conditions of intense transformation of the root-inhabited media.

It is performed a complex experiment accordance to an intensive and prolonged cultivation of plants of spring wheat and tomato on the granular mineral substrate (granite crushed rock and zeolite). The experiment demonstrated that the controlled agroecosystem is an intensive biogenic and physicochemical weathering of minerals and the formation of soil like bodies. Such processes involving root systems of plants simulate evolutionary processes of the first stages of soil formation under natural conditions. The most important consequence of this is increased activity of multiple biochemical processes of exogenous transforming rocks into soil-like bodies. These processes are accompanied by accumulation of organic matter in the root-inhabited media (RM), a change in its fractional composition, specific and numerical composition of the microbiota community (Ermakov et al., 2001; Ermakov et al., 2007). These processes occur simultaneously and in close synchronous interaction. Controlled agro-ecosystems can significantly accelerate the natural processes of soil-forming bodies. When evolutionary pedogenesis is undergoing profound changes in the conditions of weathering of mineral substrate. They are accompanied by changes in the mineral composition of soil solution and mineralization of organic matter of the root-inhabited media. This, in turn, leads to variations of chemical elements in plant tissues.

As is known, the chemical elemental composition of plants differs significantly from the composition of rocks. This causes the plants to look for ways to self-sufficiency of chemical elements and to adapt to the peculiarities of geochemical environment. This adaptation is reflected in the existence of links in the content of chemical elements in plants, that is, leads to synergism or antagonism. These interactions are due to the ability of a chemical element to inhibit or stimulate the absorption of other elements by plants. This problem is of interest both from theoretical and practical points of view. Identification of dynamic relationships allow the development the methods of elemental composition regulation for agricultural production in high farming.

Materials and Methods

Tomato plants (cultivar Ottawa-60) and spring wheat (cultivar Siete Ceros) were grown on the granite rubble for 23 vegetations under controlled conditions. In addition, we cultivated tomato (for 12 vegetations) and spring wheat on the zeolite for 11 vegetations. First tomato plants were grown from 1 to 12 of vegetations. After cultivation of tomato we were cultivated spring wheat from 13 to 23 vegetations. It was found that the intensive exploitation of mineral substrate leads to the accumulation of organic matter. Organic matter contains in its composition of physiologically active compounds, which can inhibit plant growth, as well as reduce the activity of rhizosphere microflora. In the experiment method of acid-base regeneration of mineral substrate (two versions) was used. Acid-base regeneration can effectively remove some organic matter components and thereby improve the trophic conditions of plant growth (Ermakov et al., 1987). Experience on the granite ruble was carried out for three variants: the test experiment and subject to the controlling factor (the acid-base mineral substrate for regeneration of the two variants). For the zeolite, we performed only test experiment.

In the scheme of experiment we included the following variants: variant 1 (tomato) and variant 4 (wheat). In these experiments, after each growing season, we removed the roots of plants, compost mineral substrate for 20 - 30 days, and then perform a complex acid-base working (regeneration 1). Complex acid-base regeneration is 0.01 n H_2SO_4 acid treatment of mineral substrate. Then, a water rinse of the substrate and processing of mineral alkali KOH of concentration of 0.05 n. In variants 2 (tomato) and 5 (wheat) additionally performed an acid-base treatment of mineral substrate, with the roots of growing plants: the flowering phase and the phase of fruit set (regeneration 2). Test experiments were 3 (tomato) and 6 (wheat). In these variants, we performed only cleaning and composting roots mineral substrate.

In the experiment were used luminaries based on DNaT-4 sodium lamps with a solid-state heat-absorbing colour filter. The intensity of the radiation stream corresponded to 100 ± 10 W/m^2 in the photosynthetically active radiation region. The photoperiod was 16 h/day with growth length of 75 days. Analysis of the elemental composition of plant ash after each growing season we made using X-ray fluorescent analyzer A-30. Studies have included investigations into the ash composition and the percentage of plant tissues (roots, stems, leaves, fruits and grains) of the chemical elements *Si, Al, Fe, Mg, Ca, K, P, S, Cl, Na, Mn, Zn* after each vegetation.

Results and Discussion

Experimental data were obtained for the chemical elements composition of plant tissues which for the first time have allowed to analyze quantitatively the dynamics of the chemical elements interrelation in various of plants organs under conditions of an evolutionary primary soil formation. It was found that the relationship between the chemical elements can be accompanied by a change of direction relations in the opposite direction to those elements, but in other parts of plants.

Let's show it, on an instance of interrelation dynamics of the silicon content and the potassium content in the roots and reproductive bodies of plants. It is known, that the potassium is most consumables by plants and its role in plants is multifunctional. In recent years significantly increased interest (Samsonova, 2005) in the role of silicon in plant life as a factor in boosting crop yields. This chemical element has an impact stimulating influence on development of the root system, leaves area, growth rate of plants, their dry weight. However, in the scientific literature practically there is no information on interrelation of silicon content (percent to ash) with other elements in plants. We established that in the plants root tomato and spring wheat the interrelation of the elements *Si* and *K* is antagonistic for 23 vegetations (Figure 1(a)). At the same time for reproductive bodies this interrelation is synergetic (Figure 1(b)). Cultivation of a tomato on zeolite keeps qualitatively these interrelations, but results in appreciable quantitative difference in comparison with the results that obtained at cultivation of plants on the crushed granite. The use of zeolite synergistic relationship intensifies. (an angle of slope of the trend line is more (Figure 1(b)), than for granite).

There is little information about the relationship of chemical elements manganese and magnesium, both among themselves and with other elements in plants. No experimental data on the dynamics of their content in different plant bodies. The interrelations of chemical elements *Mn* and *Mg* in roots and reproductive bodies of a tomato for all variants of experience are presented in Figure 2. For these elements the dynamics of antagonism is kept during all experience for roots, and reproductive bodies of the plants.

As statistical analysis has shown the influence of the complex acid-base regeneration of mineral substrate on interrelation of the elements *Mn* and *Mg* is insignificant. Indeed, for example, a comparison of variances S_2^2 and S_3^2 by Fisher test for variants 2 and 3 leads to a much smaller critical values: $F = (S_2/S_3)^2 = 1.06 < F^{cr}_{12,12;0.95} = 2.7$. Hence, the action of complex regeneration is not effective. This conclusion is valid for all paired interactions between the chemical elements. We found that the difference between variants 1, 2 and 3 is statistically insignificant (the similar conclusion would hold for spring wheat). At the same time the cultivation of tomato on the zeolite leads to a statistically significant difference from the results of crushed granite. However, it may be noted that the slope of the trend lines for zeolite and crushed granite about the same.

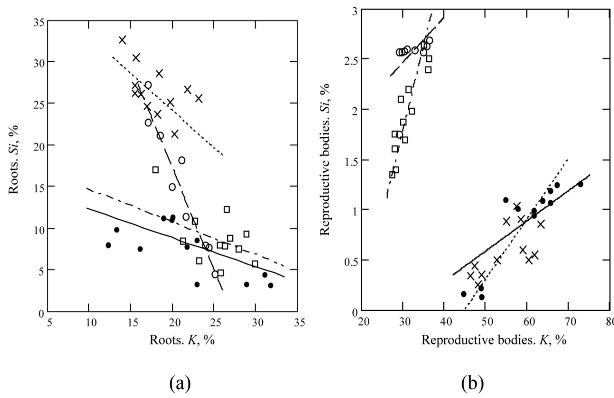


Figure 1.
Antagonism of potassium and silicon contents in root tissues (a) and synergism these elements in tissues of the reproductive bodies (b) of tomato. Crushed granite: ● - tomato; test experiment; trend ——; □ - spring wheat; test experiment; trend – · –. Zeolite: × -tomato; trend · · · ·. o -pring wheat; trend – – – . Here and below: for crushed granite experimental data are resulted only for odd growth periods; zeolite present experimental data for life cycles from first to twelfth.

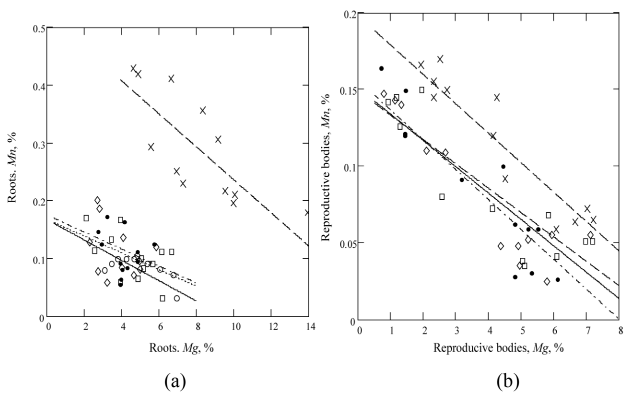


Figure 2.
Antagonism of magnesium and manganese content in root tissues (a) and reproductive bodies (b) of the tomato. Crushed granite: ● - test experiment, trend —— ; ◊ - variant 1, trend – · – ·; □ - variant 2, trend · · ·. Zeolite: × - tomato, trend — — —.

In contrast to roots and reproductive organs of plants, we found synergism of manganese and magnesium in the stems and leaves. Also there are changes in the direction of the dynamic interactions silicon and potassium. In the roots of plants, this relationship is antagonistic. At the same time, relationship for fruits and grains is synergistic between silicon and potassium (Figure 1). This result does not confirm opinion that chemical elements *Mg, Ca*, and *P* are principal antagonistic elements with respect to absorption of many other chemical elements.

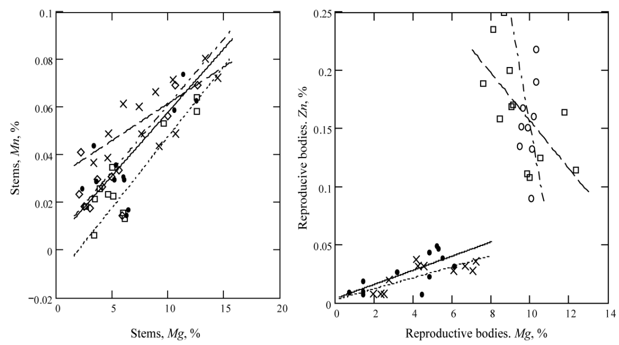
Methods of regeneration of the mineral substrate have little effect on the dynamics of synergism and antagonism of the chemical elements.

It was found that the relationships between the chemical elements might have specific difference. We have analyzed the dynamic synergistic and antagonistic relationships of among all the chemical elements. Table 1 summarizes the relationships of chemical elements in different bodies of tomato and wheat plants. In most cases, these relationships are the same. However, for some pairs of chemical elements there are species differences. Let's show it on an example of interrelation of zinc and magnesium in fruits of a tomato and wheat grain. Figure 3(b) shows that the content of magnesium in the tomato fruit has a synergetic relationship, whereas for the grain of wheat that interrelation is antagonistic. We found similar species differences for some of the other chemical elements, for example, phosphorus, and potassium (Table 1). For tomato fruit the interrelation is a synergetic, whereas for the grain of wheat the interrelation is antagonistic. At the same time, the relationship of these elements in plant stems changes direction. For tomato relationship is antagonistic, and for wheat relationship is synergetic. The nature of these specific distinctions remains the same for all variants, does not depend on the mineral substrate, control factor (that is regeneration) and of the temporary factor, i.e. the number of vegetation.

Table 1 includes the relationships between matched chemical elements only in the same plant bodies. However, the experimental data allow us to establish the dynamic relationships between the chemical elements in different plant bodies. First of all, between the roots and reproductive bodies. Identifying these relationships makes it possible to control the chemical composition of the reproductive bodies. It is important for obtaining high-quality vegetable production. Figure 4(a) shows an antagonistic relationship between the content of magnesium in the reproductive bodies of plants and silicon content in the roots. Increase of the silicon content in the roots of plants leads to the decrease of magnesium content in the reproductive bodies. It is possible to note, that for crushed granite the range changing of the silicon content in roots of spring wheat and a tomato is in the same interval of values approximately. For the tomato cultivated on zeolite the saturation of reproductive bodies by magnesium is descended at the greater in comparison with silicon content in the roots for crushed granite. Practically silicon in plant roots for all chemical elements is the antagonist to chemical elements in reproductive bodies, except for manganese (Figure 4(b)). This relationship does not change over the entire observation period, does not depend on the mineral substrate and the botanical plant species. It may be noted that for granite rubble the range of change of silicon content in the roots of wheat and tomato is located approximately in the same range of values. For zeolite this range differs markedly and magnesium saturation of reproductive organs occurs at the higher silicon content in the roots.

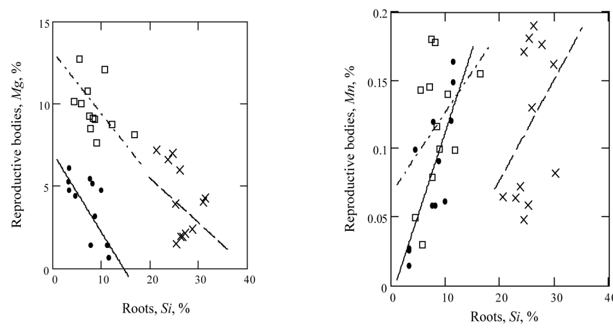
As results of experiment have shown the same chemical element may have the characteristics of synergetics and the antagonist. Figure 5 shows the dynamic relationship between the content of phosphorus in the roots of plants and content of manganese and calcium in the reproductive bodies. Phosphorus is antagonistic to the content of manganese in tomato fruits and grain of wheat. At the same time increasing the phosphorus content in the roots increases the calcium content in fruits of tomato and wheat grain. The potassium contents in the tomato fruits three times is more, than in roots of the plant. The contents of silicon in the roots of plants are ten times more, than in reproductive bodies. These relationships do not depend on the type of mineral substrate, the botanical species of plants, method of regeneration and number of vegetation.

Using statistical methods, we were able to group chemical elements according to their content in various plant bodies of four homogeneous nonoverlapping groups (Mukhomorov et al., 2009). According to an analysis of the groups composition



(a) (b)

Figure 3.
(a) Synergism of the magnesium and manganese content in tissues of the tomato stems. Crushed granite: ● - test experiment, trend —— ; ◊ - variant 1, trend – · – ·; □ - variant 2, trend - - - - -. Zeolite : × - tomato, trend — — — . (b) Interrelation of zinc and magnesium content in tissues of reproductive bodies of the tomato and spring wheat. Crushed granite: ● - tomato, test experiment, trend ——, □ - spring wheat, test experiment, trend — — — . Zeolite: × - tomato, trend · · · ·. o – spring wheat, trend – · – · – ·.



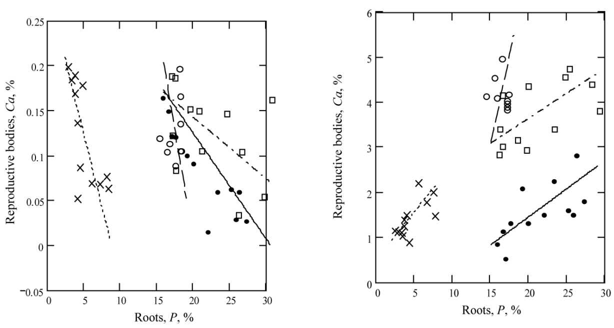
(a) (b)

Figure 4.
(a) Antagonism of silicon and magnesium contents in tissues of the reproductive bodies and roots. Cruched granite: ● - tomato, test experiment; trend —— ; □ – spring wheat, test experiment; trend – · – ·. Zeolite: × - tomato, trend – –. (b) Synergism of silicon and manganese contents in tissues of reproductive bodies and roots. Crushed granite. ● - tomato, test experiment; trend —— ; □ - spring wheat, test experiment; trend – · – ·. Zeolite: × - tomato, trend — — —.

Table 1.
Synergism and antagonism of chemical elements in plant tissues of a tomato (the first column) and spring wheat (the second column). The first line-roots, the second line-reproductive bodies, the third line-leaves, the fourth line-stems). For leaves of spring wheat the experiment was not carried out.*

	Ca		*Mg*		*S*		*P*		*Cl*		*K*		*Na*		*Mn*		*Zn*		*Fe*		*Si*	
Mg	- + + ×	- - +																				
S	- + × -	- + -	- + - +	+ + -																		
P	- + - -	- - +	+ + × +	- - +	× × - +	× - +																
Cl	× + - ×	+ - ×	× + + ×	+ × ×	× + - ×	+ - -	× + × -	- + -														
K	- - - ×	- + -	× - × -	- - -	+ - - -	- - +	× - × -	- - -	- - + -	- - -												
Na	+ × + +	× × +	+ - × -	+ - +	- + + -	- - -	× - - -	× × +	+ - - -	+ + -	- + - ×	- + -										
Mn	+ - + ×	+ - +	- - + +	- - +	× - - +	- - -	- - + ×	× + ×	- × + +	- + +	× + × -	× - -	- × - -	- × +								
Zn	× + × ×	+ × +	× + + +	× - ×	× + - +	- × ×	× + + +	+ - -	- × + -	- × ×	× - + -	- × -	- × - ×	× × ×	+ - + +	+ × +						
Fe	+ - - -	+ + +	+ - + ×	+ + -	- - - +	- + -	× - + +	- + -	+ - + -	+ - -	- + + ×	× × ×	+ × - ×	- - +	× + + -	+ - ×	- - + +	× - +				
Si	+ × × -	+ × +	- - + +	- - ×	× - - +	- - -	- - + +	- - +	× × × -	× + -	- + - ×	- + -	× + + +	- × +	+ × + ×	+ × ×	+ = + +	- - +	+ + × +	+ + +		
Al	+ + + -	+ + +	+ × + +	+ + -	- + - +	- + -	× - × ×	- - -	+ - × +	+ - +	- × - ×	- × ×	+ + × -	- × +	× - + ×	+ - ×	× × + -	× - +	+ + - +	+ + +	+ + + ×	+ + ×

*) -antagonism of chemical elements; + synergism of chemical elements; × the interrelation is not found.



(a) (b)

Figure 5.
(a) Antagonism of manganese and phosphorus contents in tissues of the reproductive bodies and roots. ● - tomato, test experiment; trend —— ; □ – spring wheat, test experiment; trend – · – ·. Zeolite: × - tomato, trend · · ·. ○ – spring wheat, trend — — . (b) Synergism of calcium and phosphorus contents in tissues of reproductive bodies and roots. Crushed granite: ● - tomato, test experiment; trend ——; □ - spring wheat, test experiment; trend – · – ·. Zeolite: × - tomato, trend · · ·. ○ – spring wheat, trend — —.

doesn't depend on the number of life cycles and the experiment variant. It is established (Ermakov et al., 2006) that between the chemical element contents in different parts of plants has a cause-and-effect correlated relationships. Therefore, it is important to know the collective state of the chemical elements in various plant tissues. Balance and harmonicity of chemical elements collective state in plants is the main condition for their normal growth and development. V. I. Vernadsky (1922) have repeatedly drawn attention to the unknown role of specific ratios of chemical elements in living matter. The study of biogeocenoses always been of considerable scientific interest. Currently these studies have gained great practical importance in connection with the ecological problems of the environment. An important direction of solution of this problem is the search of values (or descriptors) that characterize the multicomponent system as a whole.

In this work we fulfilled the analysis of the dynamics of collective (common) state of chemical elements using the methods of an information theory. An integral index of the collective state of multicomponent systems and, in particular, of chemical elements composition of plants tissues is the information function (entropy). Information approach has been used repeatedly in ecology as a measure of diversity of multicomponent ecological communities (Mc Arthur, 1955; Lurie, 1983). Information function H of a finite ensemble of heterogenous objects belonging to one set can be written in the following form: $H(t) = -\sum_{i=1}^{n} p_i \ln p_i$. This function characterizes the degree of structuredness or organizations of the relative content of n elements of the set under the additional conditions: $0 \le p_i(t) \le 1$, $\sum_{i=1}^{n} p_i(t) = 1$; p_i is the number of realizing ith event. Here we used the combinatorial approach of A. N. Kolmogorov (1987). $t = 1, 2, \cdots, 23$ are the number of the vegetations (growth periods). The values of p_i are determined by the results of the experiment to study of the ash chemical elements composition. Such realization of the method is similar to B. B. Polynov's (1956) approach that determines the contents of weight parts of chemical elements of ashes. The information approach allows us to obtain a holistic view on the evolutionary phenomena on the basis of knowledge about the structure of correlated multi-component systems. Quantitative characteristics of the measures of the multi-component systems are conditional and unconditional information functions. Methods of information theory allow us to obtain new non-trivial knowledge about the dynamics of inter-related multi-component systems.

Information function is an integral indicator of a dynamical multi-component system. This function describes a structure, diversity and the information content of the system. It is found statistically significant sequence information functions for different plant bodies. For example, for tomato (mineral substrate-granite crushed stone) averaged over all variants the sequence of information functions the following: H(roots) = 1.72 > H(leaves) = 1.62 > H(stems) = 1.50 > H(reproductive bodies) = 1.31 *nat*. It is important to emphasize that a deterministic non-random sequence of inequalities is preserved for the long- term experiment for tomato and wheat. The sequence of inequalities does not depend on the type of mineral substrate (Figure 5) and the number of vegetation, although the content of elements in plants can significantly change due to changes in the trophic conditions (Mukhomorov, Anikina, 2009). We have restricted only eleven vegetations. This makes it possible to compare the results of an experiment for granite crushed rock and zeolite. Figure 5 shows that the information content in the roots is most, and in the reproductive organs it is minimal. Heterogeneity of the chemical element contents in the reproductive organs is maximal, and at the roots is minimal. If p_i is minimally differ from each other, then it leads to an increase in the informative function. That is, it leads to an increase in disorder and structural homogeneity. The long-term exploitation of mineral substrate leads to an increase in the differences in the heterogeneity of the element content in the bodies of plants. At the same time the structural heterogeneity of the roots is reduced. Structural instability of the elemental composition of leaves, stems and reproductive organs is directed towards the increase of structuredness or structural heterogeneity (Figure 5). In this case, the values of probabilities (p_i) at the most differ from each other. Thus the elemental chemical composition of the roots, leaves, stems, fruits and grains correspond to different levels of structural organization. This structural organization does not depend on the type of mineral substrate, number of vegetation, botanical plant species and method of the regenera-

Table 2.
Information functions (in nat) for bodies of plant. Experiments 1- 6 are situated in accordance with reduction of a formed organic matter.

	Tomato. Crushed granite			
Variant	*Roots*	*Leaves*	*Stems*	*Reproductive bodies*
3	1.72 ± 0.02	1.61 ± 0.01	1.49 ± 0.05	1.28 ± 0.06
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
	Spring wheat. Crushed granite			
6	1.70 ± 0.04	-	1.56 ± 0.05	1.51 ± 0.02
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
	Tomato. Zeolite			
Test experiment	1.87±0.07	1.60 ± 0.02	1.52 ± 0.05	1.32 ± 0.04
	Spring wheat. Zeolite			
Test experiment	1.87 ± 0.03	-	1.66 ± 0.05	1.52 ± 0.04
Cucumber				
Organic RM	1.67 ± 0.04	-	-	1.29 ± 0.03
Granite crushed rock	1.88 ± 0.03	-	-	1.37 ± 0.03
Regenerated crushed granite	1.94 ± 0.03	-	-	1.29 ± 0.03
	Tomato. RM is polyethylene film			
Experience*)	1.69 ± 0.04	1.49 ± 0.03	1.46 ± 0.03	1.18 ± 0.02
Test experiment	1.50 ± 0.03	1.48 ± 0.03	1.48 ± 0.03	1.10 ± 0.02

*) In a nutrient solution are added 80 mg/L of metasilicate.

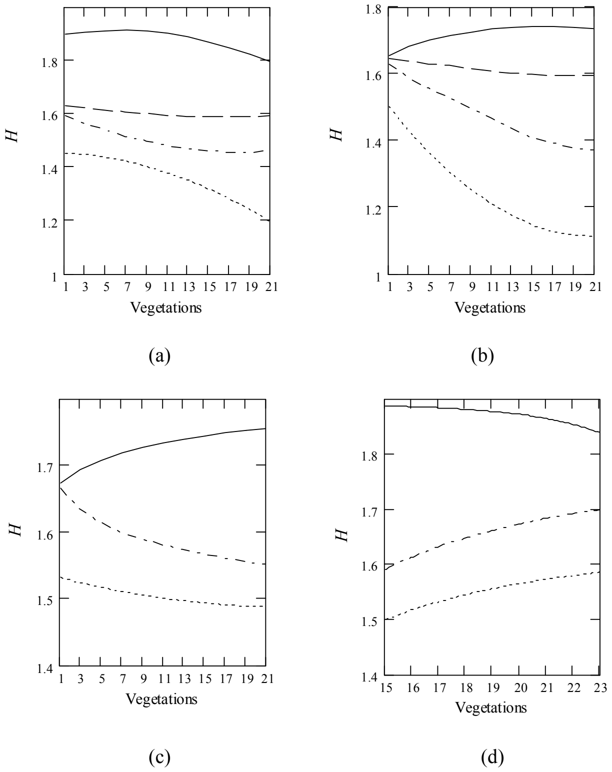


Figure 6.
The dynamics (trend) of information function H of chemical elements composition in tomato roots, reproductive bodies, stems, and leaves tissues during 11 growth periods: (a) for the tomato cultivated on zeolite, (b) for the tomato cultivated on crushed granite, (c) for spring wheat cultivated on crushed granite. Variant – test experiment. (d) for spring wheat cultivated on zeolite. Variant – test experiment. —— roots, · · · reproductive bodies, – – – leaves, — · — stems.

tion. Table 2 shows the values of the information function averaged over all the observations. In this table were added results of an experiment on the cultivation of cucumber plants. In addition to Table 2 shows the results for the cultivation of tomato plants on plastic film under controlled conditions. The sequence of inequalities for the informative function keeps in these cases.

Peculiarities of the chemical composition of plants is shown at its comparison with the chemical composition of mineral substrate after intensive operation. From the experiment should be, that the plants do not only control their own elemental content, but using the root system of influence on mineral substrate, transforming it. For example, for tomato (test experiment; granite crushed rock) values of information functions have the following sequence: H(roots) = 1.72 > H(5) =1.51 > H(4) = 1.44 > H(3) = 1.42 > H(2) = 1.18 > H(1) = .93 nat, here 1 is the chemical composition of the initial granite crushed rock, 2 is the chemical composition wash-out with the surface of granite crushed rock 15 vegetations, 3 is the chemical composition of organomineral film on the surface of the rubble after 23 vegetations, 4 is the chemical composition wash-out with the surface rubble after 23 vegetations, 5 is the chemical composition of the surface of the melkozem after 23 vegetations. This sequence of inequalities indicates that under the intense action of the root system of plants and organic matter mineral substrate is transformed. This result confirms the conclusion V.I. Vernadsky (1922) about the active geochemical role of plant vital functions.

The evolution of elemental content of mineral substrate, the available plants are shown from structured status to the chaotic state.

Conclusion

The extensive experimental material on dynamics of localization and interrelation of chemical elements in various bodies of plants under conditions of primary soil formation is obtained. The executed researches reflect a number of important features of interaction of plants and inert mineral substrates. The results of this work show that various plants bodies in different ways with the chemical elements under conditions of a long and intensive exploitation of mineral substrates. The content of chemical elements in plants varies in a complicated way. For example, the dynamics of synergism of chemical elements in the same organs of plants can be contrasted dynamics of antagonism in other organs of plants. At the same time, the collective states of chemical elements in the various plants bodies are subject to strict rule, which does not change under conditions of mineral substrates transformation. Such research has a practical value, aimed at rational use of the land and balanced mineral nutrition of plants. These studies promise a purposeful change of elemental chemical content in the plants, as well as the production of high-quality agricultural products. This is important in conditions of man-caused pollution of the environment and intensive chemicalization of agriculture.

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