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THE RADIOCAPACITY FACTOR USING IN THE STUDYING OF THE COMBINED EFFECT OF γ-RADIATION AND CADMIUM CHLORIDE ON WATER PLANT CULTURE

Objective. To show the possibility of a new approach using for the evaluation of biota's state in the ecosystem under the independent and combined effect of radiation and chemical factors. It is based on a radiocapacity factor analysis, defined as the maximum radionuclide quantity accumulated in biotic components of ecosystem that does not disturb major biota's functions.

Materials and methods. Experiments were performed in the laboratory, where water culture of maize plants served as a simplified two-component model of ecological system as a "biota-environment" type. Plants were exposed to independent and combined effects of acute and fractionated γ-irradiation and $CdCl_2$ salt application. The assessment of state of the biotic component i.e. the maize plants was performed by the growth parameters and changes of radiocapacity factors. The radiocapacity factor was defined as the ratio of current activity in water (medium) by the specifically inserted tracer – ^{137}Cs to the initial value.

Results and conclusions. According to our experimental data, the proposed parameter for the assessment of biotic components of the system state – the radiocapacity factor, proved to be very sensitive to influence of both radiation and chemical factors on the biota. Its response is corrected with the reaction of growth parameters and has been advanced compared to them. Therefore, it is appropriate to consider the possibility of radiocapacity factor using for the assessment of plants state under the harmful influences. In addition, based on the theory of radiocapacity, a model for the assessment of combined action of radiation (γ-exposure) and chemical factors (cadmium chloride) on the model of plant system has been developed and proposed. Thus, through the assessing the value of the proposed characteristics of interaction i.e. the synergism index we got an opportunity to draw the conclusions about the character of interaction of radiation and chemical factors that varies from synergy to antagonism.

Key words: radiocapacity, γ-irradiation, cadmium chloride, synergetic interaction.

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Використання фактору радіоємності у вивченні комбінованої дії γ-опромінення та хлориду кадмію на водну культуру рослин

Мета роботи. Показати можливість використання нового підходу до оцінки стану біоти в екосистемі в умовах незалежної та комбінованої дії радіаційного та хімічного факторів. Він заснований на аналізі фактору радіоємності, який визначається як максимальна кількість радіонуклідів, що накопичується в біотичних компонентах екосистеми, яка не порушує основних функцій біоти.

Матеріали та методи. Експерименти проводились в лабораторних умовах, де водна культура рослин кукурудзи слугувала в якості максимально спрощеної моделі двохкомпонентної екологічної системи типу "біота-середовище". Рослини піддавалися незалежному та комбінованому впливу гострого та фракціонованого γ-опромінення та внесення солі $CdCl_2$. Оцінка стану біотичного компонента системи – рослин кукурудзи проводилась за зміною ростових показників та фактору радіоємності. Останній визначали як відношення поточної активності у воді (середовищі) по спеціально внесеному трасеру – ^{137}Cs, до початкової.

Результати та висновки. Згідно з отриманими експериментальними даними, запропонований параметр для оцінки стану біотичного компонента системи – фактор радіоємності, виявився дуже чутливим до дії як радіаційного так і хімічного чинників на біоту. Його реакція корегувала з реакцією ростових показників і була випереджувальною в порівнянні з ними. Тому доречно говорити про можливість використання фактору радіоємності для оцінки стану рослин в умовах шкідливих впливів. Крім того, на основі теорії радіоємності, було розроблено та запропоновано модель оцінки комбінованої дії радіаційного (γ-опромінення) та хімічного (хлорид кадмію) факторів на модельну рослинну систему. Таким чином, оцінюючи величину запропонованої характеристики взаємодії – коефіцієнту синергізму – ми отримали змогу зробити висновки про характер взаємодії радіаційного та хімічного факторів, який змінюється від синергізму до антагонізму і навпаки.

Ключові слова: радіоємність, γ-опромінення, хлорид кадмію, синергізм.

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INTRODUCTION

Currently up to 30 various parameters are being used to characterize a state of an ecosystem and to find out different external effects on biota. The most valuable of them proved to be the following four, namely, biodiversity, biomass, biota abundance and reproduction velocity [1]. However these parameters are known to react on the external negative permutations with significant retardation that shows up explicitly merely after the biota's state in the ecosystem has grown worse. Therefore it is tempting to find an adequate parameter for measuring a biota's welfare which would outstrip in its manifestation the biologic growth response of biota and, consequently, be of use for the biota's state express analysis.

To assess a state and quality of any ecosystem a new theoretical approach – a theory of radiocapacity is proposed that has been developed by us in the last years. The theory is based on the following experimental and theoretical facts as well as assumptions [2–4]:

1. The radiocapacity of any ecosystem is a fundamental property of the ecosystem associated with its capability to transfer radionuclides along the trophic chains as well as to capture and accumulate environmental radionuclides without any obvious consequences for the ecosystem.

2. Ecosystem's radiocapacity can be defined quantitatively as a maximum of the radionuclide amount which is possible to accumulate and retain in the ecosystem's biota without any disturbance of its main functions, notably, biota's biomass increase, preservation and conditioning of inhabitancy.

The idea about radiocapacity or, more precisely, about the radiocapacity factor was primarily introduced by Agre and Korogodin (1960) [5]. Accordingly, the radiocapacity factor was characterized as a part of a total radionuclide quantity that had penetrated into the ecosystem and is being retained in the ecosystem's components both of inert and biotic origin. A notion of the radiocapacity was expanded by us through the introduction of a few additional definitions [6–9].

Thus, radiocapacity is a fundamental property of any ecosystem circumscribing threshold quantities of radionuclides measured in Ci or Bq, which can be

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steadily held by the ecosystem's biota without further infringement or shift of its basic functions dealing with growth, biota's biomass increase and the inhabitancy conditioning.

The radiocapacity factor is a dimensionless magnitude ranging from 0 to 1 identifying a radionuclide quantity bound to biotic and abiotic components of the ecosystem. When considering the ecosystem of a lake, for example, we can assign to each component, in particular water, bottom deposits or biota of the reservoir, its own mean of the radiocapacity factor. Thereby a corresponding model was created and the following formula for the radiocapacity factor (*F*) of water reservoirs was derived [10]:

$$F = \frac{kh}{H + kh}, \quad (1)$$

where k – accumulation coefficient for "water–ground deposits", h – width of a sorbing silt layer, H – average depth of the reservoir, F – radionuclide accumulation in ground deposits. Meanwhile 1-F shows radionuclide accumulation in the water. The latter two magnitudes define radionuclide portions of the whole radionuclide amount in the ecosystem for ground deposits and water, respectively. F value was named a "radiocapacity factor" of the reservoir. A given factor doesn't depend upon radionuclide concentration in the water (C) in the wide numerical diapason that allows computing a level of water pollution in a given reservoir provided the accumulated quantities of radionuclides inside the reservoir and on its surface are known.

F value was calculated for the fresh-water lakes of Kyshtym region and Chornobyl zone using the radiotracer ^{137}Cs. These values were shown to lie within 0.6–0.9 [10, 11].

Thus, we have designed and created the models for the assessment of radiocapacity factors in different types of ecosystems, terrestrial, aqueous, forest, mountain, meadow and urban [11]. We believe that such an universal approach for the radiocapacity simulation in various ecosystem types does allow for the adequate description of different ecosystems and, consequently, their further collation.

The question about the combined actions of different external stress-agents on the ecosystem has been already discussed in the literature [12, 13]. An exclusively new model for the synergism assessment under the impact of several agents is proposed in a present paper.

Let us analyze the influence of two factors including the γ-irradiation and heavy metal salt $CdCl_2$ on the radiocapacity factor for a given simplified ecosystem. Our objective is to estimate the quantitative values for synergetic or antisynergetic effects upon action of different factors on ecosystem's biota.

Admit in control a radionuclide absorption and a radionuclide desorption by biota is proceeding with a speed a_{12} and a_{21}, respectively. Consequently, speed ratio may be designated as

$$Z_0 = \frac{a_{12}}{a_{21}}. \quad (2)$$

It is easy to suggest that under the influence of one agent, e.g. γ-irradiation, a speed of radiotracer accumulation a_{12} should change by decreasing b-fold ($b<1$) while a_{21} would shift by increasing c-fold ($c>1$), radiotracer accumulation (a_1) and efflux (a_2) speed being equal to $a_1=a_{12}\, b$ and $a_2=a_{21}c$, respectively.

Then we receive

$$Z_1 = Z_0 \frac{b}{c}, \quad (3)$$

where Z_1 – is a speed ratio for the system under the influence of γ-irradiation, while Z_0 – is a speed ratio for the control.

In order to evaluate the effect of cadmium salt we suppose the accumulation speed of radiotracers a_{12} to change d-fold (d<1). In this case a_{21} should change e-fold ($e>1$), radiotracer accumulation and efflux being respectively $a_1=a_{12}\, d$ and $a_2=a_{21}e$.

Now we get

$$Z_2 = Z_0 \frac{d}{e}, \quad (4)$$

where Z_2 – is a speed ratio for the system under the influence of a salt $CdCl_2$.

It is easy to show that simultaneous application of both factors might be described by the following equation:

$$Z_3 = Z_0 \frac{b}{c}\frac{d}{e}, \quad (5)$$

where Z_3 – is a speed ratio for the system under the simultaneous influence of γ-irradiation and salt $CdCl_2$.

Z_3 characterizes the behavior of the radiocapacity factors in conditions of whatever synergism absence when several agents are applied. In general case we receive the following proportion:

$$\frac{Z_3}{Z_0} = \frac{b}{c}\frac{d}{e} p, \quad (6)$$

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where P is a new parameter defining synergism manifestation. A coefficient of synergism P is estimated using the following equation:

$$P = \frac{Z_{Cd+\gamma}}{Z_{Cd} \cdot Z_{\gamma}} \cdot Z_0, \qquad (7)$$

where Z_0 is a ratio of radiocapacity factors for biota in control; $Z_{Cd+\gamma}$ is a ratio of radiocapacity factors for biota under combined effect of $CdCl_2$ and γ-irradiation; while Z_{Cd} and Z_{γ} - are the analogous magnitudes in the case of separate effect of CdCl2 and γ-irradiation. If $p=1$, then no synergism would be detected in the effects of different agents on the radiocapacity factors. If $p<1$, significant contribution of synergism may be assumed, the latter representing itself the enhancement of combined effect if compared to separate actions. If $p>1$, the antisinergism should take place, a phenomenon dealing with the alleviation of the negative effect from one agent by another and vice versa.

Thereby, we have developed a scheme and introduced a special parameter for the assessment of synergism manifestation in combination of different factors using a special coefficient *P*.

MATERIALS AND METHODS

In order to study a possibility of plant ecosystem radiocapacity factor utilization as a means to characterize ecosystem's state as well as to forecast its shifts under the external effect a series of experiments was designed and realized. For this purpose a simplified model of plant ecosystem, namely aqueous culture of maize plants, was chosen. Accordingly, maize seeds were placed on moistened filter paper in thermostat at 23°C to germinate. Then seeds with 3-day seedlings were irradiated in the dose of 15 Gy by ^{60}Co in γ-device "Issledovatel" (Russia) and thereafter displaced on the top of 0.5-liter glass jars, the latter containing tap water along with ^{137}Cs. The initial radioactivity of the radiotracer was equal to 3000 Bq per jar. In one version of the experiment to the several jars aliquots of cadmium chloride ($CdCl_2$) water solution to the final concentration 50 μM/L were added. Simultaneously, the control plants were cultivated in a similar way but without $CdCl_2$. In the course of the experiment, which lasted for 14 days, the sampling of water was executed regularly to determine the residual radioactivity of the radiotracer in the medium.

The evaluation of the radiocapacity factor of biota (maize seedlings) (F_b) for each of the experimental variants was performed as follows:

$$F_b=1-A_i/A_0, \qquad (8)$$

where A_i – activity of nutrient solution in the i-th moment of observation (directly measured during the experiment), A_0 – activity of the solution at the initial moment (specially introduced activity). According to the theory of the radiocapacity (for chamber model of two-component system as "biota-water"), the ratio A_i/A_0 determines the amount of radiocapacity factor of water: $F_w=A_i/A_0$ [4].

To verify the adequacy of the radiocapacity parameter reaction and its validity to characterize the state of plant system under the action of negative factors a series of experiments was performed with the usage of both radiation and toxic agent. In one case maize seedlings were exposed to acute γ-irradiation in the doses of 5, 10, 20 and 40 Gy, respectively. In the second case maize seedlings were treated with toxic salt $CdCl_2$, which was added to the aqueous medium of biota inhabitancy to the concentration of 22, 44, 78 and 100 μM/L, correspondingly. Simultaneously all plants under experiment were placed in water with the incorporated radiotracer ^{137}Cs, the initial radioactivity of the latter being 6000 Bq/L or 3000 Bq per jar. Next day the probes of water were withdrawn from all variants of the experiment for ^{137}Cs residual radioactivity determination.

Also the experiments which were devoted to studying a separate effect of acute g- irradiation in the dose of 20 Gy on the aqueous culture of maize plants as well as a combined effect of acute γ-irradiation in the dose of 20 Gy together with the fractionated in time administering of $CdCl_2$ in the concentration 50 μM/L to the culturing medium of the same culture were carried out. The effect of synergism for the interaction of two agents using radiocapacity factors was assessed. The time interval between two fractions of $CdCl_2$ administering (concentration of $CdCl_2$ in each fraction was equal to 25 μM/L) constituted 6, 10 and 24 hours, correspondingly. Preparation and realization of the experiments was performed according to the scheme described above.

Measuring of the radioactivity by radiotracer ^{137}Cs was carried out on γ-spectrometer "SEG-05" (Ukraine).

Furthermore, the lengths of the main roots in seedlings were also identified in all the experiments.

RESULTS AND DISCUSSION

In consequence of experimental verification of the radiocapacity factor utilization as a prognostic parameter to assess the biota's reaction on various pollutants, the time dependent characteristics of the radiocapacity factors and growth parameters for a given model system were received.

The results of the research which are presented in Figure 1 show that acute γ-irradiation of maize seedlings in single dose and single post-irradiation administration of $CdCl_2$ in concentration of 50 μM/L in the medium for plant cultivation resulted in suppressing of maize root growth up to 40 % compared to control.

Consequently, in such a situation plant absorbing capacity, that is, the radiotracer dependent radiocapacity factor, might be supposed to worsen as well. Dynamics of water radiocapacity factor for a given model is shown in Figure 2. According to the graphs the control plants accumulated at the end of experiment approximately the whole amount of ^{137}Cs primarily administered in the nutritive medium. It clearly follows from the curve 1 which describes the changes of ^{137}Cs contents in the water of control variants. Accordingly, water concentration of ^{137}Cs was approaching to zero by the fifth day of plant culturing. Meanwhile the γ-irradiated plants and the plants subjected merely to the influence of 50 μM/L $CdCl_2$ were shown to accumulate only 55 % of the primary radioactivity.

It is obvious that the effect of two different stress-factors such as γ-radiation and toxic heavy metal resulted in approximately equal biological reactions as to the suppression of root growth, from the one hand, and the reduction of the plant radiocapacity factor, from the other hand. The unequivocal attenuation of the ecosystem biota's radiocapacity caused by the stress agents manifests in the oppression of the physiological processes that correlates with the changes in important radioecological characteristic known as the radiocapacity factor of biota.

In consequence of studying the radiocapacity factor behavior under the action of various stress-agents on biota, the dependence between water radiocapacity factor value and $CdCl_2$ concentration as well as γ-irradiation dose were found out (Fig. 3, 4).

The experiments showed that the increase either of irradiation dose or $CdCl_2$ concentration was accompanied by the water radiocapacity elevation and, consequently, by the biota's radiocapacity depression.

Thereby ecosystem's well-being and viability, in wide sense, are associated with its high radiocapacity. Hence high radiocapacity values for biota, which show up stability and constancy, are likely to indicate ecosystem's reliability and well functioning. In view of this, the incarnation of the radiocapacity control along with radiocapacity factor determination, especially in conditions past perturbations, can serve both as objective anticipating criterion and as evaluating technique

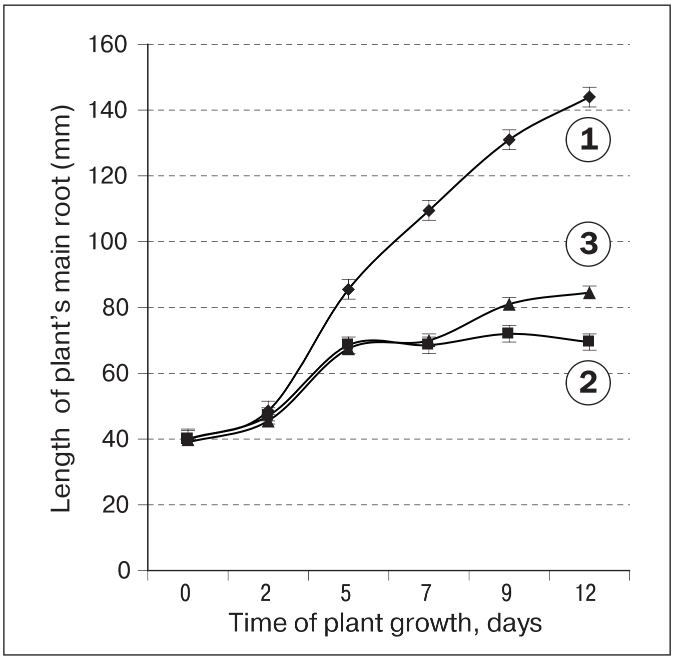

Figure 1. **Impact of a single acute γ-irradiation of maize seedlings at the dose of 15 Gy and of a single administration of $CdCl_2$ in concentration of 50 μM/L on the dynamics of root growth in aqueous culture. 1 – control; 2 – γ-irradiation at the 15 Gy dose; 3 – administration of $CdCl_2$ in 50 μM/L concentration.**

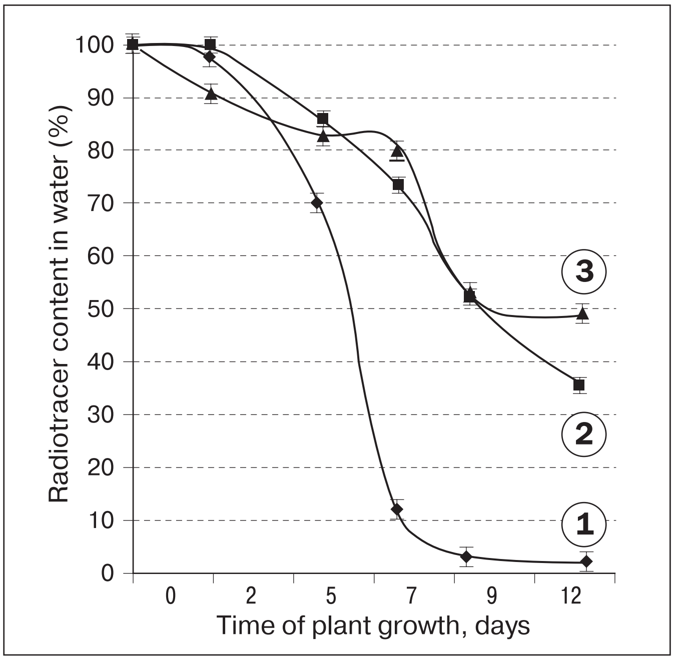

Figure 2. **The dynamics of change of the tracer contents in water: 1 – 50 μM/L $CdCl_2$; 2 – acute γ-irradiation at a dose of 15 Gy; 3 – control.**

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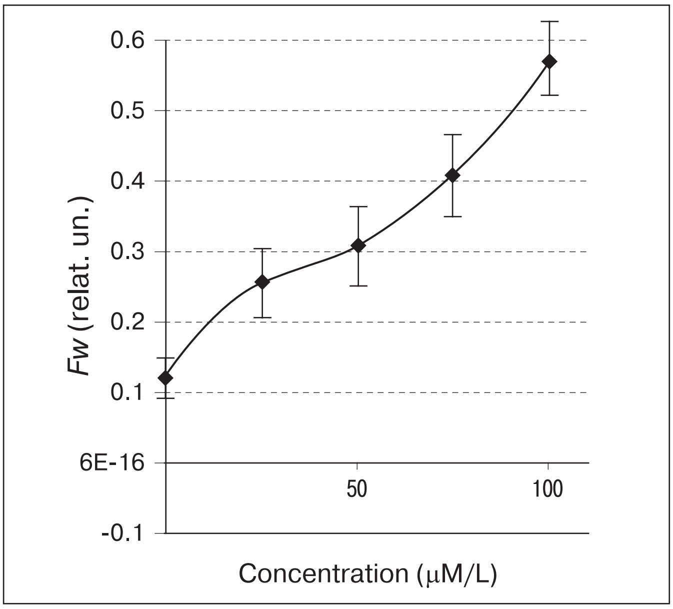

Figure 3. **The dynamics of change of water radiocapacity factor F_w depending on brought concentration of $CdCl_2$.**

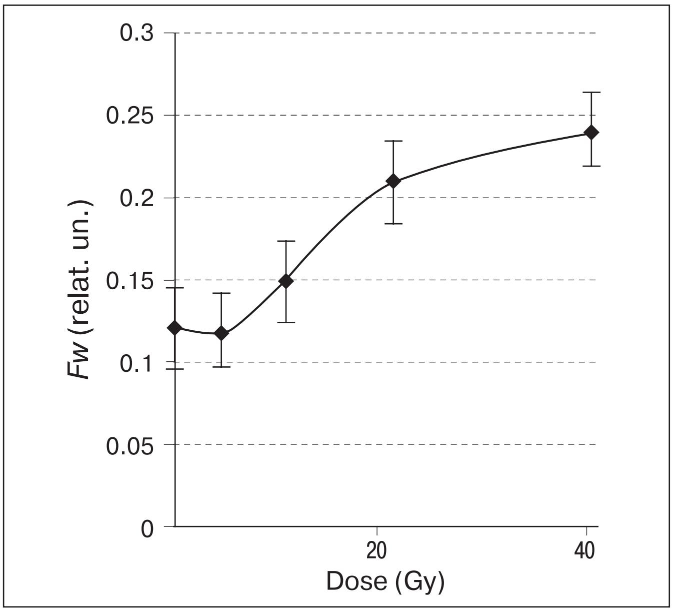

Figure 4. **The dynamics of change of water radiocapacity factor (1) depending on radiation dose.**

for the assessment of ecosystem state in the different ecosystem types, e.g. aqueous, forest or terrestrial.

Experiments for the evaluation of synergetic action of different agents on biota in model ecosystem through the determination of the radiocapacity factor changes using radiotracer ^{137}Cs have been carried out. With the aid of calculated proportions for the radiocapacity factor relation *Z* and mean values of coefficient *P* using formula 7 were estimated as well as relevant temporary dependences were built up (Fig. 5).

The graphs on Figure 5 clearly show a synergism in the course of the whole experiment due to the combined effect of acute γ-irradiation at the dose of 20 Gy

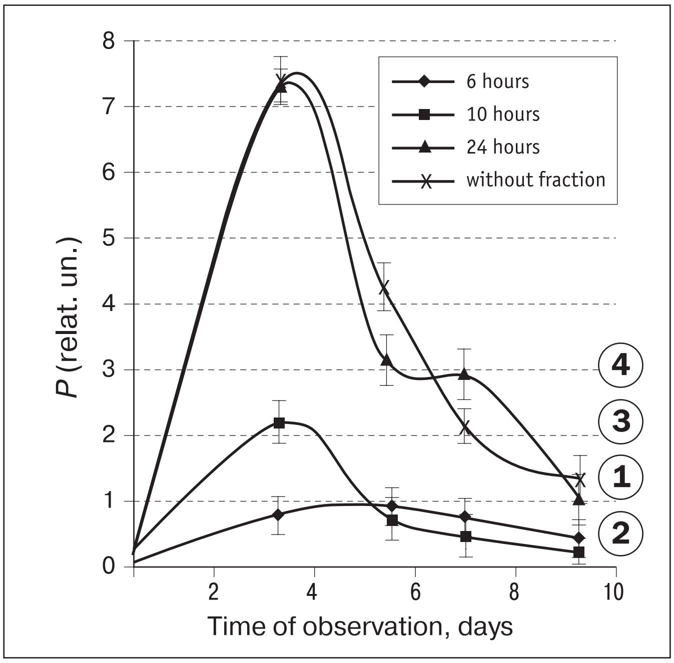

Figure 5. **The synergism index *P* time dependence. 1 – γ-irradiation at a dose of 20 Gy combined with 50 μM/L $CdCl_2$ adding with the 6 h fractions time; 2 – γ-irradiation with $CdCl_2$ adding with the 10 h fractions time ; 3 – γ-irradiation with $CdCl_2$ adding with the 24 h fractions time ; 4 – γ-irradiation with adding 50 μM/L $CdCl_2$ without fractionating.**

along with a fractionated in time $CdCl_2$ administering over an interval 6 h that is validated by the mean value of P not exceeding 1. An increase of time span between fractions caused a shift in the character of interaction between physical and chemical stress-factors towards antisynergism. Thus, in the case of $CdCl_2$ administering by 2 fractions with 10 h interruption the mutual attenuation of the negative combined effect was observed within first 4 days. Thereafter interaction character became synergetic again. When $CdCl_2$ was administered by 2 fractions with 24 h interruption or at once in the whole amount, i.e. in the concentration 50 μM/L, in the first 4 days a significant alleviation of the negative effect of acute γ-irradiation owing to the toxic metal salt $CdCl_2$ administering in the nutritive medium was revealed. Further continuation of plant culturing made *P* value approach gradually to 1.

Thereby, radiation and toxic agents were shown to affect a plant ecosystem through mutual interaction, the character of interaction in all combinations of γ-irradiation and salt $CdCl_2$ administering being non-additive. To our opinion, the vital necessity in proceeding the experiments still remains that would be tempting for further elucidation of synergism nature and mechanism for the interaction of different factors upon their application to various models.

CONCLUSIONS

On the warrant of theoretical and experimental research the radiocapacity factor measured by the aid of radiotracer ^{137}Cs was shown to react adequately on the changes of biota's state. In the experiments with maximum simplified model of plant ecosystem the action of both radiation and heavy metal was accompanied by the decrease of biota's radiocapacity factors. An established phenomenon signifies a change in biota's state and welfare that is incarnated in the redistribution of the radiotracer as test factor.

It has been elucidated that the radiation and chemical (heavy metals) factors do affect growth velocity and state of biota that in turn adequately embodies in the mean values of the radiocapacity factors. The radiotracer redistribution in the ecosystems clearly reflects the internal laws for biota's state and behavior in different types of ecosystems.

A mathematical model for the synergism assessment in the effects of several harmful agents on biota has been developed which qualifies the usage of the ecosystem's radiocapacity factors measured by radiotracer ^{137}Cs. In consequence, a significant shift of synergism coefficient was shown to take place in the dynamics of biota's growth and recovery in conjunction with phenomena of additivity and antagonism for different factors.

It has been established, that the recovery of ecosystem's biota following the radiation and chemical impact shows up explicitly as in the changes of biological growth parameters as in the improvement of the radiocapacity factors. It stands for the means of ecosystem's biota retrieval are capable to increase the radiocapacity factors.

In addition, it has been shown that the radiocapacity factor measured by the radiotracer ^{137}Cs can be utilized for the evaluation of biota's state under the anthropogenic load. Similarly, the radiocapacity factors may serve as a protective counter-measure quality and efficiency control.

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