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Mathematical and Computer Simulation of the Biological Life Support System Module 2/2. Verification of the Model and Scenarios

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According to experimental data a dynamic model of biological life support system (BLSS) module was verified. The soil-like substrate (SLS) lies in the basis of this BLSS. The module was designed for requirements of 1/30 of a virtually present human; it involves higher plants, unit for vegetable wastes processing and gas exchange for carbon dioxide and oxygen. Application of the model helped in estimation of variants of system functioning at optimal and non-optimal modes of illumination and according to the number of age groups in the phytoblock. The alternatives of system development at death of a part or the whole wheat phytomass have been demonstrated, the degree of biotic turnover closedness for C and N in different methods of system mass exchange organization has been estimated. BLSS with SLS exceed the system with physico-chemical method of matter oxidation by the degree of matter turnover closedness. From this viewpoint, SLS based experimental module can become the prototype of new generation BLSS with more high closedness of internal matter turnover.

Keywords: Mathematical modeling, biological life support system, closedness coefficient

Introduction

The mathematical model (Gubanov et al., 2009) was constructed to estimate the functioning pattern of the biological life support system (BLSS) experimental module (Tikhomirov et al., 2003a, 2003b) and its controllability. The soil-like substrate (SLS) lies in the basis of this BLSS. SLS is result of successive processing of straw cereals (wheat, rice, etc.) by fungus *Pleurotus ostreatus* and worms *Eisenia foetida*. The

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model include higher plants, block processing of vegetable waste, block physical-chemical oxidation, which simulates human digestion of useful plant biomass and returning of its products in the internal circulation, gas exchange of carbon dioxide and oxygen. The module was designed for the food and gas exchange requirements of 1\30 of a virtually present human. According to experimental data a dynamic model of BLSS module was verified.

The mathematical model of the system is able to show the alternatives of experimental system development at critical behavior likely for LSS. The model allows estimating the values of system dynamic components under various circumstances and functioning modes, especially in conditions, which are difficult to realize, and at application of expensive experimental equipment.

Application of the model helped in estimation of variants of system functioning at optimal and non-optimal modes of illumination and according to the number of age groups in the phytoblock. The alternatives of system development at death of a part or the whole wheat phytomass have been demonstrated, the degree of biotic turnover closedness for C and N in different methods of system mass exchange organization has been estimated. BLSS with SLS exceed the system with physico-chemical method of matter oxidation by the degree of matter turnover closedness. From this viewpoint, SLS based experimental module can become the prototype of new generation BLSS with more high closedness of internal matter turnover.

1. Model verification

To verify the model we relied on the data obtained in work with BLSS experimental module (Tikhomirov et al., 2003a, 2003b). Reference values of the coefficients for model verification were obtained either in the experiments with BLSS module or taken from the literature (Continuous controlled ..., 1967; Mishoustin, 1970; Gitelson et al., 1975; Vasiliev et al., 1975; Zamknutaya sistema… (Closed system…), 1979; Fishtein et al., 1983; Gubanov et al., 1996; Manukovsky et al., 1996, 1997; Gitelson et al., 1997). At that, the following values of model coefficients (in terms of dry mass) were identified in iterative calculations and used in scenarios:

$\hat{\mu}_m=0.2$ day^{-1}, $\gamma^*_m=0.02$ day^{-1}, $k=1$, $K_H=20$ g, $f=0.2$, $Q_{opt}=1500$ g, $K_Q=0.0007$ g^{-1}, $\varphi=0.5$, $Y_H=0.5$, $J_1=0.032$ m^2, $a_1=3.96$, $b_1=0.5$, $c_1=1.98$, $K_{S_1 1}=27.778$ g^{-1}, $K_{S_2 1}=222.22$ g^{-1}, $K_{S_3 1}=666.67$ g^{-1}, $t_{11}=5$ day, $k_1=0.8$, $W_{opt}=20$ g, $K_W=0.05$ g^{-1}, $E_{opt}=200$ W/m^2, $\gamma_G=0.009$ day^{-1}, $\hat{\mu}_G=0.014$ day^{-1}, $K_{GZ}=100$ g, $K_{R1}=50$ g, $\gamma_{R1}=0.01$ day^{-1}, $Y_{GR1}=0.5$, $K_{R1Z}=20$ g, $\hat{\mu}_{R1}=2$ day^{-1}, $Y_{R1Z}=0.5$, $Y_{GZ}=0.5$, $\gamma_{R2}=0.02$ day^{-1}, $K_{R2C}=0.5$ g, $\hat{\mu}_{R2}=0.05$ day^{-1}, $Y_{R2C}=0.5$, $\delta_{GR1}=0.5$, $\delta_{GZ}=0.5$, $Y_{X1S1}=10$, $\alpha^*_{R1S1}=0.1$, $\alpha^*_{R2S1}=0.1$, $\alpha^*_{U2S1}=0.1$, $t_{max1}=70$ day, $Y_{X1S2}=100$, $\alpha^*_{R1S2}=0.01$, $\alpha^*_{R2S2}=0.01$, $\alpha^*_{U2S2}=0.01$, $Y_{X1S3}=500$, $\alpha^*_{R1S3}=0.002$, $\alpha^*_{R2S3}=0.002$, $\alpha^*_{U2S3}=0.002$, $J_2=0.032$ m^2, $a_2=44$, $b_2=0.288$, $c_2=1.98$, $K_{S_1 2}=27.778$ g^{-1}, $K_{S_2 2}=222.22$ g^{-1}, $K_{S_3 2}=666.67$ g^{-1}, $k_2=0.8$, $Y_{X2S1}=10$, $Y_{X2S2}=100$, $Y_{X2S3}=500$, $F_{m\ INIT}=0.2$ g, $l_{11}=0.28$, $l_2=0.36$, $X_{INIT1}=1$, $X_{INIT2}=1$, $l_{12}=0.37$, $q=8$, $p=4$, $a_{Fm}=a_G=a_{R1}=a_{R2}=a_U=0.54$, $B=1$, $D_{Fm}=D_G=D_{R1}=D_{R2}=D_U=1$, $\mathrm{Y}_{\mathrm{XW}}=0.5$,

The values of these coefficients may be found in (Gubanov et al., 2009), proposing the mathematical model of a BLSS module.

Figures 1 and 2 compare model calculations with experimental data on the biannual yield dynamics in wheat growth chamber. It is clear that this model accurately reflects the dynamics of wheat plants mass in the stated period. Yield dynamics in model calculations, at qualitative compliance, slightly differ from experimental data quantitatively. The reason is that no special mechanisms for yield regulation in a closed experimental system were put into the model

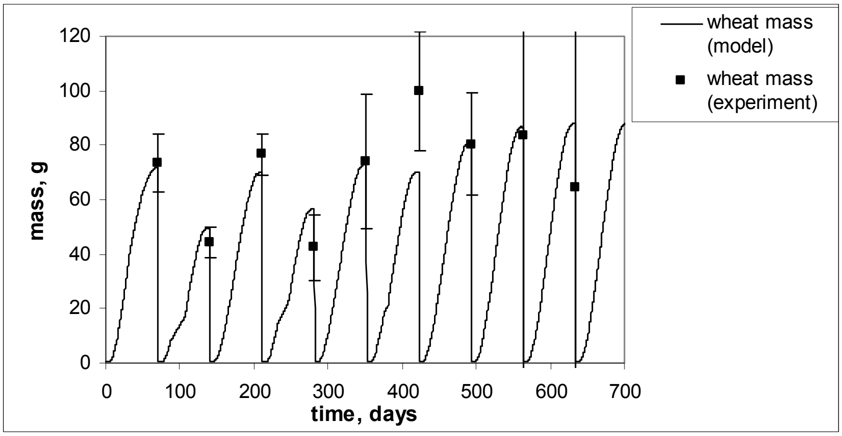

Fig. 1. Dynamics of wheat mass in a separate growth chamber: model and experimental data

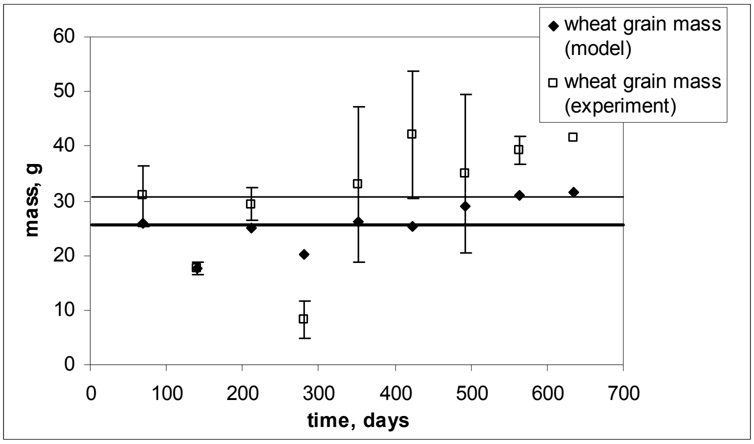

Fig. 2. Dynamics of wheat yield in a separate growth chamber: model and experimental data. The upper straight line shows the period average of the experiment, the lower – period average for the calculation data

because of lack of valid hypotheses. The model shows direct dependence of wheat (grains) and radish (edible roots) yield upon total biomass of each type of plant. However, average calculation and experimental data on the whole period are sufficiently close (Fig. 2).

Theoretical dynamic (continuous) curves are saw-toothed because of the accurate reproduction of harvesting in the actual experiment. At the same time experimental data constitute descrete quantities (point mode).

Figures 3 and 4 show the dynamics of main components calculated for radish and mushroom modules respectively. The calculation demonstrates qualitative and quantitative compliance in behavior of these components in the model and during the experiment. Radish growth rate in terms of mass and yield is not high but stable, which complies with experimental data. Mushrooms fruiting 2-3 times per cycle, with 5 g of total yield (dry mass) on each growth chamber shows the actual situation (Tikhomirov et al., 2003a).

Figure 5 illustrates the model calculation of worms` mass in growth chamber. It is obvious that mass of worms is in a quasi-stationary state (10 g) tending to reduce slightly. On the whole, it corresponds to the dynamics registered during transplanting of the higher plants (Tikhomirov et al., 2003a).

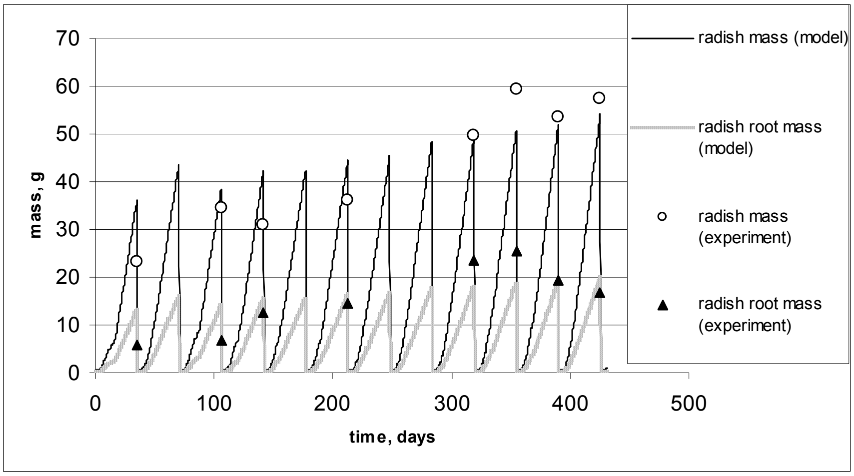

Fig. 3. Model calculation of radish mass and edible roots dynamics in a separate growth chamber

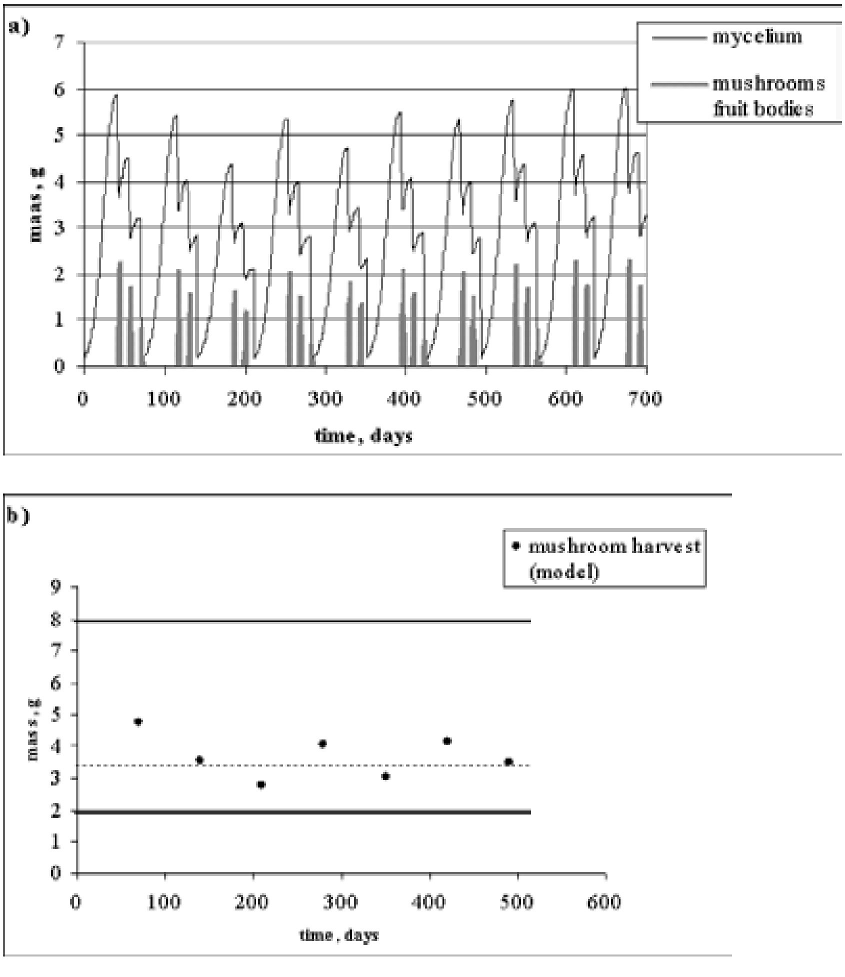

Fig. 4. Model calculation of the dynamics of micelium mass and mushroom fruit bodies. a) – dynamics, b) – yield of fruit bodies (thick lines show limits of experimental data range, thin line shows their average value)

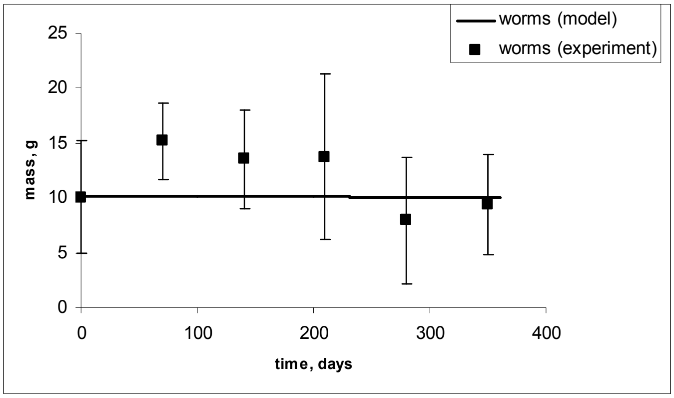

Fig. 5. Model calculation of worms` mass dynamics in the system; congruence with experimental data

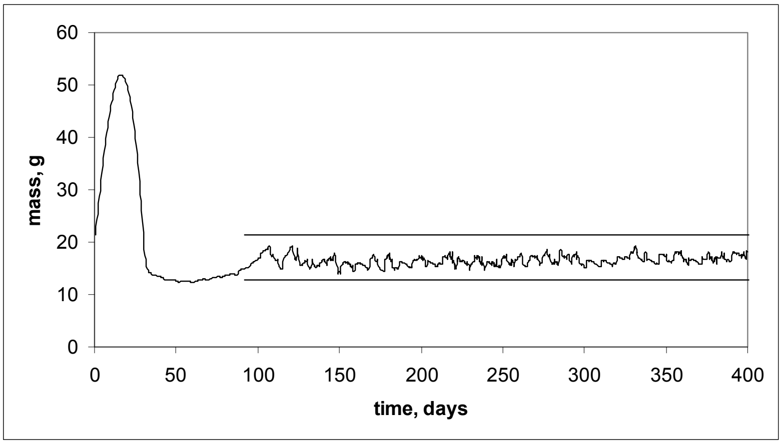

Fig. 6. Model calculation of carbon dioxide mass dynamics in the system.Thick lines show the scale of experimental data in the quasi-stationary state

Figure 6 demonstrates high qualitative accordance of estimated and experimental mass of CO_2 in quasi-stationary state of the module atmosphere (total volume of the module is 6 m^3).

Thus, in this work we have presented the verification of the model according to its main components, which in some extent can be considered as «controller units» of the BLSS module; at least they are the main and continuously controlled. Concerning other components we should note that in model calculations they correspond to experimental data and stay within their actual changes, as in Figs. 2, 4 and 6.

As verification calculations, on the whole, agree with experimental data, we can say that the proposed mathematical model is adequate to the BLSS experimental module (Tikhomirov et al., 2003a, 2003b). However, this model is not the end in itself. Despite of validity of the remark »Blind faith in what a model predicts is not the purpose of the modelling« (Grimm, 1999), we think this model can be used for preliminary estimate of scenarios of module exploitation in actual experiments, including management of its functioning. Strictly speaking, that is what the model was constructed for. Let us demonstrate some of its features.

2. Scenarios

The model allows estimating the values of system dynamic components under various circumstances and functioning modes,

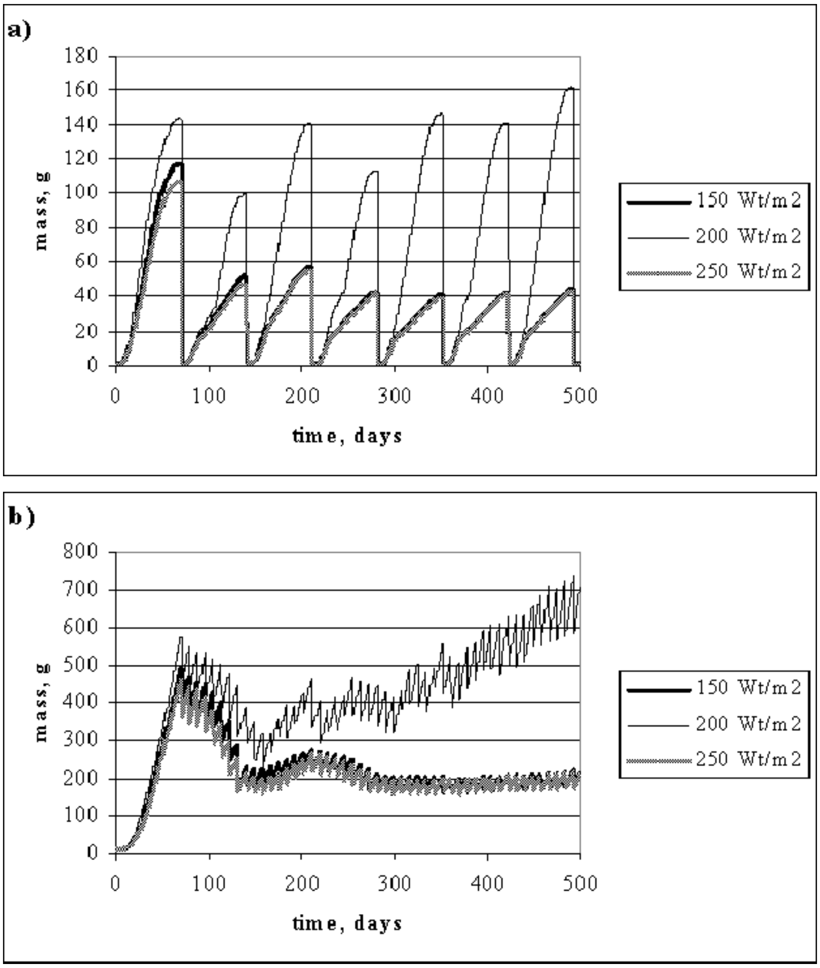

Fig. 7. Model calculation of wheat biomass dynamics at different illuminance. a) – for one growth chamber, b) – for uneven-aged conveyer with wheat as a system on the whole (total mass of wheat)

especially in conditions, which are difficult to realize, and at application of expensive experimental equipment. One of these variants can be the long-term existence of the system at illumination far from optimum. Performance of such experiment in the BLSS module would require tree times, at least once, consecutively repeated tests at different illumination. First of all, this would take much time (each test takes nearly 1 year, taking into account the period of system coming to steady state and its maintenance) and, thus be expensive. The model allows easy estimate of system development tendencies. The example of such calculation is given in Fig. 7 and Fig.8.

As can be seen from the figures, wheat mass reduces significantly at long-term non-optimal luminous mode (150 and 250 W/m^2); after several «growth-yield» cycles wheat reaches bound level with the mass 3 times lower than at optimal illuminance (200 W/m^2). On the contrary, radish displays more stable and equal growth with three different values of light intensity (difference in biomass is inessential – 1,3 times), which indicates its higher resistance to changes of light intensity in comparison with wheat.

The degree of closedness of biotic turnover (closedness coefficient) on main accountable elements i (Cl_i) is one of the most significant indices of life support systems and should be

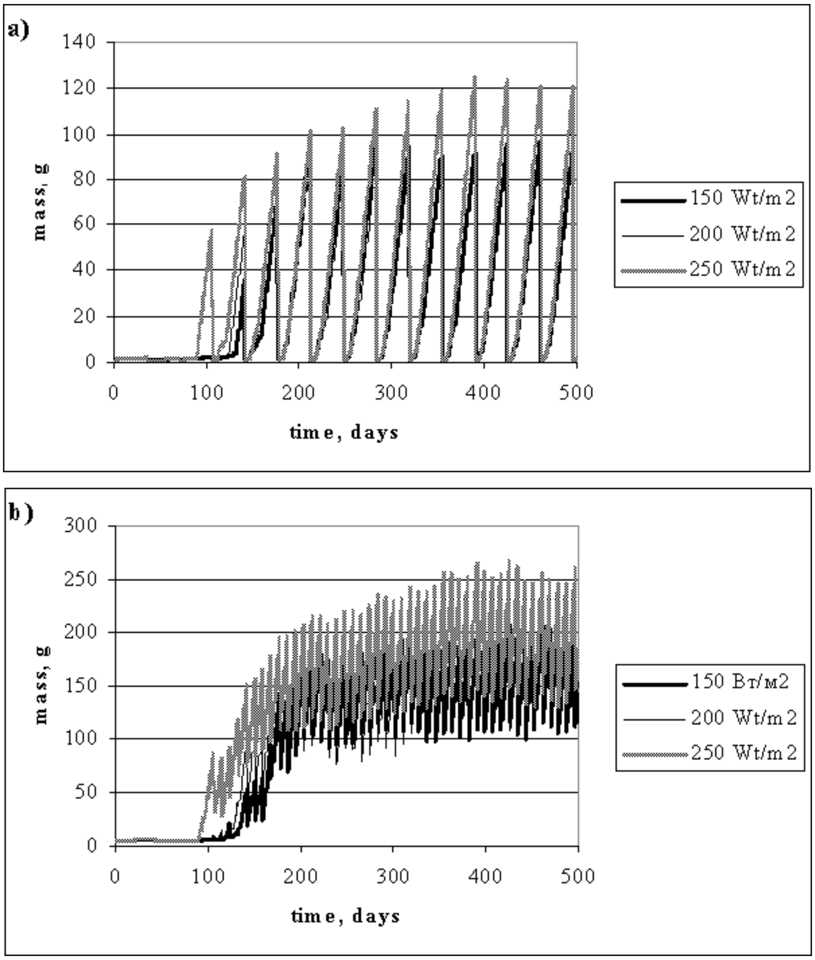

Fig. 8. Model calculation of radish biomass dynamics at different illuminance. a) – for one growth chamber, b) – for uneven-aged conveyer with radish as a system on the whole (total mass of radish)

under continuous control in the model system according to the equation (46) (Gubanov et al., 2008). It is extremely difficult to define the turnover closedness for some elements in real conditions, whereas it is possible to estimate Cl_i in the model, where the respective material flows are known. Such estimate reveals the ways of increasing the LSS bioturnover closedness for considered elements, especially C, P, N, Fe etc. The model allows calculation of closedness coefficients in their dynamics. Figure 9 shows the calculation of dynamic closedness coefficients for two main elements – carbon and nitrogen. We chose nitrogen because, on the one hand, as investigations show, of all the diverse nutrients this one is most likely to be deficient in the system with the SLS (analog of anthropogenic and natural disturbances), when the technological procedure is not properly followed. On the other hand, nitrogen is difficult to control; it forms compounds of different valence, each process of formation has its own rate and refers to other processes.

From Fig. 9 it is apparent that the system is unstable on closedness coefficient in the initial stage of constructing a uneven-aged conveyer and adjustment of components. Later, when the conveyer forms on the 70th day (after system stabilization) and the second cycle on wheat is completed (140th day), closedness coefficients

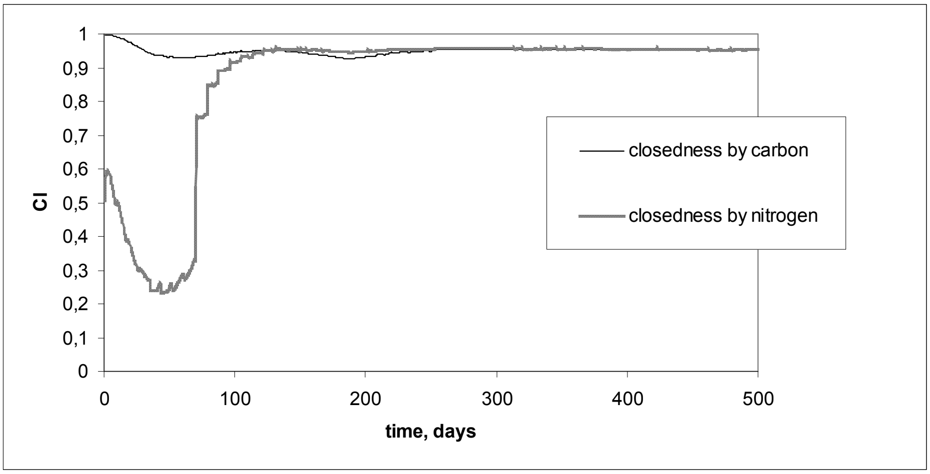

Fig. 9. Dynamics of closedness coefficient for carbon and nitrogen in the model BLSS

also stabilize with a minor tendency to reduction. Thus, the closedness coefficient can possibly serve as measure of system stability.

The values of closedness coefficients for nitrogen (0,5) and carbon (0,998) at the start time result, first of all, from the fact that the flows of these elements from heterotrophs to producers ($\dot{\Omega}_N$ and $\dot{\Omega}_C$) are formed in different ways (Gubanov et al., 2008) and, therefore, are essentially different (in one case, it is the flow of nitrogen into its background content; in the other – it is carbon flow into CO_2). Yet, they have the same dead-end flow – non-mineralized organic matter with the respective content of nitrogen and carbon. On the other hand, photosynthetic processes (the system starts at planting of phytotrophic components, their germination and the absence of photosynthetic mass for this period) are almost absent in the model system at the start and, therefore, there is no sufficient dead organic matter serving as a source of biogenic elements for the autotroph unit and as a source of dead-end matter. That is the reason why the initial matter flow and the content of biogenic elements, including nitrogen ($\dot{B}_N$) and carbon ($\dot{B}_C$), are insufficient. The content of biogens in the background (N, P, Fe etc) is equal to their content in the dead-end flow, therefore $Cl_N = 0,5$. The initial concentration of CO_2 (carbon source for phytotrophs) is sufficient, which brings the value of Cl_C to 1 (equation 57 in (Gubanov et al., 2008).

The mathematical model of the system is able to show the alternatives of experimental system development at critical behavior likely for LSS. The example of this behavior is the death of some biomass of green plants. The model calculations for different cases of wheat biomass death were carried out. As shown in Fig. 10, the death of half of wheat biomass (upon the absence of other side factors related to biomass death and **the constant functioning of conveyer**) in growth chamber does not affect phytomass total dynamics distinctly, and in 30-35 days deviations (absence of biomass death) eliminate entirely. When the half of wheat biomass in each growth chamber (8 chambers) is lost, the deviations are higher and longer, but they gradually eliminate in 80-100 days. At death of the wheat whole biomass conveyer returns to its working condition in 50-70 days, the deviations remain for more than 200 days. The conveyer is supposed to work constantly, since a human in the module seeds wheat again. For the period of plant phytomass total death the human support of the BLSS can be carried out by non-biological methods, e.g. physicochemical system. In the case

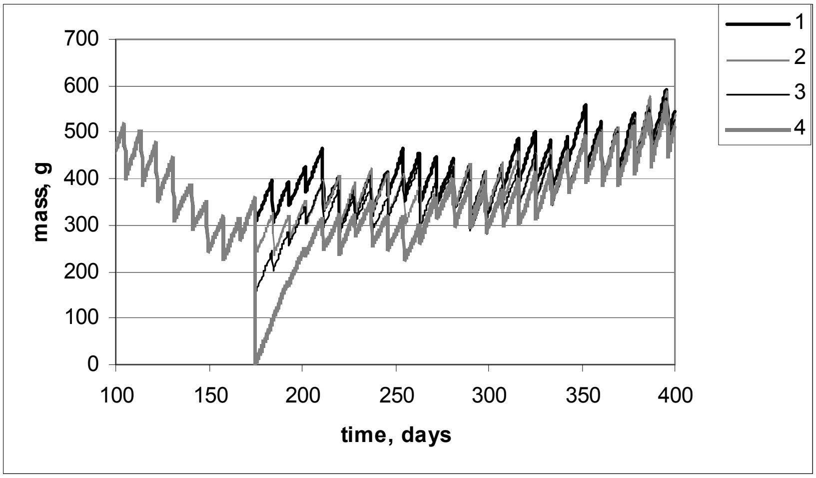

Fig. 10. Model calculation of «wheat biomass death in the BLSS». Effect in the model (death) takes place on the 175th day. 1 – control (no death), 2 – death of ½ of wheat biomass in the first growth chamber, 3 – death of ½ of wheat biomass in each growth chamber, 4 – death of the whole biomass in all growth chambers; number of growth chambers – 8

of human absence the conveyer can be maintained by automatic units.

The model allows optimization of the system on number of age groups in a conveyer. It is an essential parameter; its low value leads to instability of total mass of system components, the high value results in complication of the system and increase of its significance. Figure 11 shows the dependence of wheat and radish total mass dynamics upon the number of age groups. It is obvious that oscillations in the system (8 age groups for wheat and 4 – for radish) are sufficiently weak, further increase in the number of age groups is not required in the real system. In the model system such increase leads to total elimination of oscillations.

The increase in number of age groups also smoothes the dynamic behavior of closedness coefficient (Fig. 12). It means that we should implement more age groups to approximate the model system to the «ideal» continuous version.

Comparison of bioturnover closedness coefficients (Cl_i) for systems with different organization of mass-exchange flows reveals the ways of biotic turnover organization improvement for the purpose of increasing the system biotic closedness. Calculating the dynamics of the closedness coefficient for main biogenic elements is of high interest for comparison of methods of plant biomass utilization in the system: the system with the SLS and biological utilization of the straw; the system using the physicochemical method of straw utilization (combustion and partial re-involvement in the cycle of some elements, such as carbon and nitrogen); and the system in which the straw irretrievably leaves the mass exchange cycle (as a store). The last two variants arouse interest, as they were used in BIOS-3 system (Gitelson et al., 1975; Zamknutaya sistema… (Closed system…), 1979). During the model calculations of these variants, the fact that system contains neutral substrate (e.g. in BIOS-3 it was claydite) instead of SLS was taken into consideration. At that, all flows related to SLS specific nature were put to zero in the model. While comparing the results we depended upon the experimental data obtained in work with the BLSS experimental module under study.

Figures 13 and 14 show the variants of one of these calculations.

In all the variants the dynamics are qualitatively similar – the closedness coefficient

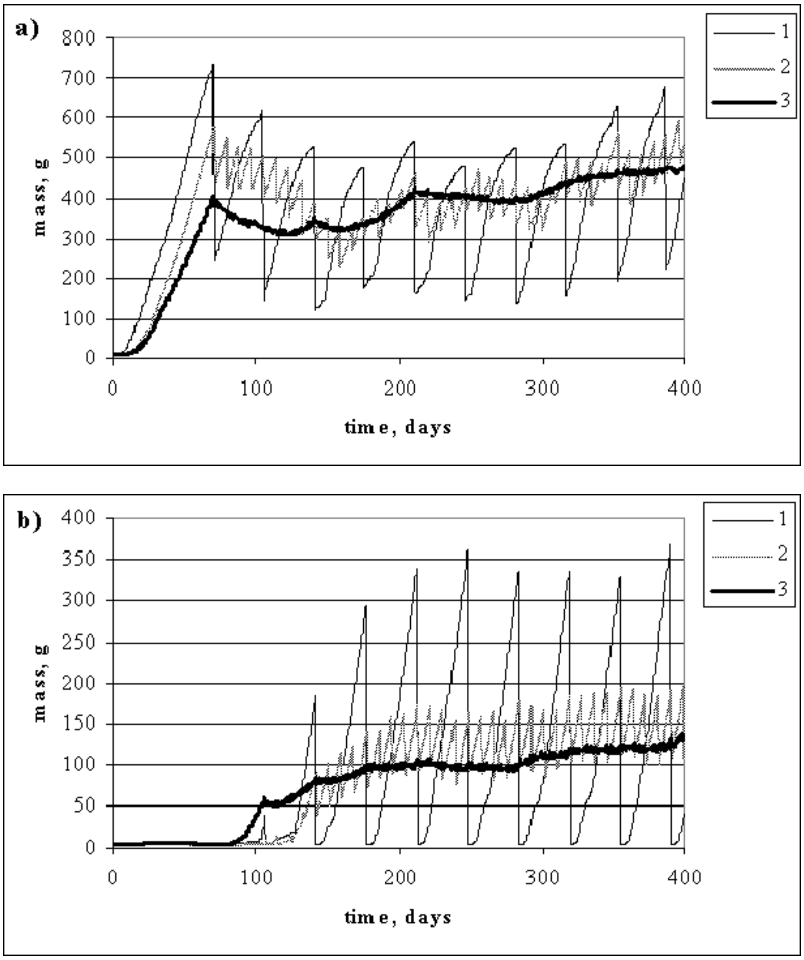

Fig. 11. Comparison of model variants for different age groups (growth chambers) in the conveyer. a) total mass of wheat in the system, b) total mass of radish in the system. 1 – 2 age groups for wheat, 1- for radish, 2 - 8 age groups for wheat, 4 – for radish (complies with experimental system), 3 - 100 age groups for wheat, 50 – for radish

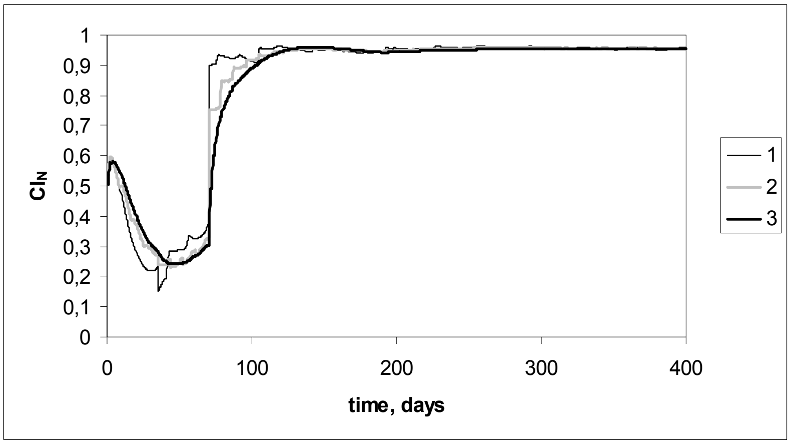

Fig. 12. Dynamics of BLSS closedness coefficient for nitrogen at different number of age groups in the conveyer. 1 – 2 age groups for wheat, 1- for radish, 2 - 8 age groups for wheat, 4 – for radish (complies with experimental system), 3 - 100 age groups for wheat, 50 – for radish

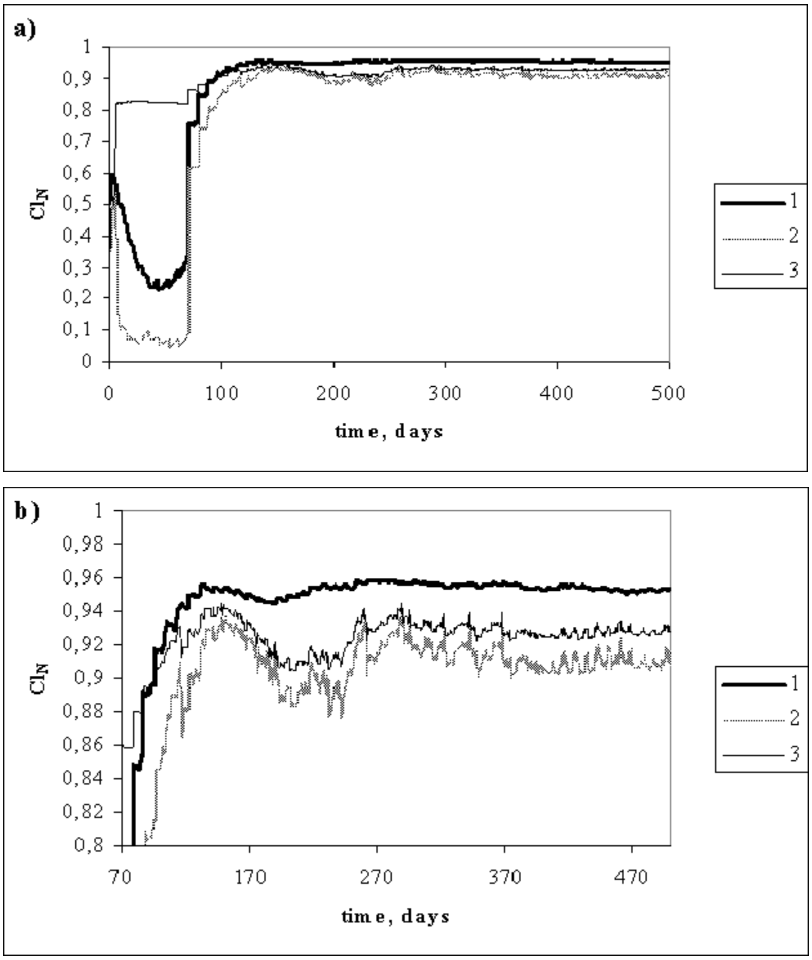

Fig. 13. Model calculation of dynamic closedness coefficents for nitrogen. 1 – system with the SLS – biological utilization of straw, 2 – system without straw utilization, 3 – system with physicochemical method of straw utilization (combustion). a) overall view, b) enlarged fragment (after 70 days)

increases in the period prior to the establishment of the quasi-stationary state (140-150 days) and then stabilizes, tending to decrease. However, the closedness coefficient for system with biological utilization of straw is the highest, and its behavior after attaining maximum is more stable as compared to other systems. From this point of view, the experimental module (based on SLS) considered in this work can become the prototype of new generation BLSS with high closedness of internal turnover.

We should note that at the initial period (formation of conveyer, 90-100 days) the coefficient of closure for nitrogen in the system with physical-chemical utilization of straw is higher than in the system with the SLS. Probably, combination of these methods of straw utilization will be expedient for the period of conveyer formation.

It is possible to find another application for the model. Once installed and adjusted, the model system can be helpful for educational purposes: students can use it to play back the possible and hypothetical variants of such systems functioning. Here is the example of hypothetical scenario. It is possible to estimate pattern of behavior of a really existing experimental system at the specific mass correlation of two interchangeable phytocomponents – wheat and radish. Basically, BLSS can exist including only one component.

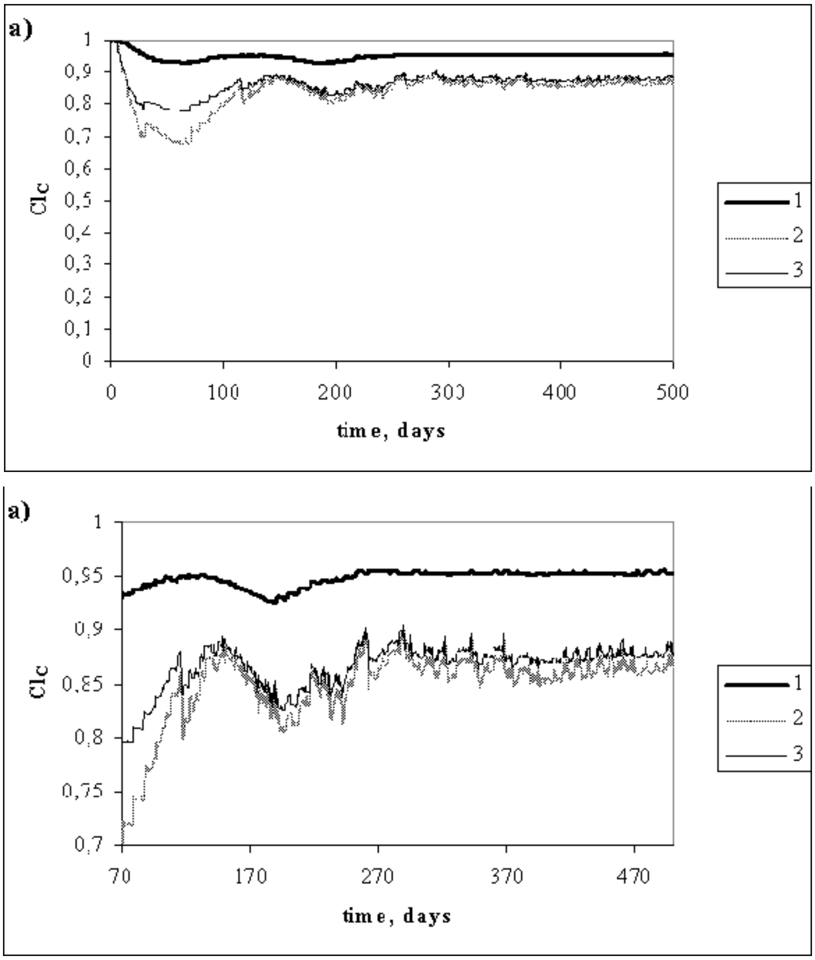

Fig. 14. Model calculation of dynamic closedness coefficents for carbon. 1 – system with the SLS – biological utilization of straw, 2 – system without straw utilization, 3 – system with physicochemical mechanism of straw utilization (combustion). a) overall view, b) enlarged fragment (after 70 days)

Model system can define the variant displaying a higher closedness coefficient. This calculation is shown in Fig. 15. Closedness parameter demonstrates the explicit advantage of system with radish. Closedness coefficient in the system with wheat only is slightly lower than in the system with both components. It is attributed to a quicker circulation of radish phytomass elements in comparison with wheat; radish tops after harvesting are left in the growth chamber but wheat straw is processed additionally in a cycle with mushrooms and only then its elements are returned to the phytotron growth chamber. Although it is obvious that closedness coefficient is not the only parameter defining the type of changes to be made in the system, still it should be taken into consideration. In this case it will be possible to analyze the development dynamics of each system component.

Conclusion

The dynamic model of the biological life support system experimental module, based on soil-like substate has been examined. The module was designed for requirements of 1/30 of a virtually present human; it involves higher plants, unit for vegetable wastes processing and gas exchange for carbon dioxide and oxygen. The coefficient of matter biotic cycle closure for systems based on matter supplies has

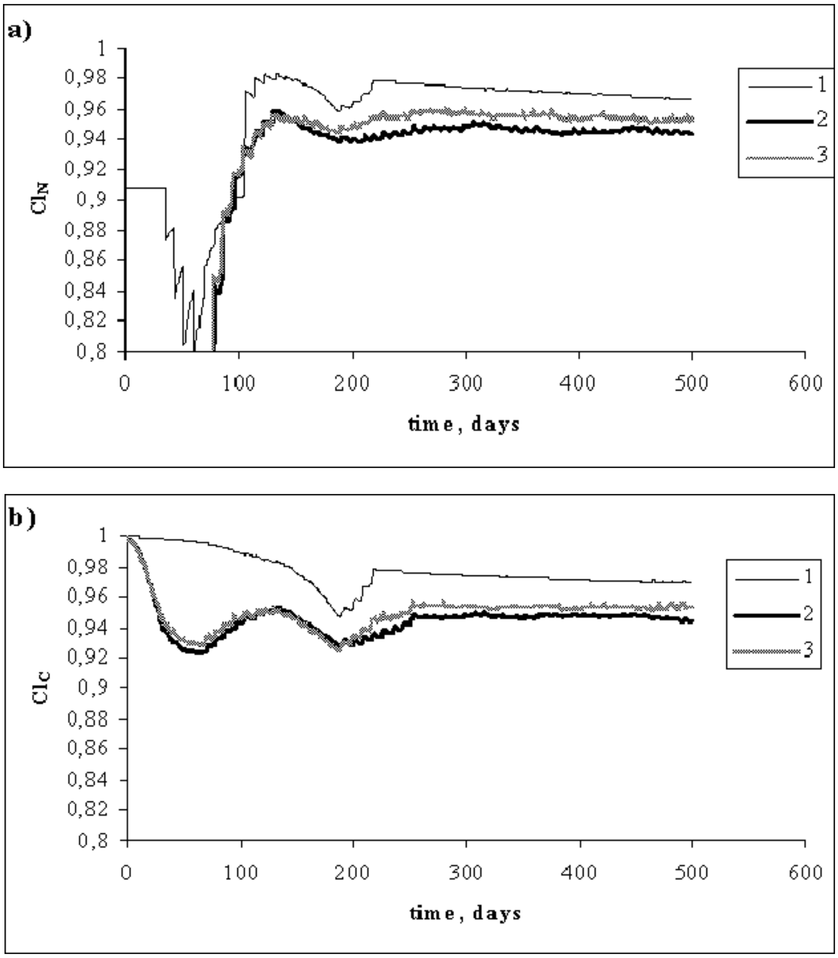

Fig. 15. Model calculation of dynamic closedness coefficients for nitrogen (a) and carbon (b). 1 – system with radish, 2 – system with wheat, 3 – system with both components

been formalized. The model has been verified according to experimental data (Tikhomirov et al., 2003a, 2003b); its adequacy to the experimental model of BLSS module has been demonstrated.

Application of the model helped in estimation of variants of system functioning at optimal and non-optimal modes of illumination and according to the number of age groups in the phytoblock. The alternatives of system development at death of a part or the whole wheat phytomass have been demonstrated, the degree of biotic turnover closedness for C and N in different methods of system mass exchange organization has been estimated. It was shown that biocycle closedness coefficient can be the measure of system stability.

BLSS with SLS exceed the system with physico-chemical method of matter oxidation by the degree of matter turnover closedness. From this viewpoint, SLS based experimental module can become the prototype of new generation BLSS with more high closedness of internal matter turnover. However, it would be expedient to combine these two approaches for the period of conveyer formation, as at the initial period (conveyer formation) the closedness coefficient on nitrogen is higher in the system with physico-chemical utilization of straw than in the system with SLS. We may recommend this model system for educational purposes as it helps anticipating various scenarios of its development.

The represented model can be used for preliminary estimate of tendencies and functioning pattern of BLSS module at carrying out long-term and sophisticated experiments, and for experiment management directly in the course of its execution.

The module itself can be used as a tool for studying some biospheric processes; in this case it will be important to determine the degree of similarity for these processes. The model can be applied for estimate of development tendencies of investigated processes in the experimental system with their further extrapolation on similar biospheric processes. For example, with its help it will be possible to estimate CO_2 dynamics depending on thermal changes in the module atmosphere, supposing that processes of CO_2 production (respiration) and consumption (photosynthesis) have different thermal optima. This contributes significantly to the determination of CO_2 role in regulation of the greenhouse effect. This experiment could be carried out in the model first and then realized in the module.

Acknowledgments

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Математическое моделирование и вычислительная имитация модуля биологической системы жизнеобеспечения

2/2. Верификация модели и сценарные расчеты

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По экспериментальным данным верифицирована динамическая модель модуля биологической системы жизнеобеспечения (БСЖО). В основе БСЖО использование почвоподобного субстрата (ППС). Модуль включает высшие растения, блок переработки растительных отходов, газообмен по углекислому газу и кислороду, и по массо-газообмену рассчитан на условное присутствие 1/30 доли человека. При помощи модели оценены варианты функционирования системы при неоптимальном и оптимальном режимах освещенности и по количеству возрастов в фитоблоке, продемонстрированы варианты развития системы для такой критической ситуации как гибель части или всей фитомассы пшеницы, оценена степень замкнутости биотического круговорота по C и N для различных способов организации массооборота системы. БСЖО с ППС по степени замкнутости круговорота вещества имеет преимущество перед системой с физико-химическим способом окисления *вещества. В этом смысле экспериментальный модуль (на основе ППС) может послужить прообразом в создании нового поколения БСЖО с повышенным замыканием внутреннего круговорота вещества.*

Ключевые слова: математическое моделирование, биологическая система жизнеобеспечения, коэффициент замкнутости