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Mathematical modeling of environmental processes at military facilities

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A R T I C L E I N F O

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A B S T R A C T

For an integrated assessment of the state of ecosystems at military proving grounds, it is proposed to apply the method of decomposition modeling, which consists in constructing a mathematical model for observing and identifying the state of ecosystems on the basis of ecosystem balance equations, taking into account the military-technologenic impact. The principle of the method is that the entire military natural-technogenic geosystem of the proving ground is divided into training facilities and independent ecological zones, and an ecosystem model is developed for each facility.

1. Introduction

The current state of the Earth's biosphere is characterized by significant changes caused by anthropogenic activities. An uncontrolled increase in the consumption of natural resources, pollution of the environment with waste from technological production, and the lack of an effective environmental conservation strategy have led to the rate of extinction of living organisms in the ecosystems of the Earth reaching, according to the most conservative estimates, 5 000 or, according to some estimates, 30 000 species per year [1].

The situation with the assessment of the environmental impact of military activities at proving grounds is a rather problematic and controversial one [2].

There are currently no methods adapted to carrying out such an assessment. In the context of the development of approaches to environmental assessment of the impact of military-technogenic factors, it will be necessary to further develop and apply a more effective mathematical apparatus based on a systematic approach involving simulation modeling, optimal control and filtering theory.

The problem of environmental assessment of technogenic impacts is quite acute for humanity. Over the past 25 years, a fairly large amount of factual and methodological material has been accumulated, which is practically not used to solve technical and technological problems in the search for approaches to ensuring the environmental safety of military activity [1].

Over the past years, great efforts have been made on the development of methods for an objective assessment of the technogenic impact on the environment. A number of such methods that have found the most widespread application are described in the relevant literature [2, 3, 4]:

– cartographic methods (layering method, method of combinations of map analysis);

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– matrix methods (Leopold matrix, Petersen matrix, matrix of interacting components, Sørensen echelon matrix);

– methods based on network diagrams;

– statistical methods;

– adaptive methods (Sondheim method, decision analysis, Holling method);

– modeling methods (simulation and optimization models, models based on the concept of a database (knowledge base), logical information models).

However, there are still no established methods for assessing the environmental impact of military activities.

Therefore, the problem of developing a method that would make it possible to carry out an operational, objective and adequate assessment of the environmental impact of various types of military activities is a relevant one.

An analysis of existing methods for assessing the impact on the natural environment confirms the significant potential for the application of modeling methods, namely simulation and optimization models, in combination with expert methods.

For an integrated assessment of the state of ecosystems, it is proposed to apply the method of decomposition modeling, which consists in constructing a mathematical model for observing and identifying the state of ecosystems on the basis of ecosystem balance equations, taking into account the military-technologenic impact of military activities.

The main technique of the decomposition modeling method is that the entire military natural-man-made geosystem of the proving ground can be divided into training facilities and independent ecological zones (eco-reservations of biocoenoses of a biome). An ecosystem model is developed for each of these facilities. Mathematical models of ecosystems of training facilities at the proving ground can be conditionally divided into:

– models with a low-intensity impact of military-technogenic factors;

– models with a high-intensity impact of military-technogenic factors.

Both types of models are rough three-dimensional mathematical models of ecosystems, which differ in that models of the first type are linear (the possibility of linearization near the point of the quasi state is allowed), while models of the second type arre nonlinear [5]. A mathematical model of free ecological zones is a multivariate linear mathematical model obtained by linearization near the stationary state point [6].

2. Problem statement

To develop a general mathematical model for a training facility of a proving ground, we shall restrict our discussion to the balance equations of terrestrial mezoecosystems, which are based on the laws of conservation of mass and energy and which describe the movement of biomass and energy between the main components of these systems: producers, substrates, and consumers [7]. Producers with biomass $P_i\left(i = \overline{1,z}\right)\ z \in N$; $P^T = [P_1, \dots .. P_z]$ are autotrophic organisms, mainly green plants, capable of producing their own food from simple inorganic compounds; substrates with biomass $S_k\ \left(k = \overline{1,x}\right)\ \ x \in N$; $S^T = [S_1, \dots .. S_X]$ are food for producers; consumers with biomass $Q_j\ \left(j = \overline{1,h}\right)\ h \in N$; $Q^T = [Q_1, \dots .. Q_h]$ are heterotrophic organisms (animals (macroconsumers), bacteria and fungi (microconsumers) that consume ready-made organic substances but do not bring the decomposition of organic matter to simple mineral components), which feed on producers and other organisms. There are first-level consumers (those consuming plants) and second-, third- and higher-level consumers (predators).

We shall assume that the intensity of the technogenic load on the ecosystem of the training facility of the military proving ground is high if more than 0.1 percent of the total biomass of producers, substrates, and consumers is destroyed.

The mesoecosystem of a technogenically loaded territory is characterized by:

– stability, which is the property of an ecosystem to return to its original state after episodic and impulse impacts on its components;

– adaptability, self-organization and self-adjustment, which is the property of an ecosystem to change the characteristics of trophic webs in a group of organisms with the purpose of self-maintenance and self-regulation (homeostasis).

3. Solution

The mathematical model of the ecosystem will be described by generalized aggregated coordinates P, Q, S (Fig. 1) [8]

$$\begin{cases} \frac{dP_i}{dt} = \left(L_P^i - D_P^i\right)P_i - \sum_{j=1}^{\eta} a_{ij}Q_j + \sum_{k=1}^{\xi} b_{ik}S_k + \Omega_{P_i} + U_{P_i} + W_{P_i},\ i = \overline{1,\xi}, \xi \in N; \\ \frac{dQ_j}{dt} = \left(L_P^j - D_P^j\right)Q_j - \sum_{k=1}^{\eta} d_{jl}Q_l + U_{Q_j} + W_{Q_j},\ j = \overline{1,\eta}, \eta \in N; \\ \frac{dS_k}{dt} = \sum_{j=1}^{\eta} e_{kj}Q_j - \sum_{i=1}^{\xi} c_{ki}P_i + U_{S_k} + W_{S_k},\ k = \overline{1,\xi}, \xi \in N; \end{cases} \quad (1)$$

where L_P^i, L_P^j are the natural growth rates of producers and consumers, respectively; D_P^i, D_P^j are the mortality rates of producers and consumers, respectively; a_{ij} is the rate of consumption of biomass of the *i*-th type producer by an individual of the *j*-th type consumer; b_{ik} is the the rate of conversion of the biomass of the *k*-th type substrate into the biomass of the *i*-th type producer; d_{jl} is the rate of consumption of the *j*-th type consumer by the *l*-type consumer; e_{kj} is the reproduction of the *k*-th type substrate by the *j*-th type consumer; c_{ki} is the rate of consumption of the *k*-го th type substrate by the *i*-th type producer; Ω_{P_i} characterizes the conversion of solar energy by the *i*-type producer; $W_{P_i}, W_{Q_j}, W_{S_k}$ are the function that characterizes the technogenic impact on the components of the ecosystem; $U_{P_i}, U_{Q_j}, U_{S_k}$ are the function that characterizes the direct restorative (rehabilitative) effect of environmental protection measures.

The coefficients *L*, *D*, *a*, *b*, *c*, *d*, *e* depend on natural and climatic factors, nature, type, intensity of pollution, internal, background and external (from technogenic objects located outside the training facility), i.e. both on the components that comprise the system and on the rhythm (chronology) and the activity of military-technogenic activities.

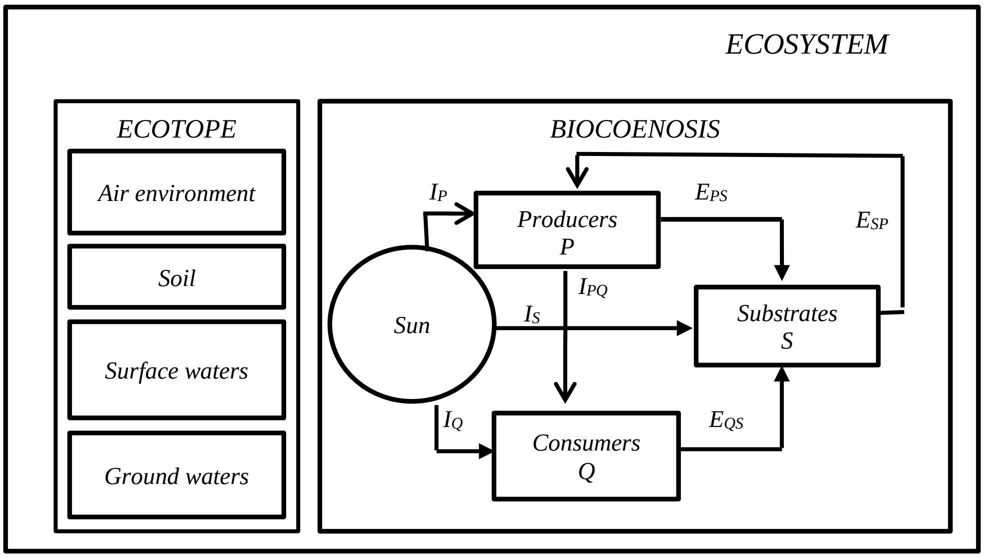

Fig. 1. Energy flows in an ecosystem

For a training facility with a low-intensity impact on the natural environment, we describe the dynamics of the deviation of the main components of the ecosystem from the linearization point using the system of equations [7]:

$$\begin{cases} \frac{dP}{dt} = (L_P - D_P)P - aQ + bS + \Delta\Omega_P + \Delta U_P + \Delta W_P \\ \frac{dQ}{dt} = (L_Q - D_Q)Q - dQ + \Delta U_Q + \Delta W_Q \\ \frac{dS}{dt} = cQ - cP + \Delta U_S + \Delta W_S \end{cases} \quad (2)$$

where:

– $L_P - D_P = D_P(I) = K_P e^{-a_P I} + K_{P_0}$ is the dependence of the difference between the growth and mortality rates of the producer on the pollution index I;

– $L_Q - D_Q = D_Q(I) = K_Q e^{-a_Q I} + K_{Q_0}$ is the dependence of the difference between the growth and mortality rates of the consumer on the pollution index I;

– $a = K_a e^{-a_k I}$ is the rate of consumption of the producer biomass by the consumer depending on the pollution index I;

– $b = K_b e^{-a_b I} + K_b$ is the rate of conversion of the substrate biomass into producer biomass depending on the pollution index I;

– $c = K_c e^{-a_c I}$ is the rate of consumption of the substrate by the producer depending on the pollution index I;

– $d = K_d e^{-a_d I} + K_d$ is the rate of consumption of phytophagous consumers by zoophagous consumers depending on the pollution index I;

– $\Delta\Omega_P = \Omega_P(t) = \Omega_{P_0} + \Omega_{P_1} \sin \omega_P t > 0$ is the impact of solar energy on the growth of producer biomass;

– $\Delta W_P, \Delta W_Q, \Delta W_S$ are the change functions, indicating the direct destruction of the correspondence of the producer, consumer and substrate of the training facility (modeled by impulse impact, which abruptly transfers the system to a new position on the corresponding coordinate);

– $\Delta U_P, \Delta U_Q, \Delta U_S$ is the change functions, modeling an external restorative effect, which consists of the sum of natural (external migration) and artificial (environmental) restorative impacts;

– I is the pollution index.

Unlike other factors, the pollution indices differ significantly in different pollution cases and significantly affect the modeling results. They are also determined by different methods. There are techniques described in the relevant literature that can be successfully applied.

Note that the following equation is used for modeling the pollution measurement process [9, 10]

$$\frac{dI}{dt} = -\alpha_I I \quad (3)$$

where $\alpha_I I > 0$ describes a gradual decrease in pollution of surface ecosystems of technogenic facilities in the time interval between technological processes at these facilities due to decay, washout, filtration, bioaccumulation of pollution.

Taking this into account, the system of equations in matrix form takes the form

$$\dot{X} = AX + \Delta\Omega + \Delta U + \Delta W \quad (4)$$

where

$$\mathrm{A} = \begin{bmatrix} L - D_P & -a & b \\ 0 & L - D_Q & 0 \\ -c & e & 0 \end{bmatrix};\ \Delta\Omega = \begin{bmatrix} \Delta\Omega_P \\ 0 \\ 0 \end{bmatrix};\ \Delta U = \begin{bmatrix} \Delta U_P \\ \Delta U_Q \\ \Delta U_S \end{bmatrix};\ \Delta W = \begin{bmatrix} \Delta W_P \\ \Delta W_Q \\ \Delta W_S \end{bmatrix}$$

Simulation modeling of complex dynamic systems is widespread in systems ecology [2, 8, 11, 12, 13]. To carry out simulation modeling, specialized software based on Simulink, VenSim, Model Vision Studium and other computer simulation systems can be used, which have found wide application in the construction of simulation models in various fields of science and technology.

On the basis of developed models (2) and (3), a software-modeling complex was created in the Simulink computer modeling subsystem of the MatLab computational mathematics environment, which made it possible to simulate the state of the ecosystem of training facilities with low- and high-intensity impact on the natural environment. By means of this subsystem, new classes are implemented from a set of libraries for constructing mathematical models, using typical elementary ones.

By changing certain attributes of the blocks, the behavior of the created classes of models was programmed and, by means of the links, an integral model of the ecosystem was created. Thus a object-oriented environment for simulation modeling of processes in technogenically loaded ecosystems was implemented.

Simulation modeling makes it possible to obtain results for assessing trends in the dynamics of ecosystem processes occurring over 10 years and to evaluate the impact of the military-technologenic load from its various factors on the general state of the ecosystem.

To carry out the modeling, we shall assume that for the ecosystem of a training facility, according to the data on the annual combat training plan, the most technogenic loads are expected precisely at the beginning of the period and during the growing season. The dynamics of the main components of the ecosystem of a training facility with a high-intensity technogenic impact can be described by a system of nonlinear equations in the form [11]:

$$\begin{cases} \frac{dP}{dt} = P(\varepsilon_1 - \gamma_{11}P - \gamma_{12}Q - V_{13}S) + \Delta\Omega_1 + \Delta U_1 + \Delta W_1 \\ \frac{dQ}{dt} = Q(\varepsilon_2 - \gamma_{21}P - \gamma_{22}Q - V_{23}S) + \Delta\Omega_2 + \Delta U_2 + \Delta W_2 \\ \frac{dS}{dt} = S(\varepsilon_3 - \gamma_{31}P - \gamma_{32}Q - V_{33}S) + \Delta\Omega_3 + \Delta U_3 + \Delta W_3 \end{cases} \quad (5)$$

where P, Q, S are the relative biomass (relative to the ecosystem of intact, wild nature) of producers, consumers and substrates in the ecosystem of the training facility, respectively; $e_i = e_i(I) = e_{i_0} - e_{i_1} \cdot I$; $g_j = g_j(I) = g_{j_0} - g_{j_1} \cdot I, i = 1.2.3;\ j = 1.2.3$ are the coefficients that depend on the facility pollution index.

The new state of equilibrium of system (5) at $\Omega_i = 0, U_i = 0, W_i = 0\ (i = 1,2,3)$ is determined by the solution of the system:

$$\begin{cases} \varepsilon_1 - \gamma_{11}P - \gamma_{12}Q - \gamma_{13}S = 0 \\ \varepsilon_2 - \gamma_{21}P - \gamma_{22}Q - \gamma_{23}S = 0 \\ \varepsilon_3 - \gamma_{31}P - \gamma_{32}Q - \gamma_{33}S = 0 \end{cases} \quad (6)$$

and, due to the dependence of the coefficients on the pollution index *I*, also depends on *I*.

Taking this into account, we determine the results of simulation modeling of the high-intensity impact of technogenic factors on the components of the facility's ecosystem. For linear and nonlinear models of ecosystems of a training object, there is a relationship between the state of producers, consumers and substrates in the ecosystem. At the moment $t_{1п}$, combat training activities begin, which are characterized by an adverse impact on the ecosystem of the training facility. Under this impact, the ecosystem over time becomes more sensitive and vulnerable to disturbances through the significant reduction in the area occupied by producers. This, in turn, leads to a significant decrease in the amount of substrates, which, due to negative feedback, provide less nutrients. A decrease in the amount of producers also leads to a decrease in the amount of phytophagous animals, the latter, in turn, leading to a decrease in zoophagous animals in the ecosystem area. Similar processes occur for the moments $t_{2п} \div t_{9п}$. At the moment t_{13} $(t_{23} \div t_{93})$, combat training activities are terminated. The ecosystem, due to succession, tries to restore the equilibrium state of biomass production, but in conditions when we observe an increase in anthropogenic pressure with the expansion of the zone, the disturbance of the internal forces of the ecosystem becomes insufficient for self-restoration.

4. Conclusion

By means of computer modeling, for each training facility of a certain natural territorial complex, it is possible to obtain integrated predictive estimates of changes in the indices of the state of ecosystems under the impact of technogenic load factors, changes in weather and climatic conditions and external anthropogenic pressure. The results of model applications show that with different rates of disturbing impacts, individual components of the ecosystem in these conditions respond to them differently.

When creating optimal conditions for self-restoration, along with intensively loaded technogenic objects, free ecological zones should be available, serving as ecosystems' springboard, from which the natural succession of edificator species, creating dominant groups of restoration of the structure of the ecosystem trophic web, will begin.

On the basis of the developed method of simulation modeling, it is possible to obtain quantitative estimates of the impact of technogenic factors on the state of ecosystems of the elements of the technosphere.

Simulation modeling allows assessing the impact of heterogeneous factors of natural, anthropogenic and technogenic origin on the state of ecosystems in dynamics. It is an effective tool in a decision support system ensuring the environmental safety of a military proving ground at the required level.

References

[1] Ecosystems and Human Well-being: Synthesis. http://www.millenniumassessment.org/documents/document.356.aspx.pdf

[2] А.Б. Садыгов, Модели и технологии решения задач управления в чрезвычайных ситуациях, Баку, “Элм”, (2017) 356 p. [In Russian: A.B. Sadigov, Models and technologies for solving problems of emergency management, Baku, Elm]

[3] Craig R. Beatty, Neil A. Cox and Mirjam E. Kuzee. Biodiversity guidelines for forest landscape restoration opportunities assessments. https://portals.iucn.org/library/sites/library/files/documents/2018-022-en.pdf

[4] Гагина Н.В. Экологическая экспертиза, менеджмент и аудит. Минск, Изд. Центр БГУ, (2011), 174 с. https://elib.bsu.by/bitstream/123456789/41083/1/УМК_полный_ЭЭМА.pdf [In Russian: Gagina N.V. Environmental impact assessment, management and audit. Minsk, Izd. Tsentr BGU]

[5] Математическое моделирование биогеоценотических процессов, Под ред. Ю.М. Свирежева, Москва, Наука, (1985) 126 p. [In Russian: Mathematical modeling of biogeocenotic processes, Ed. Y.M. Svirezhev, Moscow, Nauka]

[6] Н.Н. Моисеев, Математические задачи системного анализа, Москва, Наука, (2001) 481 p. [In Russian: N.N. Moiseyev, Mathematical problems in systems analysis, Moscow, Nauka]

[7] Ю.М. Свирежев, Д.О. Логофет, Устойчивость биологических сообществ, Москва, Наука, (2008) 376 p. [In Russian: Y.M. Svirezhev, D.O. Logofet, Sustainability of biological communities, Moscow, Nauka]

[8] Смит Дж., Модели в экологии, Пер. с англ., Москва, Мир, (2016) 184 p. [In Russian: J. Smith, Models in Ecology, Trans. From English, Moscow, Mir]

[9] A.B. Sadigov, Methods of risks assessment of life activity in environment, Proceedings Book of the 1st International Turkish World Engineering and Science Congress, 7-10 December, 2017, Antalya, Turkey, p.28-38.

[10] A.B. Sadigov, R.M. Zeynalov, Optimal control in the problems of calculating the benefit/cost ratio in emergency response, Informatics and Control Problems. 40 No.1 (2020) pp.47-56. journal homepage: www.icp.az

[11] Е.С. Бенькович, Ю.Б. Колесов, Ю.Б. Сениченков, Практическое моделирование динамических систем, Санкт-Петербург, (2012) 464 p. [In Russian: E.S. Benkovich, Y.B. Kolesov, Y.B. Senichenkov, Practical modeling of dynamical systems, St. Petersburg]

[12] C.H. Wagh, M.G. Gujar. The Environmental Impact Assessment by Using the Battelle Method. International Journal of Science and Research, Volume 3, Issue 7 (2014).
[13] R.M. May. Stability and Complexity in Model Ecosystems. 2001, 304 p.