Представлені результати моделювання системних колорометричних параметрів, які демаскують диких водоплавних птахів. В результаті проведених досліджень з використанням нового класу математичних моделей – дискретних моделей динамічних систем (ДМДС) здійснено формалізований опис системних аспектів, які відрізняють захисне забарвлення качки-крижня від колорометричних параметрів рослинних угруповань. Отримані результати відкривають нові підходи до розробки дистанційних методів вивчення умов проживання та шляхів міграцій диких водоплавних птахів

Ключові слова: водоплавні птахи, демаскування, захисне забарвлення, качка-крижень, колорометричні параметри, обробка зображень, рехронізація, системний аспект, траєкторія системи, фітоценоз

Представлены результаты моделирования системных колорометрических параметров, демаскирующих диких водоплавающих птиц. В результате проведенных исследований с использованием нового класса математических моделей – дискретных моделей динамичных систем (ДМДС) осуществлено формализованное описание системных аспектов, которые отличают защитную окраску утки-кряквы от колорометрических параметров растительных сообществ. Полученные результаты открывают новые подходы к разработке дистанционных методов изучения условий обитания и путей миграций диких водоплавающих птиц

Ключевые слова: водоплавающие птицы, демаскировка, защитная окраска, колорометрические параметры, обработка изображений, рехронизация, системный аспект, траектория системы, фитоценоз, утка-кряква

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MATHEMATICAL MODELING OF SYSTEMIC COLOROMETRIC PARAMETERS UNMASKING WILD WATERFOWL

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1. Introduction

Abrupt climatic changes of global nature cause a number of serious problems of biosafety. These problems are connected with violation of evolutionary formed relationships in communities of living beings, which determine the nature of homeostasis mechanisms. Violation of homeostasis mechanisms leads to instability of biological communities, which can be expressed, in particular, in outbreaks of development of pathogens of dangerous infectious diseases of humans and animals. It gives rise to the problem of controlling the spread of animals that can be carriers and/or reservoirs of these diseases. This problem relates to the field of veterinary medicine, to be more exact, veterinary biosecurity. A resonant example of this kind is the spread of avian influenza by wild migratory waterfowl [1], which is a source of many serious financial risks and biosafety hazards.

Monitoring of distribution and migrations of wild waterfowl should be performed on vast areas. In many cases, large parts of these territories are difficult to access both on water and on land. This determines effectiveness of the use of remote (aerospace) means, which are currently widely applied for environmental studies [2] of animals' life and habitat in the wild [3].

The size and severity of biosafety hazards, which require greater control over migrations of wild waterfowl, imply expanded arsenal of remote means of control. Causes of financial nature make it advisable to use relatively simple and cheap methods in this arsenal. Such methods include, in particular, digital photography from light unmanned aerial vehicles (UAVs). This kind of remote study of animals in the wild is becoming more popular with zoologists and people who deal with other biological disciplines [4]. While using these methods, one might encounter problems associated with protective coloration in animals. These issues may also occur when applying these methods for keeping records of wild waterfowl in natural habitat. Earlier, on the example of locust paper [5] showed the possibility of finding systemic colorometric parameters (SCP), which allow unmasking the animals with protective coloration. It goes about SCP, which can be obtained as a result of computer processing of the components of RGB-model of digital photos of phytocenosis. Protective coloration of animals, living in such plant community, imitates the contents of plant pigments in phytocenosis.

Computer processing can be implemented using a new class of mathematical models, known as discrete models of dynamic systems (DMDS) [6]. DMDS allow formalized description of various aspects of behavior of biological systems of various nature [7], including the structure and dynamics of colorometric parameters of plant communities [8]. Research [9] proposed interpretation of DMDS as a tool of the formalized description of diverse strategies of functioning of biological systems of various nature. Systemic parameters of protective coloration in animals can be considered as elements of such strategies.

This paves the way for a new approach to development of SCP, which will make it possible to unmask against vegetation background the animals, which have protective coloring. The idea is that by using DMDS, it is possible to determine parameters that are associated with dynamics of change of pigments in different phases of the life cycle of this plant community. There is a rather high probability to differentiate this dynamics from the dynamics of changing protective coloration of animals (such dynamics can be pronounced too weakly or be absent altogether). Certain aspects of these differences will enable us to find SCP, which unmask animals.

The practical aspect of relevance involves research in approaches to development of relatively simple and inexpensive methods of waterfowl unmasking against a vegetation background. We mean, in particular, the methods of waterfowl unmasking by processing the images, which can be obtained using digital photography. A relatively simple and low-cost method of digital photography in the visible spectrum, in principle, can be done remotely from light UAVs. It is supposed to use the photographic equipment, which now is usually included in the cheapest modifications of light UAVs. The possibility to mobilize and use all available amount of equipment can prove to be very relevant in some extreme situations. This may involve, inter alia, the situations of biosafety hazards, related to hotbeds of avian influenza and other diseases, the potential reservoir of which can be flocks of waterfowl. Development of remote detection technology in the extreme situations of these hotbeds on vast areas of inaccessible terrain requires approaches to solving the problem of waterfowl unmasking. The study of such approaches determines the practical relevance of this work.

The relevance of present work is also associated with finding new approaches to studying the regularities of functioning of protective coloration in animals, which use new classes of mathematical models

2. Literature review and problem statement

Currently, remote methods are widely used for studying the life of animals in the wild, in particular for studying the distribution and migration of birds. Paper [3] refers to possibilities of using analysis of space photos for keeping records of marmots in steppe regions (these animals can also be a potential reservoir of dangerous infectious diseases). In article [10], the coral reef ecosystems were explored with the use of remote methods. These ecosystems are in great danger due to global climate change that can significantly alter the nature of distribution of waterfowl – potential reservoirs for avian influenza. Paper [11] describes application of lidars to monitor birds' migration. Migration routes of wild waterfowl largely determine the nature of their contact with their domestic relatives and, respectively, the biosecurity threats, associated with avian influenza. Article [12] describes the use of remote methods for mapping the migration of birds. This can be useful in determining localization of potential hotbeds of various dangerous infectious diseases carried by birds.

In all these cases, financial costs of high-tech and knowledge-based equipment for monitoring the animal life in natural environment are rather significant. The level of required funding may reach a critical point in extreme situations, in which sources of biosafety threats will be placed on large areas. Even if such funding is available, but there is acute shortage of time, there will be no real possibility of deployment of means of detection of these sources in the required timeframe.

In this regard, the significant role belongs to technologies of controlling the animal life under natural conditions, which can be implemented using light UAVs, particularly through digital photography. At present, considerable experience of such use of drones has been accumulated.

Paper [13] explores the use of drones for studying behavior of birds, particularly of mallard ducks. The influence of color, speed and flight angle of drones on behavioral reactions of mallard ducks was described. These results create some prerequisites for using drones in activities, aimed at prevention of contacts of domestic waterfowl with their wild relatives. These contacts create potential foci of biosafety risks associated with avian influenza.

In extreme situations, causing potential threats to biosecurity, mobilization of total available UAV fleet for detection of animals can be justifiable. The use of the simplest and cheapest UAV modifications will require addressing a number of problems associated with protective coloration in animals. This also applies to wild migrant waterfowl. Digital photography equipment at such UAVS in many cases allows fixing the values of colorometric parameters only in broad bands of the visible part of the spectrum. These colorometric parameters correspond to the spectral characteristics of red, green, and blue pixel elements. In this regard, the important role is played by the opportunity to obtain information about colorometric parameters of vegetation and protective coloration of animals based on analysis of the components of the RGB-model of digital photography. In addition, control with involvement of light UAVs requires the possibility of using the original factual information with a number of shortcomings. We are talking about a relatively small volume of information array and existence of lacunas in them (due to poor visibility, weather conditions etc.). It is important that due to these shortcomings, obtained information does not always reflect dynamics of the studied processes in real time.

Implementation of these opportunities with the formalized description of the structure of relations and dynamics of colorometric parameters of vegetation and animals requires appropriate mathematical tools. Within the frameworks of this work, the role of such instruments is played by DMDS.

The use of components of the RGB-model minimizes the possibility to distinguish colorometric parameters of vegetation and of protective coloration of animals by providing relatively narrow spectral bands, which correspond only to plant pigments. To do this, it is possible to use a different approach, based on differences in dynamics of colorometric parameters of vegetation and protective coloration of animals.

While using DMDS, in a number of cases there is a possibility to give description of dynamics of the researched object based on analysis of information, contained in one image, obtained at a single moment of time. This possibility is based on the use of technique, which received the working name of rechronization. The use of rechronization is based on the assumption that separate parts of the researched object (for example, different parts of a plant community) change within one cycle, but are in its different phases. With the help of DMDS and rechronization, it is possible to construct an idealized trajectory of the system (ITS). ITS reflects dynamics of colorometric parameters of phytocenosis, on the background of which it is necessary to unmask wild waterfowl. Resulting dynamics can be quite close to real. This is mostly due to the structure of internal relations between parameters of the system. Relationships between colorometric parameters of protective coloration of animals can also be presented in a form that is similar to ITS. Since this form will not reflect dynamics, the more correct name would be: idealized pseudo trajectory of the system (IPTS). The view of IPTS of protective coloration of animals reflects only a set of colorometric parameters, contributing to disguising against the background of certain plant communities.

The nature of disguising coloration of animals is often associated with the character of colorometric parameters of plant communities in their habitat. For description of colorometric parameters of plant communities, we use vegetation indices, which represent relatively simple expressions that describe relationships between optical characteristics of plant biomass in different regions of the spectrum. These spectral regions are linked to various plant pigments. Paper [14] describes the results of research in dynamics of carotenoids in a pine forest using measurements in narrow spectrum bands, particularly in its visible region.

Article [15] describes a more complex model of relationships between carotenoids and anthocyanins in leaves of plant communities of Hawaii. Paper [16] explains how water regime of a desert plant influences reflective properties of its phytomass, which should be taken into account at remote determining of chlorophyll content in it.

A relatively simple kind of mathematical apparatus, used for remote determining of plant pigments, is compensated by using complex and expensive equipment that allows conducting measuring in narrow areas of the spectrum. In some cases, measurements are taken outside the visible spectrum.

Paper [17] shows the fundamental possibility with the use of DMDS to identify remotely the differences of colorometric characteristics of vegetation cover and protective coloration of locusts with the use of the results of rougher measurements, which correspond to broader bands of the visible part of the parameter's spectrum. We are talking about parameters, the value of which can be obtained by computer analysis of the components of the RGB-model of digital photography.

In all considered sources, during remote detection of animals there were no difficulties, related to their protective coloration. This article addresses this issue and offers an effective approach to its solution.

3. The aim and objectives of the study

The aim of present research is mathematical modeling using DMDS, systemic aspects of relationships of colorometric parameters of protective coloration of waterfowl (mallard duck) and plant communities in habitat of this species.

To accomplish the set goal, the following tasks had to be solved:

– to find a systemic colorometric parameter that will allow us to unmask the mallard duck against the background of plant communities in habitat;

– using the systemic colorometric parameter, to implement the procedure of image processing for detection of ducks in the wild.

4. Materials and methods of research in systemic aspects of relationships between colorometric parameters of protective coloration of waterfowl and plant communities in their habitat

Modeling of ITS of plant communities and IPTS of protective coloration of waterfowl was conducted using rechronization technique with the help of DMDS, which used an approach based on extended interpretation of the Liebig law and the Spearman correlation [18].

A detailed description of the DMDS model can be found in [6, 18]. The following is a brief description of the model and the tasks that it enables us to solve. The problem of modeling of relationships between components or parts of complex natural systems, which define behavior of the system, its dynamics and sustainability, is one of the most demanded in theoretical biology and ecology and provides a researcher with virtually unlimited field for creativity.

DMDS model is based on representation of the modeled system as the totality of N components, which can be designated as $A_1, A_2, \ldots, A_N$. Each component is supposed to take K of discrete values, which it is possible to write down as 1, 2,...., *K*. Time is supposed to be discrete, i. e. the state of the system at moment *t* is written down as vector $(A_1(t), A_2(t), \ldots, A_N(t))$. We also believe that dynamics of the system is determined. This means that its state of the system at moment t+1 is definitely determined by the state at moment *t*. In [6, 18], it was shown that dynamics of such a system is determined by a periodic trajectory that can be written down in matrix form

$$\begin{pmatrix} A_1(s) & A_1(s+1) & \ldots & A_1(s+\mathrm{T}-1) \\ A_2(s) & A_2(s+1) & \ldots & A_2(s+\mathrm{T}-1) \\ \vdots & \vdots & \ddots & \vdots \\ A_N(s) & A_N(s+1) & \ldots & A_N(s+\mathrm{T}-1) \end{pmatrix} \quad (1)$$

for some integers *s* and T.

Then we introduce the concept of relations between components and types of dynamics, based on these relations. It is supposed, that between each pair of components of A_i and A_j, there can exists the following relationships: (0, 0), (0, +), (+, 0), (0, –), (–, 0), (+, –), (–, +), (–, –), (+, +), well known from theoretical biology. In this case, it is not excluded that i=j; then a list of relationships includes only symmetric relations: (0, 0), (–, –), (+, +). Then we introduce the type of dynamics, which determines dynamic behavior of the system. Types of dynamics are also based on the known concepts of theoretical biology. Two types of dynamics were introduced: one of them is based on weight functions and the other – on the law of minimum of von Liebig. Each of these types permits extensive parameterization, which makes the model flexible enough to describe complex systems.

Identification of relationships between components of the system is based on the following procedure. Let us write down the table of observation of real system as

$$\begin{pmatrix} C_{11} & C_{12} & \dots & C_{1B} \\ C_{21} & C_{22} & \dots & C_{2B} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N1} & C_{N2} & \dots & C_{NB} \end{pmatrix}, \tag{2}$$

where each column represents one observation (totally, B observations were obtained). Let us note that in table (2), observations should not be placed in order of time, although the system is dynamic.

For matrix (1), we will calculate the correlation table between rows and, similarly, the correlation table between rows in table (2). It is possible to use a Pearson or a Spearman correlation coefficient. Having designated in general terms the element of the first correlation table as $r_{i,j}$ and the element of the second table as $\tilde{r}_{i,j}$, you can keep the difference measure between the correlation tables

$$D = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (r_{i,j} - \tilde{r}_{i,j})^2. \tag{3}$$

Search for inter-component relationships, as well as original conditions that determine the trajectory (1) is performed by minimizing the measure (3).

Construction of ITS and IPTS was based on the actual material which included reference snapshots of plant communities and of protective coloration of waterfowl, presented in Fig. 1, 2. The working hypothesis, formulated on the basis of comparison of the type of specified ITS and IPTS, was verified by processing the images that were obtained from the same source

Fig. 1. Reference image of plant community in the habitat of mallard duck

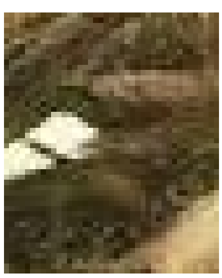

Fig. 2. Reference image of protective coloration of a female mallard duck

The reference snapshot that is presented in Fig. 1 contains colorometric parameters, associated with plant pigments. It goes about plant pigments, which play an important role in bioproduction processes of all plant communities. These plant communities include communities of higher plants in the bank zone of ponds, in habitats of waterfowl.

The reference snapshot that is presented in Fig. 2 contains colorometric parameters associated with protective coloration of ducks. These colorometric parameters of protective coloration imitate colorometric parameters of plant communities in the habitat of ducks.

5. Obtained results of research into systemic aspects of relationships of colorometric parameters of waterfowl protective coloration and phytocenosis in their habitat

The authors conducted parallel comparative analysis of the kind of IPTS of protective coloration of waterfowl and ITS of plant communities in their habitat.

Such analysis plays the role of a tool for formulating working hypotheses. Within the framework of this work, the working hypothesis describes relationships between two components of the system. We are talking about relationships, the character of which makes it possible to distinguish between colorometric parameters of plant communities and protective coloration of animals. This hypothesis at the first stage of formulation is presented by implications, the content of which is reflected in formulas (4)–(8)

$$A \to B, \tag{4}$$

statement A is true, if condition is satisfied:

$$\frac{C_1}{C_{11}} \neq \frac{C_2}{C_{22}}, \tag{5}$$

statement A is false, if condition is satisfied:

$$\frac{C_1}{C_{11}} = \frac{C_2}{C_{22}},$$

where C_1 and C_2 are the number of conditional steps in time with unique combinations of values of certain parameters, x and y (in conditional score), respectively: for ITS and IPTS, and C_{11} and C_{22} are the total number of conditional steps in time, respectively: for ITS and IPTS.

Statement B is true, if condition is satisfied:

$$V_1 \neq V_2. \tag{7}$$

Statement B is false, if condition is satisfied:

$$V_1 = V_2, \tag{8}$$

where V_1 and V_2 are the values of variability of values of indicators of relationship of parameters x and y, respectively for ITS and IPTS.

Based on processing of reference images with the use of rechronization and DMDS, which are presented in Fig. 1, 2, we obtained ITS and IPTS, the form of which is presented in Table. 1, 2.

These trajectories were obtained in the following way. The original image was divided into sections (by a rectangular grid). For each section, original parameters were calculated (components of the RGB model), and based on them, derived parameters were calculated. Such derived parameters included R/(R+G+B), G/(R+G+B), G/(R+G), R/G, having some biological sense. Using the data of derived parameters as components of the DMDS model, we obtained trajectories of IPTS and ITS.

After concretization of the hypothesis based on the data of these two trajectories, we determined the form of SCP, the effectiveness of using of which for unmasking of ducks was checked by processing relevant images. With the use of SCP, original images, which were supposed to recognize the contour of an animal, were processed. The results below show that SCP makes it possible to distinguish the images of such contours, even if the source images were superimposed by digital noise that simulates adverse visibility conditions.

The form of ITS and IPTS, presented in Table 1, 2 allows us to specify the working hypothesis, the essence of which is represented above by formulas (4)–(8), etc. In the tables, the values of colorometric parameters are represented in conditional score (1 – low, 2 – medium, 3 – high), and maximum values for this table are written down in bold.

The role of components x and y in this refined hypothesis is performed by colorometric parameters R/(R+G+B) and G/(R+G+B). The difference between theie values plays the role of relationships of these parameters, and root mean square deviation serves as indicator of variability of values of this difference. Given this specificity, the working hypothesis is to be complemented by implication, the content of which is reflected in formulas (9), (10).

$$B \rightarrow D, \tag{9}$$

statement D is true, if condition is satisfied:

$$S_1 \neq S_2,$$

statement D is false, if condition is satisfied:

$$S_1 = S_2, \tag{10}$$

where S_1 and S_2 are the values of root mean square deviation of values of difference (R – G)/(R+G+B), respectively: for ITS and IPTS. We are talking about values of root mean square deviation that are determined for a sample of microsegments, into which segments of a duck's image against the background of the vegetation community are divided.

Table 1

Form of ITS, reflecting the cycle of changes in values of colorometric parameters of plant community in habitat of mallard duck

Indicator	Number of the conditional step by time									
	1	2	3	4	5	6	7	8	9	10
R/(R+G+B)	1	1	1	2	**3**	**3**	**3**	2	1	1
G/(R+G+B)	1	2	**3**	**3**	**3**	2	1	1	1	2
G/(R+G)	1	**2**	**2**	**2**	**2**	1	1	1	1	**2**
R/G	1	1	1	1	1	**2**	**2**	**2**	**2**	1

Results of processing of the image of duck-mallard against the background of grassy vegetation in habitat of this species are presented in Fig. 3–5.

Table 2

Form of IPTS, reflecting pseudo-cycle of changes in colorometric parameters of protective coloration of mallard duck

Indicator	Number of the conditional step by time												
	1	2	3	4	5	6	7	8	9	10	11	12	13
R/(R+G+B)	1	1	1	2	**3**	**3**	**3**	2	1	1	1	1	1
G/(R+G+B)	1	1	1	1	1	2	**3**	**3**	**3**	2	1	1	1
G/(R+G)	1	1	1	1	1	1	1	2	**3**	**3**	**3**	2	1
R/G	1	2	**3**	**3**	**3**	**3**	**3**	2	1	1	1	2	3

Fig. 3. Original image of a female mallard duck against background of grassy vegetation in the habitat of this species

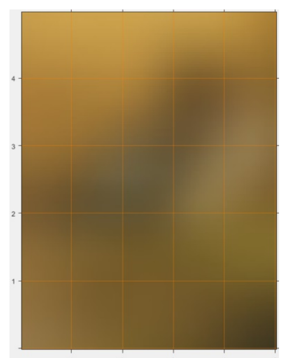

Fig. 4. Unprocessed image with computer imitation of the degraded conditions of filming

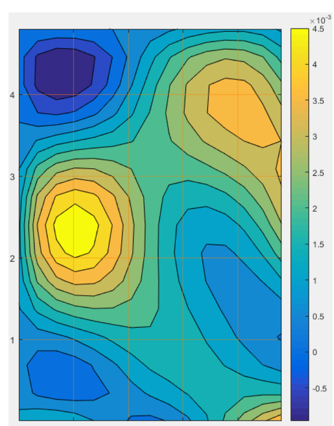

Fig. 5. Results of processing of artificially degraded image, shown in Fig. 2. On the right –scale of conditional colors, denoting values of root mean square expression (R–G)/(R+G+B)

As material in Fig. 3–5 show, processing of artificially degraded image dramatically increases its contrast range. In Fig. 5, there appears a rather clear silhouette of the duck's body parts, covered with feathers of protective coloration. At this stage, the work, directed towards development of other approaches to solution of the problem of identification of such silhouettes, was not performed, but unmasking of birds was quite effective.

6. Discussion of results of the study of systemic aspects of relationships between colorometric parameters of protective coloring of waterfowl and phytocenosis in their habitat

As a result of conducted research with the use of a new class of mathematical models (DMDS), we offered a formalized description of systemic aspects that distinguish between protective coloration of mallard ducks and colorometric parameters of plant communities. We are talking about plant communities in habitat of these waterfowl.

Results of this formalized description provide new approaches to development of distance techniques of studying living conditions and migration routes of wild waterfowl. This is related to the fact that animals often have protective colouration, greatly hampering their visual detection.

Implementation of these approaches does not imply replacement of existing remote methods of zoology and animal ecology. We are talking about supplementing of these methods with technologies that extend the scope of practical application of the specified remote methods, particularly in extreme situations.

These technologies imply the possibility of being used for detection of waterfowl, which have protective coloration, relatively simple and inexpensive methods of collection of initial information in extreme situations. We can talk about large-scale use of such methods as digital photography from light UAVs in extreme situations requiring detection of potential hotbeds of dangerous infectious diseases. Practical relevance of these studies involves finding new approaches to addressing some of the difficulties the large-scale use of these techniques and equipment. The cause of these difficulties is existence of protective coloration in waterfowl, which can be a potential reservoir of avian influenza and other dangerous infections and infestations. The approaches to elimination of these difficulties, identified in this research, are based on application of a new class of mathematical models – DMDS to image processing. The advantage of implementation of these approaches is the possibility to simplify considerably and to decrease the cost of collection of actual source material. The main disadvantage is associated with inability to achieve greater, compared with known methods, detailing of the processed image at this stage. This disadvantage may not be of crucial importance in the extreme situations, described above.

The present research is a part of a series of studies, the purpose of which is to expand the scope of practical application of DMDS. These studies are supposed to be continued in future.

7. Conclusions

1. We found systemic colorometric parameters, which allows unmasking the mallard duck against the background of plant communities in the habitat of this species of birds. To find this parameter, DMDS model was used, with the help of which dynamics of selected colorometric parameters was identified. These dynamics (in the form of a trajectory) allowed putting forth a hypothesis about SCP, which makes it possible to make the outline of an animal in the picture more contrast with the use of digital image processing.

2. The use of the resulting SCP was tested on a real snapshot with superimposed digital noise, i. e. the hypothesis, referred to in paragraph 1, was verified. Using this approach, it is also possible to detect other waterfowl, which have similar protective coloration, including those that may become potential reservoirs and carriers of dangerous infectious diseases.

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