Modeling of adaptation of pests to transgenic agricultural technology taking into account the influence of taxis

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Abstract. Despite the high-tech innovation level of cultivation and processing damage by insects - pests is still high. It causes the urgency of growing new genetically modified varieties of agriculture containing the gene of the soil bacterium called transgenic or genetically modified. This article explains the importance of mathematical modeling for the cultivation of genetically modified crops.

1 Introduction

Nowadays two modified types of crops are known, namely: genetically modified (GMO) or, as they are otherwise called, transgenic crops and hybrids and crops obtained by breeding as a result of crossing different varieties that differ in a unique genotype. And although it is forbidden to grow transgenic varieties in our country, Monsanto, a leader in the field of GMOs, is one of the largest suppliers of seeds to Russia. This, perhaps, explains the fact that the hybrids obtained by them have properties similar to transgenic plants - high resistance to drought, to certain types of pests, etc. At the same time, unlike transgenic species that have "shelters", the field is completely sown with hybrids and then treated with herbicides and insecticides. It is logical to assume that insects are moving in the direction of increasing food, which means that the combination of fields with less attractive "ordinary" varieties and hybrids for pests would make it possible to control pests and predict areas of their concentration using insecticides. Transgenic varieties and breeding hybrids also have one important common feature that affects the environment - a reduced rate of decomposition of plant residues. There is increasing evidence that agricultural pest populations are beginning to develop resistance to toxins and are beginning to feed on transgenic plants and herbicide-treated hybrids.

The detection of toxins in the root secretions of corn, rice and cotton and their long-term persistence in the soil suggests that special precautions must be taken. Unlike Bt-plants, the targets of these compounds are not insects, but mammals, including humans. Almost all of these substances are xenobiotics, but their ability to persist in the environment has not been

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sufficiently studied. It is clear, therefore, that the potential damage of growing transgenic plants synthesizing them in the environment cannot be even approximately estimated.

Thus, the study and development of demogenetic mathematical models for crop forecasting remains relevant and acquires a new meaning [1–4].

In modern demogenetic models, the influence of population taxis is still poorly reflected; many essential physiological features are omitted, such as periods of plant resource consumption and periods of reproduction. Winged insects have their own differences, for example, the most common corn pest can fly several kilometers without food, as well as the difference in the structure of male and female individuals, which is why females are the most mobile and move faster. On the other hand, physiological features do not allow this type of pest to move independently in hot weather, and then they are transported by warm air currents. This leads to the propagation of the wave mainly along these boundaries or, in any case, the propagation of the wave along the entire length is determined by surface phenomena. A similar situation arises in the ocean, where the spread of a number of species occurs only in the surface layer [5–6]. The very phenomenon of fast and slow taxis has been studied in detail in the works of many well-known mathematicians [5–7], but the effect of taxis has only recently been taken into account in demogenetic models. Such objects in Russia and abroad were studied by such researchers as V.A. Kostitsyn, Yu.M. Svirezhev, V.P. Pasekov, Yu.P. Altukhov, Yu.V Tyutyunov., E.A. Zhadanovskaya, R. Arditi, D. Abrahamson, U. Wilensky, D. Bourguet, J. Chaufaux, M. Séguin, C. Buisson, J.L. Hinton, T.J. Stodola, P. Porter, G. Cronholm, L.L. Buschman, D.A. Andow, D.W. Onstad, C.A. Guse, J.L. Spencer, S.L. Peck and others. Moreover, in the works of foreign authors imitation modeling prevails; significant contribution directly to mathematical modeling of dynamics modified cultures were introduced by Russian scientists, including the Yu.V. Tyutyunov scientific school.

2 Materials and methods

To formulate the problem, it is necessary to introduce the biomass growth R=R(x,y,t) and take into account the well-known Malthusian growth coefficient rR. The natural dynamics of plant biomass is described by the equation (1):

$$\frac{\partial R}{\partial t} = \delta_R \Delta R + r_R R(1-\frac{R}{K_R}) - aRN, \tag{1}$$

In this equation, the growth factor $r_R = r_R + g(x,y,t)$ depends on $g(x,y,t)$ – a function that takes into account the fertility of a particular area of the field. The constant KR is used to denote the capacity of the medium. This parameter is of great importance for agroecosystems, since the determination of sowing density is still one of the important tasks in agriculture.

It is further assumed that we have two types of plant resources - "common" and transgenic, or "common" and hybrid [3]:

$$R = R_1 + R_2, \tag{2}$$

$R_1 = \alpha(x,y)R$ – initial biomass of a "common" plant resource, $R_2 = (1-\alpha(x,y))R$ – the initial biomass of a plant resource of a modified species – transgenic or hybrid.

Let us introduce the functions f_{ij} in accordance with Mendel's laws, where indices *i, j* are responsible for the values of genotypes with dominant and recessive traits *ss, rs, ss.*

Let us now consider the equations of pest dynamics, in which the activity of pests is determined by the sum (3):

$$N = N^{(1)} + N^{(2)}, \tag{3}$$

where the terms $N^{(1)}$ and $N^{(2)}$ – are the density (number) of pests in the active and passive states, respectively. In an ideal model, such a division could be neglected, since the pest moves towards an increase in the concentration of plants in the passive state, and towards an increase in the concentration of its relatives in the active state, which also leads to the part of the field with more attractive plants. However, during the sowing period, insects have time to give several generations of offspring, and different age and sex composition affects the spatial distribution of pests. Perhaps it would be more logical to divide the density of pests not by the type of states - active and passive, but by sex differences, since, as mentioned earlier, female corn pests are the most mobile.

When active, the poison-resistant pest eats only the normal type of plant resource. Here, poison refers to the ability of a plant to suppress an insect in the case of transgenic species, or poison from insecticides used on certain crop varieties. With slow taxis in a passive state, all types of pests move towards increasing the density of agricultural crops, but due to acquired mutations, their dynamics is different depending on the genotype.

In all cases, the boundaries of the area under consideration are assumed to be impenetrable, which corresponds to the natural conditions of agroecosystems.

3 Results

For a numerical study of a two-dimensional demogenetic model of pest dynamics, the solution of the grid properties of the correspondence to the alternately triangular method is used, in which the uniform norm of the residual vector is quite fast. Using adaptation of the alternating-triangular method of variational effective use for convection-diffusion problems with prevailing convection and a changing velocity field by virtue of determining the convergence estimate of the method [8-9].

In order to model possible scenarios for the behavior of a biological system consisting of predators and prey, a complex was developed. We consider a two-dimensional grid of size 100x100 units, the space step is 1, the time step is 0.01. The weight for a difference scheme is equal to 0.5. At the initial time of modeling, the concentration of prey was set to a constant value equal to 1, the initial concentration of predators is shown in Figure 1. When modeling the change in population concentration, the following parameters were used: mortality rates for a plant resource $\beta 1=\beta 2=1$, we will take the predator growth factor as the product of the pest efficiency coefficients e and the efficiency of the search for a plant resource by the pest a: $ea=1$, taxis coefficients are $k^{(1)}=k^{(2)}=40$. We believe that the mobility of different moth genotypes is the same $\delta=1$, pest mortality is expressed by the coefficient $\mu=6{,}84$, the capacity of the medium is $K_r=5*106\ kg/km^2$, we will take the Malthusian growth coefficient as $r_R=25{,}3\ year^{-1}$.

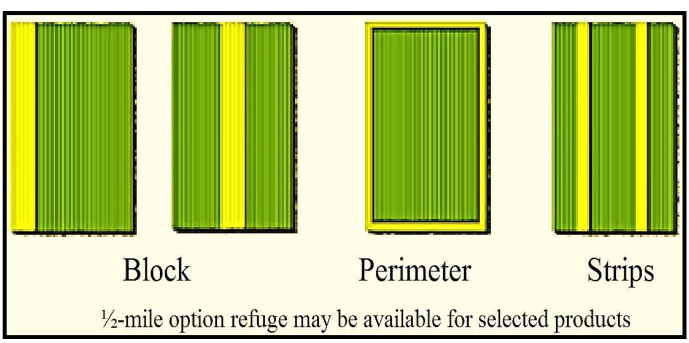

Fig. 1. Recommended ratio between field boundaries with transgenic crop species.

Pests with dominant (ss) and mixed (rs) genes that are not adapted to transgenes occur at the beginning of the study period. Pests with recessive traits (rr - genotype) appear when crossing at the end of the first month after the reproduction of the first-generation individuals. For the first few months, recessive traits appear only in slow taxiing individuals.

The dynamics of pests is directed inside the area of the site with traditional farming - "shelters" - here, interbreeding, insects lose their adaptability to transgenes. The concentration of predators is shown by the palette. The flow of colors in the drawings - as the area of the field is eaten away - occurs in accordance with the primary colors of the rainbow from red to purple.

As food is consumed, the boundaries of the area "smooth out", naturally leveling the spatial distribution of pests. The behavior of pests changes already in the second year. The dynamics of pests in the first two years varies significantly depending on the type of their activity - they feed or reproduce. The rapid grazing of a "common" type of plant resource inevitably leads pests in the direction of the biomass gradient of the transgenic plant resource. However, successful breeding is possible only in plots with "normal" crops, which shows a significant effect in the fast and slow taxi model.

Note that the main field cannot border on other modified crops. With an increase in the total area of "shelters" (>20%), the acquisition of Bt-resistance slows down, which corresponds to the generally accepted recommendations for the size of "usual" plots in GM fields - from 5% to 20%.

Figure 1 shows a fragment of the recommendations for sowing transgenic corn varieties from Syngenta (syngenta-us.com), where the impermeability of the boundaries is provided by the distance between the field sections. It is worth noting an interesting fact that the isolation of various parts of the field in the United States and many Western countries is provided by a distance of 1/2 mile [10]. Whereas in Russia and the countries of the former USSR, the fields are separated by forest belts, which prevents the active spread of pests and makes a significant difference in the description of the models.

Let us consider the uniform arrangement of four areas with “shelters”, when at the border a) there are “ordinary” plants, b) transgenic ones, which corresponds to real values. As you can see, in the first case, the eating of plants at the border of the plot occurs faster than in the central "shelters", while, unlike the field without "usual" borders, there are areas untouched by pests (highlighted in white). Green marks areas with intact root system, but damaged foliage and upper fruits.

The eating away of food in the "band" placement of "shelters" is clearly shown in Figure 2. As mentioned earlier, the presence of boundaries - "shelters" contributes to the faster eating away of the "ordinary" culture.

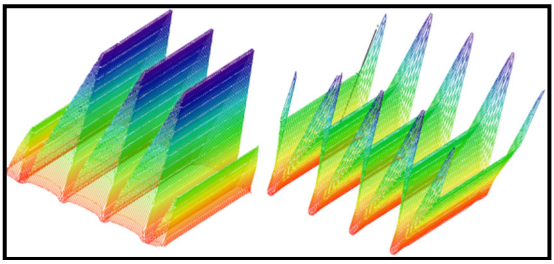

Fig. 2. Eating a plant resource in a transgenic field with four strip "shelters".

A similar effect takes place for rectangular or square shelters (Figure 3). The foliage and fruits of plants are most subject to damage from insect pests, which corresponds to natural observations
(Figures 2-3).

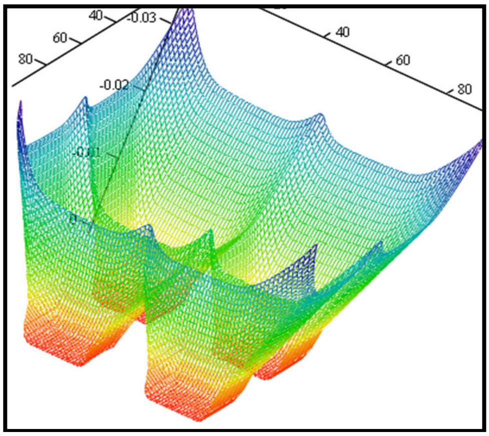

Fig. 3. Eating a plant resource in a transgenic field with four rectangular "shelters".

It is reasonable to further assume that the easier it is for pests to get to “shelters”, the faster they lose resistance to poison and, in order to make it as easy as possible for pests to reach “shelters”, we will reduce their size, keeping the ratio of 20% of the area of the main field.

As can be seen in Figure 4, over time, the number of pests moving in the direction of a partner decreases - individuals in a passive state survive. Thus, the division of the model according to the type of taxis makes it possible to more accurately predict the dynamics of pests.

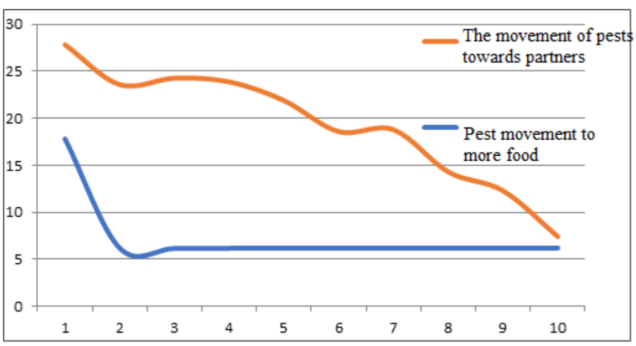

Fig. 4. The dynamics of pests in different directions of movement.

4 Discussion

As the study shows, the simple assumption of changing the dynamics of insect pests in accordance with biological needs leads to a significant change in demo-genetic patterns. A mathematical model of adaptation of pests to changes in the food supply in a field with transgenic crops has been constructed, taking into account the directions of pest movement depending on the type of their taxis, which makes it possible to predict the spatio-temporal dynamics of pests.

5 Conclusion

Numerical experiments have shown that with an increase in the area of "shelters" in the model, the acquisition of resistance significantly slows down, while the dynamics of the concentration of pests moving in the direction of the food search gradient differs significantly from the concentration of pests moving in the direction of a breeding partner. An even distribution of shelters is the most effective.

The development of effective mathematical models, modeling systems and analytical methods for studying them and obtaining sufficiently accurate predictions of the concentration of harmful organisms would reduce the cost of the crop.

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