Strategic level of agrocenoses state management

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Abstract. The aim of the work is to develop a theoretical basis for solving the problem of managing the state of agrocenoses, which contain crops of the main crop and weeds. The solution to this problem is aimed at eliminating the limitations of the existing paradigm of separate management of the state of crops and weeds. The application of mineral fertilizers simultaneously stimulates the growth and development of plants, crops and weeds, and herbicide treatments simultaneously suppress the growth of both crop plants and weeds. As a result, this leads to significant crop losses and overconsumption of fertilizers and herbicides. The proposed theory and methodology is based on taking into account the relationship between the state of crops and weeds, and their overall effect on the content of nutrients in the soil. For this, a system of mathematical models has been proposed, in which these relationships and yield losses are taken into account when the parameters of the chemical state of the soil deviate from the optimal values for crop rotation and from the effect of herbicide treatments on crop sowing. The result of solving the problem is the optimal strategies for the introduction of mineral fertilizers, ameliorants and herbicides by years of crop rotation. These strategies ensure that yield losses are minimized for all crops, rotation and agrochemical consumption. They are the main tool for planning agricultural technologies and standardizing technological operations carried out for individual years of crop rotation. The results obtained are new, since such tools are currently lacking.

1. Introduction
The transition to digitalization and intellectualization of agriculture is primarily associated with the need to automate the management of agricultural technologies in precision farming (TK). At the same time, the problem of automating the management of agricultural technologies is associated with the underdevelopment of the theoretical base in this area of science. The absence of an effective control theory has led to the fact that modern TK technology has a low economic return, since it does not have effective means of automatic control. At the same time, when creating such a theory, it must be borne in mind that in modern agrarian science, a paradigm of separate management of the state of crops has developed by optimizing the doses of mineral fertilizers, and weeds - by treating them with herbicides or mechanical soil treatments. At the same time, the fact that both crop plants and weeds grow together as part of a single agrocenoses is not taken into account, and mineral fertilizers affect the state parameters of both cultivated and weed plants, and herbicides inhibit not only weeds, but also the crops of cultivated plants cultures.

With regard to the management of agricultural technologies for the cultivation of crops, we have developed a general concept, according to which the general management task is divided into four levels of management, implemented on an annual, daily and hourly time scale [5]. For each level, a
control theory was developed and control algorithms were tested, which can become a theoretical basis for modern TK systems. However, this concept is aimed only at managing the state of crops, and does not take into account the fact that the agrocenoses contains weeds that compete with the plants of the main crop for nutrition and moisture. At the same time, the removal of moisture and nutrients by weeds can exceed the removal of cultivated plants, which reduces their yield by up to 50%.

Controlling the population of weeds (especially perennial ones) is a difficult task, therefore, a systematic approach is usually used to solve it, which combines several management components (activities) into a single strategy (Fig. 1). An effective system for suppressing perennial weeds is aimed at reducing the content of carbohydrates in plant tissues, therefore, one of the methods of influence is mechanical soil cultivation. However, the destruction and suppression of weeds by agricultural methods alone does not give the desired results. Therefore, herbicides are widely used to suppress and destroy many types of weeds. By the nature of plant damage, herbicides are conventionally divided into continuous herbicides and selective herbicides. Selective herbicides constitute the largest group used in agricultural practice. They damage cultivated crops to a minimum, but destroy or suppress the development of certain types of weeds [7]. The division of herbicides into general exterminating and selective herbicides is also conditional because continuous herbicides, often used in the form of additives in small doses to other compounds, are used as selective drugs.

![Diagram](image_url)

**Figure 1.** Components of a weed control strategy.

The presence of annual and perennial weeds in the composition of agrocenoses significantly complicates the general task of management, which indicates that here it is advisable to decompose a complex task into separate levels of management in accordance with a previously developed concept. The purpose of this study was to further develop the strategic level of management of agricultural technologies, taking into account the parameters of the state of crops of the main crops in the composition of crop rotations and perennial weeds [5,6].

**2. Materials and methods**

Let us introduce a number of conditions and assumptions under which the problem under consideration is solved:

- Among all possible methods of suppressing weeds, only the chemical method is considered, where herbicides are used;
- The problem is solved for the selected crop rotation;
- The parameters of all used mathematical models are known a priori, i.e. they are estimated in advance by carrying out identification experiments;
- For each crop of the used crop rotation, the optimal content of basic nutrients and the optimal value of the acidity indicator are known;
- A decrease in the potential crop yield occurs due to the deviation of plant nutrients (chemical parameters of the state of the soil) from optimal values, due to the use of herbicides, and also due to the competition of crops with weeds.

Verbally, the task of strategic management of the agrocenoses is formulated as follows. For the sequence of crops in the adopted crop rotation, with the designation of individual crops by the indices \( j = 1, 2, 3 \ldots N \) find a strategy for introducing the main nutrients, ameliorants and herbicide treatments in a given field, ensuring the minimization of losses in the total yield of all crops in the crop rotation, at a minimum consumption resources and given technological constraints. Such restrictions may be the doses of fertilizers, ameliorants and herbicides that are admissible according to environmental requirements.

When solving the problem of strategic management, it is necessary to keep in mind that only the chemical state of the soil environment (SE) and the biomass of perennial weeds constantly changes on an annual time scale, and the crop yields for individual years are a discrete sequence of values. With an optimal combination of parameters of the chemical state of SE, yields can reach their potential value due to other crop cultivation conditions not regulated by this strategy. To predict this value, let us introduce into consideration the vector of conditions unregulated at the given control level: \( F = [4 \times 1] \), with components: \( f_1 \) - seasonal sum of temperatures; \( f_2 \) is the seasonal amount of precipitation; \( f_3 \) is the total inflow of PAR; \( f_4 \) is the annual consumption of available forms of nitrogen. Then the potential yield levels for individual crops can be determined using the following mathematical model:

\[
B_j^T = [b_1 \quad b_2 \quad b_3 \quad b_4 \quad b_5],
\]

Assuming that for each crop of the crop rotation used, the optimal content of the main nutrients and the optimal value of the acidity index are known, any deviation, up or down from these optimal values, leads to yield losses. In addition, the use of herbicides leads to additional crop losses. Taking into account the fact that all the above indicators of the chemical state of the soil act simultaneously, then we will consider the following nonlinear form of models of yield losses of each \( j \)-th crop in the crop rotation

\[
\Delta u_j(T) = k_{1j}^T(V_j^* - V(T)) + (V_j^* - V(T))^T K_{2j}(V_j^* - V(T)) + k_3 g(T),
\]

where \( V^* \) is the optimal value of the vector of the chemical state of the soil in a given field for the \( j \)-th crop rotation, \( V(T) \) is the predicted value of the vector of the chemical state of the soil environment for the \( T \)-th year of the crop rotation, the components of which are: \( v_1 = pH \), \( v_2 = P \), \( v_3 = K \), \( v_4 = Mg \); \( P \) - phosphorus, \( K \) - potassium, \( Mg \) - magnesium; \( g(T) \) - predicted values of herbicide doses; \( T = 1, 2, \ldots N \) - indices of agricultural seasons over the entire considered control interval; \( \Delta u_j(T) \) - yield losses for the \( j \)-th crop for the \( T \)-th year of the crop rotation, arising due to the deviation of the vector of the chemical state of the soil from the optimal value and the use of herbicides; \( k_{1j}^T = [k_1 \quad k_2 \quad k_3 \quad k_4] \) - a row matrix of the parameters of the linear part of the model, which takes into account the influence of power elements; \( K_{2j} = \begin{bmatrix} k_5 & k_6 & k_7 & k_8 \\ k_6 & k_9 & k_{10} & k_{11} \\ k_9 & k_{10} & k_{12} & k_{13} \\ k_8 & k_{11} & k_{13} & k_{14} \end{bmatrix} \) - matrix of parameters of the quadratic part of the model.
\( k_{3j} = k_{15j} \) - parameter of the linear part of the model, which takes into account the effect of herbicides.

The canonical vector-matrix form of model (2) is inconvenient for identification; therefore, it must be presented in a linear vector form, convenient for estimating unknown parameters from experimental data

\[
\Delta u_j(T) = K_j^T Y_j, \\
K_j^T = \left[ k_{1j} \ldots k_{15j} \right]^T,
\]

\[
Y_j^T = \begin{bmatrix} \kappa^0 (v_1^* - v_1) & \kappa^0 (v_2^* - v_2) & \kappa^0 (v_3^* - v_3) & \kappa^0 (v_4^* - v_4) \\
\kappa^0 (v_1^* - v_1)^2 & \kappa^{10} (v_1^* - v_1) (v_2^* - v_2) & \kappa^{10} (v_1^* - v_1) (v_3^* - v_3) & \kappa^{10} (v_1^* - v_1) (v_4^* - v_4) \\
\kappa^{13} (v_2^* - v_2)^2 & \kappa^{14} (v_2^* - v_2) (v_3^* - v_3) & \kappa^{15} (v_2^* - v_2) (v_4^* - v_4) & \kappa^{16} (v_3^* - v_3)^2 \\
\kappa^{17} (v_3^* - v_3) (v_4^* - v_4) & \kappa^{18} (v_3^* - v_3)^2 & k_{19} g \end{bmatrix}.
\]

At the same time, to identify the model (3), an actually observed yield is required, which is formed by comparing the potential yield for the j-th crop for the given cultivation conditions, determined by the vector \( F \), and the predicted yield for the same conditions

\[
\Delta u_j(T) = B_j^T F(T) - u_j(T),
\]

The search for compromise solutions on the strategies for the introduction of agrochemicals, ameliorants and herbicide treatments is possible only if there are forecasts of the parameters of the chemical state of the soil and the biomass of weeds, according to which it is possible to predict the total yield losses. This requires the introduction of dynamic models of all parameters of the chemical state of the soil and the total biomass of perennial weeds

\[
\dot{v}_{ij} = a_{1i} v_{ij} (T) + b_{1i} d_{c_i} (T) + c_{1i} d_{f_i} (T),
\]

\[
\dot{v}_{2j} = a_{22} v_{2j} (T) + b_{22} d_{p} (T) + c_{22} d_{f_2} (T) - d_{2} \tilde{u}_j (T) - q_{2j} s(T),
\]

\[
\dot{v}_{3j} = a_{33} v_{3j} (T) + b_{33} d_{k} (T) + c_{33} d_{f_3} (T) - d_{3} \tilde{u}_j (T) - q_{3j} s(T),
\]

\[
\dot{v}_{4j} = a_{44} v_{4j} (T) + b_{44} d_{m_4} (T) + c_{44} d_{f_4} (T) - d_{4} \tilde{u}_j (T) - q_{4j} s(T),
\]

\[
\dot{s} = a_{65} s(T) + a_{62} v_2 (T) + a_{53} v_3 (T) + a_{54} v_4 (T) - b_{6j} g(T) + c_{61} f_1 (T) + c_{62} f_2 (T) + c_{63} f_3 (T),
\]

where: \( v_1 = pH \), \( v_2 = P \), \( v_3 = K \), \( v_4 = Mg \); \( P \) - phosphorus, \( K \) - potassium, \( Mg \) - magnesium, \( s \) - total biomass of perennial weeds; \( \tilde{u}_j (T) = B_j^T F(T) - \Delta u_j(T) \) - harvest, taking into account the loss of the type of crop; \( d_{p} (T) \), \( d_{k} (T) \), \( d_{c_i} (T) \), \( d_{m_4} (T) \) - doses of nutrients and ameliorant introduction by years of crop rotation (strategy elements); \( a_{11} - a_{44}, b_{11} - b_{44}, c_{12} - c_{42}, d_{2} - d_{4}, q_{2} - q_{4} \) - model parameters.

The introduced designations and models allow us to form a criterion for the optimality of the solution to the problem, adequate to the set goal

\[
I = (V^*- V(N))^T G (V^*- V(N)) + \\
+ M \sum_{j=1}^{N} [c_{1j} (v_1^* - V(T)) + (V^* - V(T))^T K_j (V^* - V(T)) + k_j g(T) + c_j^T D(T) + c_j g(T)],
\]

(10)
where: M is the operation of the mathematical expectation of the field area; \(c_{Tn}\) - the price of a yield unit of the T-th crop of the crop rotation, \(C_d^T\) - the vector of prices for mineral fertilizers for each food element, \(c_g\) - the price of a herbicide, \(G = \begin{bmatrix} g_{11} & 0 & 0 & 0 \\ 0 & g_{22} & 0 & 0 \\ 0 & 0 & g_{33} & 0 \\ 0 & 0 & 0 & g_{44} \\ 0 & 0 & 0 & 0 & g_{55} \end{bmatrix}\) - the weight matrix, the final values of the chemical parameters of the soil and the biomass of perennial weeds.

In criterion (10), the indices of crops j are omitted, considering that it coincides with the numbers of the years of crop rotations T. This criterion includes the following components: the quadratic penalty for deviations of the parameters of the chemical state from the optimal values, which implicitly sets restrictions on their permissible values; total yield losses of all crops in the crop rotation; as well as the costs of mineral fertilizers and herbicides. With such a composition of the components, the criterion of optimality has the meaning of the average risk of under-harvesting in the crop rotation and over expenditure of resources spent on obtaining it. As a technological limitation on the parameters of the chemical state, the 20% tolerance field of the soil acidity index near the optimal value is considered here.

When using the maximum principle to solve the problem of forming optimal strategies for the application of herbicides by years of crop rotation, it is necessary to introduce into consideration the Hamiltonian of the system (5) - (10) [2,5]

\[
H(T) = C_d^T D(T) + c_{Tn} (V' - V(T))^T K_2 (V' - V(T)) + k_g g(T) + \lambda_1 (a_{11} v_1(T) + b_{11} d_{Cu}(T) + c_{12} f_2(T)) + \\
+ \lambda_2 (a_{22} v_2(T) + b_{22} d_g(T) + c_{22} f_2(T) - d_2 \bar{u}_j(T) - q_2 s(T)) + \\
+ \lambda_3 (a_{33} v_3(T) + b_{33} d_g(T) + c_{32} f_2(T) - d_3 \bar{u}_j(T) - q_3 s(T)) + \\
+ \lambda_4 (a_{44} v_4(T) + b_{44} d_{Mb}(T) + c_{42} f_2(T) - d_4 \bar{u}_j(T) - q_4 s(T)) + \\
+ \lambda_5 (a_{55} s(T) + a_{52} v_2(T) + a_{53} v_3(T) + a_{54} v_4(T) - b_{55} g(T) + c_{51} f_1(T) + c_{52} f_2(T) + c_{53} f_3(T))
\]

(11)

where \(\lambda_1 - \lambda_5\) are conjugate variables of the problem.

The entire algorithm for forming a strategy for fertilizing and treating herbicides includes the following steps:

**Step 0.** Cyclic variable i=0 is set. Initial conditions are set for the variables of the system of models (5): \(v_{10}, v_{20}, v_{30}, v_{40}, s_0\); initial parameters of fertilization strategies by years of crop rotation: \(d_{0p}(T), d_{0k}(T), d_{0Cu}(T), d_{0Mb}(T)\), and annual doses of herbicide treatments \(g_0(T), T = 1,2,3,4,5\).

**Step 1.** The system of models (5) - (9) is solved, as a result, solutions are obtained for the years of crop rotation \(v_{1i}(T), v_{2i}(T), v_{3i}(T), v_{4i}(T), s_i(T)\). Criterion (10) \(I_i\) is calculated. If \(I_i \leq \delta\), then stop, otherwise go to step 2.

**Step 2.** The system of conjugate variables is solved in reverse time (from right to left)

\[
\dot{\lambda}_i = - \frac{\partial H(T)}{\partial v_i} = -[c_{Tn}(k_1 + 2k_5(v'_1 - v_i) + k_6(v'_2 - v_2) + k_7(v'_3 - v_3) + k_8(v'_4 - v_4) + a_{11}\dot{\lambda}_i],
\]

\(T \in (N, 0)\), \(\lambda_i(N) = 2g_{11}(v'_1(N) - v_1(N))\);
\[ \dot{\lambda}_2 = -\frac{\partial H}{\partial \lambda_2} = -[c_{T_2}(k_2 + 2k_8(v_1^* - v_1) + k_9(v_2^* - v_2) + k_{10}(v_3^* - v_3) + k_{11}(v_4^* - v_4) + a_{22} \lambda_2], \]

\[ T \in (N, 0), \quad \dot{\lambda}_2(N) = 2g_{11}(v_2^*(N) - v_2(N)); \]

\[ \dot{\lambda}_3 = -\frac{\partial H}{\partial \lambda_3} = -[c_{T_2}(k_3 + k_7(v_1^* - v_1) + k_{10}(v_2^* - v_2) + 2k_{12}(v_3^* - v_3) + k_{13}(v_4^* - v_4) + a_{33} \lambda_3], \]

\[ T \in (N, 0), \quad \dot{\lambda}_3(N) = 2g_{33}(v_3^*(N) - v_3(N)); \]

\[ \dot{\lambda}_4 = -\frac{\partial H}{\partial \lambda_4} = -[c_{T_2}(k_4 + k_8(v_1^* - v_1) + k_{11}(v_2^* - v_2) + 2k_{13}(v_3^* - v_3) + 2k_{14}(v_4^* - v_4) + a_{33} \lambda_4], \]

\[ T \in (N, 0), \quad \dot{\lambda}_4(N) = 2g_{44}(v_4^*(N) - v_4(N)); \]

\[ \dot{\lambda}_5 = -\frac{\partial H}{\partial \lambda_5} = -[a_{55} \lambda_5], \]

\[ T \in (N, 0), \quad \dot{\lambda}_5(N) = 2g_{55}(s^*(N) - s(N)) \]

Solutions are obtained in the reverse time \( \lambda_{i1}(-T), \lambda_{2i}(-T), \lambda_{3i}(-T), \lambda_{4i}(-T), \lambda_{5i}(-T), T = N, N-1, \ldots, 1. \)

These decisions unfold in direct time \( T \).

**Step 3.** Optimal strategies to be clarified:

\[ d_{Ca,i+1}(T) = d_{Ca,i}(T) - \Delta_1[c_{Ca} + b_{11} \lambda_1(T)], \]

if \( a \leq d_{Ca,i}(T) < d_{Ca1} \), then \( d_{Ca,i}(T) = 0 \),

if \( a > d_{Ca,i}(T) \geq d_{Ca2} \), then \( d_{Ca,i}(T) = d_{Ca2} \);

\[ d_{Pi,i+1}(T) = d_{Pi,i}(T) - \Delta_2[c_{Pi} + b_{22} \lambda_2(T)], \]

if \( a \leq d_{Pi,i}(T) < d_{Pi1} \), then \( d_{Pi,i}(T) = 0 \),

if \( a > d_{Pi,i}(T) \geq d_{Pi2} \), then \( d_{Pi,i}(T) = d_{Pi2} \);

\[ d_{Ki,i+1}(T) = d_{Ki,i}(T) - \Delta_3[c_{Ki} + b_{33} \lambda_3(T)], \]

if \( a \leq d_{Ki,i}(T) < d_{Ki1} \), then \( d_{Ki,i}(T) = 0 \),

if \( a > d_{Ki,i}(T) \geq d_{Ki2} \), then \( d_{Ki,i}(T) = d_{Ki1} \);

\[ d_{Mgi,i+1}(T) = d_{Mgi,i}(T) - \Delta_4[c_{Mgi} + b_{44} \lambda_4(T)], \]

if \( a \leq d_{Mgi,i}(T) < d_{Mgi1} \), then \( d_{Mgi,i}(T) = 0 \),

if \( a > d_{Mgi,i}(T) \geq d_{Mgi2} \), then \( d_{Mgi,i}(T) = d_{Mgi2} \);

\[ g_{i+1}(T) = g_i(T) - \Delta_5[c_{gi} - b_{ggi} \lambda_5(T)], \]

if \( a \leq d_{gi,i}(T) < d_{gi1} \), then \( g_{i+1}(T) = 0 \),

if \( a > d_{gi,i}(T) \geq d_{gi2} \), then \( g_{i+1}(T) = g_{i+1} \).
the cyclic variable \( i = i + 1 \) is taken and the transition to item 1 is carried out until the condition \( I_i \leq \delta \) is satisfied,

where \( \Delta_1, \Delta_5 \) - optimal steps of the algorithm, which are the result of an additional one-dimensional optimization procedure; \( d_{1C_a}, d_{1P}, d_{1K}, d_{1Mg} \) are the lower levels of restrictions on the doses of fertilizers and ameliorants, \( d_{2C_a}, d_{2P}, d_{2K}, d_{2Mg} \) are the upper levels of restrictions on the doses of fertilizers and ameliorants; \( g_m \) is the dose limitation for herbicide treatments.

3. Results

The starting point for solving the problem and a guarantee of the accuracy and reliability of the solution of the problem is the quality of the mathematical models used. At the same time, if the estimation of the parameters of the models of the potential crop yield (1) and yield losses (2) is carried out of real time, according to the results of many experimental data obtained for previous periods of research, then the identification of the system of dynamic models (5) is carried out again, after each agricultural of the year. Figure 2.3 shows the results of identification of models for the dynamics of soil acidity and the content of available phosphorus by years of crop rotation.

![Figure 2 Results of identification of the soil acidity indicator model.](image)

Menkovsky branch of the Agrophysical Institute. Modeling errors for all the models presented fit within the tolerance of \( \pm 5\% \), which is quite acceptable for solving control problems. The dynamics models of the remaining batteries have a similar look and are not shown here. It should be noted that the parameters of these models are refined according to the results of the next agricultural season, after the introduction of new data on the real parameters of the state of soil and weeds. This is the adaptation of the problem to changing conditions and the stabilization of modeling errors.
Figure 3. Results of model identification of available phosphorus content in soil.

They were obtained based on the results of long-term observations at the biopolygon of the Menkovsky branch of the Agrophysical Institute. The diagrams in Figures 4-8 show the optimal strategies for fertilizing, ameliorating and herbicide treatments by crop rotation year. It includes the sequence of the following crops: 1 - spring wheat; 2 - perennial herbs; 3 - potatoes; 4 - beetroot; 5 - winter rye. The strategies were found by minimizing the optimality criterion (10) and, in essence, represent a compromise solution between the processes of stimulating plant growth and development due to fertilizers and ameliorants and the processes of suppressing growth and development due to the influence of herbicides. This is illustrated by the diagram in Fig. 9, which shows the suppression process for the years of the crop rotation, where in the 4th and 5th years of the crop rotation the weed biomass may be even lower than the required level.

Figure 4. Optimal strategy for the introduction of ameliorant by years of crop rotation.
**Figure 5.** Optimal strategy for the introduction of phosphorus (in the Far East) by years of crop rotation.

**Figure 6.** Optimal strategy of potassium application (in RF) by years of crop rotation.

**Figure 7.** Optimal strategy for the introduction of magnesium (in the Far East) by years of crop rotation.

**Figure 8.** Optimal strategy of herbicide treatments of perennial weeds by crop rotation years.

**Figure 9.** Forecast of the dynamics of biomass of perennial weeds by years of crop rotation.
4. Discussion
For readers who first encounter the problem under consideration, the question involuntarily arises: what is the use of the result obtained and where can it be used?

Returning to the general concept of agricultural technology management, it should be noted that the resulting strategies are both the main tool for planning technologies and a means of forming restrictions on the parameters of technologies implemented during the growing seasons for each crop rotation. This makes it possible to avoid crop losses when changing crops with conflicting requirements for the content of nutrients, as well as excessive suppression of the growth and development of crop plants, which occurs everywhere in the absence of justification for the dose of herbicide treatments.

The presented article shows the first steps in solving the problem of managing the state of agrocenoses. Here, for simplicity of working out the solution technique, the simplest mathematical models and approaches are used. In the future, the number of considered perennial weeds can be expanded, the influence of annual weeds can be taken into account and other crop rotations are considered.

5. Conclusion
For the first time in modern agrarian science, the problem of strategic management of the state of the agrocenoses, which contains the main crop on the example of spring wheat and perennial weeds, has been formulated and solved. The result of solving the problem is a strategy for the introduction of mineral fertilizers, ameliorants and herbicide treatments by years of crop rotation. The strategy is the result of minimizing the criterion of optimality, taking into account the loss of yield and the consumption of consumed agrochemicals. The considered level of management is the main tool for planning agricultural technologies and standardizing technological operations carried out for individual years of crop rotation. An example of solving the problem showed the efficiency of the proposed solution methodology, as well as the validity of the software and algorithmic support used.

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