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Intelligent Agrocenoses Program Control System

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Abstract

Modernization of the agricultural sector is based on the transition to "smart agriculture". The intellectualization of agricultural technology management is of greatest interest to science and practice. At the same time, expert systems in which control decisions are made through knowledge bases (KB) are most effective. In this work, knowledge bases are formed using analytical control systems located in data processing centers. Such knowledge bases are transferred to local consumers, who make local control decisions based on them. The purpose of this work is to develop a theoretical basis for solving the problem of intelligent management of the state of agrocenoses containing crops of main crops and weeds. Solving this problem aims to address the limitations of the current paradigm of separate crop and weed management. The application of mineral fertilizers simultaneously stimulates the growth and development of agricultural plants and weeds, and treatment with herbicides simultaneously suppresses the growth of both agricultural plants and weeds. As a result, this leads to significant crop losses and excessive consumption of fertilizers and herbicides. In the presented work, for the first time, the problem of managing agrocenoses is raised and solved at the program level, implemented during one growing season. At this level of management, programs are formed that represent a sequence of technological operations for the application of mineral fertilizers, irrigation and herbicide treatments, ensuring the achievement of a given crop yield. To solve this problem, the previously developed theory modified mathematical models of the state of cultivated crops, reflecting the influence of herbicides. In addition, a model of the state parameters of the dominant weed species was introduced into the control problem, which, in addition to the doses of herbicide treatments, also reflects the influence of mineral fertilizers. The problem is solved using the example of sowing spring wheat as part of agrocenoses.

Keywords: agrocenoses; program control; intelligent expert systems; mathematical models; algorithms

Introduction

In modern crop production, the traditional paradigm of separate management of the state of crops and weeds as part of one agrocenoses has long been established. The development of precision agriculture (PA) served as an incentive to create an effective theory of agricultural technology management. But to a greater extent this was reflected in the tasks of managing the state of agricultural crops. A number of provisions of modern theory have already been developed here, starting with the creation of a general control concept and ending with control algorithms at various time levels [15]. According to this theory, it becomes possible to create control programs that represent sequences of technological operations with the optimal level of fertilizer doses and irrigation rates. As for managing the state of weeds, progress in the development of the theory is more modest, and to date the optimal doses of crop treatments with herbicides have not yet been scientifically substantiated. At the same time, the developed theoretical basis for managing the state of agricultural crops does not take into account the fact that the agrocenoses contains weeds and the application of fertilizers and watering stimulate its growth and development along with the cultivated crop. Simultaneous treatment of agrocenoses with herbicides suppresses the growth of not only weeds, but also the main crop. As a result, such separate management leads to significant crop losses, excessive consumption of fertilizers and herbicides and deterioration of environmental performance. The recent emergence of work on the simultaneous joint application of fertilizers and herbicides shows that technological science is striving to eliminate the shortcomings of the existing separate management paradigm [6, 11]. This poses new challenges for the science of managing agricultural technologies, forcing it to consider a field with an agrocenoses as a single object control (OC).

This paper considers the software level of control, in which an optimal sequence of technological operations (program) is formed that ensures the achievement of the required result [14]. Here, a field with an agrocenoses containing crops and weeds is taken as a control object (OC). They compete with crop plants for moisture and nutrients, and yield losses from crop weeds can exceed 50%. Therefore, optimal technological programs for operations during the growing season under consideration should include not only operations for applying fertilizers and watering, but also treatments with herbicides. The formation of a unified program for the simultaneous application of mineral fertilizers and herbicide treatments, consistent with the state of the main crop plants and weeds, will avoid crop losses and overconsumption of mineral fertilizers and herbicides.

At the same time, it should be borne in mind that the modernization of the agricultural sector is based on the transition to “intelligent agriculture”. “Intelligent agriculture” is agriculture based on complex automation and robotization of production, the use of automated decision-making systems, modern technologies for modeling and designing ecosystems [16]. Therefore, this work considers the aspect of intellectualization of the software control level, which ensures ease of practical application of a rather complex software and mathematical apparatus. This problem is solved using the example of an agrocenoses with the sowing of spring wheat.

The results presented in the work are fundamentally new in modern agricultural science, both in the general formulation and solution of the problem of managing agricultural technology [2, 4, 5, 7-10, 12, 20-23, 25], and in terms of the use of mathematical models and control algorithms [1, 3, 19, 24, 26].

Materials and Methods

To solve the problem, the classical theory of optimal control is used using a combination of the dynamic programming method and the Pontryagin’s maximum principle [6]. According to this theory, the starting point for solving any program management problem is the choice of an achievable goal. When we are dealing with agricultural technology, such a goal can only be to obtain a given crop yield at the end of the growing season. Any control task is based on a mathematical description of the op-amp. In the case under consideration, it is an agricultural field with an agrocenoses, which includes spring wheat crops. The fundamental basis for solving program control problems is mathematical models that describe the dynamics of state parameters OC. At the same time, in addition to the mathematical model of the main crop, the OC must be supplemented with a model of weeds. Such models should reflect the influence of external uncontrolled disturbances, the influence of controlled influences and take into account the relationship (competition) of weeds and cultivated plants through the soil environment.

To achieve the above management goal, it is necessary to select the most important target-forming parameters of the sowing state of the cultivated crop. At the same time, the crop in question is characterized both by continuum state parameters, which may include parameters of the state of the biomass of the crop itself and the soil environment, and by structural states, which include phenological phases of development (phenophases). For spring wheat, depending on the duration of the interval on a daily time scale t, these states are: when - s=1, sowing phase; at - s=2, seedling phase (1, 2, 3 leaves); at - s=3, tillering phase; at - s=4, phase exits into the tube; at - s=5, interstitial phase; at - s=6, phase flag sheet; at - s=7, reed phase; at - s=8, phase of opening of the leaf sinus; at - s=9, heading phase; at - s=10, flowering phase; at - s=11, milky ripeness phase; at - s=12, waxy ripeness phase; at - s=13, the phase is complete ripeness. The entire growing season, depending on the structure of the crop biomass, should be divided into two time intervals: from the 2nd to the 9th and from the 9th to the 13th phenophases. At the same time, fertilization, herbicide treatment and watering are carried out at fixed times during the onset of pre-selected phenological phases. Here such phenophases are: s = 3 (tillering), s = 9 (earing), s = 10 (flowering), s = 11 (milky ripeness). This leads to the need to divide the entire management interval into four intervals between selected phenophases: 1 - from tillering to heading (T_3, T_9), 2 - from heading to flowering (T_9, T_{10}), 3 - from flowering to milky ripeness (T_{10}, T_{11}), 4 - from milky ripeness to full ripeness (T_{11}, T_{13}).

For the first time interval for phenophases from 3 to 9, the model for the dynamics of the structure parameters of the crop biomass has the following form [14, 15].

$$\begin{bmatrix} \dot{x}_{1\mathrm{m}} \\ \dot{x}_{2\mathrm{m}} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}_m \begin{bmatrix} x(t)_{1\mathrm{m}} \\ x(t)_{2\mathrm{m}} \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \end{bmatrix}_m \begin{bmatrix} v_{\mathrm{N}}(t) \\ v_{\mathrm{K}}(t) \\ v_{\mathrm{P}}(t) \\ v_{\mathrm{Mg}}(t) \\ v_5(t) \end{bmatrix} +$$

$$+ \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \end{bmatrix}_m \begin{bmatrix} f_1(t) \\ f_2(t) \\ f_3(t) \end{bmatrix} - \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix}_m \begin{bmatrix} g_1(t) \\ g_2(t) \end{bmatrix}_m, \; t \in (T_3, T_9), \qquad (1)$$

where the following designations are adopted: x_{1m} - average crop biomass density (yield) over the field area, cwt•ha^{-1}; x_{2m} - average density of crop wet weight over the field area, cwt•ha^{-1}; external disturbances in both blocks are f_1 - average daily air temperature, °C; f_2 - average daily radiation level, W•(m^2•hour)$^{-1}$; f_3 - average daily precipitation intensity, mm; parameters of the chemical state of the soil: v_N - nitrogen content in the soil, kg•ha^{-1}; v_K - potassium content in soil, kg•ha^{-1}; v_P - phosphorus content in soil kg•ha^{-1}; v_{Mg} - magnesium content in soil kg•ha^{-1}; v_5 - moisture reserve in the soil, mm; $g^1_{\mathrm{m}}(t)$, $g^2_{\mathrm{m}}(t)$ - doses of herbicide treatment, kg•ha^{-1}. Due to the scientific and methodological significance of this work, we do not disclose the types of herbicides here, since the approach we are developing can be implemented for any type of herbicide.

For ease of further use, model (1) is conveniently represented in canonical symbolic vector-matrix form, where all variables are combined into vectors, and parameters into corresponding matrices.

$$\dot{\mathrm{X}}_m = \mathrm{A}_m \mathrm{X}_m(t) + \mathrm{B}_m \mathrm{V}(t) + \mathrm{C}_m \mathrm{F}(t) - \mathrm{D}_m \mathrm{G}_m(t). \qquad (2)$$

For intervals from the second (T_9, T_{10}), (T_{10}, T_{11}), and (T_{11}, T_{13}) models of the dynamics of parameters of the crop biomass structure have a general form, and differ only in the values of parameters [14, 15]:

$$\begin{bmatrix}\dot{x}_{1u}\\ \dot{x}_{2u}\\ \dot{x}_{3u}\end{bmatrix}_j=\begin{bmatrix}a_{11}&a_{12}&a_{13}\\ a_{21}&a_{22}&a_{23}\\ a_{31}&a_{32}&a_{33}\end{bmatrix}_j\begin{bmatrix}x(t)_{1\mathrm{u}}\\ x(t)_{2u}\\ x(t)_{3u}\end{bmatrix}_j+\begin{bmatrix}b_{11}&b_{12}&b_{13}&b_{14}&b_{15}\\ b_{21}&b_{22}&b_{23}&b_{24}&b_{25}\\ b_{31}&b_{32}&b_{33}&b_{34}&b_{35}\end{bmatrix}_j\begin{bmatrix}v_{\mathrm{N}}(t)\\ v_{\mathrm{K}}(t)\\ v_{\mathrm{P}}(t)\\ v_{\mathrm{Mg}}(t)\\ v_5(t)\end{bmatrix}_j+$$

$$+\begin{bmatrix}c_{11}&c_{12}&c_{13}\\ c_{21}&c_{22}&c_{23}\\ c_{31}&c_{32}&c_{33}\end{bmatrix}_j\begin{bmatrix}f_1(t)\\ f_2(t)\\ f_3(t)\end{bmatrix}-\begin{bmatrix}d_{11}&d_{12}\\ d_{21}&d_{22}\\ d_{31}&d_{32}\end{bmatrix}_j\begin{bmatrix}g_1(t)\\ g_2(t)\end{bmatrix}_j, \qquad (3)$$

$$j=1,\ t\in T_9,T_{10});\ j=2,\ t\in(T_{10},T_{11}),\ j=3,\ t\in(T_{11},T_{13}).$$

In this model, the state parameters are: x_{1u} - average crop biomass density over the field area, cwt•ha^{-1}; x_{2u} - average density of crop wet weight over the field area, cwt•ha^{-1}; x_{3u} - average mass density of ears (harvest) over the field area, cwt•ha^{-1}; external disturbances in both blocks are f_1 -average daily air temperature, °C; f_2 -average daily radiation level, W•(m^2•hour)$^{-1}$; f_3 - average daily precipitation intensity, mm; parameters of the chemical state of the soil: v_N - nitrogen content in the soil, kg•ha^{-1}; v_K - potassium content in soil, kg•ha^{-1}; v_P - phosphorus content in soil, kg•ha^{-1}; v_{Mg} - magnesium content in soil kg•ha^{-1}; v_5 - moisture reserve in the soil, mm; $g_{1u}(t)$, $g_{2u}(t)$ - doses of herbicide treatment, g•ha^{-1}; j=1,2,3 - numbers of control intervals after the heading phase.

Canonical symbolic vector-matrix form of the model.

$$\dot{\mathrm{X}}_{uj}=\mathrm{A}_{uj}\,\mathrm{X}_{uj}(t)+\mathrm{B}_{uj}\,\mathrm{V}_{uj}(t)+\mathrm{C}_{uj}\,\mathrm{F}(t)-\mathrm{D}_{uj}\,G_{uj}(t). \qquad (4)$$

As stated above, in addition to the model (4), to solve the problem, a dynamic model of the biomass of the dominant weed species is needed, the vector-matrix form of which has the following form [14].

$$\dot{\mathrm{S}}_j=\mathrm{A}_{sj}\,\mathrm{S}_j(T)+\mathrm{B}_s\,\mathrm{V}_j(T)-\mathrm{B}_{gj}\,\mathrm{G}_j(t)+\mathrm{C}_{sj}\,F(t), \qquad (5)$$

$$\mathrm{A}_s=\begin{bmatrix}a_{11}&0\\ 0&a_{22}\end{bmatrix}_s,\ \mathrm{B}_s=\begin{bmatrix}b_{11}&b_{12}&b_{13}&b_{14}\\ b_{21}&b_{22}&b_{23}&b_{24}\end{bmatrix}_s,\ \mathrm{B}_g=\begin{bmatrix}b_{11}&0\\ 0&b_{22}\end{bmatrix}_g,$$ - model parameter matrices.

$$\mathrm{C}_s=\begin{bmatrix}c_{11}&c_{12}&c_{13}&c_{14}\\ c_{21}&c_{22}&c_{23}&c_{24}\end{bmatrix}_s$$

Model (5) includes the states of two dominant weed species. For other conditions, their number and types may be different, which only clarifies the structure of the algorithms, but does not change the general approach to solving the problem.

Models (2), (4), (5) represent the main block of op-amp state parameters. In addition to this block, the op-amp contains a control transfer block, which is the soil environment (SE). It is through this block that competition between crop plants and weeds for nutrients and moisture occurs.

The model for the dynamics of soil state parameters for phenophases 3 to 9 has the following form [17]:

$$\begin{bmatrix} \dot{v}_{\mathrm{N}} \\ \dot{v}_{\mathrm{K}} \\ \dot{v}_{\mathrm{P}} \\ \dot{v}_{\mathrm{Mg}} \\ \dot{v}_5 \end{bmatrix}_{3,9} = \begin{bmatrix} a_{11} & 0 & 0 & 0 & a_{15} \\ 0 & a_{22} & 0 & 0 & a_{25} \\ 0 & 0 & a_{33} & 0 & a_{35} \\ 0 & 0 & 0 & a_{44} & a_{45} \\ 0 & 0 & 0 & 0 & a_{55} \end{bmatrix}_{3,9} \begin{bmatrix} v_{\mathrm{N}} \\ v_{\mathrm{K}} \\ v_{\mathrm{P}} \\ v_{\mathrm{Mg}} \\ v_5 \end{bmatrix}_{3,9} + \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}_{3,9} \begin{bmatrix} d_{\mathrm{N}}(t) \\ d_{\mathrm{K}}(t) \\ d_{\mathrm{P}}(t) \\ d_{\mathrm{Mg}}(t) \\ d_{\mathrm{W}}(t) \end{bmatrix}_{3,9} +$$

$$+ \begin{bmatrix} 0 & 0 & c_{13} \\ 0 & 0 & c_{23} \\ 0 & 0 & c_{33} \\ 0 & 0 & c_{43} \\ c_{51} & c_{52} & 1 \end{bmatrix}_{3,9} \begin{bmatrix} f_1(t) \\ f_2(t) \\ f_3(t) \end{bmatrix} - \begin{bmatrix} m_{11} & 0 \\ m_{21} & 0 \\ m_{31} & 0 \\ m_{41} & 0 \\ m_{51} & m_{52} \end{bmatrix}_{3,9} \begin{bmatrix} x_{1m}(t) \\ x_{2m}(t) \end{bmatrix} - \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \\ p_{31} & p_{32} \\ p_{41} & p_{42} \\ p_{51} & p_{52} \end{bmatrix}_{3,9} S(t), \qquad (6)$$

or compact symbolic form.

$$\dot{\mathrm{V}}_{3,9} = \mathrm{A}_{3,9}\mathrm{V}(t) + \mathrm{B}_{3,9}\mathrm{D}(T_3,T_9) + \mathrm{C}_{3,9}F(t) - \mathrm{M}_{3,9}\mathrm{X}_m(t) - \mathrm{P}_{3,9}S(t). \qquad (7)$$

Models of the dynamics of soil state parameters for the intervals (T_9, T_{10}), (T_{10}, T_{11}), and (T_{11}, T_{13}) have the same form, differing only in the parameter values [17].

$$\begin{bmatrix} \dot{v}_{\mathrm{N}} \\ \dot{v}_{\mathrm{K}} \\ \dot{v}_{\mathrm{P}} \\ \dot{v}_{\mathrm{Mg}} \\ \dot{v}_5 \end{bmatrix}_j = \begin{bmatrix} a_{11} & 0 & 0 & 0 & a_{15} \\ 0 & a_{22} & 0 & 0 & a_{25} \\ 0 & 0 & a_{33} & 0 & a_{35} \\ 0 & 0 & 0 & a_{44} & a_{45} \\ 0 & 0 & 0 & 0 & a_{55} \end{bmatrix}_j \begin{bmatrix} v_{\mathrm{N}} \\ v_{\mathrm{K}} \\ v_{\mathrm{P}} \\ v_{\mathrm{Mg}} \\ v_5 \end{bmatrix}_j + \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}_j \begin{bmatrix} d_{\mathrm{N}}(t) \\ d_{\mathrm{K}}(t) \\ d_{\mathrm{P}}(t) \\ d_{\mathrm{Mg}}(t) \\ d_{\mathrm{W}}(t) \end{bmatrix}_j +$$

$$+ \begin{bmatrix} 0 & 0 & c_{13} \\ 0 & 0 & c_{23} \\ 0 & 0 & c_{33} \\ 0 & 0 & c_{43} \\ c_{51} & c_{52} & 1 \end{bmatrix}_j \begin{bmatrix} f_1(t) \\ f_2(t) \\ f_3(t) \end{bmatrix} - \begin{bmatrix} m_{11} & 0 & m_{13} \\ m_{21} & 0 & m_{23} \\ m_{31} & 0 & m_{33} \\ m_{41} & 0 & m_{43} \\ m_{51} & m_{52} & 0 \end{bmatrix}_j \begin{bmatrix} x_{1u}(t) \\ x_{2u}(t) \\ x_{3u}(t) \end{bmatrix}_j - \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \\ p_{31} & p_{32} \\ p_{41} & p_{42} \\ p_{51} & p_{52} \end{bmatrix}_j S(t), \qquad (8)$$

where: $d_P(t)$, $d_K(t)$, $d_N(t)$, $d_W(t)$ - doses of nutrients, respectively, phosphorus P, potassium K, ameliorant Ca, nitrogen N and magnesium Mg, kg•ha^{-1} and watering rate, mm; a_{11}-a_{33}, c_{13}-c_{52}, m_{11}-m_{52}, p_{11}-$_{p52}$ - model parameters estimated from experimental data; t - daily time.

Model (8) in compact symbolic vector-matrix form.

$$\dot{\mathrm{V}}_j = \mathrm{A}_j\mathrm{V}_j(t) + \mathrm{B}_j\mathrm{D}_j(t) + \mathrm{C}_jF(t) - \mathrm{M}_j\mathrm{X}_j(t) - \mathrm{P}_jS(t). \qquad (9)$$

The complex multidimensional structure of the op-amp, which includes models (2), (4), (5) of the main block of state parameters and control transfer blocks (7), (9), lead to the need to solve the program control problem in two stages [14]. At the first stage, there is a program for the potential development of crop sowing throughout the entire growing season, ensuring the achievement of the set management goal. In this case, the influence of weeds is not taken into account, and the parameters of the SE state are considered as control variables without taking into account technological limitations. The control program obtained in this way is a guideline for the formation of a sequence of technological operations, including the application of fertilizers, watering and herbicide treatments.

Therefore, at the second stage there is a sequence of technological operations that should ensure a minimum deviation of the SE parameters from the optimal program obtained at the first stage. This decomposition of the program control problem significantly simplifies the synthesis of optimal control programs. In addition, the optimization results obtained at the first stage are of independent interest as a potential level of crop yield.

In accordance with the dynamic programming scheme (6), the problem of the first stage is solved from the end of the growing season to its beginning. The management goal in this task is: “obtaining a given crop yield at the end of the growing season, subject to the condition of achieving the required structure of the entire biological yield, namely, the required ratio between grain and straw, the required grain moisture, as well as reducing the biomass of weeds to a given level in agrocenoses”.

In the designated state parameters, the control goal for a given interval is formally as follows:

$$x_{1u}(T_{13}) \geq 2{,}1U^*, \;\; x_{2u}(T_{13}) \leq 0{,}15U^*, \;\; x_{3u}(T_{13}) \geq U^*, \;\; S_{uj}(T_{13}) \leq S^*_{uj}, \qquad (10)$$

where: $U^*(T_{13})$ - target yield, cwt•ha^{-1}; S^*_{uj} - given biomass of weeds.

The optimality criterion for the non-vegetation period from the 9th to the 13th phenophase, which meets the goal, has the following form.

$$\begin{aligned} \mathrm{J}_{uj}(T_{13}) &= [\mathrm{X}_{uj}(T_{13}) - \mathrm{X}^*_{uj}(T_{13})]^{\mathrm{T}}\, \mathrm{G}_u [\mathrm{X}_{uj}(T_{13}) - \mathrm{X}^*_{uj}(T_{13})] + \\ &+ [S_{uj}(T_{13})] - S^*_{uj}(T_{13})]^{\mathrm{T}} Q [S_{uj}(T_{13})] - S^*_{uj}(T_{13})], \end{aligned} \qquad (11)$$

where $\mathrm{X}^{*\mathrm{T}} = \begin{bmatrix} 2{,}1U^* & 0{,}15U^* & U^* \end{bmatrix}$ - vector whose components are: common biomass, wet weight, grain weight (yield); $G_u = \begin{bmatrix} g_{11} & 0 & 0 \\ 0 & g_{22} & 0 \\ 0 & 0 & g_{33} \end{bmatrix}_u$ - weight matrix of mass and quality components of the criterion, $Q = \begin{bmatrix} q_{11} & 0 \\ 0 & q_{22} \end{bmatrix}$ - weight matrix of weed biomass components, j=0,1,2,3 - indices of control intervals.

To form optimal programs for all control intervals, the Pontryagin’s maximum principle is used [13, 15]. In accordance with this method, the Hamiltonian of a system that includes models of culture, soil environment, and criterion (11) has the following form.

$$\begin{aligned} H_{uj}(t) &= \Psi^{\mathrm{T}}{}_{1,uj}[\mathrm{A}_{uj}\,\mathrm{X}_{uj}(t) + \mathrm{B}_{uj}\,\mathrm{V}_{uj}(t) + \mathrm{C}_{uj}\,\mathrm{F}(t) - \mathrm{D}_{uj}\,G_{uj}(t)] + \\ &+ \Psi^{\mathrm{T}}{}_{2,uj}[\mathrm{A}_s\,\mathrm{S}_{uj}(T) + \mathrm{B}_s\,\mathrm{V}_{uj}(T) - \mathrm{B}_g\,\mathrm{G}_{uj}(t) + \mathrm{C}_s\,F(\mathrm{T})]. \end{aligned} \qquad (12)$$

and the models of conjugate variables, respectively.

$$\begin{aligned} &\dot{\Psi}_{1,uj=3,i} = -\frac{\partial \mathrm{H}_{uj=3,i}}{\partial \mathrm{X}_{1,uj=3,i}} = -\mathrm{A}^{\mathrm{T}}_{uj=3,i}\Psi_{1,uj=3,i},\ t \in (T_{11}, T_{13}), \\ &\Psi_{1,uj=3,i}(T_{13}) = [\mathrm{X}_{uj}(T_{13}) - \mathrm{X}^*_{uj}]; \end{aligned} , \qquad (13)$$

$$\begin{aligned} &\dot{\Psi}_{2,uj=3,i} = -\frac{\partial \mathrm{H}_{uj=3,i}}{\partial S_{1,uj=3,i}} = -\mathrm{A}^{\mathrm{T}}_{sj=3,i}\Psi_{2,uj=3,i},\ t \in (T_{11}, T_{13}), \\ &\Psi_{2,uj=3,i}(T_{13}) = 2[S_{uj}(T_{13})] - S^*_{uj}]. \end{aligned} . \qquad (14)$$

The algorithm for the formation of an optimal program for changing the parameters of the soil environment, which ensures the achievement of the management goal, includes the following iterative procedures:

- Formation of optimal programs for changing the parameters of the substation.

$$\begin{aligned} V^{*}_{ug,i+1}(t) &= V^{*}_{ug,i}(t) - \Delta_i \, GR_{ug,i}(t), \\ GR_{ug,i}(t) &= \frac{\partial H}{\partial V_{ug,i}}(t) = B^{T}{}_{ug}\, \Psi_{1ug,i}(t) + B^{T}{}_{s}\, \Psi_{2,ug,i}(t). \end{aligned} \qquad (15)$$

- Search for initial conditions at the boundaries of phenophases.

$$X^{*}_{ug,i+1}(T_{11}) = X^{*}_{ug,i}(T_{11}) - \Delta_i \Psi_{1,ug,i}(T_{11}), \qquad (16)$$

$$S^{*}_{ug,i+1}(T_{11}) = S^{*}_{ug,i}(T_{11}) - \Delta_i \Psi_{2,ug,i}(T_{11}). \qquad (17)$$

As a result of solving the problem of the 1st stage, an optimal program for changing the vector of SE parameters V*(t) is formed, consisting of separate pieces at 4 control intervals between given phenophases. This program corresponds to the program for changing the vector of sowing state parameters X*(t) and the program for changing the vector of weed biomass parameters S*(t) at these control intervals.

The achievable goal of management at the second stage of the general solution of the problem is: "ensuring the closest approximation to the optimal programs for the content of nutrients and moisture content in the soil obtained at the first stage, due to the independent choice of the size of top dressing, watering and herbicide treatments. At the same time, fertilizer application and irrigation are carried out at fixed times of the onset of the following phenological phases: s = 3 (tillering), s = 9 (heading), s = 10 (flowering), s = 11 (milky ripeness).

As for stage 1, the problem is solved separately, for each control interval, but in the forward direction, from the beginning of the growing season to its end.

Particular optimality criteria for each j-th control interval have the same form.

$$J_j = \int_{T_{1j}}^{T_{2j}} [(V^{*}_j(t) - V_j(t))^{T} G_j (V^{*}_j(t) - V_j(t)) + C_D D_j(t)]dt, \; j = 0,1,2,3 \qquad (18)$$

$G_j = \begin{bmatrix} g_1 & 0 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 & 0 \\ 0 & 0 & g_3 & 0 & 0 \\ 0 & 0 & 0 & g_4 & 0 \\ 0 & 0 & 0 & 0 & g_5 \end{bmatrix}_j$ - weight matrix, CD-vector of unit dose prices.

Criterion (18) is formed by means of a model of soil state parameters.

$$\dot{V}_j = A_j V_j(t) + B_j D_j(t) + C_j F(t) - M_j X^{*}_j(t) - P_j S^{*}_j(t)$$

$X^{*}_j(t), S^{*}_j(t)$ - optimal programs for the parameters of the state of crops and weeds obtained at the first stage.

The Hamiltonians for all control intervals are the same:

$$H_j = [(V_j^*(t) - V_j(t))^{\mathrm{T}}\, \mathrm{G}_j (V_j^*(t) - V_j(t)) + \mathrm{C_D D}_j(t)] + \\ +\Psi_j^{\mathrm{T}}[\mathrm{A}_j \mathrm{V}_j(t) + \mathrm{B}_j \mathrm{D}_j(t) + \mathrm{C}_j F(t) - \mathrm{M}_j \mathrm{X}_j^*(t) - \mathrm{P}_j S_j^*(t)], \qquad (19)$$

where Ψ_j^{T} are the vector of conjugate variables on the j-th control intervals.

The conjugate variable models have the following form.

$$\dot{\Psi}_j(t) = -\frac{\partial \mathrm{H}_o(t)}{\partial V_j} = -[2\mathrm{G}_j((V_j^*(t) - V_j(t)) + \tilde{\mathrm{A}}_j^{\mathrm{T}}\, \Psi_j(t)], \\ t \in (T_{2j}, T_{1j}),\ \Psi_j(T_{2j}) = 0. \qquad (20)$$

The algorithm for the formation of sequences of doses of fertilizers (optimal control programs) includes the following iterative procedures for the next approximation of the vectors of doses of fertilizers and irrigation.

$$D_{i+1}^*(T_{1j}) = D_i^*(T_{1j}) - \Delta_i^* \frac{\partial H_j(T_{1j})}{\partial D_i(T_{1j})}, \qquad (21)$$

$$D_{i+1}^*(T_{1j}) = D_i^*(T_{1j}) - \Delta_i^*(C_D + \tilde{\mathrm{B}}_j^{\mathrm{T}}\, \Psi_{i,j}(T_{1j})), \text{если } \mathrm{D}_{i+1}^*(T_{1j}) \in \Omega_j; \\ D_{i+1}^*(T_{1j}) = D_i^*(T_{1j}), \text{ если } D_{i+1}^*(T_{1j}) \notin \Omega_{T_{1j}}.$$

As a result of solving the problem at the second stage, sequences of doses of fertilizer application and irrigation are formed for all management intervals $D^*_j(T_{1j})$, j=0,1,2,3, which correspond to programs for changing the parameters of the soil environment $V^*_j(t)$, sowing state parameters $X^*_j(t)$ and weed biomass parameters $S^*_j(t)$.

The found optimal sequence of technological operations (program) does not yet take into account the direct effect of herbicides on the state of crop sowing. in accordance with models (16), (17). At the beginning of the procedure for the formation of a control program, such an effect cannot be taken into account, since the initial doses of treatments are not known a priori. Therefore, it is necessary to introduce one more external optimization cycle, in which this influence is taken into account. To do this, it is necessary to close the entire procedure for the formation of an optimal control program for doses of herbicide treatment.

Models (4), (5) are used to solve the problem.

$$\dot{\mathrm{X}}_{uj} = \mathrm{A}_{uj}\, \mathrm{X}_{uj}(t) + \mathrm{B}_{uj}\, \mathrm{V}_j^*(t) + \mathrm{C}_{uj}\, \mathrm{F}(t) - \mathrm{D}_{uj}\, G_{uj}(t),$$

$$\dot{\mathrm{S}}_j = \mathrm{A}_s\, \mathrm{S}_j(t) + \mathrm{B}_s\, \mathrm{V}_j^*(t) - \mathrm{B}_g\, \mathrm{G}_j(t) + \mathrm{C}_s\, F(t),$$

where $V^*_j(t)$ is the optimal program for changing the parameters of the soil environment obtained at the second stage.

The goal of management at this stage is to select doses of herbicide treatments at all management intervals that provide the best approximation of the programs for changing the parameters of the state of crops and parameters of weed biomass to the optimal programs found at the second stage.

This goal corresponds to the following optimality criteria on separate control intervals [6].

$$J_j = \int_{T_{1j}}^{T_{2j}} [(X_j^*(t) - X_j(t))^{\mathrm{T}}\, \mathrm{G}_{1j} (X_j^*(t) - X_j(t)) + \\ + (S_j^*(t) - S_j(t))^{\mathrm{T}}\, \mathrm{G}_{2j} (S_j^*(t) - S_j(t))]dt, \quad j = 0,1,2,3 \qquad (22)$$

The algorithm for generating herbicide treatment programs is the following iterative procedure.

$$G^*_{j,i+1}(T_{1j}) = G^*_{j,i}(T_{1j}) - \Delta_i\, \mathrm{GR}_{j,i}(T_{1j}), \\ \mathrm{GR}_{j,i}(T_{1j}) = \frac{\partial \mathrm{H}_{j,i}}{\partial G_{ji}}(T_{1j}) = D_j \Psi_{1j,i}(T_{1j}) + \mathrm{B}_s\, \Psi_{2j,i}(T_{1j}). \qquad (23)$$

At the first stage, the formation of fertilizer application programs was carried out without taking into account herbicide treatment programs. Given that fertilization and herbicide treatments are carried out simultaneously, fertilizer application programs require adjustments for herbicide treatment programs. To do this, the following global steps are introduced into the algorithm:

Step.1 The global cyclic variable *k*=1 is accepted. The herbicide treatment program $G^*(T_{1j})$ for all management intervals is substituted into the interval models, solving them from the beginning *j*=0 to the end *j*=3.

$$\dot{\mathrm{X}}_j = \mathrm{A}_j\, \mathrm{X}_j(t) + \mathrm{B}_j\, \mathrm{V}_j^*(t) + \mathrm{C}_j\, \mathrm{F}(t) - \mathrm{D}_j\, G_j(t), \;\; t \in (T_{1J}, T_{2J}) \qquad (24)$$

$$\dot{\mathrm{S}}_j = \mathrm{A}_s\, \mathrm{S}_j(t) + \mathrm{B}_s\, \mathrm{V}_j^*(T) - \mathrm{B}_g\, \mathrm{G}_j(t) + \mathrm{C}_s\, F(\mathrm{T}), \;\; t \in (T_{1J}, T_{2J}) \qquad (25)$$

in this case, the final decisions on the current interval are taken as the initial ones for subsequent intervals, i.e. $\mathrm{X}_0(T_{1j+1})=\mathrm{X}(T_{2j})$, $S_0(T_{1j+1})=S(T_{2j})$. On the initial interval, the initial conditions common for the entire problem are accepted: $\mathrm{X}_0(T_{1j}=0)$, $S^0(T_{1j}=0)$. For the control interval, the global cyclic variable *k*=1, *j*=3 is taken, the criterion is calculated at the end of the vegetation interval.

$$J_{\mathrm{k}=1}(T_{13}) = [\mathrm{X}_{uj=3}(T_{13}) - \mathrm{X}^*_{uj=3}(T_{13})]^{\mathrm{T}}\, \mathrm{G}_u [\mathrm{X}_{uj=3}(T_{13}) - \mathrm{X}^*_{uj=3}(T_{13})] + \\ + [S_{uj=3}(T_{13})] - S^*_{uj=3}(T_{13})]^{\mathrm{T}} Q [S_{uj=3}(T_{13})] - S^*_{uj=3}(T_{13})] \qquad (26)$$

Step.2 If the criterion $J_{k=1}(T_{13})$ is less than the given value Δ, then STOP, otherwise the solutions of the models (8.37), (8.38) are transferred to step 1 of stage 1, all stages of the problem are repeated until a new criterion is obtained $J_{k=2}(T_{13})$.

Step.3 If the criterion $J_{k=2}(T_{13})$ is less than the criterion $J_{k=1}(T_{13})$, then transfer the solutions of the models [4, 5] to step 1 of stage 1, otherwise STOP and decisions are made for the previous criterion $J_{k=1}(T_{13})$.

Results and discussion

The starting point for the formation of the KB of an intelligent system control (IS) of program control is the range of possible values of the chemical parameters of the soil. They include: v_N - nitrogen content in the soil, kg•ha^{-1}; v_K is the content of potassium in the soil, kg•ha^{-1}; v_P - phosphorus content in soil kg•ha^{-1}; v_{Mg} - magnesium content in soil kg•ha^{-1}; v_5 - moisture reserve in the soil, mm. As for the strategic level IS, these parameters are combined into a single vector Z=[5x1], $z_1=v_N$, $z_2=v_K$, $z_3=v_P$, $z_4=v_{Mg}$, $z_5=v_5$. For each field of the served region, there is an area of possible values of the condition vector, i.e. $Z \in \Omega_z$.

This area is preliminarily divided into a sufficient number of small areas (options), denoted by indices *j*=1,2, ..., N, the number of which should be at least 100. For each option, the program control problem is solved using the above algorithm, and the resulting the decision is entered into the KB. Such a solution is the optimal program for fertilizing, watering and herbicide treatments at the onset of the following phenophases: s=3 (tillering), s=9 (heading), s=10 (flowering), s=11 (milky ripeness):

$$D_j^*(t) = [d^*{}_{\mathrm{Ca}}(t) \quad d^*{}_{\mathrm{P}}(t) \quad d^*{}_{\mathrm{K}}(t) \quad d*_{\mathrm{Mg}}(t) \quad d_5(t)]_j,\ j = 1, 2, \ldots, N,$$

$$G_j^*(t) = [g_1(t) \quad g_2(t)]_j,\ j = 1, 2, \ldots, N.$$

The knowledge base formed in this way contains N solutions of the program control problem for the entire range of possible soil chemical parameters. This base is transferred to users for making independent decisions. To make such decisions, the user submits the crop cultivation conditions vector Z to the agrotechnology control unit. In the agrotechnology control unit, the most effective version of the control program is selected based on the KB. As in the problem of strategic management, to select the optimal solution, the method of pattern recognition is used, in which each of the possible variants of crop cultivation conditions is considered as an image or class. Table 1 shows a fragment of the KB for 6 variants of conditions.

Figure 1 shows a block diagram reflecting the developing approach to the intellectualization of agricultural technology management at the software level. Here, in the data processing center (DPC), all computational procedures for the formation of controls and knowledge bases are performed. These procedures include estimating state parameters, identifying mathematical models of op-amps, and generating the optimal programs themselves. For this purpose, information from ground-based information-measuring systems and Earth remote sensing data is used. Based on these data, many options for optimal programs for managing the state of an agricultural crop are formed, which are entered into the knowledge base. Such knowledge bases can be transferred to local control systems, where the user can independently make decisions on choosing the optimal program based on their initial data. In addition to the knowledge base, the data center can provide users with individual optimal control programs, generated according to their requests and local conditions.

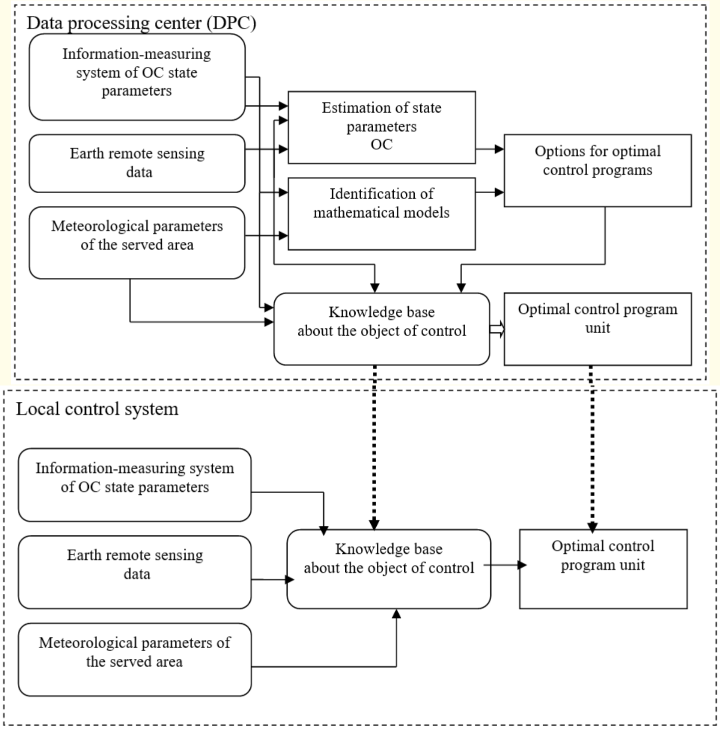

Figure 1: Block diagram of the DSS system with training from the data cente.

№ № options, *j*	***Pheno-phases***	***Soil chemical parameters***					***Optimal control programs***							***Criteria $J_{j=4}$***
		v_N	v_K	v_P	v_{Mg}	v_5	d_N	d_K	d_P	d_{Mg}	d_5	g_1	g_2	
1.	s=3	23,8	27	21,0	10,1	77,7	31,19	23,25	16,41	15,66	102,4	2,32	2,14	22,8
	s=9						185,32	183,97	106,75	93,39	383,0	2,12	2,06	
	s=10						239,09	228,58	110,02	94,23	729,7	1,75	1,43	
	s=11						336,64	307,95	148	138,05	1165	1,12	1,21	
2.	s=3	34,8	22,1	20,7	15,5	54,9	18,13	14,43	9,77	8,34	65,13	2,08	1,94	23,1
	s=9						174,58	182,94	105,29	91,19	384,0	2,00	1,86	
	s=10						241,81	231,70	111,86	95,58	732,5	1,65	1,56	
	s=11						336,53	307,86	147,98	138,03	1164,	1,15	1,21	
3.	s=3	24,6	28,8	21,2	9,75	86,8	39,51	30,38	22,44	21,08	125,9	1,86	1,72	20,6
	s=9						178,81	177,79	103,91	91,85	378,3	1,68	1,43	
	s=10						241,80	230,99	111,57	95,75	732,4	1,42	1,25	
	s=11						336,54	307,81	147,97	138,04	1164	1,16	1,00	
4.	s=3	21,3	23,1	24,6	81,2	81,2	40,60	32,53	24,36	1,67	121,3	2,31	1,87	24,4
	s=9						175,04	174,90	102,16	40,71	373,6	2,21	1,64	
	s=10						246,77	236,19	115,15	96,18	737,5	2,16	1,42	
	s=11						337,04	308,28	148,29	138,24	1165	2,0	1,36	
5.	s=3	38,0	32,1	13,3	15,1	50,4	15,74	10,46	9,32	7,19	54,1	1,65	1,55	22,9
	s=9						168,95	174,60	103,95	89,88	382,8	1,44	1,36	
	s=10						244,07	233,40	113,49	96,89	734,8	1,20	1,22	
	s=11						337,06	308,29	148,29	138,33	1165,	1,14	1,10	
6.	s=3	37,4	29,9	14,3	14,3	84,0	27,30	23,70	20,23	15,26	102,6	2,84	2,14	19,8
	s=9						173,36	178,80	105,34	91,38	379,6	2,66	1,97	
	s=10						241,85	231,23	112,04	95,76	732,4	2,31	1,44	
	s=11						336,48	307,77	147,98	138,03	1164	2,12	1,32	

Table 1: Fragment of the knowledge base for choosing the optimal agrocenoses management program.

To make decisions, a vector of conditions was presented from the knowledge base with the following components z_1=35 kg/ha; z_2=25 kg/ha; z_3=20 kg/ha; z_4=14 kg/ha; z_5=55 mm.

For the given conditions, the optimal option with the control programs given in Table 2 was selected.

Phenophases, s	***T***	***Dn***	***Dk***	***Dp***	***Dmg***	***D_5***
s=3	29	6,29	3,84	7,20	5,79	0,01
s=9	51	27,91	26,40	16,99	13,96	69,14
s=10	61	85,44	81,88	43,71	36,65	253,15
s=11	75	104,47	91,39	47,59	41,37	367,61

Table 2: Control programs for the version from the knowledge base.

This option corresponds to the value of the optimality criterion at the end of the growing season (26) at the last interphase management interval $J_{j=4}$=2360 rubles/ha.

To check the effectiveness of the control solution according to the knowledge base for the presented vector of conditions, the program control problem was solved using the algorithm (21), (23). The result of the solution is presented in Table 3.

Phenophases	***T***	***Dn***	***Dk***	***Dp***	***Dmg***	***D_5***
1	29	5,34	6,24	6,61	4,30	0,01
2	51	29,02	27,02	17,17	14,16	69,92
3	61	85,55	81,87	43,53	36,54	252,93
4	75	104,48	91,39	47,58	41,37	367,61

Table 3: Control programs for the design option based on local request.

It corresponds to the optimality criterion (26) $J_{j=3}$ =1840 rubles/ha. The loss of optimality from an error in decision-making based on the value of the criterion is 28%. To reduce losses, it is necessary to divide the region of possible values of conditions Ω_Z into a larger number of small decision-making regions.

Conclusion

The task of the program level of agricultural technology management for any crop is the formation of programs for technological impact on crops throughout the entire growing season. Due to this level of control, it is ensured that the desired crop yield is achieved with minimal expenditure of expended resources. At the same time, management programs, as a rule, are tied to the most significant phenological phases of crop sowing. Given the great complexity of the problem being solved, it is divided into two stages. At the first stage, which can be called "off-line 1," a program for the potential development of sowing is synthesized, which is implemented by freely varying the parameters of the soil environment. The solution to the problem at the second stage (off-line 2) is carried out by optimizing the size of fertilizer doses, irrigation rates and herbicide treatment doses, ensuring the best approximation of the crop development program to the potential level obtained at the first stage "off-line 1". With the intellectualization of program management and the transition to expert systems (ES), a knowledge base (KB) is formed for various crops and soil-climatic zones using a two-stage program generation algorithm. Such a knowledge base is contained in a data processing center (DPC) and is the main core of a cloud information system serving a given region. Users of the region have the opportunity to receive fragments of the knowledge base in the cloud system, thanks to which they can independently choose the optimal control programs for their conditions.

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