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Research Article

Information and Theoretical Foundations for Control of the State of Agrocenoses in Real Time

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Abstract

Objective: Presentation of a complete theory of management of the state of agrocenoses, including sowing crops and weeds. This theory makes it possible to obtain a given crop yield with the required reliability. Such management is formed on the basis of estimates of the parameters of the state of crops, soil environment and weeds, formed according to the data of Earth remote sensing in real time.

Methods: The presented theory is based on new mathematical models of the parameters of the state of agricultural crops, soil environment, weeds, as well as models of the relationship of these parameters with remote sensing (RS) data. Control factors in agricultural technology are doses of mineral fertilizers, herbicides and irrigation rates. Therefore, the parameters of the state in the management system under consideration, in addition to the parameters of the biomass of agricultural crops and weeds, are the chemical parameters of the soil environment. All technological operations are carried out at the onset of certain phenological phases of the development of crop sowing. RS data are entered precisely at such moments of time when the parameters of the state of crops and weeds are estimated on their basis. The presented theory is based on classical control principles used in modern dynamic systems. The most important feature of the proposed approach to solving the problem of agrocenoses management is the development of the principle of spatial distribution of agricultural technology parameters. It consists in using models with spatial variables, which are complemented by models of spatial approximation of controls in the form of multidimensional power polynomials. The parameters of the approximation models are evaluated according to the optimal parameters of technological operations obtained on 15-20 test sites of the field.

Results: In accordance with the proposed theory, mathematical models of agrocenoses, a real-time control algorithm using RS data and a specialized software package were developed, with the help of which the control system was tested on the example of spring wheat sowing.

Conclusion: As a result of testing a specialized software package for the implementation of the proposed theory, the operability of the proposed theory of agrocenoses control in real time and the possibility of using it in practical systems for automated control of agricultural technologies were established.

Keywords: agricultural technologies, agrocenoses, state parameters, crop sowing, weeds, parameter estimation, control, real time

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1 INTRODUCTION

At present, only certain aspects of the problem of managing agricultural technologies are considered in the works of modern researchers. These aspects include the choice of mathematical models of crops and soil environment[1,2], the development of a zonal approach to the use of mineral fertilizers and herbicide treatments[3]. The problems of risks associated with aspects of managing agricultural technologies are considered separately[4-6]. The lack of a unified theory of agricultural technology management is the main factor hindering the development of precision farming. A significant obstacle to the creation and development of a general theory of management of agricultural technologies are insignificant achievements in the field of using remote sensing (RS) data to form the quantitative parameters of crops and soil environment[7-14]. The appearance of the first works on the assessment of the parameters of the biomass of agricultural crops and the soil environment served as a stimulus for the development of a general theory of management of agrotechnologies[15-19].

The main effect of agricultural technology management is manifested in real time, when technological operations are formed according to the actual state of crops. It is here that the maximum positive effect from the use of Earth remote sensing (ERS) data is manifested, without which it is impossible to assess the current state of the control object (CO) and form optimal control actions.

At present, when solving the problems of managing agricultural technologies, only the sowing of an agricultural crop is considered as an CO, without taking into account the fact that weeds are contained in the agrocenoses of the field. The applied fertilizers stimulate the growth of not only the main crop, but also the growth of weeds, and herbicide treatments inhibit the growth of not only weeds, but also the growth of cultivated plants. In this regard, in recent years, works have appeared on the technologies of joint application of mineral fertilizers and herbicide treatments[20-22]. Such works have become a stimulus for the further development of the general theory of agricultural technology management[23].

The purpose of this work is to further develop the general theory of operational management of agricultural technology using RS data. As an example, the problem of managing the state of agrocenoses, which contains spring wheat and weeds, is considered.

2 MATERIALS AND METHODS

The fundamental basis for solving the control problem is mathematical models that describe the dynamics of the CO parameters. At the same time, in addition to the mathematical model of the main crop, the CO needs to complement the model of weeds. Such models should reflect the influence of controlled actions and external uncontrolled disturbances on the CO parameters, as well as take into account their relationship through the soil environment.

The crop under consideration as part of the agrocenoses is characterized both by continual state parameters, which can include the parameters of the state of the biomass of the crop itself and the soil environment, and by non-quantitative (structural) states, which include the phenological phases of plant development (phenophases). For spring wheat, depending on the duration of the interval in the daily time scale t, these states s are: at - s=1, sowing phase; at - s=2, shoots phase (1,2,3 sheets); at - s=3, tillering phase; at - s=4, phase exit into the tube; at - s=5, phase interstices; at - s=6, flag leaf phase; at - s=7, tongue phase; at - s=8, the phase of the opening of the leaf sinus; at - s=9, heading phase; at - s=10, flowering phase; at - s=11, phase milky ripeness; at - s=12, wax ripeness phase; at - s=13, the phase is full ripeness.

In the vegetation interval from the 3rd to the 9th phenophase, the structure of the sowing biomass can be characterized by only two components - total and wet weight. In the growing season from the 9th to the 13th phenophase, the mass of ears is added to these components. These differences in the structure of biomass lead to the need to divide the entire growing season into two management intervals, from the onset of the 3rd phenophase to the onset of the 9th phenophase (T_3, T_9) and from the 9th phenophase to the 13th phenophase (T_9, T_{13}).

Fertilization, herbicide treatments and watering are carried out at fixed times of the onset of the following pre-selected phenological phases: s=3 (tillering), s=9 (heading), s=10 (flowering), s=11 (milky ripeness). This makes it necessary to break down the entire growing season into management intervals between the 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 between phenophases from the 3rd to the 9th, the model of the dynamics of the parameters of the sowing biomass structure has the following form[24]:

$$\dot{X}_m(y,h) = A_m X_m(t,y,h) + B_m V(t,y,h) + C_m F(t,y,h) - D_m G_m(t,y,h) \quad (1)$$

Where the following designations are accepted: $X_m[2x1]$ is the vector of parameters of spring wheat sowing biomass, the components of which are: x_{1m} - plant biomass density (yield), $q \cdot ha^{-1}$; x_{2m} is the density of the fresh mass of crops, $c \cdot ha^{-1}$; F[3x1] vector of external disturbances, the components of which are: f_1 - average daily air temperature, °C; f_2 - average daily radiation level, $W \cdot (m^2 \cdot h)^{-1}$; f_3 - average daily precipitation intensity, mm; V[5x1] - vector of soil chemical state parameters with components: v_N - nitrogen content in soil, $kg \cdot ha^{-1}$; v_K is the content of potassium in the soil, $kg \cdot ha^{-1}$; v_P - phosphorus content in soil $kg \cdot ha^{-1}$; v_{Mg} - magnesium content in soil $kg \cdot ha^{-1}$; v_5 is the moisture reserve in the soil, mm; $G_m[2x1]$ - vector of herbicide treatments with components: g_{1m}, g_{2m} - doses of herbicide treatment, $g \cdot ha^{-1}$; y, h - spatial coordinates;

$A_m = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}_m$ - dynamic matrix,

$B_m = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \end{bmatrix}_m$ - control transfer matrix,

$C_m = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \end{bmatrix}_m$ - climate disturbance transfer matrix,

$D_m = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix}_m$ - herbicide treatment effect matrix.

For the intervals starting from the second (T_9, T_{10}) and subsequent intervals (T_{10}, T_{11}) and (T_{11}, T_{13}), the models of the dynamics of the parameters of the seed biomass structure have the same general form as the model (1): and differ only in the structure and parameter values[24].

$$\dot{X}_{uj}(y,h) = A_{uj} X_{uj}(t,y,h) + B_{uj} V_{uj}(t,y,h) + C_{uj} F(t,y,h) - D_{uj} G_{uj}(t,y,h) \quad (2)$$

Where $X_{uj}[3x1]$ is the vector of parameters of spring wheat sowing biomass, the components of which are: x_{1uj} - plant biomass density (yield), $q \cdot ha^{-1}$; x_{2uj} is the density of the fresh mass of crops, $c \cdot ha^{-1}$; x_{3uj} is the density of the mass of ears considered as a crop, $q \cdot ha^{-1}$;

$A_{uj} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}_j$ - dynamic Matrix,

$B_{uj} = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} \end{bmatrix}_j$ - control transfer matrix;

$C_{uj} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}$ - climate disturbance transfer matrix;

$D_{uj} = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \\ d_{31} & d_{32} \end{bmatrix}_j$ - herbicide treatment effect matrix.

Due to the fact that the CO is an agrocenoses, in order to solve the problem of managing its state, in addition to models of the state of crop sowing (2), (4), a dynamic model of the biomass of the dominant weed species is required, the vector - matrix form of which has the following form[23]:

$$\dot{S}_j = A_{sj} S_j(t,y,h) + B_s V_j(t,y,h) - B_{gj} G_j(t,y,h) - C_{sj} F(t,y,h) \quad (3)$$

Where $S_j = [s_1 \ s_2]$ is the biomass vector of the dominant weed species,

$A_s = \begin{bmatrix} a_{11} & 0 \\ 0 & a_{22} \end{bmatrix}_s$, $B_s = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \end{bmatrix}_s$,

$B_g = \begin{bmatrix} b_{11} & 0 \\ 0 & b_{22} \end{bmatrix}_g$, $C_s = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \end{bmatrix}_s$,

- model parameter matrices.

Model (3) includes the states of two dominant weed species. For other conditions, their number and types may be different, which only refines the structure of the algorithms, but does not change the general approach to solving the problem.

Models (1), (2) and (3) represent the main block of CO state parameters. In addition to this block, the OC contains a control transfer block, which is the soil environment. It is through this block that crop plants and weeds compete for nutrients and moisture.

The model of dynamics of soil state parameters for phenophases s=3 to s=9 has the following form[20]:

$$\dot{V}_{3,9}(y,h) = A_{3,9} V(t,y,h) + B_{3,9} D(t,y,h) + C_{3,9} F(t) - M_{3,9} X_m(t,y,h) - P_{3,9} S(t,y,h) \quad (4)$$

$A_{3,9} = \begin{bmatrix} a_{11} & 0 & 0 & 0 & a_{15} \\ 0 & a_{22} & 0 & 0 & a_{25} \\ 0 & 0 & a_{33} & 0 & a_{35} \\ 0 & 0 & 0 & a_{44} & a_{45} \\ 0 & 0 & 0 & 0 & a_{55} \end{bmatrix}_{3,9}$ $B_{3,9} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}_{3,9}$,

$C_{3,9} = \begin{bmatrix} 0 & 0 & c_{13} \\ 0 & 0 & c_{23} \\ 0 & 0 & c_{33} \\ 0 & 0 & c_{43} \\ c_{51} & c_{52} & 1 \end{bmatrix}_{3,9}$ $M_{3,9} = \begin{bmatrix} m_{11} & 0 \\ m_{21} & 0 \\ m_{31} & 0 \\ m_{41} & 0 \\ m_{51} & m_{52} \end{bmatrix}_{3,9}$, $P_{3,9} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \\ P_{31} & P_{32} \\ P_{41} & P_{42} \\ P_{51} & P_{52} \end{bmatrix}_{3,9}$

- system parameter matrices.

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 values of the parameters[24]:

$$\dot{V}_j(y,h) = A_jV(t,y,h) + B_jD(t,y,h) + C_jF(t) - M_jX_{uj}(t,y,h) - P_jS(t,y,h), j = 1,2,3 \quad (5)$$

The difference lies only in the structure of the matrix, which is due to the dimension of the vector of parameters of the state of crop sowing X_{uj}:

$$M_j = \begin{bmatrix} m_{11} & 0 & 0 \\ m_{21} & 0 & 0 \\ m_{31} & 0 & 0 \\ m_{41} & 0 & 0 \\ m_{51} & m_{52} & 0 \end{bmatrix}_j$$

To assess the parameters of the state of the biomass of the agrocenoses, the dynamics models must be supplemented with models for the relationship of RS data with the estimated parameters. The optical measurement model (ERS model) of the state of the seed biomass of spring wheat for the period before heading has the following form[16,17]:

$$Z_m(y,h) = P_mW(X_m(y,h)) + \Xi_m \quad (6)$$

Where: $Z^T_m(y,h)=[z_{1m}(y,h)\ z_{2m}(y,h)]$ is the vector of reflection parameters for the spatial coordinate (y,h) in the visible range (400-700nm) (z_1) and in the near infrared range (750-950nm) (z_2);

$P = \begin{matrix} P_{01} & P_{11} & P_{12} & P_{13} & P_{14} & P_{15} & P_{16} \\ P_{02} & P_{21} & P_{22} & P_{23} & P_{24} & P_{25} & P_{26} \end{matrix}$ - matrix of model parameters,

$$W(X_m(y,h)) = [1\ x_{1m}(y,h)\ x_{2m}(y,h)\ x^2_{1m}(y,h)\ x^2_{2m}(y,h)\ x^3_{1m}(y,h)\ x^3_{2m}(y,h)]$$

is a vector-function.

Where the arguments are the parameters of the sowing state: x_{1m} is the density of the sowing biomass for the spatial coordinate (y,h), cwt·ha^{-1}; x_{2m} is the density of the fresh mass of crops for the spatial coordinate (y,h), cwt·ha^{-1}; Ξ_m - random error vector of optical measurements with zero mean and covariance matrix K_z.

The model of optical measurements (ERS model) of the state of spring wheat biomass for the period from the beginning of earing to the ripening of the crop has the same form as model (6):

$$Z_u(y,h) = P_uW(X_u(y,h)) + \Xi_u \quad (7)$$

Where: $Z^T_u(y,h)=[z_{1u}(y,h)\ z_{2u}(y,h)\ z_{3u}(y,h)]$ is the vector of integrated reflection parameters in green (500-565nm) - (z_{1m}), in red (625-740nm) - (z_{2m}), in near-IR (750-950nm) - (z_{3m}),

$$P = \begin{matrix} P_{01} & P_{11} & P_{12} & P_{13} & P_{14} & P_{15} & P_{16} & P_{17} & P_{18} & P_{19} \\ P_{02} & P_{21} & P_{22} & P_{23} & P_{24} & P_{25} & P_{26} & P_{27} & P_{28} & P_{29} \\ P_{03} & P_{31} & P_{32} & P_{33} & P_{34} & P_{35} & P_{26} & P_{37} & P_{38} & P_{39} \end{matrix}$$

- matrix of model parameters,

$$W(X_u(y,h)) = [1\ x_{1u}(y,h)\ x_{2u}(y,h)\ x_{3u}(y,h)\ x^2_{1u}(y,h)\ x^2_{2u}(y,h)\ x^2_{3u}(y,h)\ x^3_{1u}(y,h)\ x^3_{2u}(y,h)\ x^3_{3u}(y,h)]$$

- is a vector function.

Where the parameters of the sowing state for the spatial coordinate (y,h) are the arguments: x_{1u} is the density of the sowing biomass, cwt·ha^{-1}; x_{2u} is the density of the fresh mass of crops, cwt·ha^{-1}; x_{2u} - grain mass density, cwt·ha^{-1}; Ξ_m - random error vector of optical measurements with zero mean and covariance matrix K_{zs}.

The model of optical measurements (ERS model) of weed biomass parameters has the form similar to model (6), differing only in the parameters:

$$Z_s(y,h) = P_sW(S(y,h)) + \Xi_s \quad (8)$$

Paired algorithms for estimating the parameters of the state of sowing and weeds have the same form for all interphase time intervals and differ only in the models used[18] - for sowing condition parameters using models (1),(6) и (2),(7)

$$\dot{\hat{X}}(t,y,h) = A\hat{X}(t,y,h) + BV(t,y,h) + CF(t) + R(t)\frac{\partial W^T(P,\hat{X})}{\partial \hat{X}}K_Z^{-1}(\tilde{Z}(t,y,h) - PW(\hat{X}(t,y,h)), \dot{R}(t) = R(t)A^T + AR(t) - R(t)\frac{\partial W^T(P,\hat{X})}{\partial \hat{X}}K_Z^{-1} \quad (9)$$

- for parameters of the state of weeds using models (3),(5)

$$\hat{S}(t,y,h) = A_sS(t,y,h) + B_sV(t,y,h) + C_sF(t) + R_s(t)\frac{\partial W^T(P_s,\hat{S})}{\partial \hat{X}}K_{zs}^{-1}(Z_s(t,y,h) - P_sW(\hat{S}(t,y,h)), \dot{R}_s(t) = R_s(t)A_s^T + A_sR_s(t) - R_s(t)\frac{\partial P_sW(S)}{\partial S}K_{zs}^{-1}\cdot\frac{\partial P_sW(S)}{\partial S}p_s^TR_s(t) \quad (10)$$

Where: R, R_s are estimation error covariance matrices.

Management of the state of agrocenosis consists in fertilizing, herbicide treatments and watering, which are carried out at the time points of the onset of the following pre-selected phenological phases: c=3 (tillering), c=9 (heading), s=10 (flowering), s=11 (milky ripeness). Due to the sequence of these phase-by-phase controls, the transfer of the state of sowing of spring wheat from the phase of seed germination to the full maturity of the grain and the achievement of the set control goal is ensured. In the indicated sowing state parameters, formally the control goal for the agrocenoses parameters averaged over the area of the field is as follows for the last $j=3$ interphase control interval at the time of grain ripening T_{13}

$$x_{1j=3}(T_{13}) \geq 2{,}1U^*, x_{2j=3}(T_{13}) \leq 0{,}15U^*, x_{3j=3}(T_{13}) \geq U^* \quad (11)$$

Where: U^* - given yield of spring wheat, cwt·ha^{-1}.

For each previous interphase time interval, optimal local control goals are set that ensure the achievement of the final goal (11). The formation of these local goals is carried out as a result of the implementation of program management of the state of agrocenoses[23]. This control stage, which precedes the real-time control stage, forms an optimal program for the evolution of the sowing state for the entire growing season. The sequence of vectors of sowing state parameters that define local control goals is denoted as follows:

$$X_m^*(T_3), X_u^*(T_{10}), X_u^*(T_{11}), X_u^*(T_{13}) \quad (12)$$

Similar goals are set for weeds as part of the agrocenoses

$$S^*(T_3), S^*(T_{10}), S^*(T_{11}), S^*(T_{13}) \quad (13)$$

For each interphase period of control, the optimality criterion is set

$$J_j = [X_j(T_j) - X_j^*(T_j)]^T G[X_j(T_j) - X_j^*(T_j)] + [S_j(T_j) - S_j^*(T_j)]^T Q[S_j(T_j) - S_j^*(T_j)] \quad (14)$$

Where: G,Q - weight matrices, through which the required ratios are established between the individual parameters of the state of sowing crops and weeds; j=0,…,3 - indices of interphase intervals of the general vegetation period.

Taking into account the introduced models and algorithms for estimating state parameters, the general real-time control algorithm includes the following steps:

Step1. From the beginning of the growing season, until the onset of the phenophase s=3 (tillering), the parameters of the sowing state are estimated (according to the algorithm (9)), the parameters of the weed condition are estimated (according to the algorithm (10)).

Step2. Estimates of the vector parameters of the biomass of crop sowing are taken as the initial condition in the model (2) when forming the control at time T_3. This control is found by minimizing the criterion (14) by the vector of parameters of technological operations D(T_3) and the vector of herbicide treatments G(T_3), into which the given value of the vector of parameters of the sowing state and the vector of parameters of the state of weeds, which must be achieved by the results of control, is substituted. Criterion (14) is minimized by the vectors D(T_3) and G(T_3) in accordance with the program control algorithm[23], which is given here due to the large volume occupied.

Step3. The obtained real-time control δD(T_3) is introduced into the model (4) of the parameters of the state of the soil environment, and the vector of herbicide treatments G(T_3) is substituted into the model (3). The transition to item 1 is carried out, and the entire sequence of operations is repeated for the phenophase s=9 and subsequent phenophases, up to the phenophase s=11 and obtaining the desired final result.

The above algorithm refers to the parameters of the state of agrocenoses averaged over the field area. The use of such an algorithm for each individual elementary section with spatial coordinates (y,h) is problematic due to their large number. Therefore, it is advisable to resort to a spatial approximation in the form of a polynomial of the 2nd degree:

$$D(T_j, y, h) = P_{1Dj}\hat{X}(T_j, y, h) + \hat{X}^T(T_j, y, h) \cdot P_{2Dj}\hat{X}(T_j, y, h),$$
$$j = 0,1, \ldots 3 \quad (15)$$

Where: P_{1Dj} is the parameter matrix of the linear part of the spatial corrector, P_{2Dj} is the parameter matrix of the quadratic part of the polynomial.

To form the matrices P_{1Dj} and P_{2Dj}, 20-25 test sites are selected, for which the control problem is solved according to the above algorithm for local estimates of the vector of planting state parameters. Based on the obtained solutions, training arrays $\{X_j, D_j\}$ are formed to estimate the parameters of the matrices P_{1Dj} and P_{2Dj}.

The matrices of the spatial corrector for controlling the state of weeds are evaluated in a similar way:

$$G(T_j, y, h) = P_{1Gj}\hat{S}(T_j, y, h) + \hat{S}^T(T_j, y, h) \cdot P_{2Gj}\hat{S}(T_j, y, h),$$
$$j = 0,1, \ldots 3 \quad (16)$$

A similar approximation is also appropriate for estimation algorithms (9), (10):

$$\hat{X}(T_j, y, h) = P_{1Xj}Z(T_j, y, h) + Z^T(T_j, y, h) \cdot P_{2Xj}Z(T_j, y, h),$$
$$j = 0,1, \ldots 3 \quad (17)$$

$$\hat{S}(T_j, y, h) = P_{1Sj}Z_S(T_j, y, h) + Z_S^T(T_j, y, h) \cdot P_{2Sj}Z_S(T_j, y, h),$$
$$j = 0,1, \ldots 3 \quad (18)$$

Where: P_{1Gj}, P_{1Xj}, P_{1Sj} are the parameter matrices of the linear parts of the approximation models (16)-(18); P_{2gj}, P_{2Sj}, P_{2Sj} are the parameter matrices of the quadratic parts of the approximation models (16)-(18).

3 APPROBATION

Approbation of the proposed control theory was carried out on the basis of experimental data obtained in the period 2016-2021 at the Menkovsky biopolygon of the Agrophysical Institute (Leningrad region, Gatchinsky district, Menkovo village). Spring wheat crops were part of a seven-field crop rotation. To form a database of experiments on the selected 20 test plots, samples of the biomass of agrocenoses and soil were taken. Simultaneously with the collection of samples, RS of the experimental field with agrocenoses was carried out using the Geoscan 200 unmanned aerial vehicle equipped

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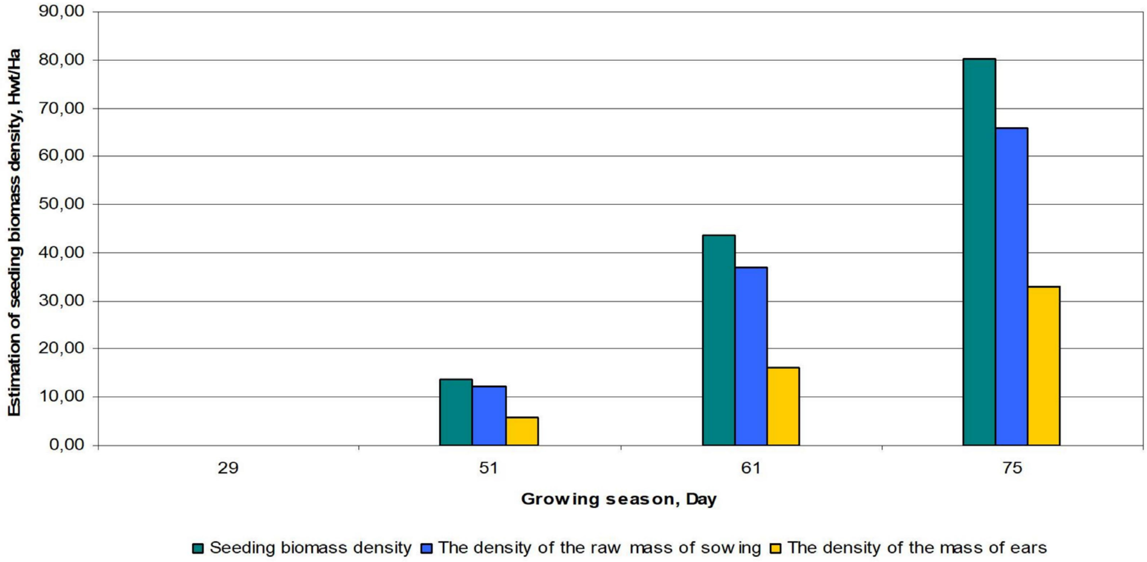

Figure 1. Diagram of vectors of parameters of the state of spring wheat sowing, setting local control goals in real time.

with an experimental multispectral optical camera GAMAYA OXI-VNIR-40 manufactured by the Higher Technical School of Lausanne (Switzerland). The camera captures reflection parameters in the range from 400 to 950nm. To determine the most effective flight altitude in terms of optical sensitivity, flights were carried out at three altitudes - 200, 300 and 400m, with a spatial resolution of 2, 3 and 4cm, respectively. Based on the analysis of the obtained data, an operating flight altitude of 200m was chosen, which corresponds to the best correlation of RS data with the calculated parameters of agrocenoses. As a result of the analysis of the information content of RS data in relation to the estimated parameters, the working ranges of the spectra were selected: 500-565nm (green), 625-740nm (red) and 750-950nm (near infrared range).

4 RESULTS AND DISCUSSION

4.1 Phenophase Management of Spring Wheat

As mentioned above, the management procedure begins with the design of an optimal agrocenoses evolution program for the planned growing season. For this, software control is used, the result of which is a sequence of vectors of parameters of the state of spring wheat sowing, setting local control goals in real time (18). For the example under consideration, this sequence is shown in Figure 1 (for a given yield of 50 cwt·ha^{-1}).

The next step of the general control algorithm is the procedure for estimating the sowing state parameters according to RS data at the phenophases in which real-time control was implemented. The sequence of such assessments is shown in Figure 2.

Based on the estimates presented in Figure 2, management is formed that ensures the achievement of local goals presented in Figure 1. These controls are shown in Figure 3.

The controls presented in Figure 3 ensure the optimal development of sowing throughout the growing season of spring wheat, shown in Figure 4.

4.2 Weed Management

Controls of the state of weeds are formed in a similar way, which are presented in Figure 5. The management presented in Figure 5 ensures the evolution of the parameters of the state of weeds over the entire growing season, shown in Figure 6.

As can be seen from the graphs in Figure 4, management in the form of doses of mineral fertilizers and irrigation rates ensures the achievement of the specified management goal (grain yield of 50 cwt·ha^{-1}). The graphs in Figure 6 shows that weed management in the form of herbicide treatment rates ensures that weed biomass is minimized at the end of the growing season. At the same time, the application of mineral fertilizers and herbicide treatments are carried out simultaneously.

4.3 Spatial Distribution of Control

Figures 1-6 show the results of the formation of control on the average over the area of the field. The use of RS data and models that reflect the spatial distribution of parameters of the state of crops and weeds, as well as approximations (16)-(18) allows us to build a spatial distribution of controls. Figure 7 shows the process of learning the parameters of the spatial corrector for the phenophases: s=9, heading (Figure 7A); s=10, flowering (Figure 7B); s=11, milky ripeness (Figure 7C).

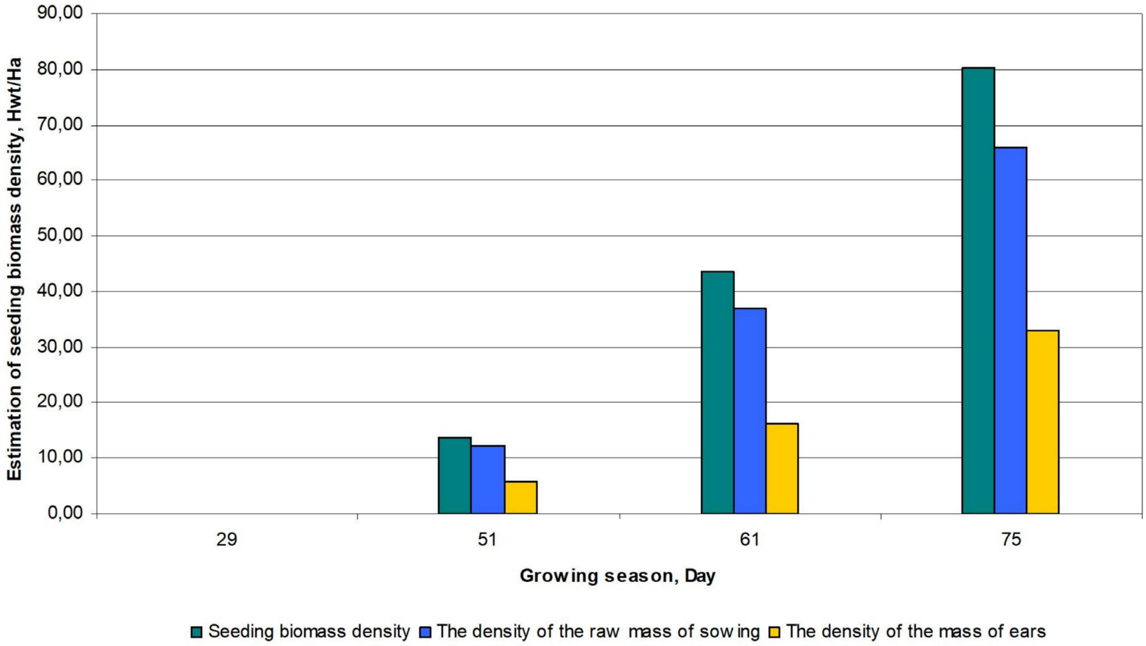

Figure 2. Estimates of the parameters of the state of spring wheat sowing at the phenophases in which the control is carried out.

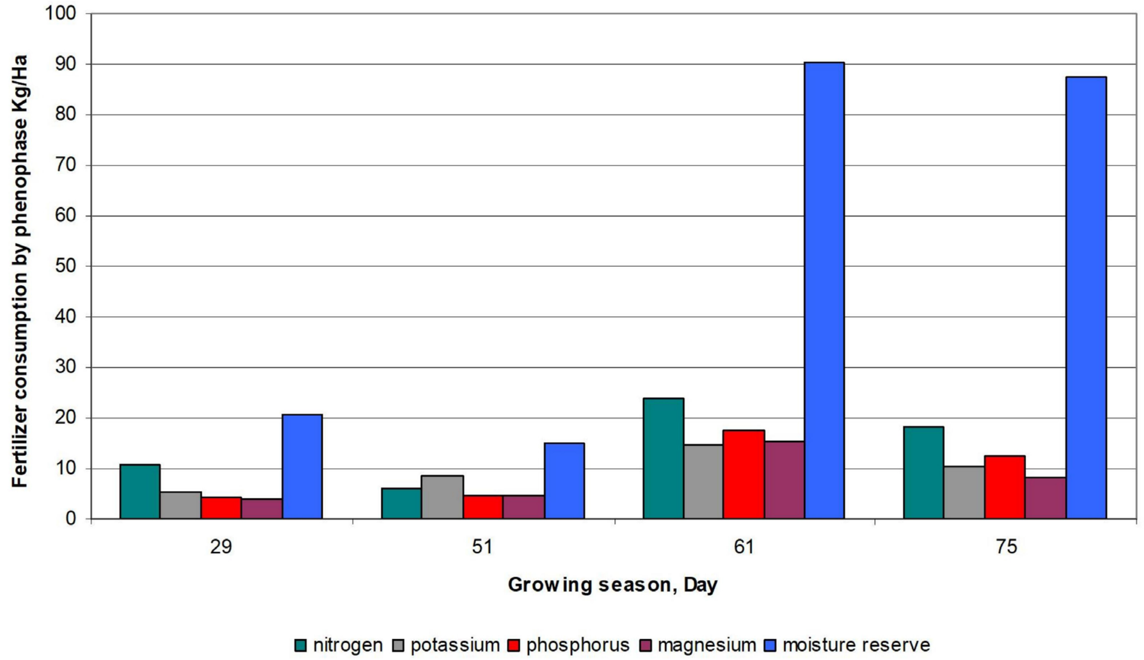

Figure 3. Management of the state of sowing of spring wheat by phenophases.

Figure 8 shows the process of learning the parameters of the spatial corrector of estimates of the parameters of the state of crop sowing (23). As can be seen from the figure, the corrector (23) provides a high accuracy of reproduction of estimates of the sowing state parameters (96%). This makes it possible to use the corrector (23) for constructing estimates over the entire area of the field using 20 reference estimates on elementary plots.

As can be seen from Figures 7 and 8, the learning process provides a sufficiently high accuracy of approximation of the spatial distribution of controls (92%). Figure 9 shows the spatial distribution of controls for the phenophase s=10, flowering. The spatial distribution of doses of herbicide treatments is not presented here due to their small values. Data on the spatial distribution of controls make it possible to use

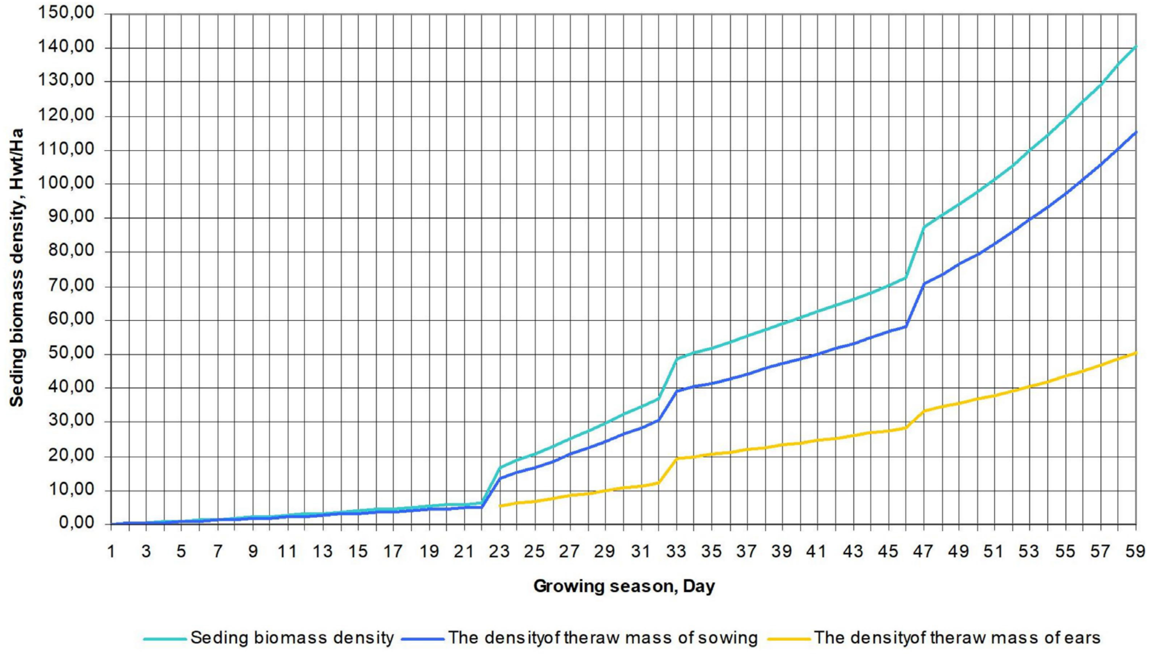

Figure 4. The optimal program for the evolution of spring wheat sowing throughout the growing season.

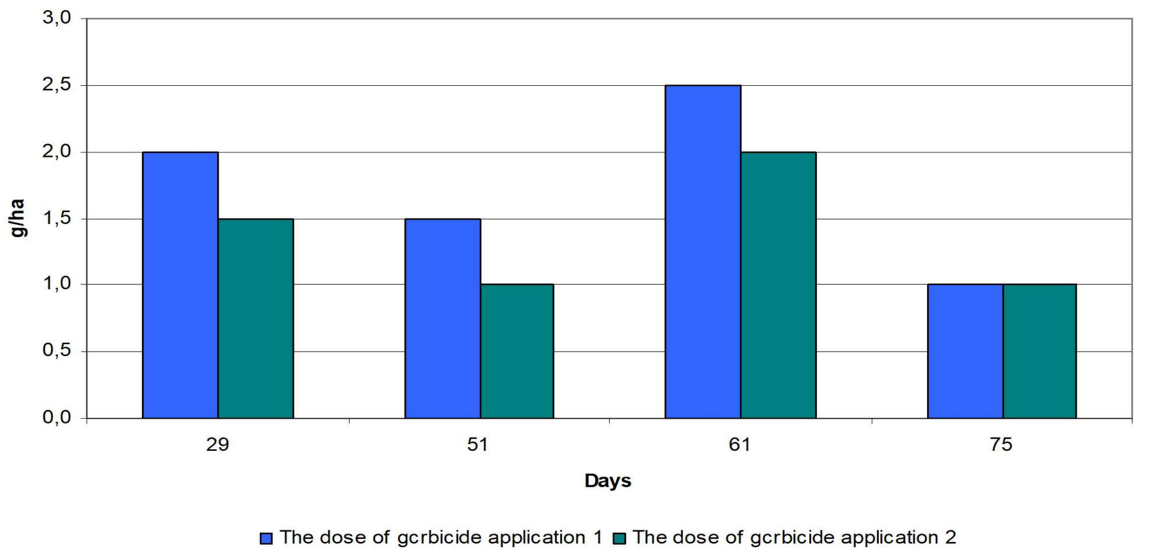

Figure 5. Management of the state of weeds of agrocenoses.

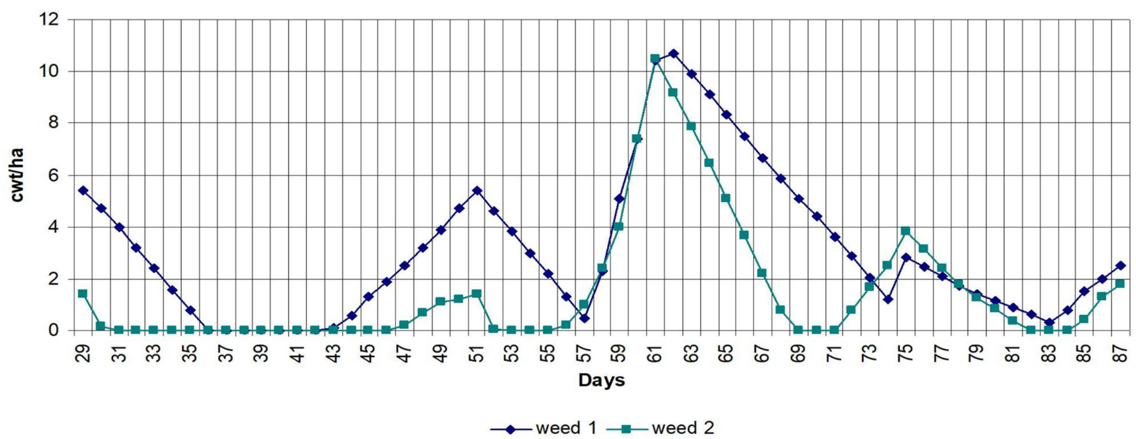

Figure 6. Evolution of the parameters of the state of weeds during the growing season.

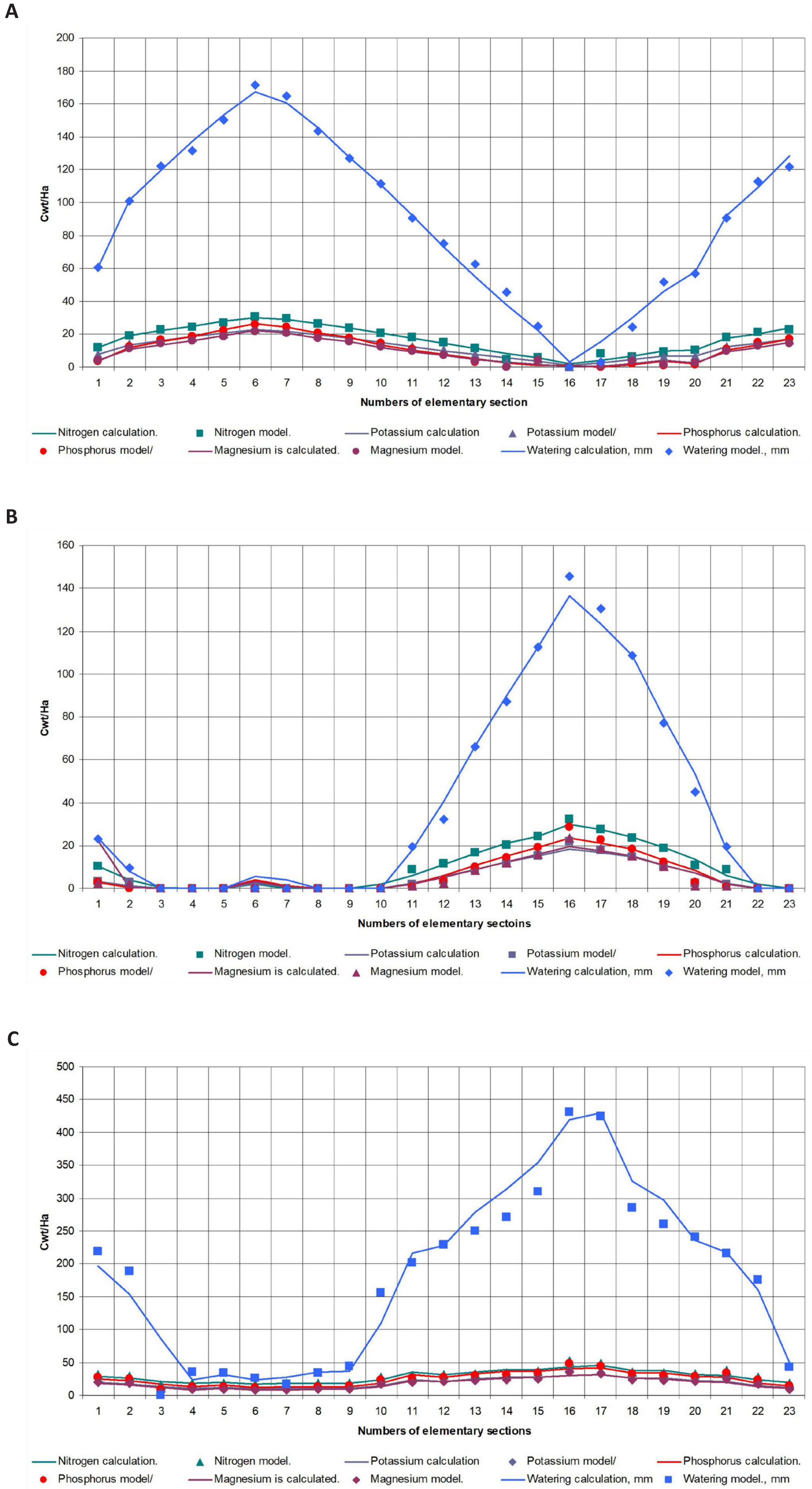

Figure 7. The process of learning the parameters of the spatial corrector for the phenophases. A: s=9 (heading); B: s=10 (blooming); C: s=10 (milk ripeness).

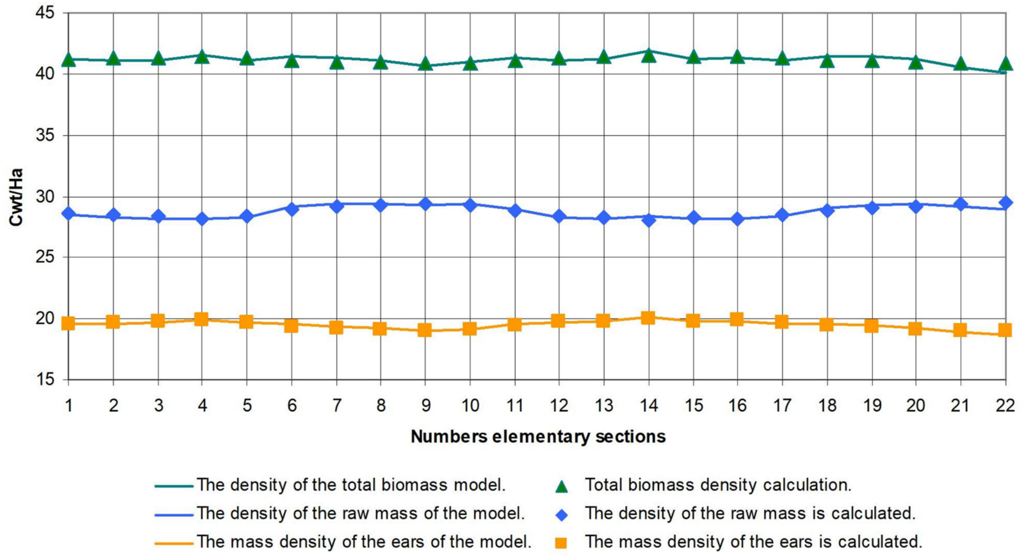

Figure 8. The process of learning the matrix of parameters of the spatial corrector of estimates of the sowing state parameters for the phenophase s=10 (flowering).

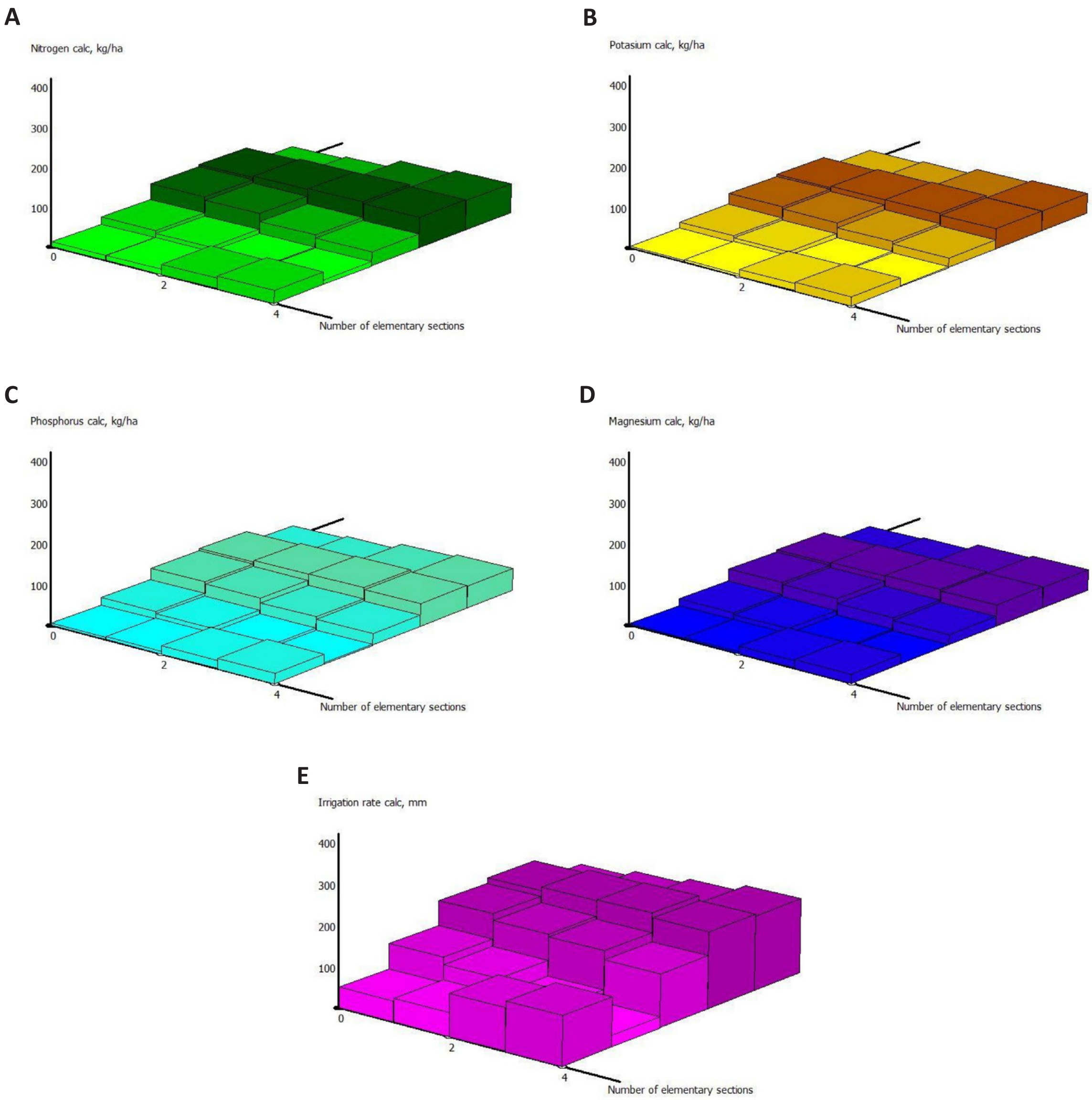

Figure 9. Fragment of the distribution of nitrogen (A), potassium (B), phosphorus (C), magnesium (D), and irrigation norms (E) doses over the field area.

modern robotic technologies for applying fertilizers and herbicide treatments, which provide independent control in elementary areas[8]. This allows people to acquire the maximum end result of agricultural technology for any climatic and landscape conditions with a high degree of spatial distribution of parameters.

5. CONCLUSION

The theory of agrocenoses state control, including sowing of spring wheat and weeds, is proposed. The theory includes algorithms for estimating the parameters of the state of sowing crops and weeds according to ERS data, as well as algorithms for generating controls for given phenological phases of crop development. The factors for managing the state of agricultural crops are the doses of mineral fertilizers and irrigation rates, and the management of the state of weeds is the dose of herbicide treatments. An important technological feature of the proposed campaign is that fertilizer application and herbicide treatment are carried out simultaneously. The basis for solving the problem of operational management is the optimal program for the development of agricultural plants obtained in advance. The program sets reference points for the development of crops, which must be achieved due to the size of technological operations, determined from the data of ERS. At the same time, on the basis of ERS data and non-linear approximation models, the spatial distribution of technological operations over the field area is constructed.

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Conflicts of Interest
The authors declared no conflict of interest. All ideas and results were obtained by the authors themselves.

Author Contribution
Mikhailenko IM developed the general concept of the article, created the theoretical basis of the work, including mathematical models and algorithms. Timoshin VN developed a specialized software package on which the developed theory was tested. The authors jointly developed the program and methodology for conducting field experiments.

Abbreviation List
CO, Control object
ERS, Earth remote sensing
RS, Remote sensing

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