Approaches to Building an Automated Control System for Plant Production in the Conditions of Greenhouse Effect Dynamics

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Abstract. The article examines the main aspects of implementing adaptive management of plant production technology in the context of the dynamics of the greenhouse effect, based on the construction of automated systems endowed with the functions of scientifically based zoning of agricultural territories, taking into account the results of model assessment and forecasting of the dispersion and accumulation of greenhouse gases. Systems of this class include a special module - a digital platform that generates and updates a complex of necessary models, algorithms, their software implementation, and a knowledge base for automated operational comparison and selection of a technological map and type of crops for their cultivation, ensuring a consistently high yield in the existing/predictable natural and climatic and man-made conditions. Effective solutions for the stated tasks and the choice of the best technology from alternatives are achieved based on the synthesized use of methods of intelligent data analysis, geoinformation technologies, and 3D modeling. The digital platform not only implements the dynamic formation and use of required predictive models and algorithms but also ensures the operational response of all components of the investigated automated system to current changes in the control object and the surrounding environment. The adaptive management scenarios generated in the system are aimed at increasing the productivity of agricultural territories based on the rational use of causal links between the natural potential of soil and plants with climatic factors.

Keywords: Automated control system · Modeling · Agricultural zoning · Agricultural productivity · Greenhouse effect

1 Introduction

Modern systems for monitoring, forecasting and technology management processes in crop production use automation tools, mathematical and computer modeling capabilities for complex data analysis, which allows them to be endowed with both traditional information collection and processing functions and decision support functions [1–3]. This is particularly important in connection with the need to take into account the following features: the participation of biological organisms in agricultural production; significant dependence on natural and climatic factors; the necessity of finding effective

A. A. Radionov and V. R. Gasiyarov (Eds.): RusAutoCon 2023, LNEE 1130, pp. 3–14, 2024.
https://doi.org/10.1007/978-3-031-51127-1_1

solutions minimizing costs of implementing intensive technologies, aggressive chemical and physical effects on soil, among others. These features generate requirements for processing multiple and diverse information, creating specialized systems of rules and algorithms for working with quantitative and qualitative parameters (their combination).

Thus, the technology of crop production includes a set of operations necessary for growing agricultural crops and ensuring the formation of the crop yield, the effectiveness of which is related not only to the choice of an interconnected complex of machines, methods of movement and modes of operation of units in soil cultivation, type and norms of material consumption (seeds, fertilizers, pesticides, soil improvers), plant protection means but also to the direct influence of natural soil fertility, weather conditions, and climatic characteristics of the territory [4]. Therefore, the efficient development of the crop production complex is directly related to ensuring the flexibility and mobility of the management system in response to current and foreseeable changes in both the organizational-technological and natural-climatic spheres. The operative development of corresponding adaptive management scenarios, rational natural-agricultural and agroecological zoning of agricultural territories should be based on the results of the analysis of data from complex monitoring and various types of model assessments and forecasts based on identified cause-and-effect relationships in the biotechnosphere, which requires the development and implementation of automation mechanisms and specialized methods and models of intelligent management support.

2 Relevance

The features of modeling automated control systems (ACS) for production processes are largely determined by the specificity of the controlled object, its state parameters, and its interaction with the external environment. When developing and studying the technology of crop production, developing corresponding ACS for technological processes and production, their main modules, attention is currently not paid enough to the close dependence of the state of soil and agricultural crops on global and regional climate change trends. In particular, in recent years, the number of scientific studies demonstrating the dependence of agricultural land productivity on changes related to the dynamics of the greenhouse effect has increased, including the results of the scattering and accumulation of greenhouse gases (GHG), primarily carbon dioxide [4–7]. Climate change forecasts for the most probable scenarios obtained using CO_2 general circulation models indicate an increase in the concentration of carbon dioxide in the surface layer of the atmosphere, due to the dynamics of natural and technogenic factors (Fig. 1).

An extensive amount of literature by domestic and foreign scientists is devoted to the study of climate change and its impact on agricultural production. A significant contribution to the study and modeling of climate change was made by: Clements R., J. Haggar [5], A. Quezada, J. Torres [6], Druzhinin P.V. [7], Pavlovsky A.A. [8], Pavlova V.N., Sirotenko O.D. [9], Siptits S.O., Romanenko I.A. [10], Shilovskaya S.A. [11], Kleshchenko A.D. [12], Ryabov I.Yu., Ponkina E.V. [13], Karmenova M.A. [14] and other scientists. It should be noted that studies by Russian and foreign authors demonstrate that there is a positive effect when the concentration of CO_2 in the atmosphere increases [3]. On average, for all types of agricultural crops, the increase in yield was

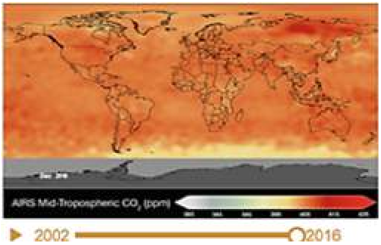

Fig. 1. Change in CO_2 concentration in the surface layer of the atmosphere.

26%, the increase in dry matter of young plants was 40%. The development of the biomass of young plants in most cases reacted more strongly to the high content of CO_2. According to the research [14], the increase in grain yield with a doubling of CO_2 concentration is almost twice as high as the increase in biomass (36 and 20%) [10]. Given the important role played by cereals in world food production, it can be expected that the patterns obtained will be of particular importance in the future with a possible increase in the concentration of atmospheric CO_2.

An increase in the agricultural productivity with the adaptation of the technological process of crop production can be achieved due to the distribution of territories according to the efficiency of growing different crops in different conditions, which are characterized by meteorological, soil indicators, and GHG concentrations in the surface layer of the atmosphere. This is necessary for the effective growth of agricultural crops, the accumulation of dry matter, and the sequestration of GHGs from the surface layer of the atmosphere. Adaptation measures for agricultural zoning should demonstrate the transition from the formed/predicted situation to the required situation in the direction of increasing the productivity of the study area backed by a scientifically based choice of parameters for its zoning: agro-ecological (a set of measures and actions for a clear and reasonable delimitation and classification of territories according to their purpose), natural and agricultural (delimitation of territories, taking into account climatic, soil, technogenic and other conditions in relation to the agrobiological requirements of agricultural plants), as well as determining the type of crop and technological map that provide the required result.

In recent years the number of scientific studies has increased demonstrating the dependence of the agricultural productivity on weather and climate changes, including the dispersion and accumulation of greenhouse gases in the surface layer of the atmosphere [4–7]. Based on a unified methodology the main modeling schools have appeared, such as AGROTOOL and WOFOST models, at the Center for the Study of World Nutrition Problems in Wageningen [11]. Thus, one of the first models of the American CERES school should be noted [14]. These studies are related to the construction of dynamic simulation models to analyze the growth and productivity of annual field crops, using information about soil parameters, photosynthetic activity of plants, and environmental conditions. Some of them may be part of a common methodological toolkit to ensure effective management of the agricultural productivity, taking into account the GE dynamics. However, it should be noted that these systems do not take into account the dynamics of CO_2 concentration in the atmosphere (it is assumed to be constant). At the moment, there are no methods and algorithms that allow the formation of adaptation scenarios for managing the technological and production processes of crop production in specific areas, determining the most effective parameters of crop growing processes in terms of yield, depending on the quantitative and spatial assessment and forecasting the level of dispersion and accumulation of greenhouse gases (GG) in the surface layer of the atmosphere [15]. The peculiarity of the technological processes of crop production in agriculture, associated with the existence of biological organisms, dependence on natural, climatic and technogenic factors, determine the close relationship between technical operations and the productivity/yield of agricultural areas.

3 Research Task

Give each table a heading (caption). Add a reference to the table source at the end of the caption if necessary. All tables should be numbered with Arabic numerals. Ensure that all tables are cited in the text in sequential order. Do not write "the following table".

The key indicator of the agroecological situation in this case is the state of the agricultural area under consideration in terms of its productivity, which determines the yield of agricultural crops located in the zone of influence of specific man-made and natural objects and/or processes that form specific GE parameters. Let us introduce the corresponding linguistic variable - *AtmGG*, which (taking into account and developing the approach proposed by D.A. Pospelov [2]) can be defined as a complex spatio-temporal assessment of the totality of characteristics: their photosynthetic activity; the state of the soil environment, which determines the productivity of the study area; their connections with the parameters of the technosphere and the external environment, which influence the formation of the level of environmental and food security.

Based on the general principles of situational modeling [2], we introduce the concepts:

- the current state of the agricultural territory located in the zone of influence of objects and/or processes of the technosphere (we will designate it as $AtmGG^{act}$ in the course of the modeling process), which is determined at a given moment;
- full state (we will designate during the implementation of the modeling process as $AtmGG^{full}$), including:
- state of $AtmGG^{act}$;
- knowledge about the state of the studied objects and/or processes of the technosphere, the state of the agricultural territory, external influences at a given time;
- knowledge about the mechanisms and technologies for managing objects and/or processes of the technosphere, the infrastructure of the territory, about cause-and-effect relationships that determine the conditions of dynamics and the possibility of optimizing their parameters.

An elementary act of agroecological situation management in the territory under consideration can be represented on the basis of a logical transformational rule:

$$AtmGG_i^{full} : AtmGG_i^{act} \underset{H_k}{\rightarrow} AtmGG_j^{act} \tag{1}$$

where, H_k – k-th control action on any parameter of the studied object and/or process of the technosphere, the infrastructure of the territory under consideration, which determines the spatial and temporal dynamics of the agroecological situation; $k = 1, M, K$, where K is the number of possible control options (possible impacts, the totality of which can provide the desired result).

Relation (1) shows the following: if in the considered agricultural area characterized by some infrastructure parameters and taking into account the influence of the external environment under the influence of GHG dispersion and accumulation, an agroecological situation has formed, determined by the state $AtmGG_i^{act}$, and the state of the technogenic objects and processes themselves, mechanisms for their implementation, the methods used and the control roadmap, defined by $AtmGG_i^{full}$ allow the application of the control action H_k, then when the latter is implemented, the current state $AtmGG_i^{act}$ is transformed into a new state $AtmGG_j^{act}$, which is associated with adaptation of technological maps in terms of GE dynamics with a corresponding increase in the productivity of the agricultural territory and crop yields. The set of possible alternative rules represents the corresponding set of adaptation scenarios.

The proposed generalized model of an ACS for crop production under the dynamics of the greenhouse effect, implementing control processes (1), is schematically shown in Fig. 2.

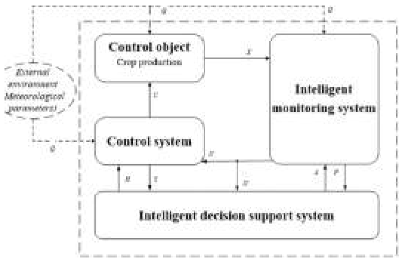

Fig. 2. General model of automated control system for crop production under the dynamics of greenhouse effect.

This automated control system consists of the following main subsystems:

- Control object - adaptation of agricultural areas in terms of GE dynamics - the state of which is described by the set X;
- Monitoring system – collects and pre-processes data (P);
- Intelligent decision support system - evaluates, predicts, makes spatio-temporal analysis and generates models of alternative control scenarios (H);
- Control subsystem - develops a set of control actions on the control object U, while Y is feedback that provides the results of the implementation of specific control scenarios;
- Q is the measured parameter of external influences.

To ensure the effective functioning of the introduced intelligent decision support system (IDSS), it is necessary to fill it with a complex of models and algorithms from the set M [3].

The structure of the IDSS for crop production in the context of the need to account for the dynamics of the greenhouse effect will be determined both by the requirements and principles of building systems of this class mentioned above and by the functions that the system implements [1–3].

We proposed a functional model of the system, which is shown in Fig. 3. With details in Fig. 4.

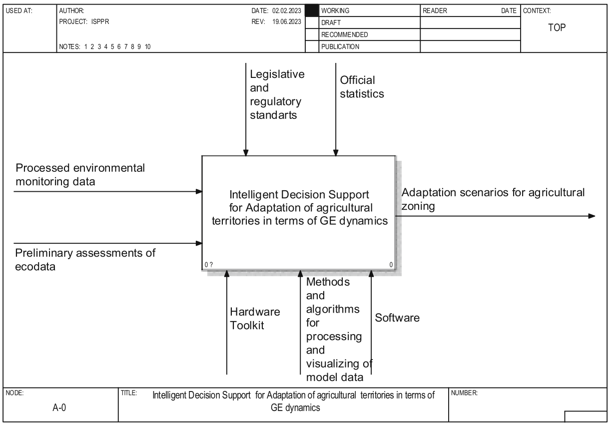

Fig. 3. Context diagram of an intelligent decision support system.

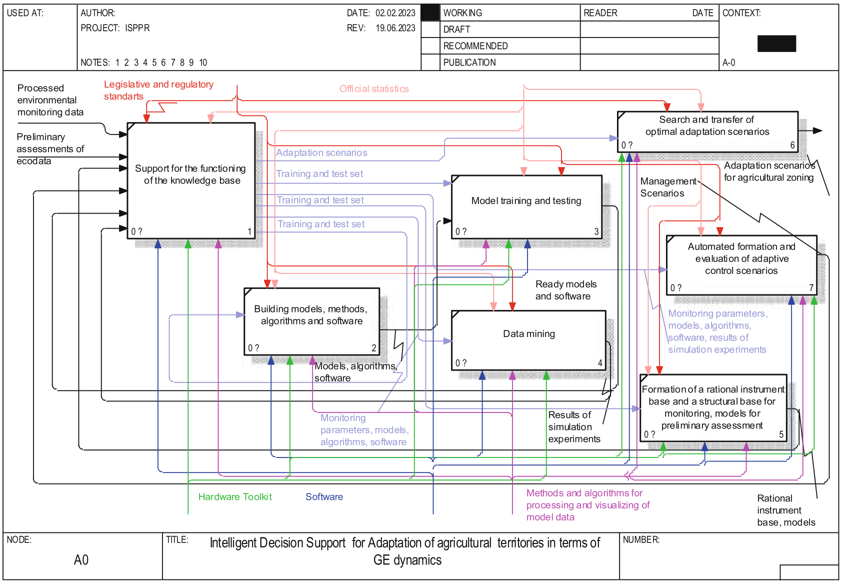

Fig. 4. Decomposition of the context diagram of the intelligent decision support process.

Data from the intelligent environmental monitoring subsystem on the state of the parameters of the biotechnosphere and preliminary assessment are received by the IDSS and stored in the corresponding databank. All the necessary information becomes available for each process in IDSS due to the generated rule base.

The corresponding schematic representation of the ACS model is presented in Fig. 5.

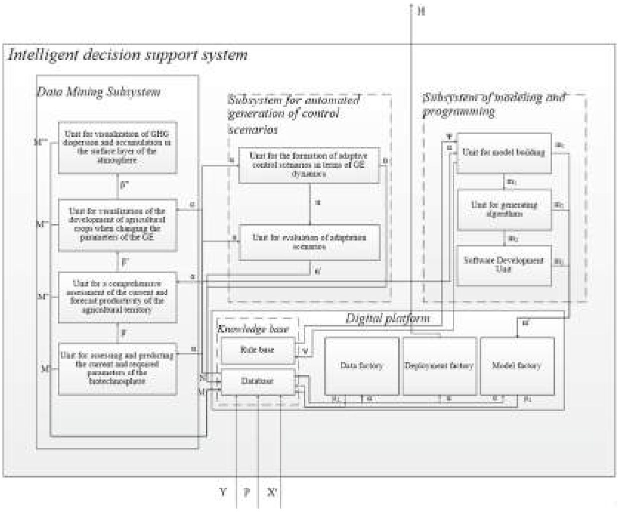

Fig. 5. Schematic representation of an intelligent decision support system as part of an automated technological process control system for agricultural zoning in terms of the greenhouse effect dynamics.

To implement the functions of IDSS, the following subsystems have been introduced into its structure:

- digital platform (σ_{dp}), which combines the knowledge base and factories of data, modeling and deployment, which allows you to transfer the signal H to the control subsystem;
- data mining subsystem (σ_{dm}), which allows to carry out various simulation experiments (prediction of current and required atmospheric parameters, a comprehensive assessment of the current and predicted plant productivity, visualization of plant development when GE parameters change);
- modeling subsystem (σ_{mod}), in which, on the basis of environmental monitoring data, the preparation of models, algorithms and software necessary for the functioning of IDSS is carried out;
- a subsystem for the formation of control scenarios (σ_{cs}), which, based on the results of simulation experiments and models, generates and transfers to the digital platform adaptation scenarios for zoning agricultural areas in terms of GE dynamics and their assessment.

The introduction of internal control loops provides an adaptive change in the structure and parameters of the automated control system. As a result, the implementation of the development of scientifically based management decisions related to the zoning of territories and the change in the technological maps used, the following scheme of zoning of territories is proposed in order to increase crop yields in the context of GE dynamics (Fig. 6).

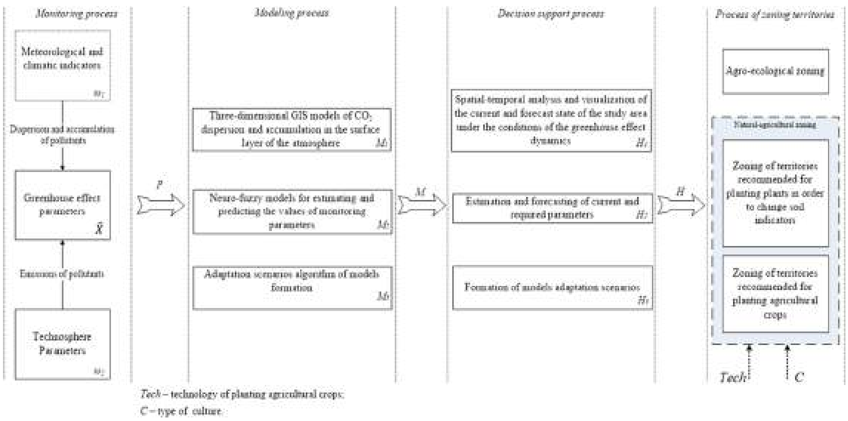

Fig. 6. Scheme of adaptive zoning of territories to increase agricultural crops in terms of GE dynamics using digital technologies.

This scheme includes the following processes:

Monitoring process, where $P = \{\omega_1, \omega_2, \tilde{X}\}$, ω_1 - the most variable, controlled but uncontrollable meteorological factor, ω_2 - technosphere parameters that determine the power and structure of pollutant emissions into the atmosphere; $\tilde{X}$ – GE parameters that are formed under the influence of meteorological and technogenic parameters (air temperature, soil heat supply and CO_2 concentration in the surface layer of the atmosphere), $\tilde{X} = f(\omega_1, \omega_2)$, while the more transducers, sensors, gas analyzers and microcontrollers will be networked together and exchange data, the more accurate forecasts and planning can be.

Modeling process, where $M = \{M_1, M_2, M_3\}$: based on monitoring data (P), GIS and 3D models (M_1) are built; neuro-fuzzy models (M_2) that determine cause-and-effect relationships $g\{\omega_1, \omega_2, X\}$; algorithm for forming models of adaptation scenarios (M_3). To implement this process, the functions of the intelligent monitoring subsystem of the proposed automated control system are updated.

Decision support process, where $H = \{H_1, H_2, H_3\}$, which provides processing of information into a form suitable for making managerial decisions.

The process of zoning territories: the implementation of specific control actions, namely, the determination of the spatial and structural parameters of the territory for planting an agricultural crop of a certain type (C) using the most optimal planting and processing technology ($Tech$) under the given conditions [11].

4 Practical Significance

To enable practical application and ensure the functioning of the ACS for crop production when updating specific systems, a software package has been developed for adapting the technological process of zoning agricultural territories in a particular region (Belgorod region). This software package allows for the following:

- conduct simulation experiments to determine the photosynthetic activity of plants in agricultural areas that are in the zone of influence of stationary sources of emissions of GG;
- conduct a comprehensive evaluation of the productivity of an agricultural territory and develop possible recommendations for crop cultivation to increase yields, based on the proposed automatic method, which is based on the use of fuzzy logic principles [16–19];
- to visualize the growth and development of plants, the dispersion and accumulation of GHGs in the surface layer of the atmosphere of the study area [18].

To implement the tasks set, an appropriate block diagram of the software package was developed (Fig. 7).

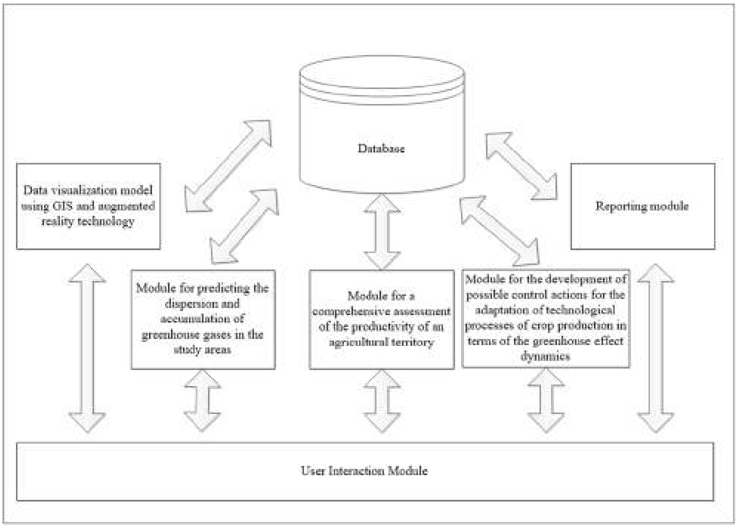

Fig. 7. Structural diagram of the software package.

The diagram shows the modules that allow to organize the work of the software package. Convenient user interaction with the software package is carried out through the use of a convenient user interface that provides access to all functions. Visualization using GIS technologies allows reflecting the dispersion and accumulation of GHGs in the study areas. Augmented reality technology is used to visualize the growth and development of plants. This is necessary to reflect the agroecological situation. A neural network model is used to predict the concentration of GHGs from stationary sources in the surface layer of the atmosphere and further determine the photosynthetic activity of an agricultural crop. To implement the ANN, the NeuronDotNet library is used. A comprehensive assessment of the productivity of an agricultural territory is based on the apparatus of fuzzy logic. The FuzzyNet library is used for implementing fuzzy inference. The development of recommendations for the cultivation of crops and zoning is implemented through a production model for the development of recommendations. Reporting is carried out within the framework of ongoing research in the form of graphs, diagrams, text and tabular reports. Data bank is used for storing information that is necessary for the operation of the software package.

For the practical application of the proposed automated control subsystem, a software package is developed using the C# programming language and the Visual Studio 2022 development environment. For example, Fig. 8 shows a screenshot form demonstrating the process of entering information about the moisture and heat supply of the agricultural territory under consideration, information about the mineral indicators of the soil, with the development of recommendations.

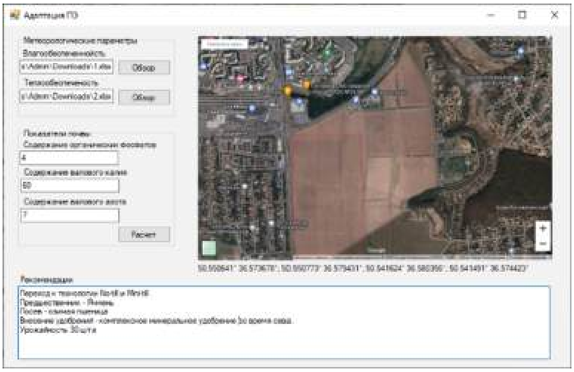

Fig. 8. Getting recommendations.

5 Conclusion

Approaches to the construction and organization of the ACS for crop production in the context of the greenhouse effect dynamics have been presented in the article. They are supposed to ensure an increase in the productivity of agricultural territories and an increase in crop yields through prompt intelligent analysis of monitoring data, including the data based on a comprehensive assessment of existing and predicted biotechnosphere parameters of the considered territories. Modeling and research of an important component of this ACS have been carried out, which provides the possibility of forming adaptive management scenarios - an intelligent decision support subsystem, including a specialized digital platform for building and updating the necessary models, algorithms, and their software implementation. The presented approaches and models can be used to form a common intelligent management network for agricultural territories at any level of administrative and territorial division. The results of such ACS work are primarily necessary for ensuring stable crop yield growth using the specifics of the natural and climatic factors impact.

Acknowledgments. The research work was financially supported by the Russian Science Foundation (project no. 22-11-20016) on the subject of "Development and research of an intelligent decision support system for the adaptation of agricultural areas in terms of the greenhouse effect dynamics".

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