The unified digital platform for agricultural production management as the basis of mathematical model for optimizing the crop rotation structure

V.I. Budzko, *V.I.* Medennikov* and *P.A.* Keyer

Federal Research Center "Computer Science and Control" of the Russian Academy of Sciences, Vavilova 44-2, 119333, Moscow, Russia

Abstract. The paper shows that although scientifically-based crop rotations in agriculture determine all technological processes in agriculture, nevertheless, widespread non-compliance with crop rotations in Russia has led to the fact that there are no models for optimizing the structure of crop rotations in the introduced digital technologies. Moreover, their analysis showed that these developments represent only fragmentary improved accounting tasks without a mathematical block of decision-making, that is, the digitalization of existing economic relations is in progress, thereby violating two basic principles of the digital economy that have developed in recent years in developed countries: the formation of an information resource management system based on their rational integration into a certain single structured space and rethinking of production management technologies on this basis. It is also shown that the implementation of these principles led to the formation of a unified digital agricultural management platform, which served as the basis for the development of a mathematical model for optimizing the structure of crop rotations at agricultural enterprise. As a result, this model will be the basis for the integration of all major digital technologies in agriculture, which are the essence of rapidly developing precision farming technologies. The paper provides a systematic analysis of the factors affecting the formation of crop rotation structure, as well as the conditions for their successful practical implementation, under which prospects will open for agriculture to switch to a single digital management platform, in which the tasks of forecasting, planning and management of the land use, as well as material, financial, labor, and information resources with various emphasis on detail at various levels of the country from the field to the federal center.

1 Introduction

Recently, agriculture has been turning into one of the active participants in the production digitalization in developed countries with the advanced development of precision agriculture (PA), based on remote sensing (RS) technologies, geoinformation systems

* Corresponding author: dommed@mail.ru

(GIS), precision manufacturing, requiring a combination of a large amount of structured data and processing technologies, a significant increase in functional tasks and intersectoral relationships, improving agricultural machinery, attracting a large number of performers with an appropriate new level of competence. These technologies also required considering a significant number of parameters of land resources with the necessary degree of their digitization and integration based on ontological modeling.

Digital technologies [6, 2, 3, 8, 4, 10] related to agriculture allow to obtain data about the state of the soil and crop, determine the composition and the required amount of chemicals, monitor farmland and the equipment used, solve various analytical problems of accounting, financing, planning, as well as agroecological assessment of land.

At the same time, optimization mathematical models are rarely used, and decisions are made by production specialists. In particular, no models have been developed to optimize the structure of crop rotations, although the system of scientifically based crop rotations is the basis of all agricultural production. Crop rotations in agriculture determine all technological processes in the industry. The nature of tillage, crop tending, methods of protective measures against land erosion, the structure and volumes of fertilizers and plant protection products applied, the systems, machinery, and equipment used, the rational placement of production units and warehouses depend on them. Crop rotations affect the efficiency of all agricultural production, allowing more efficient use of the main resource – land. This, in turn, leads to a reduction in financial costs, improves bioclimatic indicators, the quality of food and plant protection products, increases the efficiency of agricultural machinery use.

The article describes a mathematical model for optimizing the structure of crop rotations, which is implemented in the created digital management platform (DMP) for agricultural production, ontologically and functionally integrating the tasks of agricultural production from single scientifically based positions. This DMP reflects global integration trends in data and applications [12, 13].

2 Materials and methods

The need for the use of integration technologies in the digital economy (DE) is dictated by the entire course of world social development informatization. But only with the advent of Internet technologies integration technologies became widely used, which is why even the term digital platform (DP) appeared. Understanding these processes, and at the same time solving the problem of DP classification, must be sought in the laws of the information and communication technologies (ICT) evolution, the three-dimensional space of which is determined by the following main measurement axes: information resources (IR); algorithms that formalize data processing, in particular, management functions; tools in the form of software, means of communication, and electronic devices (Fig. 1).

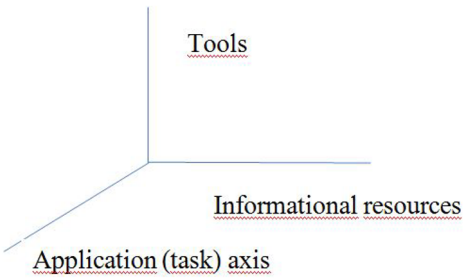

Fig. 1. Digital space of information and communication technologies.

The improvement of ICT, which led to the DE, affected all three components of the ICT space, allowing the formation of certain its subsets, which received various definitions of the DP, for some groups of users without significant software settings for their specific needs. Therefore, the classification feature of DP may be the purposes of their development with the degree of involvement of one or another ICT component in the field of activity of potential consumers: either in terms of IR, or in terms of tools, algorithms, in a mixed version. As an example of the DP in terms of tools, we can cite the development of common hardware and software by IBM. The DP definition given by Intel also applies to the ICT tool axis [7]. With the advent of Internet technologies, the rapid development of social networks, transport services, online commerce, recruitment agencies, various public services and many other systems related to the DP, focused only on two axes – instrumental and IR. Unfortunately, the analysis showed poor elaboration in the field of production digital management platform (DMP).

Any DP, and especially a DMP, at the present stage should cover a significant number of users, which requires the development of a single conceptual space not only along the IR axis, but also in terms of algorithms. This is dictated not only by the need for intersectoral integration, but also by the interdisciplinary nature of the conceptual space that already unites technological, biological and economic forms of interaction that have historically operated with their ontologies. Therefore, an effective solution for DMP formation dictates the need for the formation of digital standards on all axes of the ICT functioning space. At present, for this, great hopes are placed on the introduction of digital twins (DT), which will allow avoiding serious costs of finance, time, and human resources with the existing approach to the digital transformation of farms, when each of them begins to form unique management information systems for themselves.

At the same time, the benefits of the integrated approach are so great that users are already showing a willingness to adapt their local interests, due to the flexibility and cost-effectiveness of business actions familiar for many years, to standardized management functions in new digital technologies.

If integration processes in terms of data and algorithms are actively underway in developed countries, for which innovative development centers are being created, then in Russia the agriculture digitalization is at the mercy of large agricultural holdings. As a result of this approach, a huge number of ontologically and functionally incompatible information systems (IS) developed on the basis of the original design appeared in the industry, which, given the large number of farms, leads to a kind of digital feudalism and to extremely low efficiency of the digital transformation of the industry.

To solve this problem, [11] presents a mathematical model of the single DMP formation by crop production, on the basis of which the following were obtained: a cloud sub-platform (digital standard) of a single technological database of commercial crop production (Fig. 2); a cloud knowledge base sub-platform in the form of implemented algorithms for management tasks in the amount of 240 items.

This is consistent with global trends in the field of digital transformation of agriculture. Thus, J'son & Partners Consulting claims that only at the moment two specialized sub-platforms are being formed in the US agriculture: aggregator sub-platforms for primary data collection and accumulation and application sub-platforms [9].

It should be noted that the majority of the knowledge base of management tasks in their solution are based on the formation of rational crop rotations, which, ultimately, are the basis for the integration of all major digital technologies in agriculture that make up the essence of PA. Crop rotations in this case are understood to be scientifically based alternation of crops and fallows both in time (years) and in space in the form of their allocation in the fields.

Similarly, in the technological database of crop production, out of 946 attributes, 291 indicators are directly related to crop rotations, the rest indirectly through indicators such as plantings (38), crops (108), atmospheric and climatic conditions (111), etc.

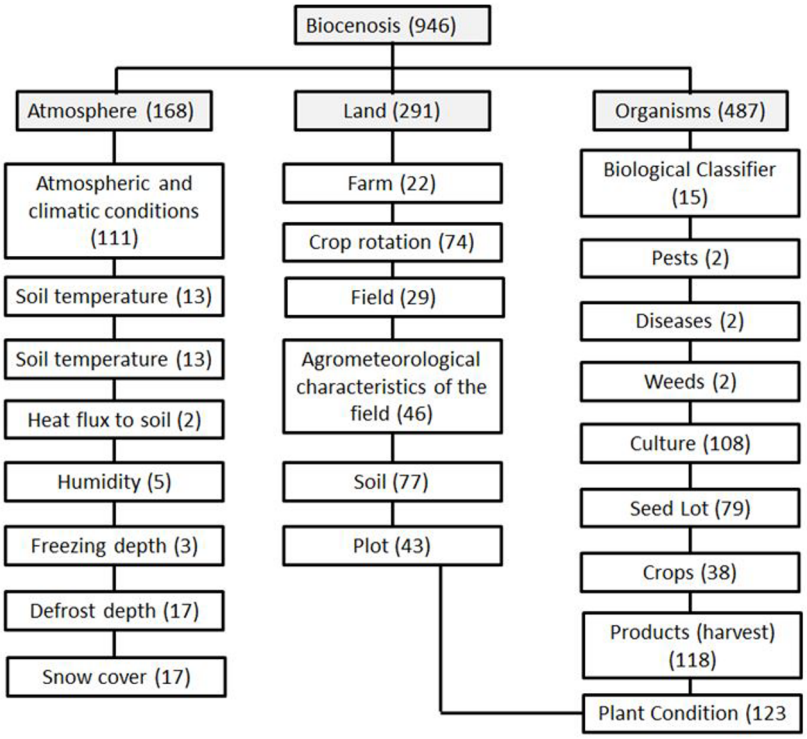

Fig. 2. Aggregated information model of crop production

This is understandable, since crop rotations in agriculture determine all technological processes in the industry (Fig. 3). The nature of tillage, crop tending, methods of protective measures against land erosion, the structure and volumes of fertilizers and plant protection products applied, the systems, machinery, and equipment used, the rational placement of production units and warehouses depend on them. Crop rotations affect the efficiency of all agricultural production, allowing more efficient use of the main resource – land. This, in turn, leads to a reduction in financial costs, improves bioclimatic indicators, the quality of food and plant protection products, increases the efficiency of agricultural machinery use.

The relevance of these studies, in addition to solving the problem of integrating all major digital technologies in agriculture, is dictated by increasing environmental problems due to violations of crop rotation, when 1.5-2 million hectares of land are degraded annually in Russia, and the natural fertility of the famous chernozems in the center of Russia has decreased 1.5-2 times over the past 10 years [5]. The relevance of research is also given by the rapid increase in the complexity of designing IS in the era of the digital economy. As mentioned above, high hopes are currently placed on the development of a DT for this. Therefore, the presented mathematical model for optimizing the structure of crop rotations, together with the initial data for it, takes into account the above factors in order to be as universal as possible and independent of the specialization and geographical location of the farms, that is, to become the core of the crop production DT with subsequent development towards the integration of crop production with logistics, with all consumers of industry products and resource providers.

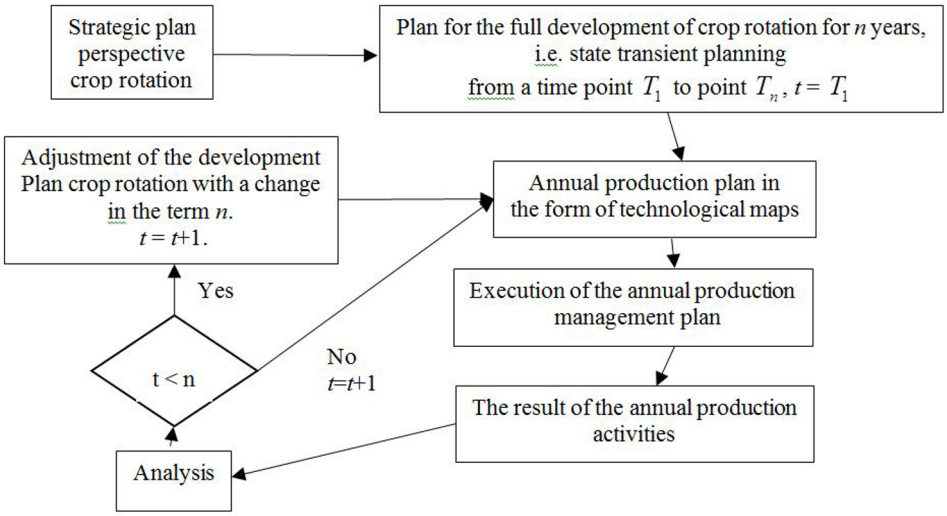

Fig. 3. The sequence of the promising crop rotation introduction

3 Results and discussion

Considering these thoughts, the task is set to determine such an optimal structure of crop rotations of the farm for some future, which would allow for maximum profit in the formation of an effective system of integration of material, labor, financial resources, considering the technological features of the main production and ensuring the competitiveness of its products. To avoid bogging down in the subtleties of diversified production, we exclude a detailed description of others associated with crop production, such as animal husbandry, processing with fixing the needs only in certain groups of animal feed involved in crop rotations on arable land, and transferring the processing needs to the general market demand for crop production. In this situation, we will exclude the feed production on natural pastures and hayfields from the description of the model. We will assume that each crop on the farm is grown using the same technology. Investments will not be considered due to the complexity of calculations of their integral characteristics in the form of an increase in crop yields. After that, we will proceed to the description of the main model blocks, giving comments in the course of the description.

m is the number of the agroecological group of the company's lands, $m \in M$;

n_m – number of crop rotation, included in the *m*-th agroecological group $n_m \in N^m$;

j is the number of the crop, $j \in J^{nm}$, where J^{nm} is the set of crops in the crop rotation n_m ;

y^1_{jnm} – the planned yield of the *j*-th crop grown in the m n_m -th crop rotation on the arable land of the *m*-th agroecological group;

x_{nm} – lands (the desired variable) allocated under the n_m th crop rotation;

T_{nm} – the value of crop rotation n_m ;

S_m – the area of arable land of the *m*-th agroecological group;

st^1_{jnm} – the costs of agricultural machinery in standard hours per unit area for growing the *j*-th crop in the n_m -th crop rotation on arable land;

r^1_{jnm} – labor costs in man-hours per unit area for growing the *j*-th crop in the n_m -th crop rotation on arable land;

JK_1 – group of crops from which concentrated feeds are obtained;

JK_2 – group of crops from which coarse feeds are obtained;

JK_3 – group of crops from which green feeds are obtained;

JK_4 – group of crops from which juicy feeds are obtained;

YJK_1 – order for the volume of crops from which concentrated feeds are obtained;

YJK_2 – order for the volume of crops from which coarse feeds are obtained;

YJK_3 – order for the volume of crops from which green feeds are obtained;

YJK_4 – order for the volume of crops from which juicy feeds are obtained.

Equations and restrictions

Let's make a number of assumptions to simplify the model. Firstly, we will assume that crops are included in the crop rotation once. Otherwise, to calculate the annual gross collection of the *j*-th crop on arable land y^2_j, the following technique can be applied – we sum up the yields of the *j*-th crop y^1_{jnm} by the number of times the crop enters the crop rotation. The amount found will be reassigned y^1_{jnm}. Then the expression will be true

$$y^2_j = \sum_{nm} y^1_{jnm} x_{nm} / T_{nm}, \quad (1)$$

where y^2_j is the gross collection of the *j*-th crop on arable land for the year.

Restrictions on the area of crop rotations

$$x^0_{nm} \le x_{nm} \le x^1_{nm} \text{ and } \sum_n x_{nm} \le s_m. \quad (2)$$

Restrictions on labor resources in crop production

$$\sum_{jnm} r^1_{jnm} x_{nm} / T_{nm} \le R^1, \quad (3)$$

where R^1 is the labor resources in the industry.

Restrictions on agricultural machinery in crop production

$$\sum_{jnm} st^1_{jnm} x_{nm} / T_{nm} \le ST^1, \quad (4)$$

where ST^1 is the number of agricultural machinery at the enterprise in standard hours.

Production financial costs in crop production F^1 consist of material costs $\sum_{jnm} c^1_{jnm} x_{nm} / T_{nm}$, maintenance costs of agricultural machinery $\sum_{jnm} cst^1_{jnm} x_{nm} / T_{nm}$, labor

costs $\sum_{jnm} cr^1_{jnm} x_{nm} / T_{nm}$, where c^1_{jnm}, cst^1_{jnm}, cr^1_{jnm}, are the corresponding cost indicators per hectare.

Then we will get restrictions on finances

$$F^1 \leq F^0 + SF, \tag{5}$$

where F^0 – own funds, *SF* – borrowed funds with their $SF \leq$ restrictions SF^T related to the possibilities of the borrowing market.

Efficiency criterion

As an efficiency criterion, let's take profit maximization

$$W^T = \sum_j p^1_j y^3_j - (F^1 + TI * SF), \tag{6}$$

where $y^3_j = y^2_j - \sum_j y^2_j \ (j \in JK_1) - \sum_j y^2_j \ (j \in JK_2) - \sum_j y^2_j \ (j \in JK_3) - \sum_j y^2_j \ (j \in JK_4)$, *TI* – the coefficient reflecting the cost of borrowed funds p^1_j - the forecast of prices for the sale of the *j*-th crop production. Obviously, the relations must be fulfilled here:

$YJK_1 = \sum_j y^2_j \ (j \in JK_1)$, $YJK_2 = \sum_j y^2_j \ (j \in JK_2)$, $YJK_3 = \sum_j y^2_j \ (j \in JK_3)$,

$YJK_4 = \sum_j y^2_j \ (j \in JK_4)$.

To simplify the model, we assume that the order for these feeds will be carried out at market prices, then the expression will be true

$y^3_j = y^2_j$.

Due to the exclusion of the investment component, expression (1) will take the form

$$W^T = \sum_j p^1_j y^2_j - F^1. \tag{7}$$

To avoid geographically link it to specific land areas, after obtaining a conditional optimal crop rotation structure, considering the previous crop rotation structure, we will assume that crop rotations are considered for the newly created farm. In order for the fluctuations of crop yields over the years to be within certain permissible limits, we will determine the initial alternations of all crop rotations in the simulation mode, adjusting the beginnings of the first crops in crop rotations. If this cannot be obtained, these restrictions will be fulfilled by varying the boundaries of crop rotation fields $x^0_{nm} \leq x_{nm} \leq x^1_{nm}$ and $\sum_n x_{nm} \leq s_m$.

Of course, in reality, when looking for a solution to most problems of production planning, it is necessary to take into account its multicriteria. There are many ways to solve multi-criteria problems, for example, reduction to a single-criteria task by criteria convolution. Or using a single-criteria optimization problem in simulation mode by varying the parameters and constraints of the model, as suggested above.

The model was tested at one of the enterprises of the Kuban southern foothill zone, which has 7725 hectares of arable land with two land groups (Mountain and Maikop), for each of which two crop rotations are recommended. Since, as noted above, there is a violation of crop rotation everywhere in Russia, technological operations performed in the

fields are almost not considered. Because of this, there were big problems with collecting the necessary initial data for a much simplified model in one farm, even for the highly developed agriculture of the Krasnodar Krai (Kuban). I had to use statistical methods to restore the missing data, both for the farm itself and for neighboring farms, to prepare them. It was necessary to restore them using statistical methods based on data from other farms. Studies have shown that currently in agriculture over 85% of data is stored either on paper or in Excell, and often not available at all.

It should be noted that the presented model for optimizing the structure of crop rotations of the economy is an adaptation of the developments of the Research Institute of Cybernetics of the AIC (VNIIK) and the Kuban Agricultural Institute to the modern realities of the DE. VNIIK was created by agreement of two academicians N.N. Moiseev and A.A. Nikonov with M.S. Gorbachev to implement the task "Electronization of Agriculture" of the Comprehensive Program of Scientific and Technological Progress of the Council for Mutual Economic Assistance back in the 80s of the last century and in anticipation of the upcoming emergence of a large number of personal computers in the country and the agro-industrial complex. At one of the reference objects, the Kuban agricultural complex, the presence of a large number of scientific institutes and pilot farms in the region made it possible to develop and implement a model using a computer not only for the optimal choice of crop rotations from the list recommended in the region, but also for the formation of new, more optimal crop rotations. The economic effect was to increase the yield of cereals and legumes by 4 centners per hectare without additional costs. The improved model has now highlighted one of the most important problems of the digital transformation of agriculture - the lack of structured, objective data, which gave rise to bring this problem into the concept of digital agriculture being developed by the Ministry of Agriculture of Russia [13].

4 Conclusions

The mathematical model has been developed for optimizing the structure of crop rotations in an agricultural enterprise that meets the basic principles of digital transformation of the economy: the formation of an information resource management system based on their rational integration into a single structured space and the rethinking of production management technologies. The implementation of these principles is presented in the form of single digital platform for agricultural production management. In this case, to link the found crop rotations to the organizational and production structure of the farm, the placement of intra farm production departments, new indicators of land quality, logistics, as well as unambiguous identification of each unit of information from the set of data included in the "Land" group of crop production database, there should be unified classifiers for land resources: classifier of soil indicators, classifier of soil zones and provinces, classifier of soils of Russia, classifier of forbidding conditions of land use, classifier of slope steepness, classifier of slope exposure, classifier of slope types, classifier of terrain forms, classifier of slope parts, classifier of types and degree of soil erosion, classifier of soil stone content degree, classifier of soil varieties by mechanical composition. The presented information model and the listed classifiers of land resources are the basis for the integration of all the above-mentioned basic digital technologies in agriculture; formed crop rotations will be the basis for solving all the tasks that make up the essence of PA.

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