Optimization models of agricultural production with heterogeneous land resources

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Abstract. The paper identifies information that takes into account the heterogeneity of agricultural land on the basis of the use of a precision farming system and geographic information technologies. The tasks of optimizing the production of agricultural products are formulated, describing the heterogeneity of land resources, for averaged and extreme weather and climatic conditions. These models are implemented for an agricultural enterprise in the Irkutsk region. Two variants of the problem are considered: with deterministic and stochastic parameters. As a random variable, the problem uses the crop yield corresponding to the probability of a drought that occurred in the region in 2015. According to the calculations, the use of various technologies of precision farming, taking into account the heterogeneity of arable land, makes it possible to increase the income of the enterprise, reducing the dispersion of the coefficients included in the optimization model agricultural production. At the same time, it is possible to reduce the risks associated with extreme hydrometeorological events, in particular, with drought.

1. Introduction

The digital transformation of agricultural production is aimed at increasing crop yields and animal productivity, reducing costs and obtaining better products and is based on the introduction of various technologies: IoT, sensors, UAVs (unmanned aerial vehicles), GPS and GLONASS, automated systems, etc. [1-6]. The use of various sensors is an important element of precision farming technology. At the same time, sensors designed to control and monitor the operating mode of engines and agricultural machines have long been referred to the standards of modern agricultural machinery, and sensors for the control and monitoring of technological parameters are still little used in practice [7]. At the same time, information on production and natural resources is an important component in planning agricultural production, since it allows a detailed assessment of the possibilities of arable land, characterized by heterogeneity in fertility, mechanical, chemical and biological composition, moisture capacity and other indicators [8, 9].

The use of precision farming technologies ensures the achievement of a number of positive effects, including: 1) cost reduction due to the rational use of equipment (increased working speed, longer use of equipment, the ability to work at night); 2) effective management of crops, higher quality of agrotechnological techniques, strict compliance with agrotechnical deadlines; 3) improving and stabilizing the crop and its quality; 4) improving the environmental safety of agricultural production; 5) the possibility of implementing new innovative technological approaches; 6) the implementation of the concept of sustainable development of agriculture.
The elements of precision farming that find practical application include the following:
1) determination of field boundaries using a global positioning system; 2) remote sensing (aerial or satellite photography); 3) systems for parallel driving of aggregates; 4) local sampling in the coordinate system; 5) mapping of soil electrical conductivity; 6) mapping of yield; 7) differentiated application of fertilizers, lime, plant protection products; 8) differentiated mechanical tillage; 9) differentiated sowing; 10) differentiated application of nitrogen and growth regulators; 11) monitoring of the phytosanitary condition of crops (weeds, diseases, pests); 12) monitoring of yield using the global positioning system; 13) monitoring of crop quality.

The increase in data flows in agricultural production and the development of modern technologies have contributed to the creation of a new concept of agricultural activity, called “smart agriculture”. To substantiate the possibility of digital transformation of agriculture with the use of modern world and domestic IT technologies by the staff of the Department of Informatics and Mathematical Modeling of the Irkutsk State Agricultural University by order of the Ministry of Agriculture of the region, the concept of digitalization of agriculture in the Irkutsk region was developed.

In continuation of research on this project, models were created for planning the production of agricultural products in conditions of heterogeneity of land resources, data on which are received from sensors of technological operations.

The purpose of the article is to describe the results of creating models for optimizing the production of agricultural products, taking into account the heterogeneity of land resources, data on which can be obtained using sensors of technological operations.

The research tasks included:
- determination of the information necessary to take into account the heterogeneity of fields based on the use of a precision farming system and geoinformation technologies;
- formulation and implementation of the task of optimizing the production of agricultural products, taking into account the heterogeneity of land resources for averaged and extreme weather and climatic conditions.

2. Materials and methods
As the initial data, the paper uses information on meteorological indicators for 1971-2018; statistical data on crop yields in the Irkutsk region for 1996-2019. When solving the problem of mathematical programming, data on production and economic indicators from the accounting reports of LLC “Irkutsk seeds” were used.

The calculations used probabilistic methods for estimating rare events and methods for solving linear programming problems.

3. Results and discussion
For qualitative analysis and processing of arrays of long-term data on the parameters used in precision agriculture, it is necessary to use Big Data technologies [7]. According to the conceptual scheme given in [7], agricultural producers accumulate information in databases that display current business processes. Data on the results of the activities of enterprises of the agro-industrial complex (balance sheets and other reports) are consolidated in the ministries of agriculture of the regions, and in the future can be used for production planning based on mathematical programming problems [10, 11]. The paper [8] presents a model of irrigation optimization taking into account the risk in conditions of uncertainty. The study [12] is devoted to the problem of the placement of agricultural crops taking into account irrigation. In addition, an important task in planning the production of agricultural products is the use of forecasts of humidity and temperature [13]. A multicriteria optimization model for solving the problem of using polluted waters according to ecological and economic criteria is considered in [14].

When planning agricultural production, an important task is to take into account the heterogeneity of land resources, since data on the state of fields or plots can reduce costs and, accordingly, increase profits. In this case, the information received from the sensors is used.

The target function of the model is focused on getting the maximum income:
\[ f = \sum_{k \in K} \sum_{j \in J} \sum_{i \in I} c_{ijk} x_{ijk} \rightarrow \text{max}, \]  

where \( c_{ijk} \) is the cost of a unit of production \( j \) from section \( k \) of field \( i \) (thousand rubles /ton); \( x_{ijk} \) are the volumes of the received product \( j \) from the section \( k \) of the field \( i \) (tons).

Restrictions associated with the area of cultivation of agricultural crops, the volume of the resulting product, labor costs, costs of fertilizers and means of protection and cost of production:

\[ \sum_{k \in K} \sum_{i \in I} x_{ijk} \leq S_j, \]  

(2)

\[ \sum_{k \in K} \sum_{i \in I} x_{ijk} \geq V_j, \]  

(3)

\[ \sum_{k \in K} k_{ijk} x_{ijk} \leq K_j, \]  

(4)

\[ \sum_{k \in K} w_{mijk} x_{ijk} \leq W_{mi}, \]  

(5)

\[ \sum_{k \in K} \sum_{j \in J} d_{ijk} x_{ijk} \leq D, \]  

(6)

\[ x_{ijk} \geq 0, \]  

(7)

where \( y_{ijk} \) is the bioproductivity of agricultural crop \( j \) on site \( k \) of field \( i \) (metric tons/ha); \( S_j \) is the area of agricultural crops \( j \); \( V_j \) is the guaranteed volume of production of culture products \( j \); \( k_{ijk} \) are the labor costs to obtain a unit of production \( j \) in the site \( k \) of field \( i \) (thousand man-hours/metric ton); \( K_j \) is the limitation of labor costs (thousand man-hours/metric ton) for the production of culture \( j \); \( w_{mijk} \) is the consumption of fertilizer \( m \) (plant protection products) on the site \( k \) of the field \( i \) of the crop \( j \) (metric tons/ha); \( W_{mi} \) is the presence of fertilizer of the type \( m \) for the field \( i \); \( d_{ij} \) is the reduced costs for obtaining products \( j \) at site \( k \) of field \( i \) (dollar/metric ton); \( D \) is the total allowable production costs (US$ million).

Since agricultural production is influenced by natural and climatic parameters, it is necessary to assess the risks of crop loss. Satellite images can be used to predict extreme natural phenomena [15]. Usually climatic and biological events are probabilistic values [8, 11], therefore, as an optimization model, you can use the linear stochastic programming problem, which is written in the form:

\[ f = \sum_{k \in K} \sum_{j \in J} \sum_{i \in I} (c_{ijk} + c_{ijk}^p) x_{ijk} \rightarrow \text{max}, \]  

(8)

\[ \sum_{k \in K} \sum_{i \in I} \frac{x_{ijk}}{y_{ijk} - y_{ijk}^p} \leq S_j, \]  

(9)

\[ \sum_{k \in K} \sum_{i \in I} x_{ijk} \geq V_j - V_j^p, \]  

(10)

\[ \sum_{k \in K} (k_{ijk} + k_{ijk}^p) x_{ijk} \leq K_j, \]  

(11)

\[ \sum_{k \in K} \sum_{j \in J} (w_{mijk} + w_{mijk}^p) x_{ijk} \leq W_{mi}, \]  

(12)

\[ \sum_{k \in K} \sum_{i \in I} \sum_{j \in J} (d_{ijk} + d_{ijk}^p) x_{ijk} \leq D, \]  

(13)
In this model $c_{ijk}^c$ is the additional cost of production due to crop losses; $y_{ijk}^p$ is an indicator of a decrease in crop yields associated with the influence of climatic and biological events, corresponding to a certain probability $p$; $V_j^p$ is the loss of production; $k_{ijk}^p$ are labor resources for performing additional technological operations $w_{ijk}^p$ are additional costs of fertilizers and plant protection products; $d_{ijk}^p$ are additional production costs, $p$ is the probability of the event, determined by the law of probability distribution.

The above optimization models were tested at the agricultural enterprise LLC “Irkutsk seeds” using the methods of simulation. At the same time, the yields in the first task were determined depending on the properties of the field and the quality of agrotechnological operations, such as fertilization, pest and weed control (Table 1).

**Table 1.** Crop yields used in solving the linear programming problem.

| A variant of solving the linear programming problem | Yield, metric tons/ha |
|---------------------------------------------------|-----------------------|
| Wheat, ha (Field 1)                              | Wheat, ha (Field 2)   |
| Wheat, ha (Field 3)                              | Oats, ha (Field 1)    |
| Oats, ha (Field 2)                               | Barley, ha (Field 1)  |
| Barley, ha (Field 2)                             |                       |
| The condition of heterogeneity of land resources |                       |
| Lower rating                                     | 1.7                   |
| Median                                           | 1.2                   |
| Upper rating                                     | 1.9                   |
| Probabilistic estimates of indicators            | 1.11                  |
| Risk accounting (drought, similar to 2015)       | 1.22                  |
|                                                  | 0.999                 |
|                                                  | 0.968                 |
|                                                  | 0.792                 |
|                                                  | 0.737                 |
|                                                  | 0.603                 |

The values of grain yield for the second problem were modelled using the laws of probability distribution (Table 2). The normal law, the Pearson type III distribution, and the three-parameter gamma distribution were used [16, 17]. The table shows the yield values in the dry year 2015 according to the data of the Irkutsk district, as well as the coefficients of variation $C_v$ and asymmetry $C_s$. On the basis of the distribution laws, the probabilities $p$ of the occurrence of events in the form of low yields caused by drought are determined.

**Table 2.** Data on the bio-productivity of agricultural crops in the Irkutsk region in 2015 (severe drought).

| Culture | Yield, metric tons/ha | $C_v$ | $C_s$ | Probability, $p$ | The law of probability distribution |
|---------|-----------------------|-------|-------|-----------------|-------------------------------------|
| Wheat   | 1.11                  | 0.20  | 0.0   | 0.0440          | Normal                             |
| Barley  | 0.67                  | 0.24  | -0.24 | 0.0104          | Three-parameter gamma distribution |
| Oats    | 0.88                  | 0.21  | -1.0  | 0.0340          | Pearson Type III                   |

Table 3 shows the results of modeling according to models (1)-(7) and (8)-(14). On the basis of the obtained optimal solutions within the framework of the lower and upper estimates of the yield of grain crops, the values of the objective function between the best and worst financial indicators fluctuate at the level of 13.0%. Compared with the results of solving the problem, in which land resources were considered as a homogeneous area, the range of optimal solutions obtained is lower.

It can be noted that the production of annual grasses for silage and green fodder ($x_4$, $x_5$) is not a priority for the farm, changing insignificantly. Therefore, the production volumes of these products are stable. The situation is similar for the production of annual grass seeds ($x_6$).
Table 3. Results of solving the linear programming problem.

| A variant of solving the linear programming problem | Optimal plan, metric tons |
|-----------------------------------------------|--------------------------|
| Wheat (field 1) | Wheat (field 2) | Wheat (field 3) | Oats (field 1) | Oats (field 2) | Barley (field 1) | Barley (field 2) | Annual grasses for silage | Annual herbs for green food | Area for seeds for annual grasses per silo | Target function, US$ million |
| $X_{11}$ | $X_{12}$ | $X_{13}$ | $X_{21}$ | $X_{22}$ | $X_{31}$ | $X_{32}$ | $X_4$ | $X_5$ | $X_6$ |
| Lower rating | | | | | | | | | | | | 1.958 |
| 170 | 13220 | 120 | 220 | 100 | 210 | 150 | 7200 | 16200 | 300 | |
| Median | | | | | | | | | | | | 2.116 |
| 120 | 383 | 100 | 14748 | 230 | 120 | 150 | 7200 | 16200 | 300 | |
| Upper rating | | | | | | | | | | | | 2.233 |
| 190 | 260 | 160 | 220 | 15562 | 200 | 180 | 7200 | 16200 | 300 | |
| Probabilistic estimates of indicators | | | | | | | | | | | | 1.077 |
| 111 | 6780 | 100 | 241 | 79 | 120 | 60 | 7200 | 16200 | 300 | |

The condition of heterogeneity of land resources

- Lower rating: 170, 13220, 120, 220, 100, 210, 150, 7200, 16200, 300, 1.958
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Risk accounting (drought, similar to 2015)

- Lower rating: 111, 6780, 100, 241, 79, 120, 60, 7200, 16200, 300, 1.077

As for the simulation results under drought conditions like 2015, there is a strong discrepancy between the values of the optimality criterion between the median value and the value obtained for extreme conditions. It was 49%.

The planning of agricultural production, taking into account the risks associated with the impact on the yield of unfavourable climatic parameters, in particular, drought, allows the correct allocation of the resources of the economy.

4. Conclusions

The paper defines a scheme for obtaining data from technological operations, which allows to form information support for optimizing the production of agricultural products on heterogeneous agricultural lands. Two models are proposed for solving management problems - with and without taking into account the risks caused by climatic events.

The task of optimizing the production of agricultural products in the conditions of heterogeneity of land resources is implemented on the example of an agricultural enterprise in the Irkutsk region. Comparison of the simulation results for generating income in conditions of homogeneity and heterogeneity of fields shows the advantages of the second models, which allow reducing the uncertainty of the model indicators.

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