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International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies

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ECONOMIC AND MATHEMATICAL MODELING IN THE SYSTEM OF PRECISION AGRICULTURE

G.A. Beznosov [a*], E.A. Skvortsov [b], A.N. Semin [c], K.V.Nekrasov [d], N.V. Ziablitckaia [e], V.I. Nabokov [e]

[a] *Federal State Budgetary Educational Establishment of Higher Education «Ural State Agrarian University» (FGBOU VO Uralsky GAU), Ekaterinburg, Karl Liebknecht st., 42, RUSSIA*

[b] *Ural Federal University, Ekaterinburg 620002, Mira st., 19, RUSSIAN FEDERATION.*

[c] *Ural State Economic University, Ekaterinburg, March 8 st. / Narodnaya Volya st., 62/45620144 RUSSIAN FEDERATION*

[d] *Ural State University of the Railway Transport, Ekaterinburg, Ekaterinburg, Kolmogorov Street, 66, RUSSIA*

[e] *South Ural State University, Chelyabinsk, pr.Lenina, 76, RUSSIA*

ARTICLEINFO

Article history:
Received 01 February 2019
Received in revised form 11 February 2019
Accepted 15 March 2019
Available online
18 March 2019

Keywords:
Economic model, optimization of production costs, resource saving, precision farming.

ABSTRACT

The article suggests an economic and mathematical tool for optimization of production costs as a tool for justifying the efficiency of resource-saving production methods in the precision farming system. In particular, an economic and mathematical model of optimization of resource saving in agricultural production has been developed, which provides the most objective, in comparison with known analogues, justification of certain resource-saving technologies for the agricultural production due to integrated consideration of natural and production factors, including the difference in the amount of production resources at areas with various agrochemical characteristics; these characteristics were identified on the basis of soil tests, crop losses, depending on a technology of crop cultivation, a degree of reproduction of soil fertility, a product quality and the environmental safety of production. The practical implementation of precision farming technologies is based on capabilities of modern geo-information systems GLONASS. Thus, the conducted studies suggest that economic and mathematical modeling, as one of the elements of the economic mechanism of resource saving, can be successfully used to optimize resource consumption in agricultural production. The approbation of the improved economic and mathematical model has proved a possibility of more accurate and objective justification of the use of one or another resource-saving method (technology) of production.

1. INTRODUCTION

In a market economy, agricultural enterprises can expand reproduction only by the most complete use of their production resources. This task is often solved by the introduction of a resource-saving method (technology) of production in the so-called system of precision farming, and the economic feasibility for choosing such a method (technology) plays a crucial role in obtaining a positive economic effect.

Resource-saving is introduced in various branches of agriculture. Precision Livestock Farming (Tullo et at., 2019) is "the application of principles and methods of technological design in animal husbandry for automatic monitoring, modeling, and management of animal husbandry". These technologies in animal breeding allow making production more cost-effective (Anestis et at., 2015), socially and environmentally sustainable (Bartzanas et at., 2015; Aguirre-Villegas et at., 2017), and this can be achieved by observing, interpreting of behaviour (Almeida et at., 2017; Andretta et at. 2016) and, if possible, individual control over animals (Alhamada et at., 2017).

The meaning of precision farming, normally based on navigation satellites (such as Anantakarn & Witchayangkoon, 2019), is determined by ensuring the differentiation of an agrotechnology (or its elements) in accordance with differences in soil fertility or a status of soil preparation, including a degree of soil degradation, weed infestation of crops, damage by pests or diseases, etc., crop productivity management with consideration of the intra-field variability of a plant habitat, an economic goal of obtaining maximum profit with optimization of agricultural production, resource saving (Shayakhmetov and Dubrovin, 2013).

The practical implementation of precision farming technologies, sometimes called information technologies, is based on capabilities of modern geo-information systems Glonass which allow on-line (real-time) determining of positioning data of operating agricultural machines and adapting of processing practice in accordance with specific conditions at particular field parts. This approach aims to maximize profits with optimizing production, substantial resource savings (of fertilizers, water, toxic chemicals, etc.) while meeting the strict requirements to environmental protection.

Economic and mathematical modeling of resource-saving projects allows finding the most efficient way (technology) of resource-saving production, as well as assessing the cost-effectiveness on its introduction with limited resources and consideration of branch peculiarities.

2. MATERIAL AND METHODS

The general concept of economic and mathematical modeling of optimization of production costs was formulated in 1960 by L.V. Kantorovich, a Nobel laureate in economics, who proposed to solve the problem of developing an optimal production plan for a certain period in such a way (a task of short-term planning) with consideration of the following terms: a) availability of resources for the planned period, it means, that certain types of production factors exist (or will be) in required quantities, b) demand in production of certain types of products in a required proportion (assortment), c) one or more technologically acceptable methods of manufacturing each type of production with an apparent cost structure, it means the availability of information about a required amount of production factors per unit of production, d) necessity of an optimal plan, that is, to indicate what product volumes of each type should be manufactured in various methods so that the total costs of production factors do not exceed the resource, and the products should be manufactured in an assortment and a maximum volume (Kantorovich, 1960).

In general, a task of the optimum allocation of resources by Kantorovich is:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{t} z_{ijk}\,x_j \le \sum_{i=1}^{m} r_i\,; \qquad (1),$$

$$\sum_{j}^{n} x_j \to max, \qquad (2),$$

where z_{ijk} is the norm of an input of the *i*-type resources for manufacturing the *j*-type products with the *k*-type method;

r_i– the amount of the *i*-type resources in a proper unit of measurement;

x_j – the required amount of an output of the *j*-type products.

The mathematical model of the task is:

$$x_1 + x_2 + \ldots + x_n \to \max; \qquad (3)$$

$$\begin{cases} z_{111}x_1 + z_{122}x_2 + \ldots + z_{1nt}x_n \le r_1, \\ z_{211}x_1 + z_{222}x_2 + \ldots + z_{2nt}x_n \le r_2, \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots, \\ z_{m11}x_1 + z_{m22}x_2 + \ldots + z_{mnt}x_n \le r_m, \\ \\ x_1 \ge 0, x_2 \ge 0, \ldots\ x_n \ge 0. \end{cases} \qquad (4)$$

The top line is about maximizing the objective function. The objective function is a sum of output for different types of products. The brace combines the system of delimitations, inequations correspond to different types of resources and production methods. Each inequality suggests that a total amount of the resource used in the manufacturing of various types of products does not exceed a total availability of this resource. The last line of the system of delimitations indicates that a product output cannot be negative. It should be noted that it can equal zero, that is, some (or even all) types of products may not be produced, although they are available for production.

3. RESULTS AND DISCUSSION

3.1 ADAPTATION OF THE MODEL

The universality of this economic and mathematical model allows its application in any sector of the national economy, however, it should be understood that the existing features of a particular branch should be considered for the solution of applied problems. Adaptation of the economic and mathematical model of optimizing the use of production resources in agricultural production can be carried out by introducing a coefficient that will allow differentiating agricultural technologies (or their elements) in accordance with differences in the soil quality. Thus, we consider, it is necessary to adjust the norms of resource costs independence with agrochemical characteristics of land for agricultural production.

To develop an economic and mathematical model of optimizing the production costs of resources in agricultural production, we take *a* land parcels with different agrochemical characteristics, give them numbers from *1* to *a*, and we mark the numbers with the letter *l* in such a way that the inequality should be $1 \leq l \leq a$. At the same time, the parcel area with the *l*-type agrochemical characteristic is marked by *s*. Thus, the task of the optimal allocation of resources in agricultural production will be:

$$\sum_{l=1}^{a}\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{t} z_{ijkl}\, x_j \leq \sum_{i=1}^{m} r_i\,; \tag{5}$$

$$\sum_{j}^{n} x_j \rightarrow max, \tag{6}$$

where z_{ijkl} is the norm of an input of the *i*-type resources for manufacturing the *j*-type products with the *k*-type method on the parcel with the *l*-type agrochemical characteristic;

r_i – the amount of the *i*-type resources in a proper unit of measurement;

x_j – the required amount of an output of the *j*-type products;

The economic and mathematical model of the task will be:

$$x_1 + x_2 + \ldots + x_n \longrightarrow \max; \tag{7}$$

$$\begin{cases} z_{1111}x_1 + z_{1222}x_2 + \ldots + z_{1nta}x_n \leq r_1; \\ z_{2111}x_1 + z_{2222}x_2 + \ldots + z_{2nta}x_n \leq r_2; \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots; \\ z_{m111}x_1 + z_{m222}x_2 + \ldots + z_{mnta}x_n \leq r_m; \\ \\ x_1 \geq 0, x_2 \geq 0, \ldots\ x_n \geq 0. \end{cases} \tag{8}$$

The desired economic and mathematical model is successfully integrated into the system of precision farming in the context of optimizing resource costs with consideration of the intra-field variability of crop habitats.

3.2 ADDITIONAL COEFFICIENTS

There are verified hypotheses of calculating the optimal ratio between a resource input on a resource-saving project (land, water, labour, material, energy, financial and others), qualitative characteristics of product output and the environmental safety of this project through the development of economic and mathematical models. The minimum input of all resources based on the complex factors of product quality and the project's environmental sustainability is taken as a model's optimality criterion (Vorotnikov, 2006). Similarly, we transform this economic and mathematical model to differentiate agrotechnologies (or their elements) in accordance with the differences in a soil qualitative status.

At the same time, to consider the crop losses in dependence on a production method (technology), let's adjust the objective function of the economic and mathematical model by a coefficient of technological losses of agricultural products produced by the *i*-type method (technology) on a parcel with the *l*-type agrochemical characteristic (z_{il}), which represents the ratio of an output of agricultural products per 1 ha of planting acreage in the physical mass after improvement (z_{il_d}) to its biological yield (z_{il_v}).

$$z_{il} = \frac{z_{il_d}}{z_{il_v}}. \tag{9}$$

Agricultural enterprises should pay particular importance to preserve (improving) the soil fertility, where crops are cultivated, and therefore we consider it necessary to introduce a coefficient of the soil fertility stability into the objective function of the economic and mathematical model of resource saving optimization.

$$y_{pp_{il}} = \frac{k_{pp_{il_1}}}{k_{pp_{il_0}}} \tag{10}$$

where $y_{pp_{il}}$ – is a coefficient of soil fertility sustainability at planting acreage where crops are cultivated by *i*-type method (technology) at a parcel with the *l*-type agrochemical characteristic;

$k_{pp_{il_0}}$ is a basic indicator of soil fertility before crop planting, when the *i*-type method (technology) is used at a parcel with the *l*-type agrochemical characteristic;

$k_{pp_{il_1}}$ is an indicator of soil fertility after crop harvesting, when the *i*-type method (technology) is used at a parcel with the *l*-type agrochemical characteristic.

To calculate the soil fertility indicators, we use the method approved by the Order of the Ministry of Agriculture of Russia dated by January 11, 2013 No. 5 «On Approval of the Method of calculating the soil fertility indicator in the Russian Federation» [11].

In accordance with this method, a fertility indicator is calculated as the average of the sum of the ratios of the actual values of four agrochemical parameters (soil acidity, humus content, the active forms of phosphorus, the content of exchange potassium) to their optimum values. And, the acid value for alkaline soils is calculated as the ratio of the optimal value to the actual value, for acidic soils - the actual value to the optimum one. In our study, we will expand the list of indicators used for calculation with a coefficient that will allow us to reveal the number of active forms of nitrogen in the soil. After transformations, the formula for calculating the soil fertility indicator will be:

$$k_{pp_{il}} = (\frac{\mathrm{G}_f}{\mathrm{G}_o} + \frac{\mathrm{F}_f}{\mathrm{F}_o} + \frac{\mathrm{K}_f}{\mathrm{K}_o} + \frac{\mathrm{N}_f}{\mathrm{N}_o} + \frac{\mathrm{pH}_{H_2O_o}\left(\mathrm{pH}_{KCl_f}\right)}{\mathrm{pH}_{H_2O_f}\left(\mathrm{pH}_{KCl_o}\right)})/5, \quad (11),$$

where $k_{pp_{il}}$ – is an indicator of soil fertility of planting acreage when crop are cultivated with the i–type method (technology) at a parcel with the l-type agrochemical characteristic;

G_f –an actual content of humus in the soil, %;

G_o– an optimal content of humus in the soil, %;

F_f – an actual content of active forms of phosphorus in the soil, mg / kg;

F_o– an optimal content of active forms of phosphorus in the soil, mg / kg;

K_f – an actual content of exchange potassium in the soil, mg / kg;

K_o – the optimum content of exchange potassium in the soil, mg / kg;

N_f – an actual content of active forms of nitrogen in the soil, mg / kg;

N_o – an optimal content of active forms of nitrogen in the soil, mg / kg;

$\mathrm{pH}_{H_2O_f}$ – an actual acidity of the soil (for alkaline soils), units;

$\mathrm{pH}_{H_2O_o}$ – an optimum soil acidity (for alkaline soils), units;

pH_{KCl_f} – an actual acidity of the soil (for acidic soils), units;

pH_{KCl_o} – an optimum acidity of the soil (for acidic soils), units;

The soil fertility indicator across the whole planting acreage for crop cultivation (k_{pp}) can be calculated as follows:

$$k_{pp} = \frac{\sum_{i=1}^{n}\sum_{l=1}^{m} k_{pp_{il}} x_{il}}{Sz}. \quad (12).$$

3.3 OBJECTIVE FUNCTION

Considering the above-mentioned facts, the objective function will be

$$F(x) = \sum_{i=1}^{n}\sum_{l=1}^{m} \frac{\mathrm{a}_{il}}{\mathrm{g}_{il}\mathrm{q}_{il}\mathrm{z}_{il}y_{pp_{il}}}(\mathrm{Z}_{il}\,\mathrm{P}_z + \mathrm{T}_{il}\mathrm{P}_t + \mathrm{M}_{il}\mathrm{P}_m + \mathrm{D}_{il})\mathrm{x}_{il} \rightarrow min. \quad (13).$$

We introduce the following parametric values:

i – a type of the method (technology) of crop cultivation;

l – an agrochemical characteristics of the soil;

x_{il} – the planting acreage for crops cultivated with the *i*-type method (technology) at a parcel with the *l*-type agrochemical characteristic, ha;

Z_{il} – the land intensity of the *i*-type method (technology) of crop cultivation at a parcel with the *l*-type agrochemical characteristic, ha / c;

T_{il} – the labour intensity of the *i*-type method (technology) at a parcel with the *l*-type agrochemical characteristic, person-hours / cent;

M_{il} – the material intensity of the *i*-type method (technology) at a parcel with the *l*-type agrochemical characteristic, rubles / c;

P_z – a unit price of land resources, rub;

P_t – an hourly average wage of an employee, rub.;

P_m– a unit price of material resources, rub;

D_{il} – costs per other units of the *i*-type method (technology) at a parcel with the *l*-type agrochemical characteristic, rubles / c;

a_{il} – crop yields at a parcel with the *l*-type agrochemical characteristic, produced with the *i*-type method (technology), c / ha;

τ_{il1}, τ_{il2}, ... τ_{ilj} – the *j*-type quality indicator of agricultural products produced with the *i*-type method (technology) at a parcel with the *l*-type agrochemical characteristic;

r_{il1}, r_{il2}, ... r_{ilj} – the *j*-type indicator of the environmental safety of the *i*-type method (technology) of production at a parcel with the *l*-type agrochemical characteristic;

τ_{nj}, r_{nj} – regulatory indicators of quality and environmental safety;

V – a production task, c;

S_z – availability of land resources, ha;

S_T – availability of labour resources, person-h;

S_M – reserves of material resources, rub.;

S_D – reserves of other types of resources, rub.;

g_{il} – a complex coefficient of quality of agricultural products produced with the *i*-type method (technology) at a parcel with the *l*-type agrochemical characteristic.

The g_{il} coefficient will be defined as the intersection of partial coefficients with consideration of certain properties of agricultural products, for example, grains: τ_{il_1} is a gluten content, τ_{il_2} is a protein content, τ_{il_3} is a carbohydrate content divided in standard quality indicators.

Thus, the complex coefficient of a grain quality is:

$$g_{il} = \frac{\tau_{il_1}\tau_{il_2}\tau_{il_3}}{\tau_{n_1}\tau_{n_2}\tau_{n_3}}. \qquad (14).$$

The complex coefficient of environmental safety of the *i*-type method (technology) of agricultural production at a parcel with the *l*-type agrochemical characteristic (q_{il}) measures harmfulness of applied types and portions of fertilizers r_{il_1} for the environment and for consumers, toxic chemicals r_{il_2}, plant-protecting agents r_{il_3} with a maximum permitted concentration (rn), that is:

$$q_{il} = \frac{r_{n_1}r_{n_2}r_{n_3}}{r_{il_1}r_{il_2}r_{il_3}}. \qquad (15)$$

4. THE SYSTEM OF DELIMITATIONS

We introduce the system of delimitations to solve the task:

The terms of a production program: $$\sum_{i=1}^{n}\sum_{l=1}^{m} a_{il}\,x_{il} = V. \quad (16)$$

Delimitation on the use of land resources: $$\sum_{i=1}^{n}\sum_{l=1}^{m} З_{il}a_{il}\,x_{il} \le S_z. \quad (17)$$

Delimitation on the use of labour resources: $$\sum_{i=1}^{n}\sum_{l=1}^{m} \mathrm{T}_{il}a_{il}\,x_{il} \le S_{\mathrm{T}}. \quad (18)$$

Delimitation on the use of material resources: $$\sum_{i=1}^{n}\sum_{l=1}^{m} \mathrm{M}_{il}a_{il}\,x_{il} \le S_{\mathrm{M}}. \quad (19)$$

Delimitation on the use of other production resources: $$\sum_{i=1}^{n}\sum_{l=1}^{m} D_{il}a_{il}\,x_{il} \le S_D. \quad (20)$$

Delimitation on the non-negativity of variables of the economic and mathematical model $$x_{il} \ge 0\ (i = 1,2,3,4,5,\dots,n;\ l = 1,2,3,4,5,\dots,m). \quad (21)$$

We introduce additional delimitations on the reduction of technological losses of agricultural products, the preservation (improvement) of its quality and environmental safety.

Delimitation on the reduction of technological losses:

$$z_{il} \ge z_n (i = 1,2,3,4,5,\dots,n;\ l = 1,2,3,4,5,\dots,m), \quad (22)$$

where z_n - is a standard indicator of technological losses established by the enterprise.

Delimitation on preservation (improvement) of quality:

$$q_{il} \ge 1\ (i = 1,2,3,4,5,\dots,n;\ l = 1,2,3,4,5,\dots,m) \quad (23)$$

Delimitations on ensuring environmental safety of production:

$$q_{il} \ge 1\ (i = 1,2,3,4,5,\dots,n;\ l = 1,2,3,4,5,\dots,m). \quad (24)$$

Delimitation on ensuring the stability of soil fertility:

$$y_{pp_{il}} \ge 1\ (i = 1,2,3,4,5,\dots,n;\ l = 1,2,3,4,5,\dots,m). \quad (25)$$

The effect of the sale of manufactured products will be as follows:

$$b = \sum_{i=1}^{n}\sum_{l=1}^{m} (c_{il} - z_{il})s_{il}; \quad (26)$$

$$b_i = \sum_{i=1}^{n}\sum_{l=1}^{m} (p_{il1} - p_{il0})s_{il0}; \quad (27)$$

$$p_i = \left((f_{il1} - h_{il1})y_{il1} - (f_{il0} - h_{il0})y_{il0}\right)s_{il0}, \quad (28)$$

where b is the economic effect of production;

b_i – the economic effect of using of the i-type method (technology) of production;

p_i – the profit from the use of the i-type method (technology) of production;

c_{il} – monetary evaluation of the results from the production per 1 ha of a land area with the l-type agrochemical characteristic with the use of the i-type method (technology) of production;

z_{il} – the cost of production per 1 hectare of land with the l-type agrochemical characteristic with the use of the i-type method (technology) of production;

c_{il} – a parcel area with the l-type agrochemical characteristic with the use of the i-type method (technology) of production.

p_{il} – a profit from producing products per 1 ha of land with the l-type agrochemical characteristic with the use of the i-type method (technology) of production;

f_{il} – a selling price of 1 centner of products produced with the l-type agrochemical characteristic with the use of the i-type method (technology) of production;

h_{il} – a cost value of 1 centner of products produced at a parcel with the l-type agrochemical characteristic with the use of the i-type method (technology) of production;

y_{il} – a yield of agricultural crops produced at a parcel with the l-type agrochemical characteristic with the use of the i-type method (technology) of production.

Thus, the improvement of the economic and mathematical model of optimization of resource saving allows considering the peculiarities of land resources identified according to the agrochemical soil survey, where an agricultural enterprise plans to produce products, focusing on keeping (improving) the product quality, preventing environmental damage, reducing technological loss and also contributes to solving the problem of ensuring the fertility sustainability for agricultural soils.

4.1 TESTING

We test the improved economic and mathematical model at the OOO “Nadezhda” in the Makushinsky district, the Kurgan region, as this enterprise, according to the results of a resource efficiency analysis, is typical by the average level of resource use at agricultural enterprises of grain specialization of the Kurgan region, which have similar climatic and economic conditions.

Having 16 parcels of 4 hectares each were allocated at one of the fields, according to the results of an agrochemical survey on the average $N\text{-}NO_3$ content in the soil before mineral fertilizers application. As the complex agrochemical survey was not carried out there, we equal the coefficient of soil fertility to one (y_{pp} = 1). A comparison between the conventional method of applying fertilizers and the differentiated method of applying mineral fertilizers was made on the basis of an improved economic and mathematical model.

5. DISCUSSION

The results of our task solution allowed justifying a certain advantage of the differentiated method of applying fertilizers in comparison with the conventional method with consideration a number of important factors, including information about the agrochemical soil survey, technological yield losses, quality of products, the environmental safety of production. And special attention in the process of optimization of resource saving is paid to ensuring the sustainability of soil fertility used in agricultural production.

At the same time, according to the results of the economic and mathematical modeling conducted at a typical enterprise, it became known that with a production task of 896.0 centners and a differentiated method of applying fertilizers (ammonium nitrate 34% a.v.) for the planned yield of spring wheat of 14.0 c/ha, production costs will be 263,605.6 rubles, the resource intensity of commercial products will be 0.792 rubles, which is 5.5% lower than with the conventional method of applying mineral fertilizers (Table 1).

Table 1: Comparison of the effectiveness of the conventional and differentiated methods of applying mineral fertilizers by the example of the Kurgan region

Indicator	The conventional method of applying fertilizers	Differentiated method of applying fertilizers	Fluctuation	
			(+/-)	%
Planting acreage of grain crops, ha	64.0	64.0	–	–
The yield of grain crops, t/ha	14.0	14.0	–	–
Grain production, c	896.0	896.0	–	–
Sold grains, c	784.0	784.0	–	–
Marketable value, %	87.5	87.5	–	–
Costs on grain production, total, rub	279024.5	263605.6	-15419.0	94.5
Price of sold products - total, rub.	333043.2	333043.2	–	–
Including 1 c, rub.	424.8	424.8	–	–
Resource intensity, rub.	0.838	0.792	-0.046	94.5
Profit (+), loss (-) from sale – total, rub.	88896.7	102388.3	13491.6	115.2
Cost effectiveness, %	36.4	44.4	8.0	–

The cost-effectiveness will be 44.4%, which is 8.0% higher than with the conventional method of applying fertilizers. Thus, the developed economic and mathematical model of optimization of resource-saving justifies the practicability of use of the differentiated method of applying fertilizers at a typical agricultural enterprise of grain specialization.

6. CONCLUSION

The conducted studies suggest that economic and mathematical modeling, as one of the elements of the economic mechanism of resource saving, can be successfully used as a tool to justify the effectiveness of resource-saving production methods in the system of precision farming. Testing of the improved economic and mathematical model proved a possibility of a more accurate and objective justification of the use of one or another resource-saving method (technology) of agricultural production by deepening the analysis process, considering more natural and production factors.

7. CONFLICT OF INTEREST

The authors confirm that the presented data do not contain a conflict of interest.

8. ACKNOWLEDGMENT

The work was prepared with the support of the Ural State Agrarian University (FGBOU VO Uralsky GAU).

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G.A. Beznosov is Candidate of Economic Sciences at Ural State Agrarian University, Russia. His scientific interests are the development of the economic mechanism of resource conservation, economic and mathematical modeling of economic processes and phenomena in the system of precision farming, the development of the organizational and economic mechanism of sustainable land management based on modern digital technologies, profitability of agricultural production.

E.A. Skvortsov is Candidate of Economic Sciences. His research interests include Robotics, Robotics in Agriculture, Efficiency of Using Robotics, Artificial Intelligence Technologies, Big Data, Internet of Things, Social and Labor Relations.

Professor Dr. A.N.Semin is Professor at Ural State Economic University, Yekaterinburg, Russian Federation. Professor Dr. A.N. Semin holds Doctor of Economic Sciences degree. Professor Semin scientific researches concentrate in the field of organizational and economic mechanisms for the reproduction of skilled agricultural personnel, as well as the technical potential of agricultural production; an effective mechanism of budget support for business entities in the agro-industrial complex; strategic planning and management.

K.V.Nekrasov is Candidate of Economic Sciences, and an Associate Professor, Ural State University of the Railway Transport, Ekaterinburg, Russia. His research interests are related to Innovation, Transport Logistics, Labor Efficiency, Corporate Culture

Professor N.V. Ziablitckaia is Professor at South Ural State University, Chelyabinsk, Russia. She holds the Doctor of Economics degree. Her research interests are Business planning, competitive advantages of the organization, lean manufacturing, development of petrochemical clusters, petrochemical industry.

Professor Dr. V.I.Nabokov is Professor at South Ural State University, Chelyabinsk, Russia. He obtained Doctor of Economics degree. His research interests are economics and management of organizations, industries. complexes; consumer market; innovation activity; problems of agrarian and industrial complex