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Algorithmization of bioproductivity management of winter grain crops adjusting the Selyaninov hydrothermal coefficient in the soil and climatic conditions of Southern Russia

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Abstract. Managing production processes in irrigated agriculture based on a comprehensive consideration of agroclimatic conditions for winter grain crop cultivation is one of the key scientific and practical tasks of modern crop production, directly related to increasing the efficiency of agrotechnical and land reclamation measures. This problem is particularly significant for the arid soil and climatic zones of southern Russia, where, in conditions of increasing environmental aridity, crop yields are determined by a complex interaction of climatic, biological, and technological factors. Numerous studies indicate a trend toward further increasing moisture deficits and other production constraints due to climate change, necessitating improved grain crop cultivation technologies that are aimed at adapting agroecosystems to challenging natural and economic conditions and consider hydrothermal parameters. The objective of this study was to eliminate the biotechnological contradiction between high yields of low quality and the production of high-quality grain that does not ensure the return on production costs. To develop a technology for cultivating agricultural crops considering the influence of hydrothermal conditions, an analysis of the soil and climatic conditions of the Volgograd region was carried out as a typical representative of the risky farming zone in Southern Russia. A "Method for Managing Agricultural Plant Production Processes in Extreme Continental Climate Conditions" (RU Patent No. 2228607) and a technology for managing winter crop bioproductivity were developed, taking into account the zonal values of the Selyaninov hydrothermal coefficient (G_{sel} = 0.3…0.6), typical of the arid conditions of southern Russia. The technology, tested under production conditions in the Volgograd region, enables the management of processes for achieving biological productivity in winter grains in arid soil and climatic conditions while simultaneously assessing their yield potential.

Keywords: cereal crops, moisture availability, aridization, patent research, production processes, high-quality grain, yield

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Introduction

Management of production processes in irrigated agriculture based on consideration of agroclimatic conditions for cultivating winter grain crops is an important task, the solution of which is relevant for assessing the effectiveness of ongoing agrotechnical and reclamation measures. This is particularly true for the arid soil and climatic conditions of southern Russia, where it is necessary to consider a combination of agro-climatic, biological, and technological factors of crop cultivation [1–3].

In extremely arid conditions, the structure of crop rotation should be selected considering not only the required production volumes in the area under consideration, but also crop vulnerability considering adverse weather events, drought probability, and their characteristics [4–7].

Increasing soil moisture content through water reclamation can be considered a traditional method of combating droughts and hot dry winds [8–11]. However, the main obstacle to the practical application of irrigation reclamation is the shortage of water resources. Another limitation of this approach, which significantly restricts its practical application even when water sources are available, is the significant investment of material and financial resources.

According to numerous studies, these problems will worsen over time due to the observed aridization of soil and climatic conditions and global warming. This justifies the relevance of developments that improve grain crop cultivation technologies under challenging natural and economic conditions, including hydrothermal ones.

The goal of the research was to eliminate the biotechnological contradiction between high yields of low quality (forage use) and low return on production costs associated with producing high-quality grain.

Materials and methods

In addition to analyzing scientific and technical literature in the research area, patent search was conducted using selected rubrics of the International Patent Classification (IPC) ***A01G 7/00***; ***A01G 22/00***; ***G01W 1/02***, etc. Patent research revealed a number of known methods for managing production processes, including those based on predicting grain yield and quality, as well as methods for reducing risks in agricultural production associated with natural phenomena hazardous to agriculture [5].

Methods of artificial precipitation enhancement from clouds, active cloud modification, etc. (including IPC ***G01W 1/02***) were also analyzed. To develop a technology for crop production considering the influence of hydrothermal cultivation conditions, an analysis of the soil and climatic conditions of the Volgograd Region was carried out, selected as a typical representative of arid farming conditions in Southern Russia.

A distinctive feature of the Volgograd Region, a typical Lower Volga region in terms of crop yield variability, is its extreme continental climate, including even early summer droughts. Years (e. g., 2010) were noted in which 4–18 mm of precipitation was observed in May-June against a norm of over 30 mm. The location and natural and climatic conditions of the Volgograd Region are characterized as a risky farming zone.

Consideration of hydrothermal conditions for crop cultivation was carried out using the Selyaninov hydrothermal coefficient (HTC), measured by the ratio of precipitation to the sum of temperatures.

The calculation of HTC, mm/°C, was performed using the dependence:

$$G_{\text{sel}} = 10 \cdot \frac{\Sigma P}{\Sigma t}, \tag{1}$$

where G_{sel} is the numerical value of HTC, mm/°C; ΣP is the total precipitation over the period during which the air temperature was above +10 °C, mm; Σt is the integral value of the sum of positive temperatures calculated for the same period, °C.

It should be noted that HTC is a complex indicator of heat and moisture availability of cultivation conditions, characterizing the evolving climatic conditions of the agricultural year in terms of heat and moisture resource availability. Modeling the interannual variability of HTC values during vegetation periods is a separate problem solved by various calculation and empirical methods, for example [12].

When developing the described technology, methods of mathematical and statistical modeling of crop yields depending on agrotechnological and natural-climatic factors described in the scientific and technical literature [6–11] were used. Regional recommendations for selecting agrotechnical parameters for cultivating cereal crops in arid conditions of the Volgograd region are available [13–16].

When substantiating rational seeding rates, the proportion of plants that do not survive until harvest period should be considered. In particular, when cultivating wheat on chernozem soils, the planting density should not be lower than 500–600 plants/m^2. When sowing quality seeds on chestnut soils, the planting density can be reduced to 300–450 plants/m^2. In the steppe and dry-steppe zones of the Volgograd region of the Russian Federation, with calendar sowing dates from August 25 to September 5, it is recommended to set the seeding rate on chestnut and dark chestnut soils at 3.5–4.0 million seeds per ha. On light chestnut soil in the semi-desert zone, it is optimal to sow winter crops in the period from September 1 to 10 with a seeding rate of 2.5…3.0 million seeds per ha at soil and air temperature during the sowing period of at least +18°…+12 °C.

Results and discussion

During a patent search conducted to develop a method for rapidly assessing potential productivity of agricultural plants, the method [6] was selected as the baseline. This method involved selecting seeds, soaking them in an aqueous solution of potassium salt, and instrumentally measuring the rate of increase in hydrogen ion concentration. The authors [6] found that the estimated potential productivity of plants is linearly dependent on this characteristic.

The method described simplifies the diagnostic technology and contributes to increasing the reliability of productivity assessments. However, a drawback is the limited range of predictions, as it is difficult to scale to other regions with different conditions.

Patent research reveals a method for assessing productivity of winter grain crops, such as winter wheat and barley, which involves optimizing the timing and rates of seeding. It is proposed to ensure that the sum of temperatures accumulated during the growing season is equal to 600 °C [1].

[2] describes a method for assessing the yield of winter grain crops grown in arid climates, including optimization of agronomic parameters at sowing temperatures within +12…+18 °C. A drawback of this method, which necessitates its improvement, is the lack of recommendations for adjusting agronomic parameters in accordance with the evolving climatic conditions of heat and moisture availability.

On the zoning map of agroclimatic indicators of the Volgograd region territory, including the sum of temperatures during the growing season exceeding 10 °C and the hydrothermal isolines of the *Gsel* coefficient (Fig. 1), dashed lines show the boundaries of administrative districts, and numerical and letter designations indicate their numbers. The contours of typical isolines of total temperatures are shown at intervals of 200 °C, and the values of hydrothermal coefficients are shown at intervals of 0.1.

In connection with the foregoing, the task was set to develop a technology for cultivating winter grain crops and predicting grain productivity and quality based on phenological observations.

To solve the problem, a “Method for Managing Agricultural Plant Production Processes in Extreme Continental Climate Conditions” [4] was developed, Patent RUS no. 2228607.

The developed modified technology for assessing potential productivity is based on optimizing agronomic timing and seeding rates and has been tested in the Volgograd Region.

The algorithmic basis of the proposed method is the adjustment of the seeding rate using the calculated numerical value of the HTC *Gsel*, determined for the grain crop growing region.

The algorithm for accounting for the influence of the HTC provides for the following adjustments to agronomic parameters depending on its value:

– At $G_{sel} < 0.5$, the seeding rate is reduced by 10–15% of the calculated values, and the row spacing is increased from 15 to 22.5 cm;

– At G_{sel} within 0.5…0.9, the seeding rate is maintained at recommended values;

– At $G_{sel} > 0.9$, the seeding rate is increased by 20–25% with a reduction in row spacing to 7.5 cm.

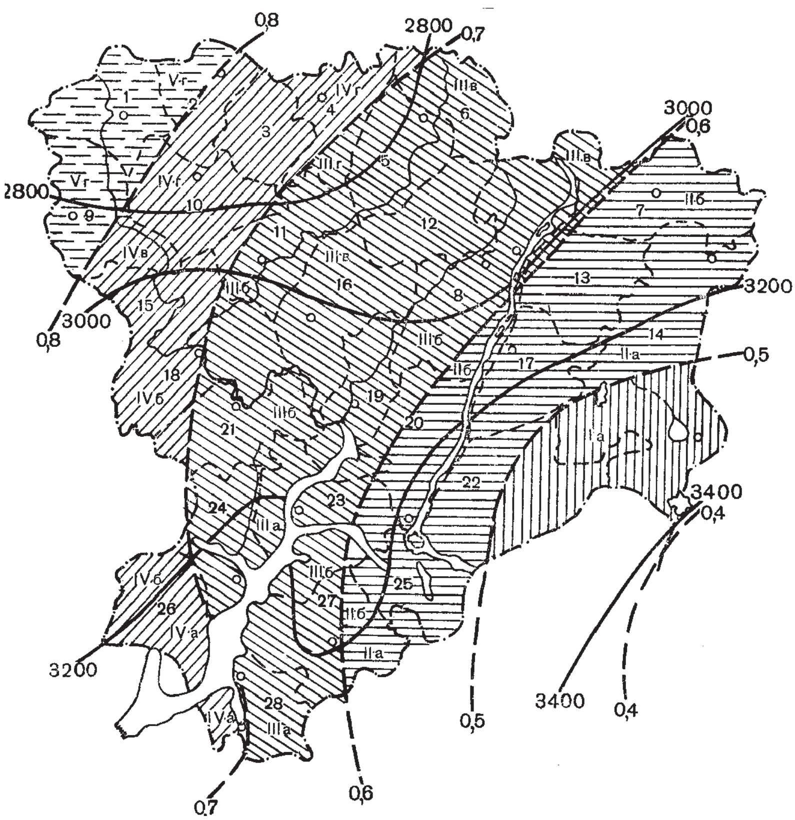

Fig. 1. Agroclimatic zoning of the Volgograd Region

Source: based on materials from the Agroclimatic Handbook of the Volgograd Region[1].

Thus, bioproductivity management during grain cultivation is achieved by accounting for the HTC value, which characterizes their actual heat and moisture availability. The HTC value is determined by calculation or graphic analysis. Implementation of the described approach allows simultaneous numerical estimation of winter grain crop yields using the formula

$$Y_{03} = aG_{sel}S + b, \tag{2}$$

where Y_{03} — the estimated yield, t/ha; a and b — parameters determined based on long-term empirical data, for example, using the least squares method; S — the cumulative sum of positive temperatures from sowing to the end of the growing season, °C; G_{sel} — the hydrothermal coefficient adopted for the agricultural production region, mm/°C.

The results of field studies examining the effect of seeding rate on yield and grain quality of winter wheat cv. Donshchina are presented in Table 1. The row spacing

[1] Rusiv ZM, Tsarkov LI. (eds.) *Agroklimaticheskii spravochnik po Volgogradskoi oblasti* [Agroclimatic handbook for the Volgograd region]. 2nd ed. Leningrad; 1967.

was 22.5 cm with a seeding depth of 5–6 cm. Field experiments were conducted from September 6 to 8 on chestnut soils in the dry steppe zone of the Volgograd Region. The G_{sel} value for the experimental farm was assumed to be 0.9.

Based on long-term observations, the values in dependence (2) were:

$a = 0.008$; $b = 0.390$.

The temperature sum constant was assumed to be $S = 600$ °C.

Numerical calculation yielded a point estimate of productivity forecast for next year using dependence (2), which was

$$Yзк = 0.008 \cdot 600 \cdot 0.9 + 0.390 = 4.71 \text{ t/ha}. \quad (3)$$

The point estimate of the productivity forecast for winter wheat cv. Don 95 for $S = 585$ °C, calculated using dependence (2), was

$$Yзк = 0.008 \cdot 585 \cdot 1.3 + 0.390 = 6{,}74 \text{ t/ha}. \quad (4)$$

Table 1

Effect of seeding rate on productivity and grain quality of winter wheat cv. 'Donshchina'

Seeding rate, 10^6 seeds/ha	Yield, t/ha	Plant loss in autumn-winter period, %	Number of stems per m² at harvesting	Protein content, %	Gluten, %
1.5	2.83	11.4	275	10.6	23.1
2.0	3.12	10.7	316	12.7	28.5
2.5	4.27	9.2	362	14.3	32.4
3.0	4.53	7.3	389	15.1	34.7
3.5	4.63	6.9	426	16.2	37.3
3.6	4.71	5.2	458	15.8	35.1
3.7	4.72	5.8	482	15.1	33.1
3.8	4.58	6.3	492	14.2	30.2
3.9	3.87	6.6	496	13.6	28.1
4.0	3.62	6.7	472	10.6	27.6

Source: compiled by D.A. Rogachev, A.F. Rogachev based on data from [4].

The influence of seeding rate on the yield of winter wheat cv. Donshchina, approximated by a quadratic polynomial, is shown in Fig. 2.

The regression dependence of productivity of winter wheat cv. Donshchina on seeding rate is approximated by formula with acceptable accuracy (determination coefficient $R^2 = 0.7943$).

$$Y = -0.7708x^2 + 4.8519x - 3.0214, \quad (5)$$

where x — the seeding rate, million seeds per ha.

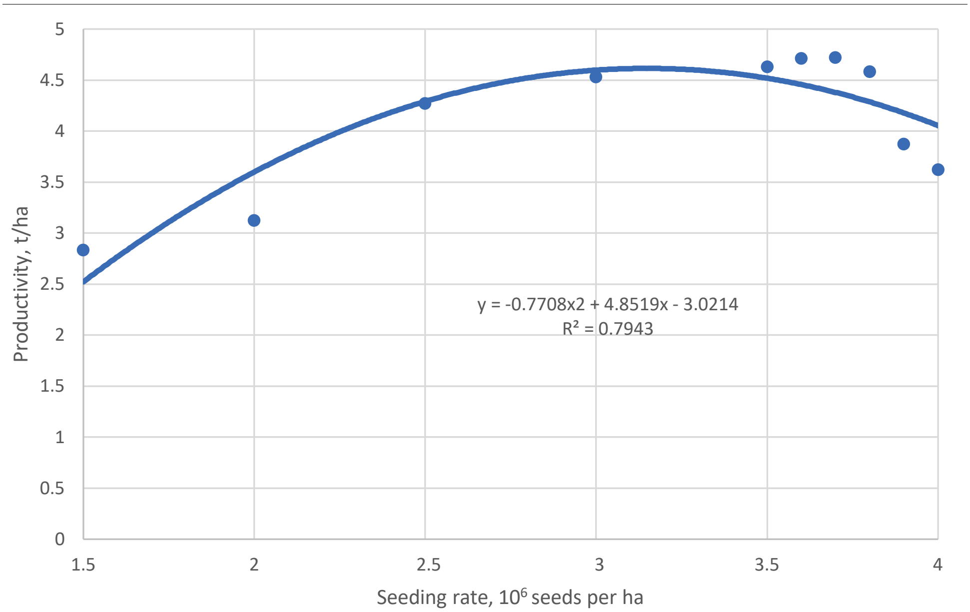

Fig. 2. Effect of seeding rate on productivity of winter wheat cv. 'Donshchina'
Source: compiled by D.A. Rogachev, A.F. Rogachev.

Experiments have shown that row spacing in winter wheat cultivation can also determine grain quality [4], as illustrated by the data presented (Table 2).

Table 2

Effect of row spacing on yield *Y*, t/ha, and grain quality (protein content *P* and gluten content *G*, %)

Cultivar	Row spacing, cm											
	7.5			22.5			30.0			15.0		
	Y	*P*	*G*	*Y*	*P*	*G*	*Y*	*P*	*G*	*Y*	*P*	*G*
1. Don 93	4.83	17.1	34.7	4.37	16.8	33.2	4.15	15.7	30.2	3.37	12.3	29.2
2. Don 95	4.13	16.2	30.2	3.99	16.1	29.8	3.78	15.6	28.7	3.15	14.2	26.3
3. Volgogradskaya 84	6.31	16.4	35.3	5.87	15.8	33.3	4.13	15.1	31.8	3.27	14.8	29.7
4. Donshchina	3.36	16.2	37.3	3.12	15.8	36.2	2.87	12.6	31.2	2.13	10.6	23.1
5. Krasnodarskaya 39	3.17	14.2	36.3	2.85	13.8	33.0	2.67	13.1	32.6	2.12	12.4	29.8
6. Mironovskaya yubileinaya	4.15	18.6	38.6	3.86	17.9	37.4	3.41	16.3	34.3	29.7	12.7	31.3
7. Saratovskaya 90	3.09	14.4	30.3	5.72	15.8	32.3	4.13	13.6	28.4	3.62	12.4	24.9

Source: compiled by D.A. Rogachev, A.F. Rogachev based on data from [4].

When studying the influence of row spacing on yield, row spacing values less than 7.5 cm were not considered due to the impossibility of technological implementation (Fig. 3).

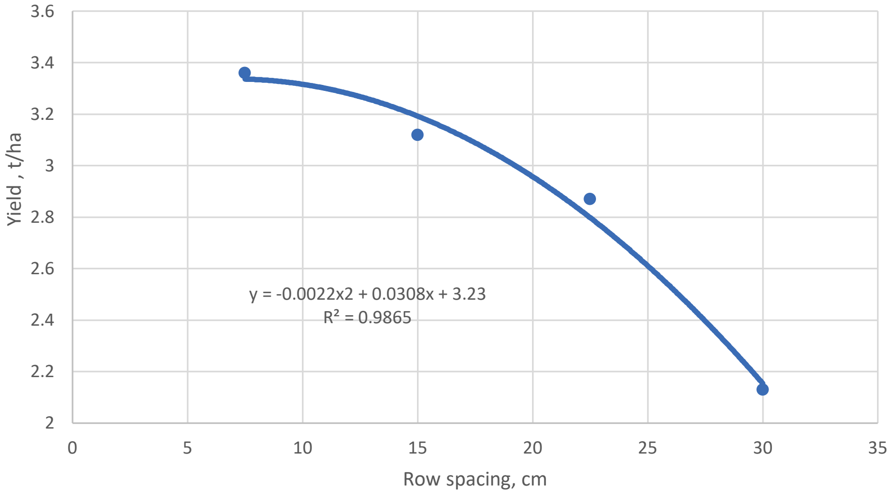

Fig. 3. Effect of row spacing on yield of winter wheat cv. 'Donshchina'
Source: compiled by D.A. Rogachev, A.F. Rogachev.

The regression dependence of productivity of winter wheat cv. Donshchina on row spacing is approximated by formula with a determination coefficient of $R^2 = 0.9865$.

$$Y = -0.0022x^2 + 0.0308x + 3.23, \quad (6)$$

where x — the row spacing, cm.

The productivity values of the analyzed winter wheat cultivars are consistent with calculations performed using formula (2), with acceptable agronomic accuracy, while the discrepancy between calculated and experimental data is within acceptable limits (LSD < 0.05).

Conclusion

The developed technology for managing the biological productivity of winter crops considering zonal hydrothermal coefficient values characteristic of the arid conditions of southern Russia, enables the management of processes for achieving biological productivity of winter grain crops in arid soil and climatic conditions while simultaneously assessing their potential yield.

The sufficiently high convergence of actual winter crop yield values with the predicted assessment of their potential productivity (LSD < 0.05) enables planning grain agricultural production results ensuring programmable efficiency for the following economic year.

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Алгоритмизация управления биопродуктивностью озимых зерновых культур с учетом гидротермического коэффициента Селянинова в почвенно-климатических условиях Юга России

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Аннотация. Управление продукционными процессами в орошаемом земледелии на основе комплексного учета агроклиматических условий возделывания озимых зерновых культур — одна из ключевых научно-практических задач современного растениеводства, напрямую связанная с повышением эффективности агротехнических и мелиоративных мероприятий. Особую значимость проблема приобретает для засушливых почвенно-климатических зон Юга России, где в условиях нарастающей аридности природной среды формирование урожайности определяется сложным взаимодействием климатических, биологических и технологических факторов. Многочисленные исследования свидетельствуют о тенденции дальнейшего роста дефицитов влагообеспеченности и других ограничений продукционного процесса вследствие изменений климата, что обусловливает необходимость совершенствования технологий возделывания зерновых культур, ориентированных на адаптацию агроэкосистем к напряженным природно-хозяйственным условиям и основанных на учете гидротермических показателей. Цель исследования — устранение биотехнологического противоречия между высоким урожаем низкого качества и получением качественного зерна, не обеспечивающего окупаемость производственных затрат. Для разработки технологии возделывания агрокультур с учетом влияния гидротермической обеспеченности провели анализ почвенно-климатических условий Волгоградской области как типичного представителя зоны рискованного земледелия на Юге России. Разработаны «Способ управления продукционными процессами сельскохозяйственных растений в условиях резко континентального климата» (патент РФ № 2228607) и технология управления биопродуктивностью озимых культур, учитывающая зональные величины гидротермического коэффициента Селянинова ($G_{сел}$ = 0,3…0,6), характерные для засушливых условий Юга России. Технология, апробированная в производственных условиях Волгоградской области, обеспечивает возможность управления процессами достижения биологической продуктивности озимых зерновых в засушливых почвенно-климатических условиях с одновременной оценкой их потенциальной урожайности.

Ключевые слова: влагообеспеченность, аридизация, патентные исследования, продукционные процессы, качественное зерно

Вклад авторов: авторы внесли равноценный вклад в получение и обработку результатов исследования, написание статьи.

Заявление о конфликте интересов. Авторы заявляют об отсутствии конфликта интересов.

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