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АДАПТИВНОСТЬ И ЭКОЛОГИЧЕСКАЯ ПЛАСТИЧНОСТЬ ЯЧМЕНЯ В УСЛОВИЯХ ЛЕСОСТЕПИ КРАСНОЯРСКОГО КРАЯ

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Представлены результаты оценки ярового ячменя в питомнике конкурсного сортоиспытания по параметрам адаптивности и экологической пластичности в условиях Красноярской лесостепи. Объектами исследования, проводившегося в 2020–2022 гг., являлись районированные сорта и линии местной селекции. В качестве стандарта принят сорт Ача. Почва опытного поля – обыкновенный маломощный чернозем. Повторность четырехкратная, метод сравнения парный. Посев проведен в оптимальные сроки – 20–25 мая, норма высева – 5,5 млн всхожих семян/га. По режиму увлажнения 2020 и 2021 гг. были избыточно влажными (ГТК = 1,84–1,89), при этом 2021 г. оказался достаточно увлажненным. В 2022 г. наблюдалась майская засуха (ГТК = 0,27). По итогам проведенных исследований выделен ценный селекционный материал. Наибольшей продуктивностью (43,2 ц/га) по отношению к стандарту отличалась линия Д-7-7057 (Л-11-38 × Буян). Сорта Ача, Красноярский 80, линия Д-7-7057 по экологической пластичности были отнесены к интенсивному типу (b_i = 1,17–1,21), сорт Кедр меньше всего реагировал на улучшение условий выращивания (b_i = 0,86). Селекционная линия В-56-6885 (Биом × Сибиряк) оказалась самой стабильной, отличалась повышенными показателями средней урожайности (41,3 ц/га), экологической стабильности (S_i^2 = 417,1, *SF* = 2,82), селекционной ценности генотипа (S_c = 6,73), имела среднюю экологическую пластичность (b_i = 1,01). Среди сортов интенсивного типа наибольший интерес представляет линия Д-7-7057 (Л-11-38 × Буян) с самой высокой урожайностью (43,2 ц/га), средними параметрами стабильности (S_i^2 = 723,9, *SF* = 4,02) и повышенной пластичностью (b_i = 1,17). В ходе эксперимента установлено, что основной вклад в формирование урожая вносят селекционные признаки, связанные с плотностью посева (число растений перед уборкой, продуктивный стеблестой и кущение) и продуктивностью отдельного растения (масса зерна с одного растения, масса 1 тыс. зерен).

Ключевые слова: ячмень, сорт, селекционная линия, урожайность, экологическая пластичность, стабильность, селекционная ценность

ADAPTABILITY AND ECOLOGICAL PLASTICITY OF BARLEY UNDER FOREST-STEPPE CONDITIONS OF THE KRASNOYARSK TERRITORY

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The results of spring barley assessment by the parameters of adaptability and ecological plasticity in the Krasnoyarsk forest-steppe conditions are presented. The objects of the study, conducted in 2020-2022, were the released varieties and lines of local breeding. The Acha variety was adopted as the standard. The soil of the experimental field is ordinary low-power chernozem. Repetition is fourfold, and the comparison method is paired. Sowing was carried out in optimal time - May 20-25, the seeding rate - 5.5 million germinated seeds/ha. In terms of moisture regime, 2020 and 2021 were excessively wet (HTC = 1.84-1.89), while 2021 was sufficiently wetted. May drought was observed in 2022 (HTC = 0.27). As a result of the research, valuable breeding material was selected. The highest productivity (43.2 c/ha) in relation to the standard showed the line D-7-7057 (L-11-38 × Buyan). The varieties Acha, Krasnoyarsk 80, line D-7-7057 on environmental plasticity were attributed to the intensive type (b_i = 1,17-1,21), the variety Kedr reacted the least to improvement of the growing conditions (b_i = 0,86). The breeding line B-56-6885 (Biom × Sibiryak) was the most stable, characterized by high indices of average yield (41.3 c/ha), environmental stability (S_i^2 = 417,1, *SF* = 2,82), breeding value of the genotype (S_c = 6.73), and had average environmental plasticity (b_i = 1.01). Among the varieties of the intensive type, the line D-7-7057 (L-11-38 × Buyan) with the highest yield (43.2 c/ha), medium stability parameters (S_i^2 = 723,9, *SF* = 4,02) and increased plasticity (b_i = 1.17) is of greatest interest. During the experiment it was found that the main contribution to the formation of the yield is made by the breeding traits associated with crop density (the number of plants before harvesting, productive stem and tillering) and the productivity of individual plants (grain weight per plant, thousand-kernel weight).

Keywords: barley, variety, line, yield, ecological plasticity, stability, selection value

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INTRODUCTION

Spring barley is the most in-demand and widespread crop in the Krasnoyarsk Territory. In 2020-2022, the area of spring barley cultivation in the region amounted to about 160 thousand hectares. Barley is widely used as both fodder and cereal crop. It is characterized by higher yields and a shorter growing season compared to wheat and oats.

Currently, cultivating varieties adapted to local conditions and having high yields is becoming increasingly relevant [1–3]. The complexity of addressing this issue is related to the region's low bioclimatic potential. For instance, while this indicator is 1.0 for Russia as a whole, it stands at 0.52-0.54 for Eastern Siberia, and 0.46-0.48[1] for areas like Transbaikal, Khakassia, and Tyva. Under these conditions, choosing a particular variety becomes a critical task. As N.A. Rodina[2] believes, any farming system starts with a variety, and essentially, a variety serves as the biological foundation of the yield. According to A.A. Zhuchenko[3], P.L. Goncharov (see footnote 1), N.A. Rodina (see footnote 2), the contribution of the variety to increasing the yield amounts to 50-70%.

[1]*Goncharov P.L.* Methodology of selection of forage grasses in Siberia. Novosibirsk, 2003, 396 p.
[2]*Rodina N.A.* Barley breeding in the North-East of the Non-Black Earth Region. Kirov, 2006, 486 p.
[3]*Zhuchenko A.A.* Adaptive potential of cultivated plants and problems of agrosphere. Moscow, 2004, Vol. 1, pp. 49-63.

In breeding for productivity, it's essential to achieve a positive combination of high yield, its stability, and the responsiveness of plants to an intensive background [4, 5]. Given the climate peculiarities of the Krasnoyarsk Territory, new varieties should simultaneously possess good resistance to external environmental stress factors, high grain yield, and quality [6].

During the research, it was determined that the potential productivity and ecological resilience of plants are controlled by different sets of genes. Thus, there is a genuine possibility of combining these characteristics in one variety. It is acknowledged that breeding is the primary method for enhancing plant adaptability and crop quality [7].

Assessing ecological adaptability based on productivity parameters allows for more targeted use of the initial material and efficiently selecting varieties for different soil and climatic conditions to maximize their potential yield.

The purpose of the study is to assess barley varieties and breeding lines in terms of yield and adaptability indicators in the conditions of the Krasnoyarsk forest-steppe.

MATERIAL AND METHODS

The research was conducted from 2020 to 2022 in the open forest steppe of the Krasnoyarsk Territory. The soil of the experimental site is typical light chernozem. The forecrop was complete fallow. The humus content in the plowing horizon ranged from 4.2% to 7.0%. The nitrate nitrogen ($N\text{-}NO_3$) content was 6.8-13.4 mg/kg of soil, phosphorus content was 17.5-22.2 mg/100g of soil, and potassium was 12.3-19.0 mg/100g of soil. The soil solution reaction (pH_{wat}) ranged from 6.1 to 6.6.

The weather conditions during the barley growing season varied in terms of average daily air temperature and the amount of precipitation from the average long-term values (see Table 1). In May and August of 2020, with elevated average daily temperatures, excessive moisture was recorded, leading to lodging of crops before harvest. In 2021, July was excessively humid, while August was warm and moderately humid. In 2020 and 2021, the hydrothermal coefficient (HTC) was 1.84-1.89, with 2021 being characterized as sufficiently humid. In 2022, May and June were warm, with June experiencing heavy rainfall.

The registration area of plots in the competitive variety test was 37-40 m^2. There was a fourfold repetition, and the comparison method was pairwise. The standard variety was "Acha". Sowing was done in optimal times, from 20th to 25th of May, with a seeding rate of 5.5 million germinated seeds per hectare.

Statistical data processing was performed according to B.A. Dospekhov [8]. To characterize adaptive potential, we calculated the ecological plasticity index (b_i) and stability (S_i^2) according to S.A. Eberhart and W.A. Russel, as presented by V.Z. Pakudin[4]. Genetic flexibility of the variety (GF) was determined according to A.A. Goncharenko[5], homeostasis (*Hom*) was determined using the methodology of V.V. Khangildin and S.V. Biryukov[6], the phenotypic variability indicator (*SF*) was based on D. Lewis[7], and the breeding value of genotypes (S_c) was as per A.V. Kilchevsky and L.V. Khotyleva[8].

RESULTS AND DISCUSSION

The yield of the varieties usually consists of individual productivity elements that mutually influence each other [9].

One of the essential factors associated with high yields is the duration of vegetation. Based on this parameter, all the varieties and lines discussed in this article were similar to the standard and were classified as medium-maturing, except

[4] *Pakudin V.Z.* Parameters for assessing the ecological plasticity of varieties and hybrids: the theory of selection in plant populations. Novosibirsk, 1976, 189 p.

[5] *Goncharenko A.A.* On adaptability and ecological stability of grain crop varieties // Bulletin of the Russian Academy of Agricultural Sciences, 2005, No. 6, pp. 49-53.

[6] *Khangildin V.V., Biryukov S.V.* The problem of homeostasis in genetic and breeding studies // Genetic and cytological aspects in agricultural plant breeding. 1984, No. 1, pp. 67-76.

[7] *Lewis D.* Gene-environment interaction: a relationship between dominance, heterosis, phenotypic stability and variability // Heredity. 1954. Vol. 8. P. 333–356.

[8] *Kilchevsky A.V., Khotyleva L.V.* Genotype and environment in plant breeding. Minsk: Science and Technology, 1989, 191 p.

Табл. 1. Агрометеорологические условия в период проведения опыта
Table 1. Agrometeorological conditions during the experiment

Indicator	2020					2021					2022					Annual average value				
	May	June	July	Au-gust	For the growing season	May	June	July	Au-gust	For the growing season	May	June	July	Au-gust	For the growing season	May	June	July	Au-gust	For the growing season
Average air tem-perature, °C	14,0	15,7	18,9	17,4	16,5	9,8	15,5	19,7	17,4	15,6	13,8	17,0	17,6	14,9	15,8	10,1	15,0	19,3	16,2	15,2
Precipitation amount, mm	44,9	96,0	109,0	79,0	328,9	30,3	121,8	48,0	63,0	263,1	15,1	75,0	49,0	65,1	204,2	29,0	44,0	65,0	61,0	199,0
HTC	1,30	2,80	1,83	1,63	1,89	2,77	2,63	0,80	1,17	1,84	0,27	1,80	0,90	1,57	1,14	1,47	1,07	1,37	1,20	1,28

for the “Takmak” variety, which practically matured 1-4 days later than other varieties (see Table 2).

The number of plants before harvest for the studied varieties was the same as for the standard “Acha” variety or lower. The maximum productive tillering (1.63-1.67 units) was observed in the “Olenek” variety and the D-7-7057 line, developed under the adaptive breeding program, as well as the breeding line D-39-7318. The highest number of productive stems (39-48 stems/m^2 more than the standard) was identified in the breeding lines D-7-7057 and D-39-7318. In terms of the number of grains per ear, the “Buyan” variety, identified by us as a donor in diallel crosses, as well as the varieties “Olenek” and “Takmak,” and the breeding lines B-56-6885 and D-39-7318, had an advantage of 1.3-3.8 grains.

The weight of 1,000 grains is a leading breeding trait, especially when grown in drought conditions, which is typically characteristic of early ripening varieties [10]. The “Kedr” and “Abalak” varieties and the breeding lines D-7-7057 and D-55-7455 had an advantage in the weight of 1,000 grains (+3.3-4.8 g).

In breeding to increase the productivity of grain crops, an important role is given to increasing productivity and the yield of grain from a single plant [11]. In terms of grain weight per plant, the “Buyan” variety and the breeding lines D-7-7057 and D-39-7318 showed an advantage over the standard (+0.15-0.20 g). The higher indicators of productive stem stand of the promising lines D-7-7057 and D-39-7318 had a positive impact on the yield size.

Based on the assessment of the adaptive potential, it was found that the “Takmak” variety and the D-7-7057 line have the highest genetic flexibility (GF = 40.4-42.2), indicating their ability to resist adverse factors while also positively responding to improved conditions. In optimal and limited conditions, these samples demonstrated the highest yield (41.5-43.2 c/ha). The combination of high genetic flexibility and a lower coefficient of variation (*CV*) indicates the real ability of the “Takmak” variety and the breeding lines D-7-7057 and D-39-7318 to produce higher yields (see Table 3).

Табл. 2. Вегетационный период и элементы продуктивности сортов и селекционных линий ячменя, участвовавших в конкурсном сортоиспытании (среднее за 2020–2022 гг.)

Table 2. Growing season and productivity elements of barley varieties and breeding lines that participated in competitive variety trials (average for 2020-2022)

Variety, line	Growing period, days		Number of plants before harvesting, pcs./m^2		Productive tillering, pcs.		Productive plant stand, pcs./m^2		Number of grains in an ear, pcs.		Weight of 1 thousand grains, g		Grain weight per plant, g	
	$\bar{X}$	*CV*, %	$\bar{X}$	*CV*, %	$\bar{X}$	*CV*, %	$\bar{X}$	*CV*, %	$\bar{X}$	*CV*, %	$\bar{X}$	*CV*, %	$\bar{X}$	*CV*, %
Acha	77	9,8	419	11,5	1,40	7,1	585	15,9	18,4	17,4	39,9	9,3	1,05	70,5
К-80	78	9,2	343	18,2	1,57	18,4	542	12,2	18,8	16,9	42,7	10,4	1,09	64,0
Kedr	79	8,7	320	12,8	1,60	12,5	510	7,6	18,0	24,4	43,9	7,2	0,97	69,8
Bakhus	78	10,0	348	9,1	1,60	25,0	547	22,8	18,0	23,3	42,9	7,5	0,95	65,3
Buyan	78	9,4	319	10,8	1,43	22,4	450	14,7	22,2	20,8	39,3	17,4	1,20	83,6
Olenek	79	9,6	306	20,8	1,67	25,0	479	10,2	19,7	23,3	39,5	7,4	0,91	69,3
Abalak	77	10,5	396	25,1	1,43	14,5	569	31,5	18,7	21,5	44,1	12,2	0,97	63,1
Takmak	80	10,5	367	10,0	1,40	7,1	551	10,8	21,0	18,1	40,6	8,4	1,03	53,1
B-56-6885	78	9,0	394	13,5	1,37	15,2	524	4,1	20,6	23,2	41,9	13,3	1,00	61,2
D-7-7057	77	9,4	395	24,9	1,63	27,6	633	21,1	17,9	16,6	44,7	10,1	1,25	86,5
D-39-7318	77	11,5	394	31,9	1,63	19,7	624	20,3	20,5	18,4	38,9	17,8	1,23	95,2
D-55-7455	76	9,8	404	11,7	1,50	13,3	596	3,3	18,2	19,4	43,2	10,3	1,04	68,5
LSD_{05}	1		46		0,20		47		0,5		3,0		0,10	

In terms of ecological plasticity, the varieties Acha, Krasnoyarsky 80, and the line D-7-7057 were classified by us as of the intensive type. This means that in favorable years, these varieties can yield the maximum harvest, but under stress conditions, they might yield lower than other varieties. The “Kedr” variety showed a weak response to varying growing conditions, as evidenced by its low ecological plasticity value (b_i = 0.86), yield variation coefficient (*CV* = 52.3%), and the highest phenotypic stability (S_i^2 = 285.8). The varieties “Bakhus”, “Buyan”, “Olenek”, “Abalak”, and the lines D-39-7318 and D-55-7455 had a medium level of ecological plasticity (b_i = 0.92–1.10) and showed better adaptability to environmental factors with yields at the standard level.

In breeding for stable productivity, the line B-56-6885 is of particular practical interest, combining a higher average yield (41.3 c/ha), ecological stability (S_i^2 = 417.1, *SF* = 2.82), semi-intensive response to the optimal background (b_i = 1.01), and an increased breeding value of the genotype (*Sc* = 6.73). For the creation of intensive-type varieties, it’s crucial for them to have, above all, high yields, a medium level of ecological stability, and a high response level to an intensive background. The D-7-7057 line meets these criteria, combining a high yield (43.2 c/ha) and medium stability (S_i^2 = 723.9, SF = 4.02). This line is promising and is planned for further study and propagation.

To determine the influence of individual breeding characteristics on the formation of the yield of the studied varieties and breeding lines, the varimax rotation method was used based on the Statistica program[9]. As a result of the analysis, considering the mutual influence of individ-

[9] *Khizhnyak S.V., Puchkova E.P.* Mathematical methods in agroecology and biology: textbook. Krasnoyarsk: Publishing house of Krasnoyarsk State Agrarian University, 2019, 240 p.

Табл. 3. Показатели адаптивности перспективных сортов и линий ярового ячменя в условиях Красноярской лесостепи
Table 3. Indicators of adaptability of the promising varieties and lines of spring barley in the conditions of the Krasnoyarsk forest-steppe

Variety, line	Origin	Yield, c/ha				Adaptability indicators						
		2020	2021	2022	$\bar{X}$	*CV*, %	ГГ	b_i	S_i^2	*Hom*	*SF*	S_c
Acha	(Paragon × Christina) × (Jet × Obskoj) × (Novosibirsky 1 × Viner)	41,3	14,2	60,2	38,6	60,0	37,2	1,21	908,9	1,7	4,24	5,45
K-80	C-80 × Una	32,8	14,7	58,6	35,4	62,4	36,7	1,17	693,1	1,6	3,99	5,53
Kedr	Viner × Birgitta	34,6	13,9	46,7	31,7	52,3	30,3	0,86	285,8	1,9	3,36	4,94
Bakhus	(Viner × Donetsky 650) × (Viner × Krasnoufimsky 95)	43,6	19,9	55,5	39,7	45,7	37,7	1,02	398,0	2,2	2,79	6,50
Buyan	Kedr × Jo 1345	33,9	16,7	56,7	35,8	56,1	36,7	1,10	581,8	1,8	3,40	5,91
Olenek	[(Viner × Krasnoufimsky 95) × (Viner × Donetsky 650)] × Acha	34,0	18,9	49,0	34,0	44,3	34,0	0,98	558,1	2,3	2,59	5,81
Abalak	(Krasnoyarsky 80 × Drop (France)) × Ca 46925 (Denmark)	38,7	19,9	52,2	36,9	43,9	36,1	0,96	540,7	2,3	2,62	6,18
Takmak	Priazovsky 9 × U-20-706	40,2	24,2	60,1	41,5	43,3	42,2	1,05	681,8	2,3	2,48	7,24
B-56-6885	Biom × Sibiryak	47,2	20,1	56,6	41,3	45,9	38,4	1,01	417,1	2,2	2,82	6,73
D-7-7057	L-11-38 × Buyan	48,8	16,1	64,7	43,2	57,4	40,4	1,17	723,9	1,7	4,02	6,17
D-39-7318	Sv.66905 × Buyan	40,1	20,7	53,3	38,0	43,1	37,0	0,92	578,3	2,3	2,57	6,37
D-55-7455	Abalak × K-22092	40,9	20,6	55,7	39,1	45,1	38,2	0,93	619,9	2,2	2,70	6,52
LSD_{05}		5,0	2,7	2,4	3,5							

ual traits for the vegetation period and six yield structure elements, two factors were obtained for each research year. These mainly included productive tillering, productive stem stand, the number of grains in the main ear, and grain weight per plant. Their influence accounted for a significant value – 32.62% and 31.18% in 2020, 32.21% and 31.34% in 2021, 42.80% and 30.16% in 2022 (see Table 4).

In 2020, the first factor included the traits that positively correlated with yield, such as the number of grains in the main ear (r = 0.880) and the grain weight from a single plant (r = 0.724), while productive tillering showed a reverse dependency (r = −0.896). The second factor comprised the number of plants before harvesting (r = 0.818) and the productive plant stand (r = 0.813), which determine sowing density. In unfavorable conditions of 2021, the positive effects on productivity were given by the first factor's traits – productive tillering (r = 0.726), the number of grains in the main ear (r = 0.742), and the grain weight from a single plant (r = 0.922). The second factor included the number of the plants before harvesting (r = 0.874) and the productive plant stand (r = 0.837). The correlations of individual productivity elements noticeably differed in 2022. The first factor was made up of the productive plant stand (r = 0.813), the weight of 1,000 grains (r = 0.719), with a negative impact noted for the vegetation period (r = −0.891). The second factor predominantly consisted of productive tillering (r = 0.896) and the grain weight from a single plant (r = 0.738).

Thus, the dominant breeding traits affecting barley yield in the conditions of the Krasnoyarsk forest-steppe are productivity elements related to sowing density and the productivity of individual plants.

CONCLUSIONS

1. The evaluation of the studied barley varieties and lines in the competitive variety testing for productivity and adaptability parameters allowed us to highlight valuable breeding material.

2. During the trials in the conditions of the Krasnoyarsk forest-steppe, the highest average yield (41.3-43.2 c/ha) was obtained from the "Takmak" variety, and the breeding lines B-56-

Табл. 4. Матрица факторных нагрузок (вращение варимакс) для изученных переменных у сортов и линий ячменя

Table 4. Factor load matrix (varimax rotation) for the studied variables in barley varieties and lines

Selection trait	2020		2021		2022	
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
Duration of the growing season	−0,035	−0,622	0,400	−0,677	−0,891*	0,087
Number of plants before harvesting	0,324	0,818*	−0,034	0,874*	0,401	−0,854
Productive tillering	−0,896*	0,0001	0,726*	0,170	0,142	0,896*
Productive plant stand	−0,020	0,813*	0,375	0,837*	0,813*	0,064
Number of grains in the main ear	0,880*	0,011	0,742*	0,243	−0,907*	0,095
Weight of 1 thousand grains	−0,276	0,583	−0,155	−0,418	0,719*	0,117
Grain weight per plant	0,724*	0,352	0,922*	−0,084	0,147	0,738*
Factor contribution, %	32,62	31,18	32,21	31,34	42,80	30,16

*$p > 0{,}700$.

6885 and D-7-7057. As a result, the varieties Acha, Krasnoyarsky 80, and the line D-7-7057 were also classified as of the intensive type (b_i = 1.17–1.21), while the early-bred “Kedr” variety was of the extensive type (b_i = 0.86).

3. In breeding for stable productivity, the line B-56-6885 of the semi-intensive type is of particular interest, combining a higher average yield (41.3 c/ha), ecological stability (S_i^2 = 417.1, *SF* = 2.82), an average response to the optimal background (b_i = 1.01), and an increased breeding value of the genotype (*Sc* = 6.73).

4. For breeding varieties responsive to improved conditions, the promising line is D-7-7057 with high yield (43.2 c/ha) and medium stability parameters (S_i^2 = 723.9, *SF* = 4.02).

5. The leading breeding traits during the research years were yield structure elements responsible for forming the sowing density and productivity of individual plants.

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