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Agroecological assessment of Sudan grass cultivars and new hybrid populations of Bashkir selection

R. A. Biktimirov[1]✉, Z. M. Sharipkulova[1], A. A. Nizaeva[1]
[1] Bashkir Research Institute of Agriculture – Subdivision of the Ufa Federal Research Center of the Russian Academy of Sciences, Ufa, Russia
✉*E-mail: biktimirov.rifx@yandex.ru*

Abstract. **The purpose of research** is to evaluate Sudan grass cultivars in terms of phenotypic plasticity and yield stability in changing environmental conditions. **Research methods.** The article presents the data of the research conducted in conditions of the Cis-Ural steppe of the Bashkortostan Republic in 2016–2019. 12 Sudan grass cultivars and hybrid populations, selected in the Bashkir Research Institute of Agriculture, being of varied ripeness, were studied for yielding capacity, stability, and plasticity. Weather conditions in the years of research on temperature and water regimes were different. That made it possible to evaluate the lines in contrasting conditions of cultivation. **Results**. The most adaptive varieties for forage cultivation were identified: Demskaya variety and populations 285, 318 and 395 with a regression coefficient b_i close and equal to one, are characterized as plastic; populations 392, 400, 446/2 are responsive to better growing conditions and characterized as intensive – $b_i > 1$. When cultivated for seeds, population 318 is defined as plastic, while Smena, Demskaya, Chishminskaya rannyaya, Yaktash cultivars, populations 276, 285, 392, 446/2 and 395 are responsive to improved growing conditions and identified as intensive. The best populations according to the comprehensive assessment of varieties for dry matter yield, plasticity and stability are: 400 (yield 69.7 c/ha; plasticity – 1.1; stability – 40.5) and 395 (69.2 c/ha; 1.0; 36.4, respectively). Populations 358 (yield 29.6 c/ha; plasticity – 1.0; stability – 5.2) and 318 (28.1 c/ha; 0.9; 4.2, respectively) were recognized as the best Sudan grass cultivars and populations in terms of seed productivity, plasticity and stability, **Scientific novelty.** The article collects and presents the materials of many years of the study on Sudan grass phenotypic plasticity and stability.
Keywords: sorghum (*Sorghum moench*), Sudan grass (*Sorghum sudanense*), yielding capacity, adaptivity, plasticity, stability.

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Introduction

Sudan grass is one of the few crops that fully meet the requirements of adaptive-landscape farming in arid regions [10, p. 56]. The crop can withstand long air and soil droughts. It grows quickly after mowing, has a high and stable yielding capacity, high feeding value, and serves multiple purposes. All these qualities make it indispensable for summer feeding of animals and forage production for winter livestock [1, p. 5], [2, p. 33], [16, p. 5], [24, p. 1563].

Forage crop varieties, being of a sufficiently high potential yield, tend to reduce it significantly in production conditions. This is due to the high responsiveness of the crop to changing agro-climatic growing conditions [2, p. 34], [17, p. 49], [18, p. 29]. In this regard, one of the most important directions in crop selection was to develop cultivars that would combine high yielding capacity, crop quality and resistance to environmental factors at the level of the variety, agrocenosis, agroecosystem [1, p. 31], [2, p. 34], [9, p. 492], [22, p. 11], [13, p. 3].

In recent years, cultivation of Sudan grass in the Republic of Bashkortostan has spread to more northern areas not favorable for its growth. This resulted in new problems in crop selection due to the fact that in some years the cultivars do not mature for seeds [23, p. 6]. Therefore, one of the main reasons preventing the expansion of the cultivated land for Sudan grass is the lack of early-matured seeds of highly productive varieties [21, p. 25]. There is an urgent need to study new Sudan grass cultivars and hybrid populations to identify samples that would be characterized by crop stability and high responsiveness to better cultivation conditions [4, p. 550], [5, p. 619], [19, p. 9]. Thus, the efforts of breeders should be aimed at creating environmentally plastic varieties that provide sufficiently high yields in conditions of unstable and sharply changing climatic conditions of the region.

There environmental tests are conducted to find stable and adaptive crop varieties and lines (including fodder crops with higher yields of forage and seed production). They detect cultivar reaction to changing weather conditions, including indicators of phenotypic plasticity and stability [3, p. 149], [11, p. 46], [12, p. 16]. The highest yields of varieties and hybrids in various soil and climatic conditions can be achieved when there is a balance between environmental plasticity and stability [3, p. 4], [14, p. 16], [15, p. 58].

The research goal is to evaluate Sudan grass cultivars in terms of phenotypic plasticity and yield stability in changing environmental conditions.

Methods

The work was done in experimental plots of the Chishminskiy crop-breeding center of the Bashkir Research Institute of Agriculture under the soil and climatic conditions of the Cis-Ural steppe zone of the Bashkortostan Republic in 2016–2019.

The soil cover of the experiment site is represented by typical carbonate chernozems of medium capacity. The soil texture is medium loam, being lighter with depth. The underlying rocks are sandstones and marls that contribute to easy infiltration. Therefore, the lack of precipitation in this zone results in the soil drought. The average humus content in the upper arable layer ranges from 7 to 9 % (according to Tiurin). It is 3.2...3.4 % at a depth of 40 ... 60 cm. The reaction of the soil solution is close to neutral being 7.1...7.4. The content of total nitrogen is 0.4 % (by Kjeldahl), exchangeable potassium (by Chirikov) and mobile phosphorus (by Chirikov) are 20.5 mg / 100 g and 10.2 mg/100 g of dry soil; the calcium content is 35 mg-EQ/100 g (by Aidinian).

The experiment involved 12 Sudan grass varieties and hybrid populations of selection of the Bashkir Research Institute of Agriculture. Chishminskaya rannyaya was chosen as a standard Sudan grass cultivar released in the Ural region and the Republic of Bashkortostan.

Cultivation methods for Sudan grass are generally accepted for the soil and climatic conditions of the Cis-Ural steppe. In all years of research, the predecessor was spring wheat. The crop was sown on May 25–28, when the soil was warmed to the minimum favorable temperatures for Sudan grass to emerge; the seeding rate was 2.0 million germinated seeds/ha. Seeding was carried out with a central-fill planter SKS-6-10 in rows (the row-width spacing was 15 cm). Two-factor experience. The plot area was 18.9 m^2, the accounting area to determine the fodder yield – 6.9 m^2, seed yield – 8.05 m^2. Varieties were placed in a random fashion; the repeatability in experiments is fourfold.

Competitive testing of Sudan grass cultivars and hybrid populations was conducted in accordance with the guidelines of the All-Russian Scientific Research Institute of Fodder named after. V. R. Williams [6], the method of the State Committee for testing of new crop varieties [26] and field experience [25].

Phenotypic plasticity (b_i) and stability ($σ^2d$) were found by the method of S. A. Eberchart, W. A. Rassel, which consists in calculating the coefficient of linear regression (bi) and the mean square deviation from the theoretical regression line ($σ^2d$), (1966) as presented by V. A. Zykin [8]. At the first stage, environmental conditions are evaluated using the *Ij* index: the higher the *Ij* value, the more favorable the conditions are. Then the linear regression coefficient (*bi*) and the mean square deviation from the theoretical regression line ($σ^2d$) were calculated. Stress tolerance of varieties and populations ($Y_{min} – Y_{max}$) is an important indicator of adaptivity and phenotypic plasticity, determined by the difference between the minimum and maximum yield in c/ha. The indicator ($(Y_{max} + Y_{min})/2$) shows the average yield of the variety (c/ha) in contrasting (stressful and non-stressful) conditions and characterizes the genetic flexibility of the cultivar, its compensatory ability. The higher is this indicator, the higher is the degree of correspondence between the variety genotype and environmental factors. These two indicators were calculated using the equations of A. A. Rossille, J. Hamblin as interpreted by A. A. Goncharenko [7, p. 50], the scale of productivity (*d*) – according to V. A. Zykin [8].

Meteorological conditions in the years of research were unstable during the growing season, which gave an objective assessment of the studied lines based on the prevailing environmental conditions, primarily due to the hydrothermal regime.

In 2016, the average air temperature in the third decade of May was 19.0 °C; the precipitation rate was 13 % of the norm. The temperature in the first third of June was below the norm by 1.2 °C, in the second third it exceeded 2.5 °C. Precipitation rates for month thirds were 47; 22 and 200 % of the norm. In July, the average air temperature and precipitation in thirds were 20.4; 21.5; 22.4 °C and 12.2; 4.4 and 1.4 mm, respectively. In August-the average air temperature exceeded the average values by 6.5; 8.8 and 5.1 °C, precipitation rates were 69; 73 and 81 % of the norm.

In 2017, the last third of May was cool (12.1 °C) and rainy (213 % of the norm). The first third of June was cool (11.8 °C), the second – moderately warm (17.3 °C), the third was also characterized by a lack of heat (17.2 °C), precipitation for the thirds were 447; 96 and 115 % of the norm. The average air temperature in July for decades was 17.2; 19.3 and 21.1 °C; precipitation rate was 30.6; 15.9 and 1.2 mm; in August, the air temperature for decades was 20.2; 17.2; and 19.6 °C and the amount of precipitation was 24.1; 4.8 and 9.1 mm, respectively.

In 2018, the third decade of May was rainy (154 % of the norm) and warm (14.7 °C). The first two decades of June were cool (12.4 and 15.6 °C, which is 4.4 and 2.1 °C below the average annual data), the third decade was warm (21.1 °C), precipitation for the decades was 16.6; 6.5 and 35 % of the norm. The average temperature in July for decades was 22.4; 21.2 and 20.6 °C, which was higher than the norm by 3.1; 1.8 and 1.9 °C, precipitation was 6.7; 12.8 and 0.0 mm. The average temperature in August for decades was at the average annual level being 20.3; 17.9; and 16.2 °C, precipitation rate was 83; 53 and 79 % of the norm.

In 2019, the third decade of May was warm (14.6 °C) and wet (24.1 mm). The air temperature for decades in June was 16, 5; 16.4; and 19.4 °C or –0.3; –1.3 and +1.3 °C of the norm, precipitation was 183.3; 22.1 and 32.0 % of the average annual values. In July, the first decade was cool being 17.9 °C (–1.4 °C); the second one was warm (+1.8 °C), and the third decade was within the norm; precipitation for decades was 148.3; 40 and 13 % of the norm. The first decade of August was cold, the second-warm, the third – cool (–3,3; + 1,4 and –1,7 °C of the norm), precipitation for the decades was 298,7; 114 and 66 % of the norm. In the first decade of September, the air temperature was below the norm by 2.0 °C, the second decade was moderately warm (+0.7 °C); precipitation for decades was 26.8; 167 % of the norm.

Summing up the general characteristics of the soil and climatic conditions of the Cis-Ural steppe zone of the Republic of Bashkortostan and in particular the Chishminskiy plant breeding center, where the research was carried out, it can be concluded that they are typical for the steppe zone. They meet the basic biological requirements of Sudan grass and are quite suitable to get high and stable yields of green mass, hay and seeds. This conclusion is based on the growing season length of 137 days with an average daily air temperature of more than plus 10 °C and the sum of active temperatures being 2230 °C. It takes an average of 1800 °C to produce high yields of conditioned Sudan grass seeds or from 1600 to 2200 °C depending on the cultivar ripeness. The Republic of Bashkortostan and other regions of the southern Urals have enough warm days to cultivate early-maturing varieties of such a heat-loving crop as Sudan grass. Early-maturing and mid-early Sudan grass varieties with a growing period of 85–100 days provide two mowings of green mass, as well as develop a high yield of conditioned seeds.

Statistical processing of the obtained data was performed using the variance analysis method with the add-in program CXSTAT for Microsoft Excel and the package of programs AGROS 2.09 for statistical and biometric-genetic analysis in crop production and selection.

Results

According to the period from "full sprouts" to "waxy ripeness of seeds", the studied Sudan grass varieties can be divided into three groups (in accordance with the climatic conditions of the research site): short-season – Chishminskaya rannyaya (80.3 days); middle-early (83.5–84.3 days) and mid-season (88.5–90.3 days) (table 1).

There has been found high potential of individual Sudan grass cultivars for collecting dry matter and seed productivity. The highest yield of dry matter was established in the hybrid population 446/2 in 2016 (88.8 c/ha) and 400 in 2017 (88.0 c/ha). The highest average yield over a four-year period was observed in the populations of the mid-season groups 446/2 (72.7 c/ha) and 392 (72.5 c/ha). The yield of these populations exceeded the standard by 24 and 25 %, respectively. Short-season and middle-early numbers had lower yields. Sudan grass cultivars had a high potential for seed productivity. The hybrid population 358 had the highest seed yield in 2019 (36.0 c/ha) and the hybrid population 276 in 2016 (34.5 c/ha). On average, over 4 years of the research, the highest productivity was shown by hybrid populations of the middle-early group: 276 (30.4 c/ha) and 358 (29.6 c/ha). Their seed yield exceeded the standard by 17 and 14 %, respectively (table 2).

The yield stability depends much on the yield scope (*d*). The lower the latter is, the more stable the productivity is in specific soil and climatic conditions. Its lowest value in terms of dry matter yield was observed in the hybrid population 358 (33.5 %), and in terms of seed productivity in hybrid populations 318 and 395 (15.7 and 16.9 %),

An important indicator of the cultivar stability to the stressful environment under changing meteorological conditions of cultivation is their adaptivity (or stress tolerance). It is determined by the difference between the minimum and maximum yield value ($Y_{min} – Y_{max}$). The adaptivity index has a negative value. The lower it is, the higher the stress tolerance of the variety. The range of adaptive capabilities is more widely represented in the variety. The most stress-tolerant Sudan grass hybrid populations in terms of dry matter yield were 400 and 446/2 (–44.5 … –44.2, respectively), as to seed productivity, the most stress-resistant variety was Demskaya (–13.1).

Stress tolerance of varieties can be supplemented by the indicator of genetic flexibility ($(Y_{max} + Y_{min})/2$). It shows the degree of correspondence between the genotypic capabilities of the variety and varied environmental factors [7, p. 50]. Among the studied numbers of Sudan grass, its value (in terms of dry matter yield) was highest in hybrid populations 446/2 (66.7) and 400 (65.7). The indicator of genetic flexibility when using Sudan grass varieties for seeds was highest in hybrid populations 358 and 276 (30.5 and 30.6, respectively). They demonstrate a strong correspondence between the cultivar genotype and environmental factors. The Yaktash variety had the lowest indicators of dry matter yield (53.8), the hybrid population 392 was of lower seed productivity (20.5).

The environmental condition index (*Ij*) determines the variability of growing conditions and can take either a positive or a negative value. The most favorable conditions are formed in years with a positive index sign, the worst - with a negative one. During the research years, the index of environmental conditions of Sudan grass numbers in terms of dry matter yield varied from 9.4 to –23, and in terms of seed productivity from 1.6 to –1.9. The best conditions for the genetic potential of cultivars were formed in 2016 and 2017, where the environment index had the highest positive values *Ij* = 1.6 and 9.4 (table 3).

Table 1

Growing period of Sudan grass varieties, days (2016–2019)

Breed, hybrid population	*Year*				*Average*
	2016	*2017*	*2018*	*2019*	
Short-season group					
Chishminskaya rannyaya (St.)	71	89	76	85	80,3
Middle-early group					
Yaktash	72	91	80	91	83,5
Smena	73	91	79	92	83,8
Demskaya	72	92	80	92	84
Population 276	71	93	79	90	83,3
Population 285	73	92	80	92	84,3
Population 318	73	93	79	92	84,3
Population 358	74	90	79	91	83,5
Mid-season group					
Population 392	81	94	82	100	89,3
Population 400	82	94	83	102	90,3
Population 446/2	81	95	83	100	89,8
Population 395	81	93	80	100	88,5

Table 2

The adaptive potential of Sudan grass varieties, 2016–2019

Breed, hybrid population	The yield of dry matter, c/ha			The yield scope, %	Stress tolerance ($Y_{min} – Y_{max}$), c/ha	Genetic flexibility ($Y_{max} + Y_{min}$)/2, c/ha
	Max	Min	Average			
By dry matter yield						
Chishminskaya rannyaya (St.)	69.3	39.9	58.1	42.5	–29.4	54.6
Yaktash	69.8	37.8	59.0	45.9	–32.0	53.8
Smena	70.3	38.6	59.0	45.2	–31.7	54.4
Demskaya	76.6	46.6	68.9	39.2	–29.9	61.6
Population 276	77.6	44.9	65.7	42.2	–32.7	61.2
Population 285	75.2	43.9	66.3	42.0	–31.3	59.5
Population 318	76.0	43.4	67.3	42.9	–32.6	59.9
Population 358	75.6	50.3	68.0	33.5	–25.3	62.9
Population 392	85.5	42.9	72.5	49.9	–42.6	64.2
Population 400	88.0	43.5	69.7	50.6	–44.5	65.7
Population 446/2	88.8	44.6	72.7	49.8	–44.2	66.7
Population 395	78.4	45.0	69.2	42.7	–33.4	61.7
By seed productivity						
Chishminskaya rannyaya (St.)	31.1	20.8	26.0	33.1	–10.3	25.9
Yaktash	31.3	21.8	25.2	30.4	–9.5	26.5
Smena	31.0	20.8	25.5	32.9	–10.2	25.9
Demskaya	33.7	20.6	27.5	38.9	–13.1	27.1
Population 276	34.5	26.8	30.4	22.3	–7.7	30.6
Population 285	31.5	24.4	28.5	22.5	–7.1	27.9
Population 318	31.3	26.4	28.1	15.7	–4.9	28.8
Population 358	36.0	25.1	29.6	30.3	–10.9	30.5
Population 392	25.4	15.7	21.9	38.2	–9.7	20.5
Population 400	27.4	19.2	22.6	29.9	–8.2	23.3
Population 446/2	26.8	19.7	23.8	26.5	–7.1	23.2
Population 395	28.0	23.3	25.2	16.9	–4.7	25.6

Table 3

Productivity, phenotypic plasticity and stability of Sudan grass varieties

Breed, hybrid population	Yield, c/ha					Plasticity, b_i	Stability, $σ^2d$, c/ha
	2016	2017	2018	2019	Average		
Dry matter							
Chishminskaya rannyaya (St.)	69.3	61.1	62.2	39.9	58.1	0.8	30.5
Yaktash	69.8	64.8	63.5	37.8	59.0	0.9	29.0
Smena	70.3	63.8	63.4	38.6	59.0	0.9	29.0
Demskaya	75.8	76.6	76.5	46.6	68.9	1.0	45.7
Population 276	77.6	74.4	66.0	44.9	65.7	0.9	28.9
Population 285	75.2	72.1	74.0	43.9	66.3	1.0	45.7
Population 318	75.3	74.8	76.0	43.4	67.3	1.0	45.7
Population 358	70.8	75.6	75.2	50.3	68.0	0,7	18.9
Population 392	84.8	85.5	76.9	42.	72.5	1.3	59.5
Population 400	73.3	88.0	74.0	43.5	69.7	1.1	40.5
Population 446/2	88.8	82.4	75.2	44.6	72.7	1.3	60.3
Population 395	78,4	76.6	76.6	45.0	69.2	1.0	36.4
Ij	9.4	8.4	5.2	–23	–	–	–
HCP_{05}	6.24	9.01	9.63	6.92	–	–	–
Seeds'							
Chishminskaya rannyaya (St.)	28.0	20.8	24.1	31.1	26.0	1.2	9.6
Yaktash	31.3	22.5	25.1	21.8	25.2	1.2	7.5
Smena	31.0	25.6	24.7	20.8	25.5	1.7	14.8
Demskaya	28.9	33.7	26.9	20.6	27.5	2.5	32.9
Population 276	34.5	31.7	26.8	28.8	30.4	1.6	13.3
Population 285	30.7	31.5	24.4	27.2	28.5	1.5	11.9
Population 318	31.3	28.0	26.4	26.7	28.1	1.0	5.2
Population 358	25.5	31.9	25.1	36.0	29.6	0.9	4.2
Population 392	23.2	25.4	23.4	15.7	21.9	1.6	13.2
Population 400	19.2	27.4	23.8	20.0	22.6	0.5	1.3
Population 446/2	25.5	26.8	23.2	19.7	23.8	1.5	11.9
Population 395	24.8	28.0	24.6	23.3	25.2	1.4	10.0
Ij	1.6	1.6	–1.3	–1.9	–	–	–
HCP_{05}	3.48	3.39	4.52	5.61	–	–	–

According to S. A. Eberhart, W. A. Russell, plasticity is a positive response of the genotype to improved growing conditions. As a parameter for evaluating this response, they proposed the calculation of a linear regression coefficient, which can be greater than (high responsiveness) and less than (weak responsiveness) unit, as well as equal to one (changes in yield fully correspond to changes in conditions).

In our experience, the highest responsiveness to better growing conditions ($b_i > 1$) was observed in Sudan grass hybrid populations 392, 400, 446/2 in terms of dry matter yield, and in terms of seed productivity in varieties Smena, Demskaya, Chishminskaya rannyaya, Yaktash and hybrid populations 276, 285, 392, 446/2 and 395. All these varieties of intensive type, develop high yields in optimal soil and climatic conditions. However, their productivity decreases sharply under unfavorable conditions or poor farming practices.

Chishminskaya rannyaya, Yaktash, Smena varieties and hybrid populations 276 and 358 had a plasticity coefficient lower than one ($b_i < 1$) in terms of dry matter yield. Hybrid populations 358 and 400 had a similar coefficient in seed productivity. These cultivars have a genotypic potential that is characterized by low responsiveness to changes in farming practices. They are best grown on an extensive background, where they can provide the greatest return at the lowest cost.

The Demskaya variety and hybrid populations 285, 318 and 395 had coefficient of plasticity equal to or close to one ($b_i = 1$) in terms of dry matter yield, the hybrid population 318 had the same index in seed productivity. These numbers have the highest correspondence of changes in yield to changes in growing conditions.

Following the model of S. A. Eberhart and W. A. Rassell, the varieties that have plasticity (b_i) close to 1, and the insignificant stability index ($σ^2$d) should be considered as the most valuable in breeding and practical terms. These cultivars, along with a high stable yield, have high responsiveness to improved conditions, which is typical for intensive type varieties. According to the results of the research, the following numbers of Sudan grass can be attributed to them: Yaktash, Smena, hybrid populations 276 and 395 (by dry matter yield) and hybrid populations 318 and 358 (by seed productivity). Among the varieties presented in the studies, the most stable in dry matter yield were hybrid populations 358 and 276 ($σ^2d$ = 18.9 and 28.9, respectively), and in seed productivity hybrid populations 400, 358, and 392 ($σ^2d$ = 1.3; 4.2 and 5.2, respectively). Hybrid populations 446/2 and 392 ($σ^2d$ =60.3 and 59.5) were the most unstable in terms of dry matter yield, while varieties Demskaya and Smena ($σ^2d$ = 32.9 and 14.8) were the most unstable in terms of seed productivity. Cultivars of plasticity (bi) less than 1, regardless of the stability index value ($σ^2d$), should be considered as unpromising, since they lack an important biological and economic feature as an adequate response to improving growing conditions.

Discussion and Conclusion

The most perspective for breeding and farming practice are cultivars of phenotypic plasticity to get high yields under favorable cultivation conditions. It depicts their high responsiveness to better conditions. They slightly reduce productivity in stressful conditions, that shows the stability of genotypes in adverse conditions. The conducted research on the analysis of phenotypic plasticity and stability made it possible to identify the most adaptive varieties when cultivating them for food in the Republic of Bashkortostan. Demskaya variety and hybrid populations 285, 318 and 395 with a plasticity coefficient b_i close to and equal to one, are characterized as plastic; hybrid populations 392, 400, 446/2 are responsive to improved growing conditions and are characterized as intensive – $b_i > 1$. When cultivated for seeds, population 318 is defined as plastic, while Smena, Demskaya, Chishminskaya rannyaya, Yaktash cultivars, populations 276, 285, 392, 446/2 and 395 are responsive to improved growing conditions and identified as intensive.

Based on a comprehensive assessment of varieties by the value of the average yield of dry matter, phenotypic plasticity and stability, the best numbers are recognized as populations 400 (yield 69.7 c/ha; plasticity – 1.1; stability – 40.5) and 395 (69.2 c/ha; 1.0; 36.4, respectively). When cultivating seeds for yield, plasticity and stability, populations 358 (yield 29.6 c/ha; plasticity – 1.0; stability – 5.2) and 318 (28.1 c/ha; 0.9; 4.2, respectively) were distinguished. Thus, the new Sudan grass hybrid populations have an advantage in productivity compared to previous varieties and numbers regardless of weather conditions.

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Authors’ information:
Rifkhat A. Biktimirov[1], candidate of agricultural sciences, head of the forage crop breeding and seed production laboratory, leading researcher, ORCID 0000-0001-7800-9521, AuthorID 158709; *+7 906 376-13-70*, *biktimirov.rifx@yandex.ru*
Zulfira M. Sharipkulova[1], chief agronomist of the forage crop breeding and seed production laboratory, ORCID 0000-0002-4788-7353, AuthorID 611923; *+7 927 088-57-45*
Asiia A. Nizaeva[1], chief agronomist, head of the forage production department, ORCID 0000-0002-1936-2204, AuthorID 994019; *+7 927 343-06-48*, *nizaeva_a@mail.ru*
[1] Bashkir Research Institute of Agriculture – Subdivision of the Ufa Federal Research Center of the Russian Academy of Sciences, Ufa, Russia