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PHENOTYPIC MANIFESTATION OF ASSOCIATIVE MORPHOGENETIC TRAITS IN SINGLE-CROSS STERILE HYBRIDS OF WINTER RYE (*SECALE CEREALE* L.)

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Topicality. *The study of phenotypic parameters of quantitative morphological traits that associatively affect the productivity of winter rye plants allowed developing theoretical predictions on the effectiveness of their breeding improvement.* ***Purpose***. *To determine the level of phenotypic manifestation, variability and type of phenotypic dominance of morphogenetic traits of winter rye in single-cross sterile hybrids as a maternal component and to select the best breeding samples.* ***Material and Methods***. *Six cytoplasmic male-sterile (CMS) and six self-fertile sterility maintainer (SM) lines of short-stemmed winter rye determined by dominant gene hl (except for SM line 4) were studied. The study was carried out according to quantitative morphogenetic characteristics, using the methods of the State Testing of Plant Varieties for Suitability for Distribution in Ukraine. The level of phenotypic manifestation of traits of single-cross sterile hybrids in relation to the parental forms was estimated as a percentage of the pollen-sterile (CMS) line and unrelated sterility maintainer (SM), and by the assessment of the dominance of hp calculated according to the formula of G.M. Bale and R.E. Atkins.* ***Results.*** *The coefficient of variation in plant height was increased in 54.5 % of hybrid combinations in comparison with parental forms, in the vast majority of CMS lines and SMs this trait was classified as low-variable, 63.6 % of single-cross sterile hybrids inherited plant height by intermediate type and negative dominance and depression, resulting in short-stemmed plants, and increased lodging resistance. The number of productive shoots is a medium and highly variable trait (depending on the genotype), and depression was detected in 72.7 % of the combinations (hp ranged from -1.1 to -5.2). Spike length, as a trait, was characterised by low variability, and 45.4 % of the single-cross sterile hybrids inherited the trait by intermediate type and heterosis. In terms of the number of florets in the spike of single-cross sterile hybrids, 36.3 % of combinations showed heterosis for this trait. Spike density was a relatively stable trait in terms of variation of phenotypic values, and 45.4 % of single-cross sterile hybrids inherited the trait by intermediate type and heterosis. According to the fertility trait, 54.5 % of hybrid combinations showed heterosis (the degree of phenotypic dominance hp was in the range of 1.0–17.0).* ***Conclusions.*** *It was found that the manifestation of heterosis and positive dominance in single-cross sterile hybrids in relation to parental forms expand the combinative variability of quantitative traits, which allows more efficient selection of the best pairs as components of crossing. In many cases, the inbred depression of the pollen-sterile form is eliminated, as a result of which an increase in the number of heterotic combinations in the final hybrids of winter rye is predicted.*

Key words: *winter rye, pollen-sterile lines, sterility maintainers, heterosis*

Introduction. In the current wartime conditions, when significant areas of agricultural land have been withdrawn from use, the problem of improving the yield of agricultural crops, and especially grain crops, is extremely relevant [1]. It is known that the winter rye yield can be increased in various ways, and the breeding improvement of the crop is of great importance in this regard [2, 3].

Modern breeding increases the productivity of winter rye not only through different types of selection and crosses, but also through heterosis, which involves cytoplasmic male sterility. For this purpose, cytoplasmic pollen-sterile (CMS) lines with sterility maintainers (SM) are developed. Given that CMS of rye lines are often depressed due to enrichment with the genome of the SM (closely related crosses), an improved maternal component like single-cross sterile hybrids obtained from hybridisation of CMS line with an unrelated sterility maintainer is used to relieve inbred depression [4, 5].

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Thus, in many combinations, a pollen-sterile maternal form with improved anatomical and morphological characteristics is obtained, which affects the crop yield [6]. Improved maternal and paternal components [7] are necessary to obtain heterosis in the final (commercial) hybrid as an excess of the quantitative trait of not only the best parental form, but also standard varieties (competitive heterosis). According to scientists P. P. Litun, H. K. Adamchuk, A. F. Zdrylko, V. P. Derevianko and others, the heterotic effect in grain crops is considered economically significant when its level exceeds 20 %, although some scientists consider the heterotic effect at 15 % and 10 % to be economically significant [8, 9].

The effect of heterosis depends on the action and interaction of the genes (the components of hybridisation) [10]. However, certain requirements are imposed on the crossing components: high pollen formation and fixation ability for the fertility maintainer, short-stemmed plants to prevent lodging, resistance to abiotic stress factors, combining ability, high values of morphogenetic traits that are associative, i.e., affect the overall productivity of winter rye plants [11–14]. The study of the patterns of inheritance of these traits and their variability will allow for the purposeful selection of pairs for the formation of heterotic winter rye hybrids [15].

Research is aimed at determining the level of phenotypic manifestation, variability and type of phenotypic dominance of morphogenetic traits of winter rye in single-cross sterile hybrids as a maternal component and selecting the best breeding samples.

Materials and Methods. The research was conducted in 2015–2020 at the laboratory of Grain Crops Breeding and Seed Production of the Verkhniachka Experimental Breeding Station as part of breeding programmes for development of the maternal component of winter rye hybrids based on CMS. The object of the study was six male sterile (MS) and six self-fertile sterility maintainer (SM) lines of winter rye with genetically determined (hl) short-stemmed plants (except for SM line 4). The vast majority of the involved lines were from the Yuriev Plant Production Institute, lines CMS 21 and SM 3 from the collection of local forms, and line SM 4 was obtained from the Nosivka Breeding and Research Station. The study was carried out according to quantitative morphogenetic traits: plant height (cm), productive tillering (pcs.), spike length (cm), number of florets per spike (pcs.), fertility of the spike (%), spike density (pcs.), using the method [16]. The level of phenotypic manifestation of traits of single-cross sterile hybrids in relation to parental forms was evaluated as a percentage of pollen-sterile (CMS line) and unrelated sterility maintainer (SM), as well as by the estimation of dominance hp (degree of phenotypic dominance), calculated by the formula of G. M. Beil and R. E. Atkins [17].

The climatic and weather conditions in the area of the experimental station were characterised by a moderate continental climate, corresponding to the zone of unstable moistening. According to the Khrystynivka weather station, the average long-term precipitation is 472 mm, the average daily air temperature (long-term average) is 7.0 ℃.

Winter rye cultivation was carried out according to the generally accepted practice [18], which is used in the Forest-Steppe zone of Ukraine.

Results and Discussion. Experimental assessment of the combining ability of a large number of source material of crops with a low reproduction factor, such as winter rye, leads to an increase in the volume of breeding work and labour costs, so practical verification of the effectiveness of the theoretical prediction of the suitability of winter rye lines for heterotic breeding is of some scientific and practical interest.

For practical breeding, the combinations with a high level of competitive heterosis are the most valuable. Based on the variety testing of the maternal component with a linear structure (CMS lines) with their sterility maintainers (SM) and single-cross sterile hybrids, only 11 samples were selected from the crossing of linear components, which showed a reliable level of heterotic effect. Therefore, to clarify the morphogenetic features of heterosis and determine its level, a comparative characterisation of the genetic and statistical parameters of single-cross sterile hybrids and their parental forms was performed on the basis of independent sampling (32 plants from each) by the Student's method (Fisher's criterion).

Based on the values of plant height of the source lines and hybrid samples of winter rye, the type of phenotypic inheritance and coefficients of variation in these samples were determined. Compared to the parental forms, the tallest hybrid combinations were CMS-20 / SM-6, CMS-20 / SM-8, CMS-13 / SM-8, but no significant heterotic effect was found for them, since the vast majority of lines were short-stemmed with the recessive genes (hl) control. The coefficient of variation of plant height in breeding materials ranged from 1.9 to 12.8 % (Table 1). In CMS lines, 27.0 % were characterised by relative stability of the trait manifestation (coefficient of variation V was up to 10.0 %), plant height of 96.9 % of sterility maintainers was classified as a low variable trait. The coefficient of variation in 54.5 % of single-cross sterile hybrids was in the range of 10.0–20.0 %, which indicates an increase in plant height variability in single-cross sterile hybrids of winter rye. The degree of phenotypic manifestation for plant height trait (dominance score or degree of phenotypic dominance hp) in different combinations ranged from -8.0 to 1.4, i.e. the trait was inherited by type from depression and negative dominance to intermediate type, positive dominance and heterosis.

Table 1. Phenotypic manifestation of the plant height trait in single-cross sterile hybrids of winter rye and their parental components, 2017–2020

Line, hybrid	Average, cm (X+Sx)	Coefficient of variation, % (V+Sv)	Range of variability, cm	F_1 in % to ♀ i ♂, hp dominance score for F_1
1	*2*	*3*	*4*	*5*
CMS-16	75.8 ± 4.5	18.9 ± 4.2	60–94	107 0.5 76***
CMS-16 / SM-6	81.4 ± 3.7	14.5 ± 3.2	68–99	
SM-6	107.1 ± 2.4	7.0 ± 1.6	95–118	
CMS-20	106.1 ± 2.7	7.9 ± 1.8	98–120	104 -1.8 109
CMS-20 / SM-6	109.8 ± 2.5	7.2 ± 1.6	100–118	
SM-6	100.6 ± 3.1	9.8 ± 2.1	90–117	
CMS-20	108.3 ± 2.3	6.6 ± 1.5	94–117	104 -1.8 109
CMS-20 / SM-8	113 ± 2.9	7.9 ±1.8	93–128	
SM-8	103.9 ± 2.9	8.8 ± 1.9	90–115	
CMS-21	106.2 ± 3.6	10.7 ± 2.4	90–120	98 1.4 89**
CMS-21 / SM-7	104.6 ± 3.7	11.3 ± 2.5	88–124	
SM-7	117 ± 2.9	7.8 ± 1.7	105–133	
CMS-13	114.6 ± 0.9	2.5 ± 0.6	110–118.5	101 -2.0 103
CMS-13 / SM-8	115.8 ± 3.3	9.1 ± 2.1	110–142	
SM-8	112 ± 1.9	5.3 ± 1.2	100–120	
CMS-13	82.3 ± 0.6	2.5 ± 0.6	79–85	102 0.86 92*
CMS-13 / SM-1	83.6 ± 2.9	10.9 ± 2.4	69–99	
SM-1	91.4 ± 0.6	1.9 ± 0.4	89–94	
CMS-16	88.8 ±1.7	6.1 ± 1.4	80–100	89 1.4 98
CMS-16 / SM-3	79.2 ± 2.1	8.2 ±1.8	70–88	
SM-3	81.2 ± 2.7	10.5 ±2.4	70–90	
CMS-14	98.5 ± 3.5	11.3 ± 2.5	85–120	83 0.5 106
CMS-14 / SM-4	81.6 ± 3.1	11.9 ± 2.3	62–94	
SM-4	76.9 ± 1.7	6.9 ± 1.5	70–85	
CMS-18	80 ± 2.1	8.4 ± 1.9	70–88	101 0.9 77**
CMS-18 / SM-7	80.7 ± 3.3	12.8 ± 2.9	68–96	
SM-7	105.4 ± 0.9	2.8 ± 0.6	100–108	
CMS-13	71.6 ± 1.3	5.6 ± 1.3	64–76	107** -8.8 109***
CMS-13 / SM-3	76.7 ± 1.2	5.1 ± 1.1	69–80	
SM-3	70.2 –0.9	4.1 ± 0.9	66–74	
CMS-13	104.3 ± 2.2	6.6 ± 1.5	92.5–112.5	102 -2.0 102
CMS-13 / SM-4	105.9 ± 3.8	11.2 ±2.5	85–124	
SM-4	104.2 ±2.9	8.8 ± 1.9	90–122	

*Note: * - significantly at P≤05; ** - significantly at P≤01; *** - significantly at P≤001;*
F_1 - single-cross sterile hybrid.

Thus, short-stemmed single-cross sterile hybrids of winter rye, which inherited plant height by the type of depression, negative dominance or intermediate type (63.6 % in this experiment), did not reduce the plant resistance to lodging. Thus, they can be used in the development of final heterotic hybrids suitable for economic use.

The number of productive shoots of winter rye is a morphogenetic trait that affects the overall productivity of this crop. Comparative arithmetic averages of productive tillering of single-cross sterile hybrids and their parental components are given in Table 2. Number of productive shoots trait in breeding samples of winter rye was characterised by high (20.8–60.0 %) and medium (15.6–20.1 %) coefficients of variation. The type of phenotypic dominance in 72.7 % of combinations is depression and negative dominance, which requires more careful selection of pairs for crossing in the development of single-cross sterile hybrids of winter rye.

Table 2. Phenotypic manifestation of the trait for number of productive shoots in single-cross sterile hybrids and their parental components of winter rye, 2017–2020

Line, hybrid	Average, cm (X+Sx)	Coefficient of variation, % (V+Sv)	Range of variability, cm	F_1 in % to ♀ i ♂, hp dominance score for F_1
1	*2*	*3*	*4*	*5*
CMS-16	7.4 ± 0.4	15.9 ± 3.5	6–9	103 -2.5 107
CMS-16 / SM-6	7.6 ± 0.7	29.7 ± 6.6	5–10	
SM-6	7.1 ± 0.5	21.6 ± 4.8	5–9	
CMS-20	8.9 ± 0.3	9.8 ± 2.2	8–10	107 -1.5 134**
CMS-20 / SM-6	9.5 ±0.7	22.3 ± 4.9	5–12	
SM-6	7.1 ± 0.8	35.5 ± 7.9	3–10	
CMS-20	11.4 ± 1.3	34.9 ± 7.8	5–18	132* -4.3 210***
CMS-20 / SM-8	15.1 ± 0.7	15.3 ± 3.4	11–17	
SM-8	7.2 ± 0.9	39.0 ± 8.7	3–11	
CMS-21	8.5 ± 0.6	21.7 ± 4.8	6–11	139** -3.1 120
CMS-21 / SM-7	11.8 ± 2.9	60.0 ± 17.9	3–34	
SM-7	9.8 ± 1.0	32.6 ± 7.3	6–15	
CMS-13	8.0 ± 0.7	28.3 ± 6.3	5–11	145* -5.2 166*
CMS-13 / SM-8	11.6 ± 1.6	43.7 ± 9.8	7–24	
SM-8	7.0 ± 0.5	24.7 ± 5.5	5–10	
CMS-13	7.9 ± 0.5	20.2 ± 4.5	5–9	114 -0.4 94
CMS-13 / SM-1	9.0 ± 1.1	38.5 ± 8.6	4–14	
SM-1	9.6 ± 0.3	9.2 ± 2.1	8–11	
CMS-16	9.3 ± 0.2	5.2 ± 1.2	9–10	115 -1.1 124*
CMS-16 / SM-3	10.7 ± 0.6	16.9 ± 3.8	8–13	
SM-3	8.6 ± 0.5	17.6 ± 3.9	5–10	
CMS-14	10.0 ± 0.5	15.6 ± 3.5	7–13	90 -1.5 108
CMS-14 / SM-4	9.0 ± 1.2	42.7 ± 9.5	4–13	
SM-4	8.3 ± 0.5	20.8 ± 4.6	6–11	
CMS-18	11.6 ± 0.8	21.2 ± 4.7	9–15	104 -1.5 120
CMS-18 / SM-7	12.0 ± 1.5	40.2 ± 8.9	6–22	
SM-7	10.0 ± 0.5	17.3 ± 3.9	8–13	
CMS-13	8.1 ± 0.6	22.1 ± 4.9	5–10	112 0.03 182***
CMS-13 / SM-3	9.1 ± 0.9	32.7 ± 7.3	4–14	
SM-3	5.0 ± 0.4	22.4 ±5.0	3–7	
CMS-13	8.2 ± 0.7	28.0 ± 6.3	5–12	107 0.67 64**
CMS-13 / SM-4	8.8 ± 0.7	26.5 ± 5.9	3–11	
SM-4	13.7 ± 1.2	26.6 ± 5.9	9–18	

*Note: * - significantly at P≤05; ** - significantly at P≤01; *** - significantly at P≤001.*

The average values of the trait varied within 6–10 stems per plant. The lowest extreme values (from 3) of the number of productive shoots were found in hybrid combinations CMS-21 / SM-7, CMS-13 / SM-4. The highest average of the trait was in hybrid combinations CMS-20 / SM-8, CMS-13 / SM-8 and CMS-21 / SM-7 and was 17, 24 and 34 pcs, respectively.

Some authors point out that the indicator of productive tillering is extremely variable and depends mainly on environmental factors. In crosses of winter rye, higher tillering dominates in the progeny, and the influence of maternal cytoplasm on this trait is also noted [20]. In addition, hybrids show greater homeostasis, i.e. increased stability of traits in comparison with parental forms, which is one of the advantages of using single-cross sterile hybrids as a maternal component, and the reasons for increasing the overall tillering in hybrids. It has been determined that the number of productive shoots in breeding samples of winter rye depended on the genotype, and phenotypically this trait was highly and moderately variable. It was noted that single-cross sterile hybrids in the vast majority (72.7 %) inherited the number of productive shoots with a lower value of the trait compared to sterile lines, evidencing the importance of selecting parental pairs, considering their combining ability.

In winter rye, a high negative correlation was found between spike length and spike density [19]. When crossing varieties with different spike length and density, it is possible to increase the number of florets per spike, and thus potentially increase the productivity of the spike. The average spike length in the original lines and in single-cross sterile hybrids ranges from 8.3 to 11 cm, and the coefficient of variation is low and varies within 1.9 to 10.3 % (Table 3).

According to the spike length, 45.4 % of single-cross sterile hybrids inherited the trait by intermediate type and heterosis (hp in the range of 0.4–13.0), and this trait was characterised as low-variable. In hybrid combinations CMS-20 / SM-6, CMS-20 / SM-8, CMS-13 / SM-8, CMS-16 / SM-3, CMS-18 / SM-7, CMS-13 / SM-3, inheritance of such trait as spike length was characterised as complete dominance, since the average value of the trait in the hybrid was higher than in both original lines. In the studied samples of winter rye of single-cross sterile F_1 hybrids, the effect of heterosis or dominance of longer spikelets can be obtained with the correct selection of pairs for crossing. When crossing lines with different spike length and density, the number of flowers per spike can be increased.

Table 3. Phenotypic manifestation of the spike length trait in single-cross sterile hybrids and their parental forms of winter rye, 2017–2020

Line, hybrid	Average, cm (X+Sx)	Coefficient of variation, % (V+Sv)	Range of variability, cm	F_1 in % to ♀ i ♂, hp dominance score for F_1
CMS-16	9.6 ± 1.2	5.9 ± 1.3	8.5–10	98
CMS-16 / SM-6	9.4 ± 0.2	7.9 ± 1.8	8.2–10.5	-0.4
SM-6	8.9 ± 0.5	6.4 ± 3.7	7–11	106
CMS-20	9.2 ± 0.2	6.9 ± 1.5	8–10	120
CMS-20 / SM-6	11.0 ± 0.3	9.0 ± 0.2	9.9–12.3	-11.0
SM-6	8.9 ± 0.2	6.4 ± 1.4	3–10	124
CMS-20	10.4 ± 0.3	10.1 ± 2.3	9–12.1	113
CMS-20 / SM-8	11.8 ± 0.2	6.0 ± 1.3	10.8–12.7	-2.9
SM-8	9.3 ± 0.3	10.3 ± 2.3	7.5–10.9	127
CMS-21	10.3 ± 0.2	5.7 ± 1.3	9.5–11	83*
CMS-21 / SM-7	8.5 ± 0.5	5.8 ± 4.1	5.7–10.7	13.0
SM-7	10.6 ± 0.5	14.1 ± 3.2	8–13	80**
CMS-13	10.5 ± 0.3	8.2 ± 1.8	9.5–12	101
CMS-13 / SM-8	10.6 ±0.2	6.7 ± 1.5	9.3–11.5	-1.1
SM-8	9.0 ± 0.3	10.1 ± 2.3	7.3–10.3	118

Table 3 continuation

CMS-13	9.6 ± 0.1	4.3 ± 1.0	9–10	95*
CMS-13 / SM-1	9.1 ± 0.2	7.0 ± 1.6	8–10	1.0
SM-1	9.1 ± 0.1	3.1 ± 0.7	8.9–9.7	100
CMS-16	10 ± 0.1	1.9 ± 0.4	9.8–10.5	104
CMS-16 / SM-3	10.4 ± 0.2	5.2 ± 1.2	9.6–11.4	-2.6
SM-3	9.5 ± 0.1	3.9 ± 0.9	8.9–10	109***
CMS-14	11 ± 0.1	3.8 ± 0.8	10.3–11.7	85***
CMS-14 / SM-4	9.3 ± 0.3	8.9 ± 2.0	8–10	6.5
SM-4	10.4 ± 0.2	6.8 ± 1.5	9–11	89**
CMS-18	9.0 ± 0.2	5.7 ± 1.3	8–9.5	104
CMS-18 / SM-7	9.4 ± 0.3	8.9 ± 2.0	8.3–11	-3.0
SM-7	9.2 ±0.1	3.2 ± 0.7	8.8–9.6	102
CMS-13	9.3 ± 0.2	7.1 ± 1.6	8.5–10	101
CMS-13 / SM-3	9.4 ± 0.1	5.2 ± 1.2	8.7–10	-1.0
SM-3	5.7 ± 0.2	9.1 ± 2.0	4.9–6.3	165
CMS-13	9.7 ± 0.2	7.0 ± 1.6	8.3–10.3	105
CMS-13 / SM-4	10.2 ± 0.8	2.6 ± 5.9	6.3–15.5	0.4
SM-4	11.6 ± 0.3	8.0 ± 1.8	10–13	88

*Note: * - significantly at P≤05; ** - significantly at P≤01; *** - significantly at P≤001.*

Increasing the number of florets per spike with a simultaneous increase in grain content, which is determined by genotype, is one of the ways to increase the productivity of winter rye spike. The data of Table 4 shows heterosis of single-cross sterile hybrids and their parental forms for the trait of number of florets per spike. Such heterotic combinations accounted for 36.3 % of all hybrid samples studied. The trait was not very variable (V was in the range of 1.3–10.1 %).

The average values of the trait (X+Sx) in single-cross sterile hybrids varied within 42...88 florets per spike. The highest value was in the combination of crosses CMS-20 / SM-6, CMS-20 / SM-8, CMS-18 / SM-7, they were 87.6, 88.0 and 77.7 pcs., respectively, and the lowest value was in the progeny of CMS-21 / SM-7 – 52.4 pcs.

Table 4. Phenotypic manifestation of the trait – the number of florets per spike – in single-cross sterile hybrids and their parental forms of winter rye, 2017–2020

Line, hybrid	Average, cm (X+Sx)	Coefficient of variation, % (V+Sv)	Range of variability, cm	F_1 in % to ♀ i ♂, hp dominance score for F_1
CMS-16	58.4 ± 0.7	3.5 ± 0.8	56–60	99
CMS-16 / SM-6	57.6 ± 0.9	5.4 ± 1.2	50–60	1.6
SM-6	61.6 ± 1.9	10.1 ± 2.3	54–70	94
CMS-20	57.0 ± 0.7	4.1 ± 0.9	52–60	154***
CMS-20 / SM-6	87.6 ± 1.9	6.9 ± 1.5	82–96	16.6
SM-6	59.6 ± 1.3	7.1 ± 1.6	54–66	147
CMS-20	85.4 ± 0.7	2.7 ± 0.6	82–90	103
CMS-20 / SM-8	88.0 ± 1.9	6.9 ± 1.5	82–102	-1.1
SM-8	61.8 ± 0.6	3.0 ± 0.7	58–64	142
CMS-21	63.6 ± 0.8	4.1 ± 0.9	60–64	82
CMS-21 / SM-7	52.4 ± 0.8	4.6 ± 1.0	48–56	3.0
SM-7	57.3 ± 16	9.1 ± 2.0	52–64	91
CMS-13	62.4 ± 1.4	6.9 ± 1.5	58–70	103
CMS-13 / SM-8	64.0 ± 1.5	7.3 ± 1.2	56–70	-7.0
SM-8	61.3 ± 0.7	3.6 ± 0.8	58–64	104

Table 4 continuation

CMS-13	65.6 ± 0.3	1.3 ± 0.3	64–66	99 1.0 100
CMS-13 / SM-1	65.1 ± 1.7	8.4 ± 1.9	58–76	
SM-1	64.9 ± 0.5	2.2 ± 0.5	64–68	
CMS-16	61.8 ± 0.8	3.9 ± 0.9	60–68	100 -1.0 102
CMS-16 / SM-3	61.8 ± 0.9	4.4 ± 0.9	60–68	
SM-3	60.4 ± 0.8	4.0 ± 0.9	56–64	
CMS-14	66.9 ± 1.0	4.9 ± 1.1	62–72	87*** -2.3 98
CMS-14 / SM-4	58.2 ± 1.4	7.8 ± 1.7	52–64	
SM-4	59.3 ± 1.3	6.7 ± 1.5	52–64	
CMS-18	74.2 ± 0.9	3.7 ± 0.8	70–78	105 -1.0 102
CMS-18 / SM-7	77.7 ± 1.8	7.2 ± 1.6	70–88	
SM-7	76.0 ± 1.1	4.6 ± 1.0	70–80	
CMS-13	60.4 ± 1.2	6.4 ± 1.4	56–66	100 -1.0 126***
CMS-13 / SM-3	60.4 ± 1.2	6.4 ± 1.4	56–66	
SM-3	47.8 ± 1.9	10.0 ±2.9	38–54	
CMS-13	59.8 ± 1.4	7.3 ± 1.6	52–68	108 -1.3 101
CMS-13 / SM-4	64.8 ± 3.9	9.4 ± 4.3	42–86	
SM-4	64 ± 1.3	6.3 ± 1.4	60–72	

*Note: * - significantly at P≤05; ** - significantly at P≤01; *** - significantly at P≤001.*

Depending on the hybrid combinations, the coefficient of variation ranged from 1.3 to 10.1 %, indicating the relative stability of this trait. Higher number of flowers in the spike makes it possible to increase the spike productivity under the condition of high grain content.

According to V. V. Skoryk [20], a sufficiently intensive selection for the number of florets per spike in most varieties can contribute to a significant genetic shift in the desired direction. Thus, the number of florets per spike in winter rye samples can be changed both by selection and by heterotic selection of hybrids, considering specific combinations, which is consistent with the data of other authors [21].

The spike density positively correlates with grain yield in many grain crops. The average values of the trait in the studied samples of the winter rye collection varied within 5.5–8.5 pcs./cm (Table 5).

Table 5. Phenotypic manifestation of the spike density trait in single-cross sterile hybrids and their parental forms of winter rye, 2017–2020

Line, hybrid	Average, cm (X+Sx)	Coefficient of variation, % (V+Sv)	Range of variability, cm	F_1 in % to ♀ i ♂, hp dominance score for F_1
CMS-16	6.0 ± 0.1	3.3 ± 0.7	5.9–6.6	102*** 1.1 88**
CMS-16 / SM-6	6.1 ± 0.1	4.4 ± 0.9	5.7–6.6	
SM-6	6.9 ± 0.2	7.2 ± 1.6	6.4–7.7	
CMS-20	6.2 ± 0.1	3.2 ± 0.7	6.0–6.6	127 5.0 118***
CMS-20 / SM-6	7.9 ± 0.1	2.9 ± 0.7	7.6–8.3	
SM-6	6.7 ± 0.1	2.5 ± 0.6	6.4–6.9	
CMS-20	8.3 ± 0.2	7.9 ± 1.8	7.4–9.3	90* 0.1 112*
CMS-20 / SM-8	7.5 ± 0.2	8.4 ± 1.9	7.0–9.0	
SM-8	6.7 ± 0.2	7.8 ± 1.7	5.9–7.7	
CMS-21	6.2 ± 0.1	5.6 ±1.2	5.6–6.8	127*** 0.4 144***
CMS-21 / SM-7	7.9 ± 0.4	15.8 ± 3.5	6.5–10.1	
SM-7	5.5 ± 0.2	9.1 ± 2.0	4.9–6.5	

Table 5 continuation

CMS-13	5.9 ± 0.1	1.3 ± 0.3	5.8–6.1	132
CMS-13 / SM-8	7.8 ± 0.1	6.0 ± 1.4	6.9–8.5	-2.3
SM-8	6.9 ± 0.2	7.6 ± 1.7	6.2–7.9	113***
CMS-13	6.9 ± 0.1	3.5 ± 0.8	6.6–7.1	104
CMS-13 / SM-1	7.2 ± 0.2	7.3 ± 1.6	6.7–8.4	-1.6
SM-1	7.1 ± 0.1	1.1 ± 0.2	6.9–7.2	101
CMS-16	6.2 ± 0.1	2.2 ± 0.5	5.9–6.5	118***
CMS-16 / SM-3	7.3 ± 0.2	7.2 ± 1.6	6.7–8.1	-8.0
SM-3	6.4 ± 0.1	1.7 ± 0.4	6.3–6.6	114***
CMS-14	6.1 ± 0.1	1.4 ± 0.3	5.9–6.2	125***
CMS-14 / SM-4	7.6 ± 0.2	8.7 ± 1.9	6.5–8.6	-7.2
SM-4	5.7 ± 0.2	9.2 ±2.1	5.1–6.7	133***
CMS-18	7.4 ± 0.8	3.7 ± 0.8	7.8–8.8	112
CMS-18 / SM-7	8.3 ± 0.2	8.5 ± 1.9	7.2–9.6	-1.8
SM-7	5.9 ± 0.1	2.6 ± 0.6	5.6–6.0	141***
CMS-13	6.5 ± 0.1	3.2 ± 0.7	6.2–6.8	111
CMS-13 / SM-3	7.2 ± 0.2	8.2 ± 1.8	6.5–8.4	0.2
SM-3	8.5 ±0.3	10.0 ± 2.8	6.7–10	85***
CMS-13	6.2 ±0.1	2.9 ± 0.7	6.0–6.6	105
CMS-13 / SM-4	6.5 ± 0.3	16.3 ± 3.6	4.4–8.0	-1.8
SM-4	5.5 ± 0.2	10.3 ± 2.3	4.9–6.4	118*

*Note: * - significantly at P≤05; ** - significantly at P≤01; *** - significantly at P≤001.*

The highest spike density (7.9 pcs./cm) was characterised by the hybrid combination CMS-20 / SM-6, and the lowest values by the hybrid combinations CMS-16 / SM-6, CMS-13 / SM-8, CMS-16 / SM-3 were 6.1, 6.0 and 5.9 pcs./cm, respectively. The average variability in terms of spike density in the set of samples was distinguished by combinations of CMS-13 / SM-4 (V = 16.3 %) and CMS-21 / SM-74 (V = 15.8 %), while other lines and single-cross sterile hybrids showed relative stability of the trait (V in the range of 1.5–10.3 %). Selection for increasing the spike density has a negative correlation of this trait with the spike length, because often heterosis in the spike length leads to a decrease in its density.

The fertility of the spike shows the degree of realisation of the potential of the spike, i. e. the grain percentage in relation to the number of florets per spike. In our studies (Table 6), the spike fertility was characterised as average (66–90 %), because fertility of more than 90 % is considered high in winter rye.

According to the fertility trait, 54.5 % of

Table 6. Phenotypic manifestation of the spike fertility trait in single-cross sterile hybrids and their parental forms of winter rye, 2017–2020

Line, hybrid	Average, cm (X+Sx)	Coefficient of variation, % (V+Sv)	Range of variability, cm	F_1 in % to ♀ i ♂, hp dominance score for F_1
CMS-16	93.9 ± 0.9	33.3 ± 0.7	89–100	97
CMS-16 / SM-6	91.4 ± 1.9	6.9 ± 1.5	80–98.3	0.1
SM-6	88.5 ± 1.7	6.2 ± 1.4	77.4–96.8	103
CMS-20	86.1 ± 2.3	8.6 ± 1.9	71.2–95	76**
CMS-20 / SM-6	65.5 ± 4.9	23.6 ± 5.3	50–96	17.0
SM-6	89.2 ± 2.2	7.7 ± 1.7	75.8–95.2	73***
CMS-20	81.6 ± 2.1	8.2 ± 1.8	72–91	97
CMS-20 / SM-8	79.5 ± 3.6	14.5 ± 3.2	60.8–97.6	1.0
SM-8	79.6 ± 4.4	17.6 ± 3.9	48–45.2	100

Table 6 continuation

CMS-21	80.9 ±4.6	18.0 ± 4.0	45.5–95	114 -2.1 140***
CMS-21 / SM-7	91.9 ± 2.9	10.3 ± 2.3	75.9–100	
SM-7	65.7 ± 2.9	13.9 ±3.1	51.6–80.8	
CMS-13	83.1 ± 1.4	5.3 ± 1.2	77.6–90	94 2.0 98
CMS-13 / SM-8	77.9 ± 3.3	13.6 ± 3.0	64.1–94.9	
SM-8	79.1 ± 4.4	17.7 ± 3.9	57.8–94.8	
CMS-13	87.4 ± 1.1	3.8 ± 0.9	80.3–90.9	71*** 5.4 80***
CMS-13 / SM-1	62.4 ± 3.3	16.5 ± 3.7	45.6–81.6	
SM-1	78.2 ± 1.8	7.1 ± 1.6	69.1–89.1	
CMS-16	91.2 ± 1.6	5.6 ± 1.2	82.3–98.3	105* -4.3 108**
CMS-16 / SM-3	95.9 ± 0.7	2.3 ± 0.5	91.7–98.4	
SM-3	88.8 ± 2.1	7.3 ± 1.6	81.7–98.2	
CMS-14	95.2 ± 1.5	4.8 ± 1.1	84.7–98.5	92 -0.3 112
CMS-14 / SM-4	87.6 ± 3.5	12.8 ± 2.8	65.4–98.5	
SM-4	78.5 ± 3.5	14.2 ± 3.2	65–92.8	
CMS-18	64.7 ± 1.7	8.1 ± 1.8	57.1–73.7	94 0.1 107
CMS-18 / SM-7	61.1 ± 1.7	8.6 ± 1.9	53.0–67.1	
SM-7	56.9 ± 2.4	13.4 ± 3.0	47.5–70	
CMS-13	78,8 ± 1,6	6,5 ± 1,4	69,7–85,7	81 2,0 79**
CMS-13 / SM-3	64,0 ± 4,5	22,3 ± 4,9	48,5–96,4	
SM-3	80,7 ± 3,5	13,5 ± 3,0	70–100	
CMS-13	86,3 ± 2,6	9,7 ± 2,2	70,6–98,4	89* 2,6 95
CMS-13 / SM-4	76,9 ± 2,4	9,9 ± 2,2	64,3–92,9	
SM-4	81,2 ± 3,8	14,8 ± 3,3	65,6–95,8	

*Note: * - significantly at P≤05; ** - significantly at P≤01; *** - significantly at P≤001.*

hybrid combinations manifested heterosis. The trait had high values in the parental line CMS-16 (93.9 %) and in hybrids CMS-16 / SM-6, CMS-16 / SM-3 developed on its basis (91.4 and 95.9 %, respectively). The fertility of the CMS-14 line and the single-cross sterile hybrid CMS-21 / SM-7 also exceeded 90 %. The coefficients of variation of the fertility trait in the original lines and hybrid samples were characterised by low and medium variability, and in the line CMS-16 it exceeded 33 %, i.e. was highly variable. The spike fertility of the was inherited as depression in only two combinations, in three – by intermediate type, and 54.5 % of combinations showed heterosis.

Thus, in most cases, the overall increase in the number of florets per spike in the hybrids led to an increase in the number of kernels. Spike density correlated negatively with spike length. By breaking this relationship and combining a long and dense spike, we can achieve an increase in florets per spike and potentially increase spike fertility.

Conclusions

1. As a result of the analysis of morphogenetic traits of CMS lines, SM and single-cross sterile hybrids of winter rye, it was found that the manifestation of positive dominance and heterosis in relation to the original forms eliminates the inbred depression of the maternal component in the selected samples, increases the combinative variability of quantitative traits, resulting in higher efficiency of breeding work.

2. Short-stemmed forms should be involved in the formation of single-cross sterile hybrids (control of the trait by recessive genes), due to which such single-cross sterile hybrids will have resistance to lodging. The best single-cross sterile hybrids should be selected among combinations that inherit the trait by the type of depression or negative dominance.

3. The number of productive shoots in winter rye was characterised by high (20.8–60.0 %) and medium (15.6–20.1 %) coefficients of variation. The type of phenotypic dominance in 72.7 % of combinations was depression and

negative dominance (hp ≤ *1.0;* hp ≤ *0.5).* This indicates insufficient selection of samples for this trait, which requires additional selections aimed at improving it in components, and when developing hybrids requires more careful selection of pairs for crossing.

4. The number of florets per ear was not very variable trait. Three single-cross sterile hybrids with the highest expression of this trait (CMS-20 / SM-6, CMS-20 / SM-8, CMS-18 / SM-7 – 87.6, 88.0 and 77.7 pcs.) were selected).

5. The spike length trait was inherited by 45.4 % of the single-cross sterile hybrids according to the intermediate type and heterosis (hp was in the range of 0.4–13.0), and this trait was described as relatively stable.

6. In genetic improvement of the spike density, correlation dependencies should be taken into account (positive correlation with grain yield, negative correlation with spike length). A single-cross sterile hybrid CMS-20 / SM-6 with the highest spike density (7.9 pcs./cm) was selected.

7. In terms of the spike fertility, a significant heterotic effect was found in 54.5 % of single-cross hybrid combinations.

8. The single-cross sterile hybrids with the best morphogenetic traits that affect the overall productivity of winter rye should be used as a maternal component in the breeding process of developing highly heterotic (commercial) hybrids.

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З. О. Мазур [1], М. О. Корнєєва[2], С. Д .Орлов[2]. Фенотиповий прояв асоціативних морфогенетичних ознак у простих стерильних гібридів жита озимого (Secale cereale* L.*).
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Актуальність. За результатами дослідження фенотипових параметрів прояву кількісних морфологічних ознак, які асоціативно впливають на продуктивність рослин жита озимого, зроблено теоретичні прогнози щодо ефективності їхнього селекційного покращення. **Мета досліджень.** З'ясувати рівень фенотипового прояву, мінливість та тип фенотипового домінування морфогенетичних ознак жита озимого у простих стерильних гібридів як материнського компонента та виділити кращі селекційні зразки. **Матеріал і методи.** Досліджено шість чоловічо-стерильних (ЦЧС), шість самофертильних ліній закріплювачів стерильності (ЗС) жита озимого з генетично детермінованою (hl) короткостебловістю (крім лінії ЗС 4). Вивчення проводили за кількісними морфогенетичними ознаками використовуючи методики Державного випробування сортів рослин на придатність до поширення в Україні. Рівень фенотипового прояву ознак простих стерильних гібридів (ПСГ) за відношенням до батьківських форм оцінювали у відсотках до пилкостерильної (ЦЧС лінії) і неспорідненого закріплювача стерильності (ЗС), та оцінкою домінантності hp вирахованою за формулою Г. М. Бейла і Р. Е. Аткінса. **Результати.** Коефіцієнт варіації висоти рослин у 54,5 % гібридних комбінацій збільшувався, порівняно з батьківськими формами, у переважної більшості ЦЧС ліній і ЗС ця ознака класифікована як маломінлива – 63,6 % простих стерильних гібридів успадковували висоту за проміжним типом та від'ємного домінування і депресії, що впливає на короткостебловість рослин і посилює стабільність до вилягання. Число продуктивних пагонів – ознака середньо- і високомінлива (залежно від генотипу), у 72,7 % комбінацій виявлено депресію (hp коливалося від -1,1 до -5,2). Довжина колоса, як ознака, характеризувалася низькою мінливістю, а 45,4 % ПСГ успадковували ознаку за проміжним типом та гетерозисом. За кількістю квіток у колосі простих стерильних гібридів проявили гетерозис за цією ознакою 36,3 % комбінацій. Щільність колоса була відносно стабільною ознакою за варіацією фенотипових значень, а 45,4 % простих стерильних гібридів успадковували ознаку за проміжним типом і гетерозисом. За ознакою фертильності 54,5 % гібридних комбінацій проявили гетерозис (ступінь фенотипового домінування hp був у межах 1,0–17,0). **Висновки.** Прояв гетерозису і позитивного домінування у простих стерильних гібридів за відношенням до батьківських форм розширює комбінативну мінливість кількісних ознак, це дозволяє більш ефективно проводити добори кращих пар як компонентів схрещування. У багатьох випадках усувається інбредна депресія пилкостерильної форми, внаслідок чого прогнозується збільшення кількості гетерозисних комбінацій у кінцевих гібридів жита озимого.

***Ключові слова**: жито озиме, пилкостерильні лінії, закріплювачі стерильності, гетерозис*