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ORIGINAL RESEARCH PAPER

Statistical correlations in winter triticale hybrids

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Abstract

The aim of the study was to evaluate the correlations between the hybrids F_1, F_2, and F_3, obtained by different methods, their plasticity and stability, as well as to identify the probability of cytogenetic balances formed in F_3 and the possibility to perform selection in this generation. Correlations in 38 triticale hybrids (F_1, F_2, and F_3), obtained by different methods were evaluated in the conditions of the Middle Volga region, Russia. Simple intraspecific, complex and interspecific cross breeding was performed. Thirty-eight hybrids were evaluated. Correlation (68 features), variance, and genetic analyses were conducted. Relatively constant correlations in intraspecific hybrids of the F_1, F_2, and F_3 generations were documented between the length of the ear and its components: the number of spikelets, the mass of one ear, and the number of grains per ear. An increase in spike length in interspecific hybrids leads to an increase in the number of spikelets, but a decrease in fertility productivity. In hybrids of the second generation, the number of significant functional correlations increases significantly. In the third generation, the correlations are almost the same as in the first generation. The interrelation of spike length with internode length decreases ($r = 0.12–0.14$), while the weight of one spike ($r = 0.07–0.12$) increases with the number of spikelets ($r = 0.82–0.87$). The coefficient of variation in the number of kernels per ear in the F_3 generation of intraspecific and interspecific hybrids varied from 21.01% to 69.57%. The variance of this feature was lower in simple intraspecies hybrids (21.01–25.15%) and higher in interspecies hybrids with winter wheat (36.40–38.30%) and winter rye (60.0–69.57%). The analysis of the stability and plasticity of the hybrids indicates their instability. The selection of elite ears and plants in the early stages of formation of the hybrid is not effective.

Keywords

intraspecific; interspecific hybrids; rye; wheat; triticale; cross breeding combinations; correlation

Introduction

The main goal of a breeder is to create new generation varieties. To achieve this goal, it is not enough to rely only on the breeder's intuition, but one needs optimal schemes of the selection process and modern methods of evaluation of the parent and hybrid material [1].

The success of breeding improvement of triticale depends on methods of improvement of the parent material. A significant gene pool of triticale allows breeders to create new perspective varieties, using recombinant hybridization: crossing octoploid triticale with hexaploid, interhexaploid triticale breeding, octoploid and hexaploid triticale with wheat and rye.

Genetically, cytologically, and physiologically more balanced forms were bred, which allowed the breeders to reduce many unfavorable features. A great number of highly potential lines and varieties of winter triticale were bred for different regions of the world [2].

Genetic diversity of triticale can be enriched by means of interspecies crossbreeding of hexaploid triticale with soft winter wheat and rye. However, in the F_1 generation, the genome D of wheat winter and the genome R of rye are in a haploid condition, which leads to meiosis failures in further generations.

In distant hybrids, meiosis is abnormal: multivalent associations, univalents, or univalents and multivalents in one sample are formed [3].

To improve the quality of grain in triticale and increase the resistance to unfavorable environmental factors, the researchers performed hybridization of hexaploid forms of triticale with wheat. Due to the different functional capacity of heterosome gametes and competition in F_1 hybrids, the fertilization is primarily performed by the gametes with a balanced amount of chromosomes or close to it [4]. A promising area of research is the use of wheat with foreign chromosomes or their fragments [5].

Interhexaploid triticale cross breeding increases the effectiveness of intraspecific hybridization. These crossings allow the breeders to select genotypes with a complex of economically beneficial features [6].

Still, both interspecies and intraspecies crossbreeding results in an increase in biodiverse hybrid forms, which enriches the gene material.

The purpose of the present study was to evaluate correlations of F_1, F_2, and F_3 hybrids created by different methods, their plasticity and stability, and to assess the possibility of appearance of cytogenetically balanced forms in F_3 and selection in this generation.

Material and methods

To assess the impact of weather conditions on the elements of productivity, a correlation analysis of 68 features was carried out [7]. The tests on the influence of climate on yield and elements of triticale productivity were performed from 2002 to 2014 on the fields for breeding of the Samara Agricultural Research Institute. The initial materials were the results of the analysis of the 13-year study on climate change.

The tests were carried out in 2002–2014, 2013, 2015, and 2017 on the experimental fields of the Samara Agricultural Research Institute located in the central zone of Samara Oblast.

The F_1 hybrids were planted with parent forms in fall 2012. Ninety-six samples were planted: 34 hybrids and 62 parent forms, but some parent forms did not survive the winter.

Hybridization was performed by the Krasnodar method: the maternal form was castrated, a stake was driven, and a bottle of water with the paternal form was tied to the stake. Then, the combined plant was closed with an insulator.

The F^2 hybrids were planted in fall 2014; 24 hybrids were planted with parent forms: 16 intraspecies and eight interspecies. The F_3 hybrids were planted in fall 2016; 67 samples were planed: 24 hybrids (Tab. 1).

Distribution of parameters by one or several features of F_3 dynamics was performed by the method of Wolf [8]. Correlation and variance analyses were performed in Excel 2013.

The main methods of hybridization were (***i***) intraspecies, (***ii***) complex, and (***iii***) interspecies crossbreeding.

The phenotypic features presented in Tab. 2 were studied.

Ecological plasticity (bi) and phenotypic stability (S^2di) were evaluated by the mathematical model of Eberhart and Russel [9].

The structural analysis was performed by the method of the All-Russian Institute of Plant Breeding [10]. Agrometeorological data was provided by the Bezenchukskaya weather station [11].

Meteorological conditions

The climate in Samara Oblast, as in the entire steppe trans-Volga region, is continental. It is characterized by sharp temperature fluctuations and precipitation deficit. The annual amplitude of air temperature fluctuations in the hottest period in July and coldest

Tab. 1 The best hybrids used in the experiment, their origin and parental forms.

Mother line, origin	Hybrid	Father line, the origin
Legion, Russia, Rostov region	Legion / Tsekad 90	Tsekad 90, Russia, Novosibirsk region
Tsekad 90, Russia, Novosibirsk region	Tsekad 90 / Legion	Legion, Russia, Rostov region.
SW Algalo, Sweden	SW Algalo / Consul	Consul, Russia, Rostov region.
Marko, Poland	Marko / Agraf	Agraf, Russia, Rostov region
Pawo, Poland	Pawo / Colina	Colina, Romania
Union, Russia, Krasnodar Talva 100, Russia, Lipetsk	Union / Talva 100 // 4113 / Sagittarius	4113, Russia, Moscow Sagittarius, Russia, Krasnodar
Caprice, Russia, Rostov region	Caprice / Bezenchuk 790	Bezenchuk 790, winter wheat, Russia, Samara region.
Krokha, Russia, Samara region	Kroha / Bezenchukskaya 790	Bezenchuk 790, winter wheat, Russia, Samara region.
Varvara, Russia, Samara region	Varvara / Bezenchukskaya 616	Bezenchukskaya 616, winter wheat, Russia, Samara region
1876 T 35-3, Russia, Krasnodar Bernburger, winter rye, Germany	1876 T 35-3 / Bernburger / Talovskaya 41	Talovskaya 41, winter rye, Russia, Voronezh
Agraph, Russia, Rostov region	Agraph × Rokot 85	Rokot 85, winter rye, Russia, Tatarstan
Sagittarius, Russia, Krasnodar	Sagittarius / Morning	Morning, winter rye, Russia, Tatarstan

Tab. 2 Phenotypic features investigated in the study.

Cenotic characteristics	Biological yield, aboveground biomass yield, number of plants to be harvested, number of ears per 1 m^2, number of stems per 1 m^2, weight of ears per sheaf
Ear characteristics	Grain weight per spike, number of grains per spike, thousand-kernel weight, spike length, number of spikelets per ear, single ear weight, number of flowers per ear
Plant characteristics	Weight of ears per plant, weight of grain per plant, number of grains per plant, weight of one plant, productive bushiness, plant height, internode length

period in January is 38–41°C. The average annual air temperature is 4.6°C. Normal growth of winter grain crops in Samara Oblast is observed when the precipitations level in May–June is not lower than 50 mm. In Bezenchuk, such level of precipitation is recorded in 75% of years, i.e., 3 years out of 4. Annually, dry windy and drought periods are observed. The number of days with dry winds during the warm period is on average 8–16 days, and in certain years – 23–25 days.

There was good plant development in the fall of 2012, but in December abnormally low temperatures persisted at the depth of tillering nodes (−17°C), which caused the death of the aboveground part of the crop.

By the beginning of the growing season in 2013, the crops were in poor condition, but due to the root system development in the spring, the crop began to grow and even out, and by the earing stage the varieties and hybrids were scored 3–5 points. The mean air temperature for August–July was 12.5°C, which was 2.2°C below normal (14.7°C). The amount of precipitation (439.3 mm) during this period exceeded the norm (429.6 mm) by 9.7 mm. Excessive moisture was observed during the sowing period (13.7%) and the harvest period (20.2%). The year was characterized by elevated temperatures in November–April (−3.8°C) compared to the long-term annual average (−8.4°C). At the same time, precipitation in this period (192.1 mm) exceeded the norm (169.5 mm) by 22.6 mm. Also, excessive moisture was observed during the period of April–August (242.3 mm), which exceeded the long-term annual average (195.2 mm) by 47.1 mm. Elevated temperatures in the fall and winter and excess moisture in the spring contributed to the occurrence of rust pustules on the crops. This disease reduced the yield from 0.2% to 50%, depending on the degree of damage and the phase of development in which the pathogen was detected. The yield was much worse than the average values.

Insufficient precipitation during the planting season in 2014 (less than 50% of the norm) did not affect field germination, growth, development, and overwintering of the plants. By the beginning of the growing season (April 14), the crops were in satisfactory condition. Until the end of May, plant development was good. However, from May 28 to June 29, there was an atmospheric drought for 22 dry days. Due to the development of large leaf-stem mass and moisture consumption, in the absence of precipitation, soil drought was recorded in the triticale fields. The precipitation in the first 10 days of July did not significantly improve the situation and did not allow for high yields. The increased temperature regime was observed in February (2.5°C) and spring–summer (May, June) (1.3°C and 3.5° C higher than the long-term annual average), and atmospheric and soil drought was observed.

Due to heavy rains in September 2016 (324.1% of the norm), drilling of winter crops was stretched over time, resulting in winter crops completing growth at the germination and tillering stages. In 2017, a good harvest of winter triticale was obtained due to favorable humid conditions in the spring–summer period. Increased temperature was observed in February, March, and August (1.5–2.50°C higher than the long-term annual average). In May and June, the temperature was lower by 1.4–3.10°C than the average annual values.

During April and May, the reserves of productive moisture were higher and within the norm, which ensured good growth and development of plants under favorable temperature conditions.

Results

Weather conditions on the elements of productivity

The analysis of the influence of weather conditions on the elements of productivity of triticale varieties showed that the main abiotic factor that influenced triticale productivity was the hydrothermal coefficient (HTC) during the vegetation period (r = 0.93 ±0.193). The level of precipitation before drilling had a positive effect (r = 0.37 ±0.71). Partial death of plants during drilling (r = −0.37 ±0.123) and at the beginning of vegetation (r = −0.51 ±0.105) was observed because of the moisture excess in these periods. During the vegetation, the air temperature rose (r = −0.39 ±0.71) and moisture excess (r = −0.32 ±0.63) reduced the productivity.

The estimation of the influence of weather conditions by growth stages on the productivity and its elements showed the following results:

- Excess rain during the time of earing and ripening (r = −0.39 ±0.121) indicated the negative effect of moisture during this period, which led to the appearance of unseeded spikelets.
- TKW (thousand kernel weight) did not depend significantly on the precipitation in fall and spring (r = 0.32 ±0.40), but closely correlated with the precipitation during the period of booting (r = −0.82 ±0.047).
- A medium negative correlation between precipitation and number of kernels per ear (r = −0.39 ±0.121) and TKW (r = −0.33 ±0.127) was observed during the earing–ripening phase. During this period, excessive precipitation led to the formation of fine grains.
- Shriveling of grain was observed after high temperatures during the planting–germination stage (r = −0.72 ±0.068) and excess moisture during booting (r = −0.63 ±0.086).
- The number of productive stems negatively correlated with the level of precipitation during the entire vegetation period. The dependence on precipitation confirmed the significance of productive tillering in the conditions of the steppe trans-Volga region.
- During the period of planting and booting, high air humidity had a positive effect on TKW per ear (r = 0.36 ±0.65).
- TKW depended on air humidity during planting (r = 0.67 ±0.078).
- Increased air humidity during heading and ripening decreased the parameters of productivity and yield in general (r = −0.26 ±0.44).
- Plants positively reacted to the temperatures above 10°C (r = 0.43 ±0.80) during the period of earing–ripening.

The coefficient of hybridization in the present study during simple intraspecific and complex cross breeding (12.0 ±81.3%) was significantly higher than during hybridization between triticale and wheat (4.4 ±10.0%) and rye (1.7 ±1.9%).

In the hybrids of triticale and wheat, seed setting did not exceed 40% and varied depending on the crossing combination [12,13].

The comparative analysis of the interspecies hybrids was complicated because of low germination and poor survival rate.

Plant height

Plant height, especially in distant hybrids, can be determined by maternal or paternal genes and their interaction. Rye varieties that participate in hybridization as a paternal form are short-stem carriers of the dominant allele of the gene. This short-stem gene *Hl* is responsible for better tillering, decrease in plant height, elongation of ears, and increase of grain size [14,15]. This type of short stem is widely used in breeding. In the recessive allele *hl hl*, the homozygous state of the gene leads to a decrease in the short-stem feature and contributes to the formation of long stem plants. Varieties, involved in hybridization, have an average length of the stem. Competitive varieties of triticale have the *Rht-B1b* gene responsible for the short stem in wheat [16].

In the intraspecific F_1 hybrids, a correlation was observed between plant height and internode length (r = 0.45 ±0.79), ear length (r = 0.03 ±0.66), and number of ears (r = −0.07 ±0.53). At the genotypic level, the functional correlation was recorded only with internode length (r = 0.90).

In the F_2 generation of these hybrids, at the phenotypic level, height correlated with internode length (r = 0.23–0.68), single ear weight (r = 0.48 ±0.64), weight of kernels per ear (r = 0.51 ±0.72), number of kernels per ear (r = 0.47 ±0.66), and number of kernels per plant (r = 0.23–0.49).

The correlation varied from insignificant to high with ear length (r = −0.08–0.74), number of ears (r = −0.02–0.55), and weight of kernels per plant (r = −0.10 – −0.57). At the genotypic level, a close correlation was established only with internode length (r = 0.93), and at a medium level with kernel weight per plant (r = 0.31).

In the F_3 hybrids, at the phenotypic level, there was a correlation with weight of spikelets per plant (r = 0.21–0.70), internode length (r = 0.41–0.93), ear length (r = 0.28–0.61), number of kernels per plant (r = 0.26–0.37), and weight of kernels per plant (r = 0.22–0.56).

The correlation varied from insignificant to medium with single spikelet weight (r = −0.19–0.52) and number of spikelets (r = 0.02–0.62). At the genotypic level, a close correlation was observed only with internode length (r = 0.91), and a medium correlation with ear length (r = 0.29) and number of kernels per plant (r = −0.29).

In the interspecific hybrids with rye in the F_1 generation, plant height negatively correlated with internode length (r = −0.68…−0.25), single ear weight (r = −0.51…−0.30), and weight of kernels per ear (r = −0.47…−0.25).

In the hybrids with wheat, a correlation between plant height and all the structural elements was observed. A correlation was found with internode length (r = 0.00–0.89), productive tillering (r = −0.51–0.16), ear length (r = −0.44–0.38), number of ears (r = −0.26–0.35), number of kernels per ear (r = −0.21–0.34), single ear weight (r = −0.17–0.45), weight of kernels per ear (r = −0.21–0.36), weight of ears per plant (r = −0.24–0.14), number of kernels per plant (r = −0.26–0.23), and weight of kernels per plant (r = −0.24–0.26). At the genotypic level, there was a close correlation with internode length (r = 0.89) and ear length (r = 0.79).

In the F_2 hybrids, the correlations changed. In the hybrids that involved rye, height closely correlated with weight of ears per plant (r = 0.98), ear length (r = 0.83), single ear weight (r = 0.93), number of kernels per ear (r = 0.89), weight of kernels per ear (r = 0.71), number of kernels per plant (r = 0.99), and weight of kernels per plant (r = 0.96), while at a medium level with productive tillering (r = −0.62) and number of spikelets (r = 0.68). In the wheat hybrids, height correlated at a medium level with weight of ears per plant (r = 0.69), internode length (r = 0.57), number of spikelets (r = 0.59), ear weight (r = 0.44), number of kernels per ear (r = 0.41), kernel weight per ear (r = 0.42), number of kernels per plant (r = 0.67), and kernel weight per plant (r = 0.66).

At the genotype level, a close correlation was observed between plant height and ear length (r = 0.70), number of kernels per ear (r = −0.85), kernel weight per ear (r = −0.86), while a medium correlation was found between internode length (r = 0.64), TKW (r = −0.61), and weight of kernels per plant (r = −0.48). Changes in genotypic correlations can be caused by the redistribution of genetic environmental factors, the most significant of which are weather conditions [17].

In the F_3 generation, at the phenotypic level, the hybrids with rye had no functional correlations, but medium correlations were found with productive tillering (r = −0.64), weight of ears per plant (r = −0.39), internode length (r = 0.68), ear length (r = 0.47), number of ears (r = 0.53), number of kernels per plant (r = −0.38), and kernel weight per ear (r = −0.37). In the hybrids with wheat, a medium correlation was observed with weight of ears per plant (r = 0.29), ear length (r = −0.28), single ear weight (r = −0.41), number of kernels per ear (r = −0.52), weight of kernels per ear (r = −0.51), number of kernels per plant (r = 0.47), and kernel weight per ear (r = 0.51).

Productivity of the main ear

Productivity of the main ear is a complicated feature that is comprised of traits such as ear length, number of ears, number of flowers per ear, and ear fertility.

In our study, ear length depended on the hybrid. In the F_1 intraspecific hybrids, it varied from 7.9 to 11.1 cm, in the interspecies hybrids – from 8.6 to 13.8 cm. In the F_2 hybrids, the ear length was 9.05–12.61 cm and 9.94–13.3 cm, respectively. In the F_3 hybrids, the ear length was 8.34–12.36 cm and 9.0–13.9 cm, respectively. Ear length is a constant feature. In the intraspecific and interspecific hybrids, this parameter increased in the F_3 generation, as compared to the F_1 generation, by 5.6–11.3% and 0.7–4.6%, respectively.

In the triticale and rye hybrids, the ear length and number of ears were on average higher than in both parents [18].

In the intraspecific F_1 hybrids, ear length correlated with number of spikelets (r = 0.52–0.93), weight of ears per plant (r = 0.24–0.50), number of kernels per plant (r = 0.33–0.49), and weight of kernels per plant (r = 0.24–0.48). The correlation varied from insignificant to medium for single ear weight (r = −0.12–0.77), weight of kernels per ear (r = −0.01–0.59), and number of kernels per ear (r = 0.02–0.52). At the genotypic level, ear length correlated with all ear and plant features (r = 0.33–0.59).

In the F_2 generation of these hybrids, ear length correlated with number of spikelets (r = 0.76–0.90), number of kernels per ear (r = −0.59–0.39), weight of kernels per ear (r = 0.30–0.32), single ear weight (r = −0.30–0.48), weight of kernels per plant (r = −0.61–0.58), and weight of ears per plant (r = 0.36–0.75). The correlation varied from insignificant to medium for productive tillering (r = −0.19–0.42), number of kernels per plant (r = 0.07–0.40), and internode length (r = −0.04–0.39). No significant correlations were found at the genotypic level.

In the F_3 generation, a correlation was observed between ear length and number of spikelets (r = 0.58–0.85), single ear weight (r = 0.22–0.81), number of kernels per ear (r = 0.20–0.73), and internode length (r = 0.26–0.57). The correlation varied from insignificant to medium for weight of kernels per ear (r = 0.17–0.78), weight of ears per plant (r = 0.02–0.61), number of kernels per plant (r = 0.15–0.40), and weight of kernels per plant (r = 0.00–0.48). At the genotypic level, ear length correlated with all features of the ear and plant (r = 0.47–0.92).

The interspecific F_1 hybrids with wheat had no significant functional correlations with ear length. There was an unstable correlation, depending on the combination, with number of spikelets (r = 0.13–0.76), weight of ears per plant (r = −0.18–0.22), number of kernels per plant (r = −0.09–0.25), and weight of kernels per plant (r = −0.08–0.18). In the F_3 hybrids, ear length correlated with the main features: number of ears (r = 0.55–0.57), single ear weight (r = 0.61–0.82), number of kernels per ear (r = 0.25–0.82), weight of kernels per ear (r = 0.26–0.78), internode length (r = −0.28–0.55), weight of ears per plant (r = 0.26–0.29), number of kernels per plant (r = 0.14–0.15), and weight of kernels per plant (r = 0.21–0.22).

In the F_1 hybrids with winter rye, depending on the hybrid, ear length also correlated with the following ear features: number of spikelets (r = 0.64–0.74), single ear weight (*r* = −0.51–0.35), kernel weight per ear (*r* = −0.60–0.38), number of kernels per ear (*r* = −0.31–0.34), and the plant features: weight of ears per plant (*r* = −0.52 – −0.15), number of kernels per plant (*r* = −0.48–0.12), weight of kernels per plant (*r* = −0.55–0.12). Elongation of the ear in such hybrids led to an increase in the number of spikelets, but a decrease in fertility. In the second-generation hybrids, the number of significant functional correlations increased significantly. In the third generation, the correlations were almost the same as in the first generation. The correlation of ear length with internode length (*r* = 0.12–0.14) and single ear weight (*r* = 0.07–0.12) decreased, whereas that with number of spikelets per ear (*r* = 0.82–0.87) increased.

The coefficient of variation in ear length in the simple intraspecific hybrids and in the third generation hybrids with winter wheat did not vary significantly (7.68–10.48%). In the interspecific hybrids with winter rye, it varied from 14.68% to 14.87%.

Number of kernels per ear

Number of kernels per ear is important in the selection for productivity. This indicator is greatly influenced by weather conditions.

In the intraspecific F_1 hybrids, number of kernels per ear significantly correlated with weight of kernels per ear (*r* = 0.85–0.99). The correlation varied from insignificant to high for number of spikelets per ear (*r* = 0.089–0.93), number of kernels per plant (*r* = 0.39–0.95), and weight of kernels per plant (*r* = 0.41–0.89). At the genotypic level, number of kernels per ear correlated with all features of the ear and plant (*r* = 0.45–0.71).

In the second generation of these hybrids, number of kernels per ear significantly correlated with weight of kernels per ear (*r* = 0.88–0.98). The correlation varied from insignificant to medium for weight of ears per plant (*r* = −0.02–0.54), ear length (*r* = 0.34–0.59), single ear weight (*r* = 0.43–0.93), number of spikelets (*r* = 0.27…−0.53), number of kernels per plant (*r* = −0.007–0.16), weight of kernels per plant (*r* = −0.18–0.43), and internode length (*r* = −0.002–0.78). At the genotypic level, significant correlations were found with weight of kernels per ear (*r* = 0.95), number of kernels per plant (*r* = 0.72), and weight of kernels per plant (*r* = 0.81).

In the third generation, a significant correlation of number of kernels per ear with single ear weight (*r* = 0.71–0.83) and weight of kernels per ear (*r* = 0.88–0.97) was found. The ratio varied from insignificant to medium for ear length (*r* = −0.20–0.73), weight of ears per plant (*r* = 0.03–0.48), weight of kernels per plant (*r* = −0.08–0.53), plant height (*r* = −0.47–0.18), internode length (*r* = −0.25–0.28), at the average level – with the number of spikelets (*r* = 0.51–0.65), and number of kernels per plant (*r* = −0.28–0.46). At the genotypic level, number of kernels per ear correlated with ear length (*r* = 0.56), weight of kernels per ear (*r* = 0.82), number of kernels per plant (*r* = 0.74), and kernel weight per ear (*r* = 0.75). A relatively constant correlation in the hybrids of the first, second, and third generations remained between number of kernels per ear and weight of kernels per ear. In the second and third generations, the number of correlations at a medium level increased significantly.

In the interspecific first-generation hybrids of wheat, significant functional correlations could be observed between single ear weight (*r* = 0.93–0.97), kernel weight per ear (*r* = 0.98–0.99), weight of ears per plant (*r* = 0.89–0.95), number of kernels per plant (*r* = 0.88–0.99), and weight of kernels per plant (*r* = 0.79–0.99). In the second generation, the correlations changed. A functional relationship at a high level was observed with weight of kernels per ear (*r* = 0.87–0.95) and single ear weight (*r* = 0.78–0.80). A medium-level correlation was noted with plant height (*r* = 0.39–0.42), weight of ears per plant (*r* = 0.37–0.43), internode length (*r* = 0.52–0.63), ear length (*r* = 0.36–0.50), and number of spikelets per ear (*r* = 0.49–0.52). The third generation retained significant functional correlations between number of kernels per ear, single ear weight (*r* = 0.75–0.89), and weight of kernels per ear (*r* = 0.95–0.96). A medium-level correlation was observed with plant height (*r* = −0.23…−0.52), weight of ears per plant (*r* = 0.24–0.37), and internode length (*r* = −0.31–0.43).

The correlation ranged from insignificant to medium and high for ear length (*r* = 0.25–0.82) and number of spikelets per ear (*r* = 0.08–0.59). In the first-generation hybrids with winter rye, depending on the hybrid, number of kernels per ear correlated with all the features at a medium level: internode length (*r* = −0.22–0.35), productive tillering (*r*

= −0.44–0.37), ear length (*r* = −0.31–0.34), number of spikelets (*r* = −0.32–0.25), weight of ears per plant (*r* = 0.59–0.63), number of kernels per plant (*r* = 0.48–0.66), and weight of kernels per plant (*r* = 0.54–0.66). The correlation varied from insignificant to high for single ear weight (*r* = 0.52–0.99) and weight of kernels per ear (*r* = 0.56–0.97). At the genotypic level, functional correlations were observed between number of kernels per ear and weight of kernels per ear (*r* = 0.85), number of kernels per plant (*r* = 0.92), and weight of kernels per plant (*r* = 0.72). In the second generation of hybrids, the number of functional correlations significantly increased. Number of kernels per ear correlated with all the features from medium to high (*r* = −0.50–0.99). In the third generation, a high level correlation was observed between number of kernels per ear and weight of kernels per ear (*r* = 0.93–0.99), the average weight of ears per plant (*r* = 0.30–0.32), internode length (*r* = −0.25–0.30), ear length (*r* = −0.41–0.48), number of spikelets (*r* = −0.36–0.38), single ear weight (*r* = 0.50–0.65), number of kernels per plant (*r* = 0.28–0.30), and weight of kernels per plant (*r* = 0.29–0.30).

The coefficient of variation in the number of kernels per ear in the third-generation of interspecific and intraspecific hybrids was 21.01–69.57%. The number of kernels per ear varied less in the simple intraspecific hybrids (21.01–25.15%) and more in the interspecific hybrids with winter wheat (36.40–38.30%) and winter rye (60.0–69.57%).

Stability and plasticity

The coefficient of regression bi indicated the specificity of hybrids, i.e., their ability to adapt to changing conditions (Tab. 3).

By weight of kernels per ear, the hybrids with wheat (bi = 1.8), complex hybrids (bi = 1.14), and reciprocal ones (bi = 2.07) had a coefficient >1, i.e., they had better plasticity and specific adaptation. The direct reciprocal (bi = 0.89) hybrids and hybrids with winter rye (bi = 0.01) were characterized by low plasticity. The hybrids with a high bi coefficient and low S^2di are of practical interest to researchers. Such criteria are met by the hybrids obtained using winter wheat (bi = 1.80, S^2di = 0.17) and by the simple reciprocal hybrids (bi = 2.07, S^2di = −0.28). As regards the adaptivity feature, all the hybrids were unstable, and the complex hybrids showed the greatest effect. Selection for adaptivity, based on stability, affects the grades of hybrids. The best hybrids, combining high kernel weight per ear, general adaptive capacity and relatively good plasticity, were the complex hybrids.

The increase in the hybrid's sensitivity to favorable and unfavorable conditions indicated an increase in phenotypic plasticity, as expressed by the coefficient of regression bi. The reason for such correlation is in the genetic determination of the reaction norm, whose phenotypic expression depends on environmental factors and their intensity.

Tab. 3 Parameters of adaptive capacity and stability by weight of kernels per ear.

Genotype	Xi	Adaptivity	Selection value	bi	S^2di
Triticale × Wheat	1.78	0.17	0.14	1.80	0.17
Triticale × Triticale (direct crossing)	1.41	−0.20	0.96	0.89	−0.20
Triticale × Triticale (reciprocal crossing)	1.33	−0.28	−0.23	2.07	−0.28
Triticale × Rye	1.14	−0.47	0.98	0.01	−0.47
(Triticale × Triticale) × (Triticale × Triticale)	2.09	0.48	1.20	1.14	0.48

Discussion

In the studied crossing combinations, it is quite difficult to obtain a long-stem plant with a short internode and a short-stem plant with a high number of kernels per plant.

Such features as ear weight, kernel weight, and number of kernels per ear correlated in all the varieties, but depended on the height of all the varieties separately. There were no correlations observed between ear length, number of spikelets per ear, and kernel weight per ear in the reciprocal crossing.

As can be seen in the second generation, at the phenotypic level, the correlations with height became much closer, but they were not stable and fluctuated.

In the hybrids of the F_1, F_2, and F_3 generation, the lack of correlation or low correlation was observed in the reciprocal combination. This is explained by the fact that the studied features in a reciprocal combination are controlled by the cytoplasm and are inherited by the maternal line.

No functional correlations were revealed. In such hybrids, the increase in plant height led to a decrease in such parameters as single ear weight, weight of kernels per ear, number of kernels per ear, weight of ears per plant, number of kernels per plant, and weight of kernels per plant. In other words, in general the productivity decreased.

The increase in the height of wheat hybrids led to a decrease in such features as productive tillering, ear length, and number of spikelets per plant.

The interspecific hybrids, obtained by crossing with rye, hardly survived the germination phase [18]. In the present study, there were some plants that produced tillers but did not produce ears, depressed plants of small size with thin straw and small ears or very high plants with pyramid- or spindle-shaped ears, awned and semiawned.

Hybridization with wheat was characterized by low seed setting. Probably, it is explained by the fact that one of the parent forms had gametes with an unbalanced number of chromosomes.

The studies by Orlovskaja et al. [19] and Divashuk et al. [20] showed that distant hybridization in the fourth generation of triticale hybrids was characterized by the incomplete stabilization of the meiosis. The presence of telocentric chromosomes of wheat and rye initiates the process of splitting and form building. Based on this data, in our study the process of splitting into morphotypes continued in hybrids of the F_3 generation.

In the hybrids F_1, F_2, and F_3, relatively constant correlations remained between ear length and ear characteristics: number of spikelets, single ear weight, and number of kernels per ear.

In comparison with the hybrids F_1, the number of significant correlations in the hybrids F_2 and F_3 was significantly higher. It is explained by the fact that the hybrids F_2 and F_3 have a wider range of genotypic and phenotypic variability. The splitting in F_2 and further generations was quite diverse, because the parent varieties varied between each other by a great number of features. The process of stabilization of the hybrids F_3 was incomplete; apart from the gene recombination, the process of stabilization of the ploidy level was incomplete. The obtained hybrid material attracts researchers' theoretical interest for further genetic studies and practical interest in further breeding.

The interspecific hybrids with winter wheat in the first generation had much more significant functional correlations as compared to the hybrids of the second and third generations, which had more correlations at a medium level. The interspecific hybrids of winter rye were characterized by a greater number of functional significant correlations in the hybrids of the second generation. In the intraspecific hybrids, the number of correlations in the second and third generations was much greater.

Plasticity is the degree of variability of features that allows an organism, as a carrier of the genotype, to adapt to the changing environmental conditions. As potential productivity increases, the problem of resistance of new varieties and hybrids to the effect of abiotic and biotic stresses becomes more acute [21]. Weather conditions have a significant impact on the development of a number of economically beneficial features that determine productivity [22,23]. In unfavorable soil and climatic conditions, not only potential productivity is of great importance, but also environmental sustainability [24].

The analysis of the stability and plasticity of the hybrids indicated their instability. The selection of elite ears and plants in the early stages of hybrid formation is not effective.

Conclusions

- In this study, the main abiotic factor affecting triticale yield was the hydrothermal coefficient (HTC) determined during the growing season of the crop. An increase in the air temperature in spring reduces yield. Precipitation before sowing has a positive impact on yield.
- The number of significant correlations in the second and third generation hybrids is much higher compared to the first generation hybrids.
- F_2 and F_3 hybrids have a wider range of genotypic and phenotypic variability than F_1 hybrids.
- The stabilization process of the F_3 hybrids is incomplete; however, the hybrid material attracts the theoretical interest of researchers' in view of further genetic research and further breeding.
- The increased sensitivity of the hybrid to favorable and unfavorable conditions indicates an increase in phenotypic plasticity expressed by the regression coefficient bi. The reason for this correlation lies in the genetic determination of the reaction rate, the phenotypic expression of which depends on environmental factors and their intensity.
- Choosing elite ears and plants in the early stages of hybrid formation is not effective.

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Statystyczna analiza korelacji u mieszańców pszenżyta ozimego

Streszczenie

Celem pracy była ocena korelacji pomiędzy mieszańcami pokolenia F_1, F_2 i F_3 uzyskanymi różnymi metodami, ich plastycznością i stabilnością, a także określenie prawdopodobieństwa powstania stabilności cytogenetycznej w F_3 i możliwość dokonania selekcji w tym pokoleniu. Po raz pierwszy w warunkach regionu Środkowej Wołgi dokonano oceny korelacji cech mieszańców pszenżyta F_1, F_2 i F_3 uzyskanych różnymi metodami. Przeprowadzono prostą wewnątrzgatunkową oraz złożoną, międzygatunkową hodowlę krzyżową. Oceniono korelację (68 cech), wariancję i wykonano analizy genetyczne. Stosunkowo stałą wartość współczynnika korelacji obserwowano u wewnątrzgatunkowych mieszańców F_1, F_2 i F_3 dla długości kłosa, liczby kłosków, masy jednego kłosa i liczby ziarniaków w kłosie. Wzrost długości kłosa u mieszańców międzygatunkowych prowadził do wzrostu liczby kłosków, ale obniżał produktywność i płodność. U mieszańców F_2 liczba statystycznie istotnych wartości współczynnika korelacji znacznie wzrosła. U mieszańców F_3 wartości współczynników korelacji były prawie takie sama jak w F_1. Współzależność pomiędzy długością kłosa a długością międzywęźli ($r = 0.12–0.14$) i masą jednego kłosa ($r = 0.07–0.12$) była niższa, a wzrosła pomiędzy długością kłosa a liczbą kłosków ($r = 0.82–0.87$). Współczynnik zmienności liczby ziaren w kłosie w pokoleniu F_3 u mieszańców wewnątrzgatunkowych i międzygatunkowych wahał się od 21.01% do 69.57%. Wariancja tej cechy była niższa wśród mieszańców wewnątrzgatunkowych (21.01–25.15%) a wyższa u mieszańców międzygatunkowych z pszenicą ozimą (36.40–38.30%) i żytem ozimym (60.0–69.57%). Wybór kłosów i roślin we wczesnych etapach tworzenia mieszańców nie jest skuteczny, gdyż wykazują one niestabilność i dużą plastyczność cech.