Ecological variability of winter rye yield in the Middle Volga region

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Abstract. Rye grain yield in the Russian Federation has had a positive trend over the last 12 years, with an increase of 0.45 kg/ha per year. The Volga Federal District is the centre of rye growing in Russia. We evaluated the adaptability of Tatarstan winter rye varieties of own selection - first (Tatarskaya 1, Radon) and last generation (Tantana and Zilant) in terms of grain yield. From 2019 to 2023, these varieties will be tested in a competitive variety trial at the Tatar Agricultural Research Institute, FRC Kazan Scientific Centre of RAS. The breeding strategy was not focused on increasing the "upper limit" of yield, but on reducing the varieties' sensitivity to the environmental conditions of the production area. Cultivar plasticity ranged from 0,743 (Tatarskaya 1) to 1,246 (Radon). The research results showed that the latest generation varieties (Zilant, Tantana) are characterised by higher yields, plasticity and good stability compared to earlier developed varieties. The cultivar Zilant achieved the optimum balance of ecological variability parameters.

1 Introduction

Rye is a multipurpose crop that is widely used for baking, animal feed, alcohol, biogas and biofuels [1-2]. Another valuable advantage of rye is its high tolerance to abiotic stresses (low temperature, drought, soil poorness and degradation). This makes it economically less costly to grow than other crops [3-4]. In terms of nutritional and physiological value, rye grain has many advantages over wheat [5]. Rye products form the basis of modern healthy diets due to their high content of bioactive compounds and non-digestible carbohydrates, balanced composition and prebiotic properties [6-7]. Other important competitive advantages of rye are related to the reduction of greenhouse gas emissions by about 20% and carbon footprint by 8% compared to wheat, making it an indispensable crop for a resource-efficient and competitive bioeconomy [8].

In the Russian Federation, winter rye is not only the second most important cereal crop, especially under changing climatic and economic trends, but also a socially important and healthy food for the population [9-10]. Its leading role in the country's crop production is not limited to food and raw material value, but also includes important agrotechnical,
economic and environmental significance for most regions of the country, especially for areas with complex soil and climatic conditions.

The production of winter rye in the Russian Federation has been experiencing serious difficulties due to the undervaluation of the cereal and its status as a secondary cereal crop over the last few years. In 2022, Russia ranked third among the world's largest producers of rye grain, producing 2.21 million tonnes, which is about 20% of the world's production of this crop. However, in 2023 the sown area of winter rye reached an absolute minimum of 831 thousand hectares, 7% (61.3 thousand hectares) less than in 2022 and 10 times less than in 1989.

The Volga Federal District is the centre of rye cultivation. In 2022, 67% of all sown rye areas in Russia (1.051 thousand hectares) were sown here. The Republic of Tatarstan takes the third place among the subjects of the Volga Federal District in terms of the area sown with winter rye. The gross harvest of winter rye grain in the Volga Federal District amounted to 1.5 million tonnes, in the Republic of Tatarstan - 200 thousand tonnes [11].

The purpose of our work is to determine the ecological variability of yield in winter rye varieties of different stages of selection.

2 Materials and methods

The official reference data of the Russian Federal State Statistics Service [11] and the Food and Agriculture Organization of the United Nations, as well as the results of our own research on the grain yield of 4 commercial winter rye varieties of our own selection, served as the material for the research. In the period from 2019 to 2023, in Tatar Research Institute of Agriculture, FRC Kazan Scientific Center of RAS, in a competitive variety trial on plots of 12 m² in four replicates, experimental work was carried out to assess the adaptability of winter rye varieties. The design of the trial and the analysis of the varieties' yields were carried out in accordance with the Methodology of State Variety Testing of Agricultural Crops.

The agroclimatic conditions of the Republic of Tatarstan are strongly continental with a long winter (up to 5 months) and dry spring-summer vegetation, contrasting with which was observed during the research period. In the last few years, weather anomalies have become more frequent in the different periods of the vegetation of the crop, which has affected the level of the yield. Thus, in 2019, winter rye suffered significantly from snow mold damage due to the prevalence of warm periods during the winter. In 2023 and especially in 2021, acute spring-summer drought was observed. The methodology of S. A. Eberhart, W. A. Russel as described by V. A. Zykin et al. [12] and the Exsel 2007 programme package were used for statistical processing of yield values, construction of graphs and regression relationships by years.

3 Results and Discussion

Winter rye yield in Russia has shown a positive trend over the last 12 years (+0.45 c/ha per year). However, it lags significantly behind the more export-oriented crops - wheat and barley, for which the annual increase is 0.99 and 0.91 c/ha, respectively (Figure 1). The reasons are the low intensity of rye breeding and the low number of research institutions who developed breeding programs for rye. Furthermore, rye is usually sown on low-fertility or sandy soils that are not suitable for wheat. The amplitude of variation is 15.2...25.3 c/ha and the coefficient of variation is 15.3% with an average yield of 19.8 c/ha.
A number of researchers are of the opinion that rye has lost its fundamental role as a main ingredient for baking, and it is therefore increasingly called a 'minor' cereal [13-14]. However, in our opinion, the main reason for this is the lack of breeding for environmental plasticity and stability.

The choice of breeding directions in the development of new varieties is usually the first step in determining the importance of different factors of yield increase. In European countries, yield improvement in winter rye has been achieved by developing breeding programs to create hybrid varieties and by exploiting heterosis, which in Germany has been about 10% [15]. The share of hybrid rye in this country was more than 77%. Under Polish conditions, hybrid varieties provide an annual yield increase of 7.4-8.5 c/ha [16]. In the Russian Federation, population varieties dominate with 95% of the rye area. Therefore, the effect of breeding improvement is not so significant and rapid.

As is well known, there is a need for locally selected varieties in each region, as these are best adapted to the agro-climatic conditions of the area in which the varieties are grown[17].

We evaluated the adaptability of Tatarstan winter rye varieties of own selection - first (Tatarskaya 1, Radon) and last generation (Tantana and Zilant) in terms of grain yield. All these varieties have a wide area of zoning and have been included in the State Register of the Russian Federation in three or more regions. Their development is based on the method of recurrent breeding, the aim of which is to increase grain yield and improve adaptive traits in the breeding population through targeted crossing, recombination and selection of combinational valuable forms.

The analysis of the yield of winter rye varieties for the years 2019-2023 showed that the maximum value was achieved by the variety Zilant in 2022 (5.53 t/ha), and the lowest - by the variety Radon in 2021 (2.91 t/ha) (Figure 2).

The value of average yield of a variety in contrasting environmental conditions shows the highest degree of correspondence between variety genotype and environmental factors [18]. The high yield on average for 5 years had the variety Zilant (4.52 t/ha), the middle positions were occupied by the varieties Tatarskaya 1 and Tantana (4.27 t/ha and 4.24 t/ha, respectively), the low yield was demonstrated by the variety Radon (4.05 t/ha).

The influence of the growing conditions can be best characterised by the indices of the environmental conditions (Ij), the higher value of which indicates the favourable manifestation of the yield potential of the varieties (Table 1). The growth conditions for the years 2019-2023 were diverse, as the Ij varied from -1.07 to 0.98.
The best conditions for growth and development of winter rye varieties occurred in 2020 and 2022, when the environmental index reached the highest positive value, while in the other three years \( I_j \) was -0.5, -1.07 and -0.31 in 2019, 2021 and 2023 respectively, which characterises the weather conditions of the year as unfavourable. These data point to the need for an assessment of the environmental variability of crop yields.

A desirable combination of plasticity and stability parameters would be: a value of regression coefficient \( (b_i) \) equal to or close to 1, a lowest value of stability parameter \( \delta^2 \), and a highest value of average yield. The contrasting years were reflected in the average yield of the varieties, which was 1.6 times higher in the favourable years compared to the unfavourable years. The varieties' plasticity ranged from 0.743 (Tatarskaya 1) to 1.246 (Radon). The cultivars of first generation selection were more responsive to variations in growing conditions and their productivity varied significantly. On the basis of the linear regression coefficient \( (b_i) \), the Radon variety was characterised by a higher sensitivity to the intensity of cultivation and a significantly lower yield under unfavourable conditions. The variety Tatarskaya 1 responded weakly to the improvement of external factors. At the same time, the yield reduction in unfavourable conditions is not so significant. Such varieties are more stable in yielding, it is better to use them in extensive background, because in this case they will give maximum yield at minimum cost. Medium-intensity winter rye varieties, which are able to give a stable yield in all conditions at low cost, are more often demanded by small farms and farmers. The intensive varieties are the most valuable for large farms with material resources.
With the aim of increasing the competitiveness of newly developed winter rye cultivars in agricultural production systems, the breeding strategy has focused on reducing the sensitivity of cultivars towards the environmental conditions of the area of production, rather than on increasing the "upper limit" of yield. The main objectives of the breeding work of the last decade have been the reduction of yield losses due to lack of winter hardiness, lodging, snow mould and other pathogens and other causes and, to a lesser extent, the reduction of yield losses due to more efficient and intensive use of environmental resources.

Full correspondence of varietal yield variation to variation in growing conditions is observed when the bi coefficient approaches 1. In our study, the optimal ratio of all environmental parameters was characterised by the last generation variety Zilant (average yield 4.52 t/ha, \( b_i = 1.061, \delta_i^2 = 0.005 \)). Better winter and drought resistance, lodging resistance due to shorter and stronger stem, and disease resistance contribute to the high yield of this cultivar.

The variety Tantana had a good combination of plasticity and stability. However, its yield was 0.28 t/ha lower, than that of Zilant (Figure 2).

The position of the regression line for Zilant shows that its yield is higher than other cultivars in all environments, except in 2021 when it lost the lead to Tatarskaya1 (Figure 3). It is particularly important that this variety does not significantly reduce its productivity in unfavourable annual conditions compared to other varieties, but effectively responds to the improvement of growing conditions in favourable years with a significant increase in yield.

![Fig. 3. Regression lines of theoretical yield of winter rye varieties on indices of environmental conditions.](image)

Thus, the results of the research have shown that the varieties of the latest generation (Zilant, Tantana) are characterised by higher yields, plasticity and good stability in comparison with the varieties developed earlier. The degree of realization of their yield potential under different growing conditions is a valuable characteristic of these varieties.
4 Conclusion

Statistical analysis of rye grain yield in the Russian Federation over the last 12 years has shown a positive trend, increasing by 0.45 kg/ha per year. Our research has shown an increase in the realisation of the yield potential of varieties as their average yield increases. The priorities of the breeding work in Tatar Research Institute of Agriculture, FRC Kazan Scientific Center of RAS have been changed by the transition from the breeding of varieties with high productivity potential to the creation of varieties with adaptability and ecological plasticity. Such varieties develop their potential best under favourable conditions and provide stable yields under the action of a complex of stress factors, as well as under a sufficient diversity of meteorological and agrotechnical conditions.

The best yielding variety was Zilant, which outperformed previously developed varieties not only in productivity but also in environmental plasticity and stability. Higher realisation of yield potential under contrasting environmental conditions was characteristic of the latest generation varieties.

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