

Article

Evaluation of Population and Hybrid Varieties of Winter Rye in the Conditions of Eastern Siberia

Anatolii V. Pomortsev , Nikolay V. Dorofeev * , Svetlana Yu. Zorina, Natalia B. Katysheva, Lada G. Sokolova, Anna S. Zhuravkova and Elena V. Mikhailova

Laboratory of Physiological and Biochemical Adaptation of Plants, Siberian Institute of Plant Physiology and Biochemistry of the Siberian Branch of the Russian Academy of Sciences, 664033 Irkutsk, Russia; pomorcevanatolii@mail.ru (A.V.P.); zorina@sifibr.irk.ru (S.Y.Z.); mitanova2014@yandex.ru (N.B.K.); sokolova.lada@sifibr.irk.ru (L.G.S.)

* Correspondence: nikolay.v.dorofeev@gmail.com

Abstract: Winter rye has a high adaptive capacity to abiotic and biotic stressors compared to other winter crops (wheat, triticale, barley, and oats). High resistance of winter rye to adverse environmental factors and a wide range of its uses increase interest in this crop. The purpose of this research was to evaluate the adaptive capacity of population and hybrid varieties of winter rye and to identify varieties suitable for the soil and climate conditions of Eastern Siberia. A number of winter rye varieties of various geographical origins were tested during three field seasons. In all the field seasons, the population varieties (Tagna, Mininskaya, and Chulpan) were the most productive and most resistant to adverse environmental factors compared to the hybrid wheat (KWS Aviator, KWS Prommo, and KWS Ravo). Statistically significant ($p < 0.001$ in 2019/2020 and $p < 0.001$ in 2021/2022) differences in field survival and yield between the population and hybrid varieties were noted.

Keywords: winter rye; varieties; yield; winter hardiness; field survival



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1. Introduction

Rye (*Secale cereale* L.) is grown mainly for food and fodder purposes. For instance, in Europe, more than 41% of the total winter rye crop is used for food, 32% for fodder, and about 27% for other purposes [1]. In Russia, more than half of winter rye grain is used for the production of flour [2].

In unfavorable agro-climatic conditions, winter rye is the most sustainable crop compared to other winter crops (wheat, triticale, barley, and oats) [3]. Winter rye can grow in the northern territories, where other winter cereals freeze out. The value of this crop is that it has high frost and winter hardiness [4,5], and can grow in poor soils with minimal production costs [6].

Winter rye is actively cultivated in Russia. Thus, the mean yield of rye grain in Russia has increased from 1.53 to 2.1 t/ha over the past 20 years (2000–2021, FAOSTAT). The low productivity of winter rye was due to high haulm stand and low resistance to abiotic and biotic environmental factors; the varieties were characterized by low grain quality (low falling number). Modern breeding of winter rye is aimed at creating varieties that combine a set of economically valuable characteristics (increased winter hardiness, short stemming, high and stable yield of the grain of good quality, resistance to adverse winter environmental factors, etc.) [5–7].

In recent years, the mean productivity of rye in Europe has increased to 3.6 t/ha; in the USA, its amount is lower by more than 1.0 t/ha [8]. For the growing seasons 2020–2021, the mean productivity of winter rye grain in Germany exceeded 5.0 t/ha (5.5–5.3 t/ha, FAOSTAT), which is significantly higher than the mean rye productivity in Russia [9,10]. Germany is the world's largest exporter of rye seeds, with a potential yield of up to 10 t/ha; this contributes to the spread of hybrid varieties to other countries, such as Denmark,

Austria, Poland, Latvia, and Russia [11,12]. German hybrids are grown in about 60–70% of the total area of rye fields in Europe due to their high yield and better homogeneity compared to population varieties. However, some studies indicate that German hybrids do not always answer expectations under severe climatic conditions and are inferior to local varieties, especially in unfavorable years [13,14]. Previously, it was found that rye production depends on both climatic conditions and the adaptability of varieties to changing growth environments [15]. Therefore, it is necessary for each agricultural region involved in the winter rye production to have varieties of the local selection that are most adapted to the specific soil and climatic conditions.

Resistance to low-temperature stress of winter cereal crops, including winter rye, increases during cold acclimatization due to physiological, biochemical, genetic, and structural changes [16–18]. Rye is a more winter-hardy species compared to other cereals [19,20]. After low-temperature adaptation, where plants are exposed to low but non-freezing temperatures, rye can withstand low negative temperatures down to about $-30\text{ }^{\circ}\text{C}$ [21]. Other researchers have found that the frost resistance of rye acquired during cold acclimatization reaches $-23\text{ }^{\circ}\text{C}$ compared to wheat ($-19\text{ }^{\circ}\text{C}$), triticale ($-16\text{ }^{\circ}\text{C}$), and barley ($-13\text{ }^{\circ}\text{C}$) [22]. According to the observations of I. Tumanov [23], even in winters with little snow, rye is able to tolerate frosts down to $-25\text{ }^{\circ}\text{C}$ – $-35\text{ }^{\circ}\text{C}$. Resistance to low negative temperatures and to the complex of unfavorable environmental factors will vary considerably depending on the variety specificity. In addition, an important factor of field survival of winter cereal crops, including winter rye, is their resistance to low temperatures with reduced winter hardiness (freeze-thaw cycle), especially in the absence of snow cover. The return of low negative temperatures after warming leads to plant damage or death [24].

In the agro-climatic conditions of Eastern Siberia, difficulties in the cultivation of winter crops are mainly associated with their overwintering [25]. Unfavorable conditions of the winter period (especially the end of winter) can cause damage to plants, even to crops such as winter rye. Therefore, the purpose of this research was to evaluate the adaptive capacity of population and hybrid varieties of winter rye of different geographical origin and to identify varieties suitable for the soil and climate of Eastern Siberia.

2. Materials and Methods

2.1. Place and Conditions of the Field Study

Field experiments on hybrid and population varieties of winter rye (Table 1) were carried out at the agroecological station of the Siberian Institute of Plant Physiology and Biochemistry of the Siberian Branch of the Russian Academy of Sciences ($53^{\circ}33'58.75''\text{ N}$ and $102^{\circ}35'23.90''\text{ E}$) during three field seasons (2019/2020, 2020/2021, and 2021/2022).

Table 1. Winter rye genotypes studied for winter and frost hardiness.

Sample	Origin	Originator	Group	LT ₅₀
Mininskaya	Russia	Federal Research Center “Krasnoyarsk Science Center of the Siberian Branch of the Russian Academy of Sciences”	P	−14.3
Tagna	Russia	Siberian Institute of Plant Physiology and Biochemistry of the Siberian Branch of the Russian Academy of Sciences	P	−14.3
Chulpan	Russia	Bashkir Research Institute of Agriculture	P	−13.6
KWS Aviator	Germany	KWS LOCHOW GMBH	H	−13.3
KWS Prommo	Germany	KWS LOCHOW GMBH	H	−13.4
KWS Ravo	Germany	KWS LOCHOW GMBH	H	−13.3

Note: P—population varieties; H—hybrid varieties.

Weather conditions for the experiment periods are presented in Table 2. During the three-year field experiments, the height of the snow cover and low negative temperatures in winter did not differ significantly.

Table 2. Weather conditions for the studied periods.

Parameters	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2019/2020												
Max temperature, °C	25.5	15.9	10.8	−1.6	−7.2	−0.4	11.7	27.6	28.5	31.8	34.0	29.0
Min temperature, °C	−4.3	−13.5	−30.5	−43.8	−33.8	−37.6	−23.4	−9.7	−5.2	0.6	23.0	1.9
Mean temperature, °C	10.1	0.2	−13.2	−17.6	−21.4	−18.1	−3.3	6.8	11.5	16.4	19.3	16.5
Precipitation, mm	77	15.4	12.2	30.5	2.6	2.5	9.6	10.9	16.8	50.6	68.8	100.6
Snow cover depth, cm	-	-	7.0	30.0	27.0	27.0	4.0 *	-	-	-	-	-
2020/2021												
Max temperature, °C	25.8	17.6	7.3	0.0	−8.6	−2.5	6.9	18.4	19.8	31.2	31.3	29.6
Min temperature, °C	−3.9	−13.9	−25.7	−39.0	−39.8	−42.6	−34.4	−9.2	−6.0	2.5	4.7	2.7
Mean temperature, °C	9.3	−0.3	−8.2	−20.8	−21.4	−18.9	−7.4	1.9	8.0	15.1	19.2	16.1
Precipitation, mm	131.9	20.1	11.8	5.9	27.1	14.0	5.2	7.9	69.3	85.6	36.3	56.9
Snow cover depth, cm	-	5.0	8.0	13.0	30.0	32.0	1.0 **	-	-	-	-	-
2021/2022												
Max temperature, °C	25.8	15.9	4.8	−0.2	−5.8	19.4	−8.8	2.9	12.3	37.4	32.5	29.3
Min temperature, °C	−5.8	−13.5	26.7	−39.4	−35.4	3.4	7.9	24.7	31.5	−1.1	6.7	−1.6
Mean temperature, °C	7.5	0.4	−8.3	−18.8	−20.1	38.6	−27.4	−10.3	−6.3	17.3	17.1	14.1
Precipitation, mm	31.2	8.0	11.8	11.9	12.3	2.2	3.0	20.5	11.3	62.4	82.7	63.1
Snow cover depth, cm	-	1.0	9.0	16.0	31.0	27.0	1.0 ***	-	-	-	-	-

Note: Snow cover depth in cm is recorded for March 19 *, 28 **, and 30 ***.

An important factor in the field survival of plants is the date of the loss of snow cover as well as the air temperature during the snowless period at the end of winter (Figure 1). According to these parameters, the end of the 2020/2021 winter can be considered favorable for winter crops to overwinter. The end of the 2019/2020 and 2021/2022 winter periods can be considered unfavorable for winter crops to overwinter; this is associated with the long snowless period and the effect of low negative temperatures. In 2019/2020, the duration of the snowless period was 13 days; the air temperature dropped to -14.7 °C. The snowless period at the end of the 2021/2022 winter was short. Nevertheless, a prolonged effect of low negative temperatures on plants was noted. The temperature dropped to -17 °C; the snow cover was low and loose (from 1 to 8 cm) (Figure 1).

The soil of the trial plot is Luvic Retic Phaeozem (Loamic, Aric) [26]. This type of soil is predominant in the arable fund of the region studied [27]. The soil characteristics were analyzed using standard methods [28]. The density of the arable layer (0–20 cm) varied within 1.04 – 1.22 g/cm³. This value corresponds to the optimal parameters of the bulk density of loamy soils (1.00 to 1.30 g/cm³). The humus level, according to the classification [29], is “low” (3.27–3.45%); total nitrogen is 0.18–0.20%. The pH values of the aqueous and salt suspensions characterized the weak acid reaction of the medium (6.05–6.38 and 5.02–5.35 pH units, respectively). The cation exchange capacity (CEC) was relatively low (30.1–36.9). The supply of mobile forms of phosphorus is “high” (240–252 mg/kg). The available potassium content is “increased” (120–129 mg/kg).

2.2. Test for Determining the Relative Frost Hardiness of Seedlings of Population and Hybrid Varieties

The seedling freezing test was performed by the gradual temperature decrease using a BINDER test chamber [30]. To pass the first stage of cold acclimation, winter rye seedlings from 5 to 8 mm were kept at $+2$ °C for 7 days. Then, the temperature was decreased to -4 °C (3 days) to pass the second stage of cold acclimation. Next, the temperature was gradually decreased to -7 , -10 , -12 , -14 , -16 , -18 , and -20 °C. The seedlings were kept at these temperatures for 24 h. The decrease in temperature was 1 °C per hour. After that, the plants were thawed at 2 °C for 48 h. Then, the plants were placed into the temperature regime from 20 to 25 °C. Each experiment was repeated 3 times. The temperature at which 50% of the seedlings died after the freezing was noted as LT₅₀.

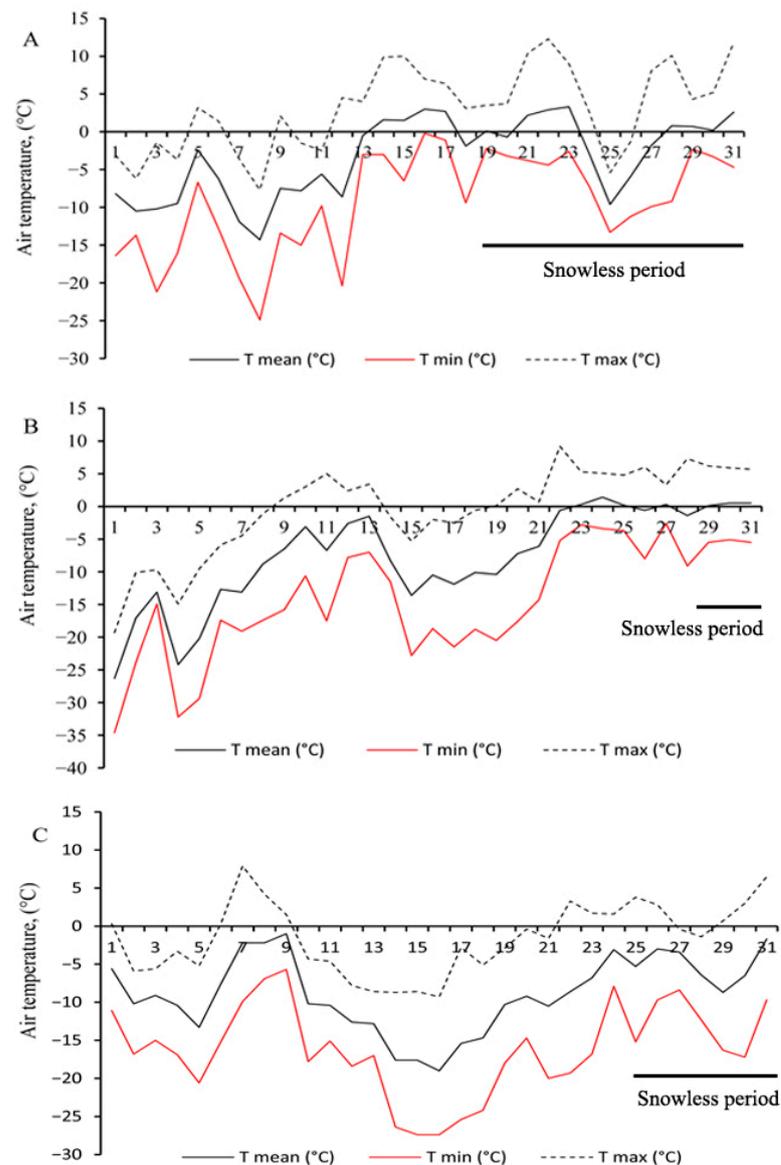


Figure 1. Maximum, minimum, and mean daily temperature regime in March. (A) 2020 year; (B) 2021 year; (C) 2022 year.

2.3. Measurements Taken before and after Harvesting

The winter hardiness of plants was determined by calculating the ratio between the number of plants in the autumn period and their number in the spring period after the start of the growing season. Winter rye sampling was carried out from each plot. The number of plants, number of spikes, the number and weight of kernels per ear, and the 1000 kernel weight were determined. After sheaf sampling, the plots were harvested with the selection combine (Sampo 130). After harvesting, the weight and moisture content of the berries of each sample were measured, and the yield capacity was adjusted to the standard moisture content of 14%.

2.4. Statistical Analysis

The results were processed using the Sigma Plot from Windows Version 14.0 package. The normality of distribution was evaluated using the Shapiro-Wilk test. The statistical data processing was performed using one-way and two-way analyses of variance (ANOVA) (Fisher's LSD method). The statistically significant differences were taken at $p < 0.05$. Correlation data analysis was performed using the Pearson's test.

3. Results

3.1. Survival of Winter Rye Plants in the Field and Laboratory Conditions

The highest survival of winter rye plants, of both hybrid and population varieties, was after the winter period 2020/2021: the mean number of the survived plants for all the varieties was 91.2% (Figure 2B).

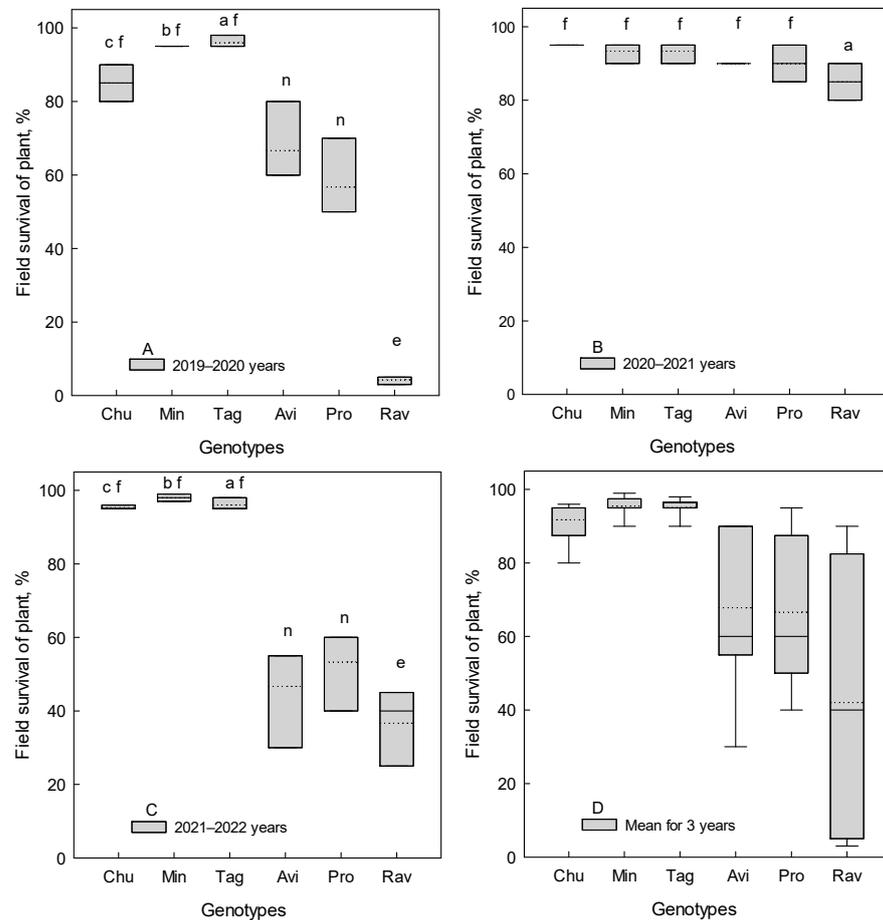


Figure 2. Survival of hybrid and population varieties of winter rye of different geographical origin in the field in (A) 2019/2020, (B) 2020/2021, (C) 2021/2022, and (D) mean for 3 years. The solid line represents the median and the dotted line represents the mean value. The upper and lower parts of the box correspond to the first and third quartiles (25th and 75th percentiles) ($n = 3$). The upper and lower whiskers represent the outlying data. The different lowercase letters represent statistically significant differences at $p < 0.001$, while the identical letters represent the absence of differences. Chu—Chulpan; Min—Mininskaya; Tag—Tagna; Avi—KWS Aviator; Pro—KWS Prommo; Rav—KWS Ravo.

This result was due to the long period of snow cover occurrence as well as the favorable temperature conditions (Figure 1). Plant survival in 2019/2020 was low (69.1% on mean) due to the long period of sharp temperature changes in the absence of snow cover (Figure 2A). Plant survival in 2021/2022 was similar to the period of 2019/2020 (74.5% on mean) (Figure 2C). During all three years of study, the population varieties (Tagna, Mininskaya, and Chulpan) demonstrated a high and stable level of overwintering (93.3–96.0%, mean = 95.3%) (Figure 2D). The overwintering level of the hybrid varieties (KWS Aviator, KWS Prommo, and KWS Ravo) was low (4.3–90.0%; mean = 57.0%). The two-way analysis of variance indicated statistically significant differences between plant survival over the years of study as well as interrelation between the parameters analyzed.

The varietal characteristics of winter rye plants had the main effect on their field survival (58.6%); the weather conditions had a lesser effect (12.6%). Plant survival depended

on the interaction of the two factors, by 24.7%. For the group of plants of the population varieties, the effect of the genotype and the year was at the same level (21.7% and 20.9%). For the hybrid varieties, the main factor affecting plant survival was the year (57.4%); the variety and their interaction had a lesser effect (18.6% and 16.4%).

In the laboratory, the freezing of winter rye seedlings demonstrated that there were no differences in survival in all the studied varieties at $-7\text{ }^{\circ}\text{C}$, $-10\text{ }^{\circ}\text{C}$, and $-12\text{ }^{\circ}\text{C}$ (Figure 3). The hybrid variety KWS Ravo was the exception: it had the highest number of dead seedlings at $-12\text{ }^{\circ}\text{C}$. The statistically significant differences in the resistance of the seedlings to low temperatures were revealed at $-14\text{ }^{\circ}\text{C}$; the local population varieties (Tagna and Mininskaya) demonstrated a high survival rate of seedlings compared to the population (Chulpan) and hybrid varieties (KWS Aviator, KWS Prommo, and KWS Ravo) from the other regions.

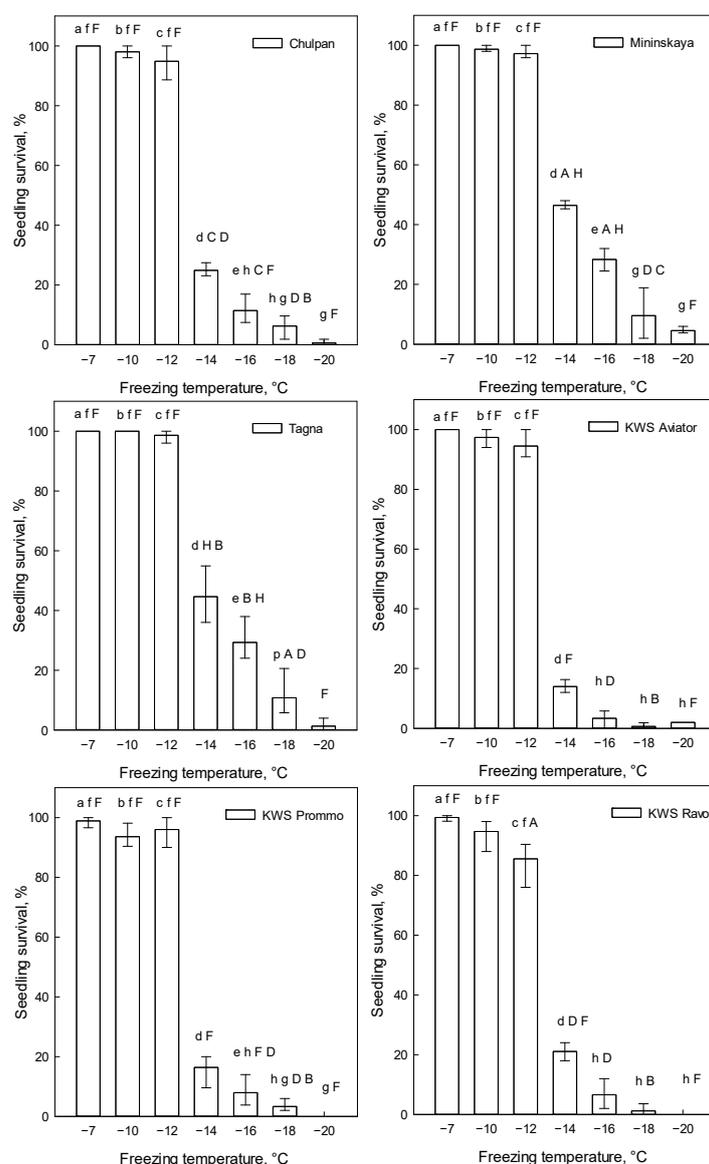


Figure 3. Resistance of seedlings of winter rye population and hybrid varieties to low negative temperatures. The data are presented as a mean, the bars represent the maximum and minimum ($n = 3$). The different lowercase letters represent differences in the survival of plants of the same variety at different temperatures ($p < 0.001$). The identical lowercase letters represent the absence of differences. The uppercase letters represent statistically significant differences between the genotypes at each freezing temperature. The identical uppercase letters represent the absence of differences.

Freezing at lower temperatures (−16 °C, −18 °C, and −20 °C) significantly reduced the survival of the seedlings of all winter rye varieties. The differences in the resistance of the seedlings among the varieties were still noticeable at −16 °C, but they were less pronounced. At −18 °C and −20 °C, the number of damaged seedlings of all the varieties leveled out. The laboratory experiments on the effect of low negative temperatures on winter rye seedlings confirmed that the varieties with high field survival had the highest LT₅₀ values. Only in the population variety Chulpan, LT₅₀ did not statistically differ from that value of KWS Aviator, KWS Prommo, and KWS Ravo (Table 1).

3.2. Productivity and Yield Components of Population and Hybrid Varieties of Winter Rye

The measured parameters of yield components (number of plants, number of spikes, 1000 kernel weight, number and weight of kernels per ear, and grain yield) demonstrated some differences between the hybrid and population varieties (Table 3). A significant effect of the year, genotype, and their interaction on seed productivity, number of plants, number of productive stems, and 1000 kernel weight was found (Table 4).

Table 3. Characteristics of grain yield and its components of various winter rye varieties in different growing seasons.

Cultivar	Group	Yield, t/ha			Number of Plants, m ²			Number of Spikes, m ²			1000 Kernel Weight, g			Weight of Kernels Per Ear, g			Number of Kernels Per Ear		
		2020	2021	2022	2020	2021	2022	2020	2021	2022	2020	2021	2022	2020	2021	2022	2020	2021	2022
Chulpan	P	6.5	6.6	4.8	373.0	418.0	461.0	807.0	921.0	764.0	32.5	34.9	35.7	1.5	1.6	1.4	43.0	45.0	41.0
Mininskaya	P	6.2	6.8	5.4	348.0	348.0	537.0	795.0	793.0	917.0	24.5	25.9	25.8	1.2	1.2	1.1	46.0	49.0	43.0
Tagna	P	8.6	7.8	5.0	422.0	350.0	647.0	761.0	859.0	1069.0	28.4	29.4	29.5	1.5	1.4	1.5	43.0	50.0	48.0
KWS Aviator	H	4.5	5.3	4.5	261.0	370.0	149.0	464.0	703.0	586.0	34.9	34.9	40.4	1.6	1.7	1.8	48.0	48.0	46.0
KWS Prommo	H	3.4	5.1	2.9	276.0	420.0	226.0	561.0	756.0	520.0	35.8	36.3	35.6	1.7	1.8	1.7	47.0	47.0	46.0
KWS Ravo	H	0.5	5.5	1.7	64.0	370.0	149.0	184.0	809.0	436.0	35.7	38.3	36.4	1.5	1.7	1.6	40.0	42.0	38.0
Significance of differences		***	***	***	***	ns	***	***	ns	***	***	***	***	*	*	*	*	*	***
LSD value		1.3	0.5	1.5	93.3	-	93.3	123.0	-	193.8	2.2	1.7	2.8	0.26	0.29	0.22	6.0	7.0	4.0
n		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Mean	P	7.1	7.0	5.1	381.0	372.0	548.0	787.0	857.0	916.0	28.4	30.0	30.3	1.4	1.4	1.3	44.0	47.0	44.0
	H	2.8	5.3	3.0	200.0	386.0	174.0	403.0	756.0	514.0	35.4	36.5	37.4	1.6	1.7	1.7	45.0	45.0	43.0
CV, %	P		19.4			18.6			11.7		13.6			18.5			6.8		
	H		45.6			36.8			22.8		5.1			4.9			5.1		

Note: P—population varieties; H—hybrid varieties; significance level of differences *— $p < 0.050$, ***— $p < 0.001$, ns—no differences ($p > 0.050$). LSD—the smallest significant difference between the mean in the column. n—the number of samples analyzed for each cultivar. CV—variation coefficient.

Table 4. Statistical processing of grain yield and its components.

	Data Variability, Years and Varieties	Mean Values of Rye Yield Parameters for 3 Years			Analysis of Variance and Components of Variances		
		2020	2021	2022	Year (Y)	Variety (V)	Y × V
Yield, t/ha	0.5–8.6	5.3	6.2	4.5	***	***	***
Number of plants, m ²	64.0–647.0	297.0	368.0	353.0	***	***	***
Number of spikes, m ²	184.0–1069.0	595.0	775.0	700.0	***	***	***
1000 kernel weight, g	24.4–45.7	33.4	34.9	35.6	***	***	**
Weight of kernels per ear, g	1.2–1.8	15.6	15.6	16.5	***	ns	ns
Number of kernels per ear	35.0–49.0	43.0	45.0	43.0	***	ns	ns

Note: significance level of differences **— $p < 0.01$, ***— $p < 0.001$, and ns—no differences ($p > 0.050$).

The grain yield ranged from 0.5 to 8.6 t/ha, depending on both the variety and the year (Table 3). The yield was most affected by varietal characteristics (57% of the variance), while the conditions of the cultivation year contributed only 17% of the total variance (Table 4). In terms of yield, the hybrid varieties were by 30 or more percent lower compared to the population strains (Table 3). The highest yields were obtained in the more favorable growing season of 2020/2021, when the mean productivity of all the studied samples

was 6.2 t/ha, compared to 5.5 t/ha in the 2019/2020 growing season and 4.5 t/ha in the 2021/2022 season (Table 3).

The number of plants of the hybrid and the population varieties ranged from 64 to 647. During the 2019/2020 and 2021/2022 growing seasons, the number of plants of the hybrid varieties was statistically significantly less than that of the population varieties (Table 3). During the 2020/2021 field season, the number of plants, both the hybrid (KWS Aviator, KWS Ravo, and KWS Prommo) and the population varieties (Tagna, Mininskaya, and Chulpan) did not statistically differ from each other. In the studied varieties, the effect of the genotype on the number of plants was high (44.9% of the total variance), compared to effect of the cultivation year (6.9%) (Table 4); the interaction of these factors had a slightly lesser effect (37.9%).

The number of spikes among the studied winter rye samples had a significantly greater variation (from 184 to 1069). That was due to the number of plants per unit area (Table 3). The smallest number of spikes was noted in the hybrid varieties, with the exception of the 2021 field season. The number of spikes was most affected by the variety (40%); the cultivation year conditions and the interaction of these factors had the least effect (24.5% and 20.6%, respectively) (Table 4).

The 1000 kernel weight varied from 24.4 g to 45.7 g (Table 3). To a greater extent, this indicator was affected by the genotype (88%) and to a lesser extent, by the cultivation year conditions (2%); the interaction of these factors was also insignificant (5%) (Table 4). By the 1000 kernel weight, the population varieties were lower than the hybrid rye, regardless of the field season (Table 3). The exception was the population variety Chulpan: the 1000 kernel weight was at the level of the hybrid varieties and exceeded 30 g.

The weight of kernels per ear was in the range from 1.2 g to 1.8 g. During all the field seasons, the weight of kernels per ear was higher in the hybrid varieties than in the population strains (Table 3). The smallest weight of kernels per ear was in the sample of the population variety Mininskaya. The variety had the greatest effect on the weight of kernels per ear (60.9%); the effects of the cultivation year conditions and of the interaction of these factors were insignificant (4.4% and 3.3%) (Table 4).

During all the years of study, the number of kernels per ear in all the studied winter rye samples had a slight difference from each other. The effect of the genotype had a more significant effect on the number of kernels per ear (32.6%) compared to the effect of the cultivation year conditions and the interaction of the factors (4.7% and 14.9%) (Table 4).

The interrelation between grain productivity, field survival, and yield components were analyzed. The correlation between productivity and field survival was the highest (Table 5) in the general group and hybrid varieties.

Table 5. Factors affecting winter rye grain productivity in Eastern Siberia.

Factors	Correlation Coefficient		
	HP	H	P
Field survival, %	0.84 ***	0.90 ***	−0.31 ^{ns}
Number of plants, m ²	0.56 ***	0.77 ***	−0.53 *
Number of spikes, m ²	0.61 ***	0.80 ***	−0.39 *
1000 kernel weight, g	0.19 ^{ns}	0.47 *	0.05 ^{ns}
Weight of kernels per ear, g	−0.18 ^{ns}	0.42 *	0.52 **
Number of kernels per ear	−0.46 **	−0.02 ^{ns}	0.14 ^{ns}

Note: *— $p < 0.050$, **— $p < 0.001$, ***— $p < 0.0001$, ^{ns}—no differences ($p > 0.050$). HP—all the varieties, H—hybrid varieties, P—population varieties.

At the same time, high correlation was observed between the yield, the number of plants, and the number of spikes, both in the general group and in the hybrid varieties. The correlation between the grain yield, the field survival, the number of plants, and the number of spikes in the population varieties was low and negative both in one and in the other case (Table 5). In the hybrid varieties, the interrelation between productivity and 1000 kernel weight was low, although in the population varieties and in the group as a

whole it was low and unreliable. The weight of kernels per ear positively correlated with grain productivity, both in the hybrid and the population varieties, although in the group as a whole, a negative and unreliable correlation was noted. The low and negative unreliable correlation between the grain productivity and number of kernels per ear in both groups of the varieties was illustrated (Table 5).

4. Discussion

In the field, during the winter period, plant damage can be caused not only by the action of low temperatures, but also by other abiotic and biotic factors, including freeze-thaw cycles [31–35]. Under the conditions of Eastern Siberia, the critical stage in the overwintering of plants is the period of late winter and early spring, when plants are exposed to a complex of adverse environmental factors and have reduced resistance to stress. In this particular period, damage and death of plants in the winter crops is noted [25,36].

A principal requirement for winter crops grown in the soil and climate of the forest-steppe of Eastern Siberia is their high resistance to the adverse environmental factors of the winter period [37]. According to the analysis of the field experiments, the survival of the population varieties in all the years is 38% higher than that of hybrid rye. The varietal factor had the greatest effect on plant viability (more than 50%).

The productivity of the population varieties in the conditions of Eastern Siberia was higher than that of the hybrid rye. The grain yield of the population varieties was near 40% (2.1 t/ha) in 2022 and near 60% (4.3 t/ha) in 2020, higher than that of the hybrid varieties. Despite the successful overwintering in 2021, the productivity of the hybrid varieties was statistically significantly lower by 24% (1.7 t/ha) than that of the population varieties (Table 3). It is to be supposed that these hybrid varieties turned out to be less resistant to the soil and climate of Eastern Siberia than the local population varieties. This fact does not fit into the well-known regular pattern about the superiority (in most cases) of hybrid varieties in a number of agronomic parameters (yield, resistance to diseases, drought, low temperatures, etc.) over population varieties [8,10,38]. It was previously demonstrated that in the field conditions of Finland, under favorable growing conditions, the German hybrid variety Picaso performed better than the Finnish population varieties; however, when stressful conditions (such as drought) occurred, Picaso lost its superiority [14]. According to our data, the decrease in productivity of the hybrid varieties (KWS Aviator, KWS Ravo, and KWS Prommo) compared to population varieties (Mininskaya, Tagna, and Chulpan) did not depend on stressful growing conditions during the 2020/2021 season. During that period, the temperature regime and amount of precipitation were at the level of long-term mean values, with minor deviations. It is not yet entirely clear what caused the decrease in yield of the hybrid varieties under favorable growing conditions. Therefore, it is necessary to continue field experiments with a large number of hybrid varieties under study.

According to the results of the present research, changes in yield components were caused by varietal characteristics (Table 3). The main component of winter rye productivity, which demonstrated significant differences, depending on the field season and genotype, are the number of plants and quantity of spikes. The number of plants and spikes in the hybrid varieties in unfavorable seasons (2019/2020, 2021/2022) was 40% lower than those in the population strains. The change in the number of plants and spikes, both in the hybrid and population varieties, did not affect the number of kernels per ear, the weight of kernels per ear, or the 1000 kernel weight (Table 3), although there were isolated cases of a slight increase/decrease in individual parameters.

The yield value of winter rye was closely dependent on winter hardiness, both in the general group of plants and in the hybrid varieties: the correlation coefficient was statistically significant ($p < 0.0001$) ($r = 0.84 \dots 0.90$) (Table 5). This result demonstrates that the productivity of hybrid varieties of the foreign selection in the conditions of Eastern Siberia largely depends on the resistance of plants to adverse conditions in the winter period. On the contrary, in the population varieties, the correlation was negative and unreliable, which indicates the effect of other factors on grain productivity, and is not

directly related to the field survival of plants. This result may be due to the different responses of the varieties to the temperature and hydrothermal regimes of the particular field season in certain stages of plant development.

On mean, the dependence between the yield, the number of plants, and the number of spikes in the hybrid varieties was significantly high ($r = 0.77$ and $r = 0.80$), while in the general group of plants, the dependence was medium positive and significant ($r = 0.56$ and $r = 0.61$) compared to the popular varieties. Szuleta et al. [8] found a negative and insignificant correlation between productivity and the number of stems in hybrid varieties (KWS Bono, KWS Brasetto, and KWS Serafino). The opposite pattern of correlations between the productivity and number of stems in the hybrid varieties is possibly due to the high number of overwintered plants, regardless of the sowing time in Kentucky conditions during the study period, and, as a result, high productivity.

The differential characteristic of the hybrid varieties, compared to the population strains, is the 1000 kernel weight and weight of kernels per ear. In general, the hybrid varieties, in terms of the 1000 kernel weight and weight of kernels per ear, were higher than the population strains by 20–28% and 18–22%, respectively. Despite the fact that the hybrid varieties had a higher 1000 kernel weight and weight of kernels per ear than the population strains, they could not compensate for the difference in productivity. The 1000 kernel weight was not closely related to grain yield in the general group of varieties (the hybrid and population varieties) and separately in the population varieties, while in the hybrid varieties the correlation was significantly mean ($r = 0.47$). A slight correlation of weight of kernels per ear with grain yield in both the population and the hybrid varieties was noted ($r = 0.52$ and $r = 0.42$), although in the general group, the relation was weak and negative. The correlations between the number of kernels per ear and grain productivity (both for the general group of varieties and for the individual categories) were mutually weak and negative. Earlier, a close significant relation between the grain yield and number of kernels per ear was found [10]. Research also demonstrated the close relation between yield and number of kernels per ear ($r = 0.70$) [39]. Some authors demonstrated that the increase in grain productivity in hybrid varieties is mainly due to the number of kernels per ear and ear density, while the 1000 kernel weight is an important parameter for increasing the productivity of population varieties [10,40,41].

5. Conclusions

In the conditions of Eastern Siberia, the main limiting factor in the grain productivity of winter rye is the level of overwintering. That fact is confirmed by the high correlation between the productivity and field survival of plants. In the setting of Eastern Siberia, the main components of grain yield in the hybrid varieties of the foreign selection are the number of plants and quantity of productive stems per unit area; this is confirmed by the high correlation. The grain productivity of local population varieties largely depends on the set of agro-climatic conditions during the period of plant growth and development.

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