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Frost resistance and survival of winter wheat after spring rape in the conditions of the Northern Steppe of Ukraine

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Abstract. The gradual climate warming is leading to emergence of more intensive varieties of winter wheat and therefore urges scientists to improve the technology of its cultivation. Research of the reaction of winter wheat varieties to an atypical predecessor (winter rape), sowing dates and seed sowing rates is gaining relevance. The study was carried out on the research field of the Scientific and Educational Center of Practical Training of the Dnipro State Agrarian and Economic University in 2018–2020 on common low-humus medium-thick silty-medium loam black soil on the loess. Winter wheat plants that had been sown on 25th and 15th of September had the highest values of the frost resistance index. On average, over the years of research, when the plants were frozen at the temperature of –16 ºC for 72 hours, the frost resistance of the Zolotokolosa variety from these sowing dates was 98.1% and 96.7%, respectively. Highest tolerance to low temperatures was exerted by the Selianka variety, equaling 98.4% and 97.1%, and the tolerance of the Podolianka variety was the lowest, 98.1% and 96.3%, respectively. The maximum number of survived winter wheat plants was in the variants of the experiment where sowing was carried out in September 25–26 (97.1%). The survival of winter crops was lower if sown on October 5 (96.0%) and September 15–17 (95.1–96.1%), and the lowest if sown on September 5–7 (94.0–95.0%). The maximum yield (4.90 T/ha) was produced by the Selianka variety sown on 25th–26th of September, at the rate of 5.0 million intact seeds/ha. The Zolotokolosa variety produced the highest yield after being sown on 25th–26th of September at the rate of 5.0 million intact seeds/ha (4.20 t/ha) and sown on 5th–7th of October at the rate of 6.0 million intact seeds/ha (4.21 t/ha). The highest yield from the Podolyanka variety was obtained after sowing in the first decade of October, the sowing rate being 6.0 million seeds/ha (3.76 t/ha).

Keywords: winter wheat; variety; frost resistance; survival rate; sowing rate; sowing time; productivity.

Introduction

Increasing the production of high-quality wheat grain is one of the priority tasks of the modern agricultural sector of Ukraine. Solving this problem requires using modern innovations in wheat cultivation, which would be zonally adapted and ensure the formation of the maximum level of grain productivity. The main factors that determine high yields of winter wheat are predecessors, varieties, sowing dates and seed sowing rates (Laurent et al., 2020; Gandía et al., 2021).

The gradual climatic changes towards warming and the emergence of more intensive varieties of winter wheat are urging scientists to solve the issue by improving the technology of its cultivation. Research of the reaction of winter wheat varieties to an atypical predecessor (winter rape), sowing dates, and seed sowing rates is becoming relevance.

Stressful conditions for the development of winter crops are often caused by abiotic (lack of moisture in the soil, excessively low and critically high air temperatures) and biotic factors (development of harmful mycoflora, pests). The magnitude of their influence on the grain productivity of winter wheat is determined by the soil, climatic, and agrotechnical conditions of crop cultivation (Linina et al., 2018; Bakumenko et al., 2019; Mostipan et al., 2021; Yarchuk et al., 2021; Zapisotska et al., 2021; Vinyukov et al., 2022). That is why the relevance of the issue of improving agrotechnical methods of cultivating winter crops has been recently growing rapidly, which is also due to the increase in the share of oil crops (rape, sunflower, etc.) in the structure of the acreage of the Steppe Zone, which are used as predecessors of wheat in crop rotation. In order to increase the grain productivity of an agrocenosis, it is important to account for the biological features of modern high-yielding varieties of winter wheat, which have high yield potential and react differently to growing conditions. The influence of a variety on the yield of winter wheat was 11%, and that of the predecessor was 19%. Weather conditions of the year had the largest share of influence (70% on average) (Linina et al., 2018; Arora, 2019).

Other than sowing dates and weather conditions, some of crucial and available means are the varieties, which can increase yield productivity to 20–25%. Correction of sowing dates, selection of varieties and predecessors will ensure obtaining higher yield values of winter wheat (Zaiets, 2019).

In order to obtain stable high yields of wheat grain, it is important to optimally use the varietal adaptive potential, which already makes it possible to produce 23–25 million tons of grain, and in the future could produce over 30 million tons (Kryzhanivskyi et al., 2020). The size and quality of the wheat harvest significantly depend on the varieties, the selection of which must be carried out based on their characteristics, taking into account the zoning, as well as its sowing dates according to the sowing rates, etc. (Krivenko et al., 2018; Demydov, 2021; Sakaliy et al., 2021).

The objective of the study was to identify the peculiarities of the formation of grain productivity of different varieties of winter wheat under the influence of sowing dates and seed sowing rates if sown after spring rape.

Materials and methods

The study was carried out in the research field of the Scientific and Educational Center of Practical Training of the Dnipro State Agrarian and Economic University in 2018–2020, on common low-humus medium-thick silty-medium loam black soil on loess. The soil was characterized by high potential and effective fertility (humus content in 0–30 cm layer was 3.90%, total nitrogen – 0.22%, phosphorus – 0.13%, potassium – 2.20%).

The winter wheat was grown according to the generally accepted technology for the Steppe Zone of Ukraine. The predecessor of winter wheat was winter rape. After harvesting the predecessor (rape), the soil was treated (two times) with heavy disc harrows Pallada 2400 with 10–12 cm depth. In August and September, we carried out KSO – 4H cultivation. The latter was done just before sowing winter wheat at the depth of 6.0–8.0 cm. Fertilization of the soil was carried out separately, with $N_{15}P_{15}K_{15}$when sowing under pre-sowing cultivation and $N_{30}P_{30}K_{30}$ in in the tillering phase.

During the experiments, we observed a high variability in the values of weather elements, in particular, the air temperature regime and the amount of atmospheric precipitation, which fell unevenly during the years of research. Analyzing the weather conditions of the 2018–2020 growing season, it should be noted that, in general, they were favorable for the growth and development of winter wheat plants.

After spring rape, the following varieties of winter wheat were sown: Selianka, Podolianka, and Zolotokolosa. Seed sowing rate of the wheat varieties was 4, 5 and 6 million intact seeds/ha. Sowing was carried out in four periods: September 5–7, 15–17, 25–26, and October 5th–7th. Due to the weather conditions during the research period, it was not possible to sow winter wheat according to the experiment calendar scheme each year. In some years, the sowing dates were shifted 1–2 days later than planned. Frequency in the experiment was three times with consistent systematic organization of plots.

The following observations and studies were carried out in accordance with the existing methodological recommendations: the depth of the tillering node and the number of nodal roots, frost resistance and plant survival, leaf surface area, and productivity (Vovkodav, 2001; Vogegova et al., 2014). The complexity of the influence of weather conditions and agrotechnical techniques studied in the experiments created unequal conditions for the growth and development of the winter wheat plants during the autumn growing season.

The data were analyzed in the Statistica 8.0 (StatSoft Inc., USA) software. The data are presented in the tables as x ± SD (mean ± standard deviation). Differences between the values in the experimental groups were determined using the Tukey test, where the differences were considered reliable at $P < 0.05$ (taking into account the Bonferroni's Correction).

Results

According to the research results, the plants of wheat varieties that had been sown earlier tilled more intensively than those sown in late periods. On average, over the years of study, the coefficient of tillering was in the range of 3.80–4.90 in wheat sown on September 5–7, depending on the variety and sowing rate, 3.40–4.10 for September 15–17 wheat, 2.30–2.80 for September 25–26 wheat, and for 1.10–1.20 October 5–7 wheat. That is, there was a marked tendency towards decrease in the coefficient of tillering in winter crops after shifting sowing dates from early to late.

We determined the influence of the sowing rate on the tillering coefficient of winter wheat. The highest indicators were observed for the rate of 4 million intact seeds/ha, and the subsequent increase in the sowing rate gradually and rapidly reduced the coefficient of plant tillering, especially for the sowing rate of 6 million intact seeds/ha: 17.5% decrease in Zolotokolosa variety sown on September 5–7; 18.5% and 17.1% in varieties Selianka and Podolianka; 10.6%, 12.3%, and 10.4% after sowing on September 15–17; and 11.6%, 14.4%, and 14.7% decreases after sowing on September 25–26, respectively.

At low sowing rates (4.0 million intact seeds/ha), plants had a larger nutrition area and experienced no deficiency of light. In such crops, the competition for life factors was significantly lower than in plants that were sown at the rates of 5 and 6 million seeds/ha.

In the course of the subsequent growing season, the difference between winter wheat plants that were sown later decreased, and after sowing on October 5–7, the coefficient of tillering was almost the same regardless of sowing rates and variety. Therefore, after sowing in this period, the tillering coefficient of the Zolotokolosa and Podolianka varieties was 1.2 for all seed sowing rates, and 1.3 for the Selianka variety (Table 1).

Variety Selianka had the maximum tillering, the plants of which formed a greater number of shoots than varieties Zolotokolosa and Podolianka. Depending on the sowing rate, winter wheat of the Selyanka variety formed 4.1–5.0 shoots per plant after sowing on September 5–7, 3.7–4.2 on September 15–17, 2.5–2.9 on September 25–26, and 1.3 shoots/plant after October 5–7 sowing. On the other hand, the Zolotokolosa variety had the lowest tillering coefficient, in some variants being the same as in the Podolianka variety (October 5–7 sowing). It was 3.9–4.7 in winter crops that were sown during this time; 3.5–3.9, 2.4–2.7, and 1.2 shoots/plant. The Podolianka variety formed 4.0–4.8 shoots/plant after being sown on September 5–7, 3.6–4.0 after sown on September15–17, 2.40–2.80 after September 25–26 sowing, and 1.20 shoots/plant after October 5–7 sowing.

The difference in the number of tillering shoots between wheat plants of different sowing periods was that winter wheat that had been sown in early periods used high air temperatures much more effectively and, compared with the late-periods plants, tended to tiller more intensively. The decrease in the average daily air temperature, which we noted for the late-periods populations, caused a decrease in the intensity of tillering. At the end of vegetation in autumn, the highest number of nodal roots was formed by the wheat plants sown on September 5-7. Depending on the sowing rate, after sowing in this period, the number of nodal roots was 5.4–5.8 per plant in the Zolotokolosa variety, and 5.6–6.0 and 5.3–5.7 per plant in the Selianka and Podolianka varieties, respectively.

Table 1
Peculiarities of the formation of shoots and the root system in plants of various varieties of winter wheat under the influence of sowing dates and sowing rates in 2018–2020 (x ± SD, n = 8)

Sowing terms	Sowing rates, million similar seeds/ha	Coefficient of tillering			The number of nodal roots per plant		
		Zolotokolosa	Selianka	Podolianka	Zolotokolosa	Selianka	Podolianka
5th–7th of September	4.0	4.7 ± 0.3^{a}	5.0 ± 0.3^{a}	4.8 ± 0.3^{a}	5.8 ± 0.3^{a}	6.0 ± 0.4^{a}	5.7 ± 0.3^{a}
	5.0	4.5 ± 0.2^{a}	4.8 ± 0.4^{a}	4.6 ± 0.4^{a}	5.5 ± 0.3^{a}	5.7 ± 0.4^{a}	5.4 ± 0.4^{a}
	6.0	3.9 ± 0.2^{ab}	4.1 ± 0.3^{ab}	4.0 ± 0.3^{ab}	5.4 ± 0.4^{a}	5.4 ± 0.3^{a}	5.3 ± 0.3^{a}
15th–17th of September	4.0	3.9 ± 0.4^{ab}	4.2 ± 0.3^{ab}	4.0 ± 0.2^{ab}	4.1 ± 0.4^{b}	4.2 ± 0.3^{b}	4.1 ± 0.3^{b}
	5.0	3.7 ± 0.3^{ab}	3.9 ± 0.4^{ab}	3.8 ± 0.3^{ab}	3.6 ± 0.3^{b}	3.7 ± 0.3^{b}	3.6 ± 0.3^{b}
	6.0	3.5 ± 0.3^{ab}	3.7 ± 0.2^{ab}	3.6 ± 0.4^{ab}	3.4 ± 0.3^{b}	3.5 ± 0.3^{b}	3.4 ± 0.4^{b}
25th–26th of September	4.0	2.7 ± 0.3^{b}	2.9 ± 0.3^{b}	2.8 ± 0.2^{b}	3.0 ± 0.2^{bc}	3.1 ± 0.2^{bc}	3.0 ± 0.3^{bc}
	5.0	2.6 ± 0.2^{b}	2.8 ± 0.3^{b}	2.7 ± 0.3^{b}	2.6 ± 0.3^{bc}	2.7 ± 0.3^{bc}	2.5 ± 0.2^{bc}
	6.0	2.4 ± 0.3^{b}	2.5 ± 0.4^{b}	2.4 ± 0.3^{b}	2.3 ± 0.4^{c}	2.4 ± 0.2^{c}	2.2 ± 0.3^{c}
5th–7th of October	4.0	1.2 ± 0.2^{c}	1.3 ± 0.2^{c}	1.2 ± 0.2^{c}	1.2 ± 0.3^{d}	1.4 ± 0.2^{d}	1.2 ± 0.2^{d}
	5.0	1.2 ± 0.2^{c}	1.3 ± 0.2^{c}	1.2 ± 0.1^{c}	1.2 ± 0.2^{d}	1.4 ± 0.2^{d}	1.2 ± 0.3^{d}
	6.0	1.2 ± 0.3^{c}	1.3 ± 0.2^{c}	1.2 ± 0.1^{c}	1.2 ± 0.1^{d}	1.4 ± 0.1^{d}	1.2 ± 0.2^{d}

Note. Different letters indicate the values that are significantly different one from another within a column of Table 1 according to the Tukey test ($P < 0.05$) with the Bonferroni's Correction.

After later sowing periods, this led to decreases in the tillering and the number of plant roots. The minimum number of nodar roots was noted in the variants where the wheat was sown on October 5–7. Depending on the density of crops, their number in varieties Zolotokolosa, Selianka, Podolianka was 1.1, 1.3 and 1.1 per plant, respectively (Table 1).

The study revealed that the deepest nodule of tillering in our experiments was in winter wheat plants of the Selianka variety. In this variety, the depth of its occurrence, depending on the rate of sowing seeds, was 3.1–3.3 cm for September 5–7 sowing, 2.7–2.9 cm for September 15–17, 2.5– 2.7 cm for September 25–26, and 1.5–1.7 cm for October 5–7 sowing. Plants of the Podolianka variety had the lowest depth of the tillering node. After similar sowing periods, it was 2.9–3.1, 2.5–2.6, 2.3–243 and 1.3–1.4 cm, respectively. The Zolotokolosa variety, according to the size of the indicator, had an average value. At the end of autumn vegetation, the tillering node of plants was 3.0–3.2 cm depth after sowing on September 5–7, 2.5–2.6 cm on September 15–17, 2.4–2.5 cm on September 25– 26, and 1.4–1.5 cm after sowing on October 5–7 (Table 2).

Table 2
The depth of the tillering node (cm) in different varieties of winter wheat before wintering, depending on time of sowing and the sowing rate, for 2007–2009 (x ± SD, n = 8)

Sowing period	Sowing rates, million intact seeds/ha	Varieties		
		Zolotokolosa	Selianka	Podolianka
September 5-7	4.0	3.2 ± 0.2^{a}	3.3 ± 0.3^{a}	3.1 ± 0.4^{a}
	5.0	3.1 ± 0.3^{a}	3.1 ± 0.4^{a}	3.0 ± 0.3^{a}
	6.0	3.0 ± 0.4^{a}	3.1 ± 0.3^{a}	2.9 ± 0.5^{a}
September 15-17	4.0	2.6 ± 0.3^{ab}	2.9 ± 0.2^{a}	2.6 ± 0.4^{a}
	5.0	2.6 ± 0.5^{ab}	2.7 ± 0.3^{ab}	2.5 ± 0.4^{ab}
	6.0	2.5 ± 0.4^{ab}	2.7 ± 0.2^{ab}	2.5 ± 0.4^{ab}
September 25-26	4.0	2.5 ± 0.5^{ab}	$2.7 \pm .4^{ab}$	2.4 ± 0.3^{ab}
	5.0	2.4 ± 0.4^{ab}	2.6 ± 0.3^{ab}	2.3 ± 0.3^{ab}
	6.0	2.4 ± 0.3^{ab}	2.5 ± 0.3^{ab}	2.3 ± 0.2^{ab}
October 5 -7	4.0	1.5 ± 0.4^{b}	1.7 ± 0.2^{b}	1.4 ± 0.2^{b}
	5.0	1.4 ± 0.4^{b}	1.6 ± 0.3^{b}	1.3 ± 0.3^{b}
	6.0	1.4 ± 0.3^{b}	1.5 ± 0.2^{b}	1.3 ± 0.2^{b}

Note: see Table 1.

During the winter period, partial damage to plants or their complete death often occurs due to low air temperatures, which are below the critical limits. Changes in the temperature regime of air, when low temperatures are followed by higher ones, after which the temperature drops steeply again, are especially threatening for the normal wintering of winter crops. Absence of snow on winter-crop fields during the negative impact of low air temperatures significantly increases the probability that the plants would freeze. In order to determine how winter wheat is resistant to frost and winter, we used the method of freezing plants, taken in earth cubes, in special freezing chambers. The results of freezing make it possible to identify the ability of plants to withstand the action of low temperatures, i.e. their frost tolerance.

For the freezing of plants in earth cubes, we used plants of different varieties and sowing dates. To identify the frost resistance, we sampled only the plants of the variants in which the sowing rate of 5 million intact seeds/ha. According to the research results, winter wheat plants sown on September 25 and 15 had the highest values of the frost resistance index. When the plants in cubes were frozen at the temperature of –16 ºC for 72 hours, the frost resistance of the Zolotokolosa variety for these sowing dates was 98.1% and 96.7%, respectively. Resistance to low temperatures was the highest in the Selianka variety, 98.4% and 97.1%, and the lowest in the Podolianka variety, 98.1% and 96.3%, respectively (Table 3).

A similar trend was also observed after freezing at lower temperatures. In particular, after freezing the winter crops at the temperature of –18 ºC, the frost resistance of winter wheat plants of the Selianka variety was the highest among the varieties. High value of this indicator was also noted in winter crops sown on September 25, measuring 74.3%. The frost resistance of the Zolotokolosa plants sown on this specific date was lower than such of the Selianka variety, accounting for 73.7%, and such of the Podolianka variety was even lower – 73.0%. It should be noted that crops of the early sowing period (September 5–7) were characterized by the lowest frost resistance. Thus, on average for 2018–2020, when the plants in cubes were frozen at the temperature of –18 ºC, the frost resistance of the Zolotokolosa plants was 54.4%, and such of the Selianka and Podolianka varieties was 54.8 and 53.8%, respectively. A decrease in the freezing temperature to –20 ºC within 72 hours led to a sharp decrease in the level of frost resistance of plants of different sowing dates. Depending on the sowing time, this indicator ranged 5.1% to 20.2% in the Zolotokolosa variety, 5.4% to 20.7% in the Selianka variety, and 4.9% to 19.6% in the Podolianka variety.

The analysis of frost resistance of plants of different varieties of winter wheat for each year of the study separately showed that the lowest values of frost resistance were observed in the conditions of 2020. Thus, when plants were frozen at –16 ºC, the frost resistance of the Selianka variety, depending on the sowing time, was 78.1–95.0%, and such of the Zolotokolosa and Podolianka varieties equaled 77.3–94.3% and 76.9–94.0%, respectively. In the conditions of 2018, this indicator of those varieties was the highest – 80.2–100.0%, 79.5–100.0%, and 79.0–100.0%, respectively. In order to identify the further vitality of the plants in the sampled earth cubes, winter wheat of different sowing periods was left to grow after preliminary being frozen at –18 ºC for 72 hours (Fig. 1).

The presented figure shows that on the twentieth day of growth after freezing, winter wheat plants did not lose their viability. However, at the same time, it is clearly visible that the color of the plants was different, depending on sowing timing. The leaf laminae of winter wheat that had been sown on September 25–26 and October 5–7 were greener, which certainly indicates a better state of development, better plant resistance to the negative effects of low temperatures. The leaves of plants of the early sowing period (September 5–7) were lighter. In addition, there was a significant difference in density of the plants sown on different dates. The figure shows that the number of winter wheat plants in earth cubes increased from early to late sowing periods.

Table 3
Frost resistance of plants of different winter wheat varieties (%) depending on the sowing dates for 2018–2020 (x ± SD, n = 8)

Sowing period	Freezing temperatures with exposure for 72 hours			
	–14 ºC	–16 ºC	–18 ºC	–20 ºC
Zolotokolosa variety				
September 5-7	86.3 ± 2.5^{b}	78.7 ± 2.8^{b}	54.2 ± 2.1^{b}	5.1 ± 0.5^{b}
September 15-17	99.3 ± 2.8^{a}	96.7 ± 3.1^{a}	72.7 ± 1.9^{a}	18.2 ± 1.2^{a}
September 25-26	99.7 ± 2.7^{a}	98.2 ± 3.5^{a}	73.7 ± 2.2^{a}	20.2 ± 1.3^{a}
October 5-7	97.9 ± 3.1^{a}	92.3 ± 2.9^{a}	69.3 ± 2.5^{a}	10.6 ± 0.6^{ab}
Selianka variety				
September 5-7	86.8 ± 3.2^{b}	79.5 ± 2.8^{b}	54.8 ± 1.8^{b}	5.4 ± 0.4^{b}
September 15-17	99.4 ± 3.3^{a}	97.1 ± 3.2^{a}	73.1 ± 1.7^{a}	18.8 ± 1.1^{a}
September 25-26	99.8 ± 3.6^{a}	98.4 ± 3.3^{a}	74.3 ± 1.9^{a}	20.7 ± 1.3^{a}
October 5-7	98.2 ± 3.8^{a}	92.8 ± 3.5^{a}	69.8 ± 2.2^{ab}	11.1 ± 0.8^{b}
Podolianka variety				
September 5-7	85.8 ± 2.7^{b}	78.3 ± 2.8^{b}	53.8 ± 2.2^{b}	4.9 ± 0.4^{b}
September 15-17	99.1 ± 3.1^{a}	96.3 ± 3.3^{a}	72.1 ± 2.3^{a}	17.8 ± 1.1^{a}
September 25-26	99.5 ± 3.5^{a}	98.1 ± 3.3^{a}	73.0 ± 2.8^{a}	19.6 ± 1.3^{a}
October 5-7	97.4 ± 2.9^{a}	91.7 ± 3.2^{a}	68.7 ± 2.5^{a}	9.9 ± 0.7^{ab}

Note: sampling on January 25 in areas with the seed sowing rate of 5 million intact seeds/ha.

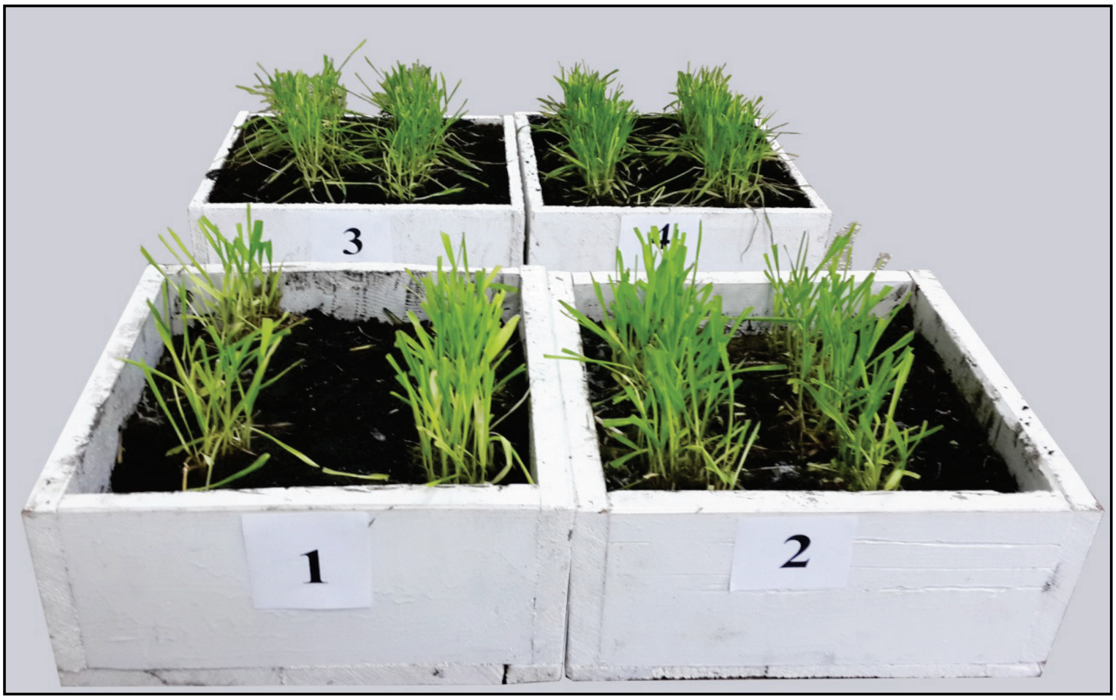

Fig. 1. Winter wheat plants of different sowing dates on the 20th day of growth after freezing at –18 ºC for 72 hours: September 1–5; September 2–15; September 3–25; October 4–5

The studies revealed a difference in the survival rate of plants during the winter period, depending on the sowing time. The largest number of survived winter wheat plants was seen in the variants of the experiment where sowing was carried out on September 25–26 (97.1%). The survival rate of winter crops was somewhat lower for the plants sown on October 5 (96.0%) and September 15–17 (95.1–96.1%), and the lowest for plants of September 5-7 sowing (94.0–95.0%). The number of shoots that remained after the wintering period depended on many factors, in particular, the time of sowing. Thus, the smallest number of survived shoots was recorded for the plants of the early sowing period (September 5–7) and was, depending on the rate of seed sowing, 72.0–73.0% in the Zolotokolosa variety, and 68.0–70.0% and 72.0–74.0% in the Selianka and Podolianka varieties, respectively. With the shift of sowing dates to later ones, shoot survival in winter crops gradually increased, being the highest in the variants where wheat was sown after spring rape on October 5-7. After being sown in this period, the survival of the shoots after the winter period was 96.1% in Zolotokolosa and Podolianka, 96.0–97.0% in Selyanka, which certainly indicates relatively better conditions for the survival of late crops (Table 4).

We observed the influence of the rate of seed sowing on the survival of plants. According to the results, sowing on September 5–7 and 15–17, increasing the seed sowing rate to 6 million intact seeds/ha, led to 1% decrease in the plant survival rate. The plants sown on later dates did not have this difference in this indicator.

According to the results, the area of the leaf surface in our experiments depended on the varietal characteristics of the plants and the time of sowing. In some years, the process of formation of the assimilation surface in the plants had signs of individuality. For example, in the phase of spring tillering, this indicator in the Zolotokolosa variety, depending on the sowing time, was 17.1–18.1 thousand m²/ha in 2018; 12.2–13.7 thousand m²/ha in 2019, 14.5–15.9 thousand m²/ha in 2020. In the Selyanka variety, it was 17.9–19.0 thousand m²/ha, 16.2–17.8 thousand m²/ha, and 16.9–18.4 thousand m²/ha; in the Podolianka variety, it equaled 17.8–18.6 thousand m²/ha, 13.3–15.7 thousand m²/ha, and 15.4–17.3 thousand m²/ha, respectively.

The largest area of wheat plant leaves was formed in the earing phase. However, at the final stages of organogenesis, we saw a gradual decrease in the assimilation surface due to death of the leaf apparatus in the lower parts of the stem, and later in the upper part.

In our experiments, the time of sowing had a significant influence on the formation of the leaf surface area of the winter wheat plants. The highest values of this indicator were seen in the variants where sowing was performed between the middle of the third decades of September (September 25–26) and the first decade of October (October 5–7).

Among the studied varieties, the largest leaf surface area was seen in the Selianka variety sown on September 25–26. In these variants of the experiment, it was 49.4 thousand m²/ha in the earing phase. In varieties Zolotokolosa and Podolianka, the largest leaf surface area was attained after sowing on October 5–7 and 47.3 and 45.9 thousand m²/ha, respectively (Table 5).

The study also revealed the influence of the rate of sowing on the formation of the leaf surface area by plants. The largest leaf area was observed in the plants on plots with the sowing rate of 4 million intact seeds/ha. Thickening of crops was accompanied by a decrease in the area of leaves per plant. The yield of winter wheat heavily depended on varietal characteristics, sowing dates, and sowing rates.

High yield indicators, on average for 2018–2020, were provided by all the studied varieties sown on September 25–26 and October 5–7. The Selianka variety turned out to be the most productive among the varieties. The grain productivity of this variety varied under the influence of growing conditions, on average ranging 3.43–4.91 t/ha over the years of the research. This variety had the greatest productivity (4.91 t/ha) after being sown on September 25–26, with the sowing rate of 5 million intact seeds/ha.

Wheat of the Zolotokolosa variety formed a somewhat lower yield (3.32–4.22 t/ha) compared with the Selianka variety. Its most productive population was the one sown on October 5–7 with the sowing rate of 6 million intact seeds/ha (4.22 t/ha) and on September 25–26 with the sowing rate of 5 million intact seeds/ha (4.21 t/ha).

The yield of the Podolianka variety was the lowest among the varieties, ranging 3.1 to 3.77 t/ha. Its maximum grain productivity (3.77 t/ha) was formed by the plants sown on October 5, with the seed sowing rate of 6 million intact seeds/ha. The minimum yield of the winter wheat varieties was formed in populations sown on September 5–7. Under the influence of the seed sowing rate, it was 3.32–3.49 t/ha in the Zolotokolosa variety, 3.43–3.69 and 3.10–3.20 t/ha in the Selianka and Podolianka varieties, respectively.

We should also note the significant influence of sowing rates on grain productivity of winter wheat. The yield level of plants that had been sown at the rate of 4 million intact seeds/ha was the lowest. An increase in the rate of seed sowing promoted increase in the yield of the crop. Analysis of the yield of winter wheat in relation to year of the research revealed that it was the largest in 2018 and, depending on the studied factors, was 4.30–5.23 t/ha in the Zolotokolosa variety, 4.53–5.00 in the Selianka and Podolianka varieties, 58 and 4.10–4.89 t/ha, respectively.

Table 4
Survival of the plants and shoots (%) of different varieties of winter wheat during the wintering period, depending on the sowing dates and sowing rates for 2018–2020 (x ± SD, n = 8)

Sowing time	Sowing rates, million/ha	Quantity per m^2 per period				Saved, %	
		end of vegetation		resumption of vegetation			
		plants	shoots	plants	shoots	plants	shoots
Zolotokolosa variety							
September 5–7	4.0	318.0 ± 12.1[a]	1463.0 ± 55.6[c]	302.0 ± 10.8[a]	1057.0 ± 40.2[ab]	95	72
	5.0	400.0 ± 12.9[b]	1760.0 ± 62.3[b]	380.0 ± 11.1[b]	1292.0 ± 44.5[a]	95	73
	6.0	484.0 ± 14.1[c]	1839.0 ± 64.5[ab]	455.0 ± 13.8[c]	1320.0 ± 46.3[a]	94	72
September 15–17	4.0	314.0 ± 15.0[a]	1193.0 ± 40.3[cd]	302.0 ± 11.0[a]	966.0 ± 35.6[b]	96	81
	5.0	399.0 ± 17.2[b]	1436.0 ± 53.2[c]	383.0 ± 11.5[b]	1149.0 ± 42.2[ab]	96	80
	6.0	482.0 ± 19.0[c]	1639.0 ± 60.5[bc]	458.0 ± 13.5[c]	1282.0 ± 43.6[a]	95	78
September 25–26	4.0	316.0 ± 17.0[a]	822.0 ± 35.6[d]	306.0 ± 11.0[a]	765.0 ± 31.2[c]	97	93
	5.0	398.0 ± 13.4[b]	995.0 ± 39.5[d]	387.0 ± 11.3[b]	929.0 ± 38.5[b]	97	93
	6.0	474.0 ± 18.8[c]	1090.0 ± 40.3[d]	460.0 ± 12.8[c]	1012.0 ± 40.2[ab]	97	93
October 5–7	4.0	301.0 ± 12.4[a]	331.0 ± 16.2[e]	289.0 ± 10.1[a]	318.0 ± 15.6[de]	96	96
	5.0	378.0 ± 14.6[b]	416.0 ± 18.9[e]	363.0 ± 12.5[b]	3990 ± 16.5[d]	96	96
	6.0	449.0 ± 17.1[c]	494.0 ± 18.2[e]	431.0 ± 15.2[c]	474.0 ± 15.2[d]	96	96
Selianka variety							
September 5–7	4.0	330.0 ± 13.0[a]	1617.0 ± 60.1[bc]	313.0 ± 13.1[a]	1127.0 ± 40.2[ab]	95	70
	5.0	413.0 ± 1.9[b]	1941.0 ± 67.5[a]	393.0 ± 12.2[b]	1336.0 ± 55.6[a]	95	69
	6.0	500.0 ± 20.1[c]	2000.0 ± 70.5[a]	470.0 ± 13.1[c]	1363.0 ± 54.3[a]	94	68
September 15–17	4.0	328.0 ± 14.2[a]	1345.0 ± 55.6[c]	314.0 ± 12.2[a]	1068.0 ± 40.1[ab]	96	79
	5.0	413.0 ± 17.2[b]	1569.0 ± 55.6[bc]	396.0 ± 13.1[b]	1228.0 ± 42.3[a]	96	78
	6.0	491.0 ± 19.0[c]	1768.0 ± 63.2[b]	466.0 ± 16.1[c]	1351.0 ± 44.0[a]	95	76
September 25–26	4.0	317.0 ± 13.2a	888.0 ± 36,6[d]	307.0 ± 11.2[a]	798.0 ± 30.9[bc]	97	90
	5.0	405.0 ± 14.2[b]	1094.0 ± 41.2[d]	394.0 ± 12.9[b]	985.0 ± 37.5[b]	97	90
	6.0	482.0 ± 15.6[c]	1157.0 ± 40.4[cd]	468.0 ± 16.0[c]	1030.0 ± 39.8[ab]	97	89
October 5–7	4.0	296.0 ± 11.2[a]	355.0 ± 12.3[e]	286.0 ± 10.0[a]	343.0 ± 12.8[de]	96	97
	5.0	372.0 ± 14.6[b]	446.0 ± 15.1[e]	357.0 ± 13.2[b]	428.0 ± 13.1[d]	96	96
	6.0	441.0 ± 17.0[c]	529.0 ± 15.6[e]	423.0 ± 13.2[c]	508.0 ± 16.2[d]	96	96
Podolianka variety							
September5–7	4.0	311.0 ± 10.5[a]	1462.0 ± 58.8[c]	295.0 ± 11.1[a]	1062.0 ± 43.1[ab]	95	73
	5.0	389.0 ± 18.0[b]	1751.0 ± 64.2[b]	369.0 ± 12.1[b]	1292.0 ± 44.0[a]	95	74
	6.0	471.0 ± 19.1[c]	1837.0 ± 67.5[ab]	442.0 ± 15.2[c]	1326.0 ± 45.2[a]	94	72
September15–17	4.0	315.0 ± 12.5[a]	1229.0 ± 42.3[cd]	303.0 ± 10.5[a]	1000.0 ± 40.1[ab]	96	81
	5.0	398.0 ± 17.1[b]	1473.0 ± 51.2[c]	383.0 ± 12.2[b]	1187.0 ± 42.2[ab]	96	81
	6.0	475.0 ± 16.5[c]	1663.0 ± 55.5[bc]	450.0 ± 15.1[c]	1305.0 ± 45.8[a]	95	78
September25–26	4.0	304.0 ± 12.1[a]	821.0 ± 35.9[d]	295.0 ± 11.3[a]	767.0 ± 31.1[bc]	97	93
	5.0	388.0 ± 14.5[b]	1009.0 ± 42.2[d]	377.0 ± 14.2[b]	943.0 ± 37.8[b]	97	93
	6.0	462.0 ± 13.2[c]	1063.0 ± 43.0[d]	449.0 ± 16.8[c]	988.0 ± 38.0[b]	97	93
October 5–7	4.0	305.0 ± 12.3[a]	336.0 ± 12.5[e]	293.0 ± 9.8[a]	322.0 ± 11.5[de]	96	96
	5.0	378.0 ± 13.5[b]	416.0 ± 15.2[e]	363.0 ± 12.2[b]	399.0 ± 13.0[d]	96	96
	6.0	449.0 ± 15.5[c]	494.0 ± 14.8[e]	431.0 ± 13.0[c]	474.0 ± 15.8[d]	96	96

Note: see Table 1.

Table 5
Leaf surface area of plants of various varieties of winter wheat (thousand m^2/ha) under the influence of sowing dates for 2008–2010 (x ± SD, n = 8)

Development phase	Variety	Sowing terms			
		5th–7th of September	15th–17th of September	25th–26 th of September	5th–7 th of October
Spring bushing	Zolotokolosa	15.9 ± 1.2[a]	15.2 ± 0.1[a]	15.1 ± 1.0[a]	14.6 ± 1.2[a]
	Selianka	18.4 ± 1.2[ab]	17.9 ± 1.1[ab]	17.3 ± 1.2[ab]	17.0 ± 1.3[ab]
	Podolianka	17.2 ± 1.4[ab]	16.3 ± 1.0[ab]	16.2 ± 1.1[ab]	15.5 ± 1.2[ab]
Exit into the tube	Zolotokolosa	31.9 ± 1.5[b]	32.4 ± 1.4[b]	32.9 ± 1.3[b]	32.0 ± 1.5[b]
	Selianka	31.8 ± 1.8[b]	33.6 ± 1.5[b]	34.0 ± 1.4[b]	33.2 ± 1.5[b]
	Podolianka	29.3 ± 1.7[b]	30.8 ± 1.6[b]	31.3 ± 1.2[b]	30.6 ± 1.5[b]
Earing	Zolotokolosa	44.3 ± 2.1[c]	46.2 ± 1.3[c]	46.9 ± 1.6[c]	47.3 ± 1.7[c]
	Selianka	45.7 ± 2.0[c]	48.0 ± 1.4[c]	49.4 ± 1.6[c]	48.5 ± 1.5[c]
	Podolianka	41.2 ± 1.9[c]	42.2 ± 1.5[c]	45.0 ± 1.7[c]	45.9 ± 1.6[c]

Note: the indicators are given for the sowing rate of 5 million intact seeds/ha.

The lowest crop yield was formed in the conditions of 2019. In the Zolotokolosa variety that year, it was 2.13–3.29 t/ha, and 2.22–4.28 and 2.03–2.69 t/ha in the Selianka and Podolianka varieties, respectively.

It should be noted that in the conditions of 2018 and 2019, the maximum yield of all the varieties was formed in populations sown on September 25 at the rate of 5 million intact seeds/ha. In these versions of the experiment it was 5.23 and 3.29 t/ha in the Zolotokolosa variety, 5.58 and 4.28 t/ha in the Selianka variety, 4.89 and 2.69 t/ha in the Podolianka variety, respectively. In the conditions of 2020, the largest grain yield of the varieties was formed in the experimental plots where winter wheat was sown on October 5 at the rate of 6 million intact seeds/ha.

Discussion

According to foreign researchers, winter wheat varieties differ significantly in their ability to germinate timely and synchronously against the background of the same laboratory seed germination (Machado et al., 2008). According to Matssi et al. (2003), during the initial stages of development, lines of semi-dwarf forms of winter wheat were characterized by the greatest resistance to high temperatures.

Research focusing on effects of sowing dates on frost resistance and yield formation in new varieties revealed that being sown early, winter wheat crops accumulate more carbohydrates in the nodes of the stems and more intensively use reserve substances during winter than plants of optimal and late sowing dates (Bergjord Olsen et al., 2003; Bylavka et al., 2018; Jarcuk et al., 2018; Krivenko et al., 2018; Mostipan, 2019; Astahova et al., 2021; Pirych et al., 2021; Korkhova et al., 2022). According to scientists, the optimal period for sowing winter wheat is considered to be the period during which the plants have time to form a necessary number of shoots before winter begins (Tkacyk et al., 2020).

According to studies of influence of sowing dates on the winter hardiness of winter wheat, most winter-hardy plants are those of optimal sowing dates. Plants of early and late sowing periods are less prepared for adverse winter conditions (Gemela et al., 2012; Polyoviy et al., 2018; Krivenco et al., 2019).

Our studies show that winter wheat plants that had been sown after winter rape formed the largest number of shoots (coefficient of tillering was 3.8–4.9) and nodar roots after sown on September 5–7, but the best indicators of frost resistance and winter hardiness were exerted by plants of winter wheat sown on 25th and 15th of September. Thus, when plants in earth cubes were frozen at –16 ºC for 72 hours, the frost resistance of the Zolotokolosa plants sown on those dates was 98.1% and 96.7% respectively. The lowest plant survival was observed in the population sown on September 5–7 (94.0–95.0%). Plants with the best indicators of frost resistance and winter resistance formed the maximum grain yield, in particular the Selianka plants that had been sown on September 25–26 at the rate of 5 million intact seeds/ha – 4.90 t/ha.

Our and foreign studies show and confirm theses regarding the increase in productivity of winter wheat, which depends significantly on varietal characteristics and the adaptability of the variety to a climatic region it is being cultivated in, sowing dates, sowing rates, etc. This issue is especially relevant in conditions of the climate change, continuous emergence of new varieties, hybrids, elements of cultivation technology, etc. Considering all of the above, in our opinion, research should be continued in this direction with the goal of increasing the yield of high-quality grain and solving the food problem of humanity as a whole.

Conclusions

The varieties of winter wheat varied in linear and weight increments. During the autumn vegetation period, in the initial period, plants of the Selianka variety had the highest intensity of vegetative-mass growth. These plants had an increased ability to form shoots, formed a larger number of nodal roots, accumulated above-ground mass, and had the greatest depth of the tillering node. However, the highest rates of linear growth were seen in the plants of the Zolotokolosa variety, which were the tallest. The biggest difference in the intensity of plant tillering, depending on the rate of seed sowing and variety, was noted in the populations sown on September 5–7 (3.8–4.9). The plants that had been sown in earlier periods in autumn were more responsive to the thickening of plants than the populations sown in later sowing periods.

At the end of the autumn vegetation, the winter wheat plants that had been sown on September 5–7 formed a larger number of nodal roots. Depending on the sowing rate, the number of nodar roots in the Zolotokolosa variety was 5.4–5.8 per plant and 5.6–6.0 and 5.3–5.7 per plant in the Selianka and Podolianka varieties, respectively. The later periods of sowing led to decrease in the tillering of winter crops and a decrease in the number of roots.

The deepest tillering node was seen in the Selianka plants. Its depth, depending on the rate of seed sowing, was 3.1–3.3 cm in the populations sown on September 5–7, 2.7–2.9 cm after sowing on September 15–17, 2.5–2.7 cm on September 25–26, and 1.5–1.7 cm on October 5–7.

The winter wheat plants that had been sown on September 25 and 15 had the highest values of the frost resistance index. On average, over the years of research, when plants in earth cubes were frozen at –16 ºC for 72 hours, the frost resistance of the Zolotokolosa plants sown on those dates was 98.1% and 96.7% respectively. Resistance to low temperatures was the highest in the Selyanka variety, equaling 98.4% and 97.1%, and was the lowest in the Podolianka variety, measuring 98.1% and 96.3%, respectively. The maximum number of survived winter wheat plants was observed for the variants of the experiment where sowing was carried out on September 25–26 (97.1%). The survival rate was somewhat lower in the populations sown on October 5 (96.0%) and September 15–17 (95.1–96.1%), and the lowest on September 5–7 (94.0–95.0%).

The maximum yield (4.90 t/ha), on average over the years of the research, was produced by the Selianka variety sown on September 25–26 at the rate of 5 million intact seeds/ha. The grain yield of the Zolotokolosa variety was high after sowing on September 25–26 with the sowing rate of 5 million intact seeds/ha (4.2 t/ha) and after sowing on October 5–7 with the sowing rate of 6 million intact seeds/ha (4.21 t/ha). Such of the Podolianka variety was observed in the population sown in the first decade of October, the sowing rate of 6 million intact seeds/ha (3.76 t/ha).

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