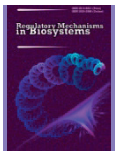

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Peculiarities of the biological potential of winter wheat (*Triticum aestivum*) under cultivation technologies of different intensity in the conditions of climate change

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The importance of the wheat crop on a global scale for overcoming the problem of hunger determines the relevance of research on increasing its productivity and sustainability in the face of climate change. Research on the realization of the genetic potential of winter wheat is an important step towards ensuring food security, improving agricultural efficiency and preserving the environment. The realization of the genetic potential of winter wheat (*Triticum aestivum* L.) stands as a pivotal element in elevating its productivity. Cultivation technologies of varying intensities play a crucial role in its achievement, as they hold the capacity to ensure high yields and grain quality for this crop. These technologies are developed with considerations for the biological characteristics of the crop and its responses to changing climatic conditions. The research presented here aimed to investigate the influence of cultivation technologies of different intensities on unlocking the genetic potential of winter wheat. Models of cultivation technologies were examined, which differed in the rates of mineral fertilisers applied, the insertion of pea straw residues, and the application of the plant protection system. Through morpho-physiological investigations, fundamental patterns in the initiation of florets within the spike meristems of central and tiller stems were established, along with the number of florets (grains) depending on the phenological development stages of the plants and cultivation technology. The impact of cultivation technologiy on stem density dynamics was examined, optimal parameters were determined, and the degree of productive stem expression and reduction magnitude were assessed. Potential yield values were calculated at the main phenological development stages of the plants, and their realization level was assessed. The highest yield was obtained under a highly-intensive cultivation technology 1, with an application of $P_{80}K_{100}N_{240}$ with the straw residues of the preceding crop and integrated plant protection. Morpho-physiological research attributed such productivity to a productive stem density of 770 stems/m^2 and an average ear productivity of 1.42 g. The level of potential yield realization of winter wheat at phenological development stage of plants 65 was at 36.4%, while the realization of productive stem expression was 36.9%, and 34.7% of the total number of florets was retained from phenological development stages of plants 32 to 92.

Keywords: *Triticum aestivum*; morphophysiological indicators; productive stem density; potential yield; cultivation technologies.

Introduction

Increasing grain production through agricultural land expansion requires large resources, human and environmental costs (Hochman et al., 2014; Qi et al., 2018). Therefore, it is necessary to develop highly productive and efficient agriculture, in particular by maximizing the genetic potential of crops (Alam et al., 2024). Of particular note is the solution to the dual problem of ensuring food security and environmental sustainability of agricultural production, which concludes the problem.

Cereal crops are among the most important element in the human diet, and the global demand for them is growing rapidly. Wheat (*Triticum aestivum* L.) is the third most cultivated cereal crop in the world after maize and rice and one of the key crops in global food security, which occupies about 219 million hectares of land (Shiferaw et al., 2013; de Sousa et al., 2021; Dadrasi et al., 2023). Wheat yields should increase by 1.7% annually to meet demand and food security (Alrajhi et al., 2024). Production of approximately 21% of food on our planet depends on annual wheat harvests. Its consumption is expected to increase in all regions, including countries with transition economies, in the coming years.

Ukraine is a leading producer and supplier of wheat grain to world markets and constantly pays attention to improving the genetic resource and finding the culture's tolerance to stress factors (Cheremisina, 2021; Beznosko et al., 2023; Demydov et al., 2021). Global cereal production is projected to grow by 12% by 2026, mainly due to increased yields (Sukhostavets & Solovey, 2019). Therefore, increasing winter wheat production in Ukraine is of great importance for food security and export potential.

One of the sustainable development goals in the Resolution adopted by the United Nations General Assembly in 2015 for the period up to 2030 is to improve the quality of food and contribute to the stabilization of the agricultural production. To achieve this, it is necessary to ensure the creation of sustainable systems of food production and to introduce methods of agricultural management that facilitate an increase in sustainability and productivity, increase production volumes, contribute to the preservation of ecosystems, increase crop resilience to climate change and ensure sustainable use of land resources (https://sdgs.un.org/2030agenda).

One of the important tasks of ensuring food security, nutrition and health of the population, guaranteeing everyone access to sufficient, safe, nutritious, sustainable food forms the basis of the European Green Deal in the agricultural sector presented by the European Commission in May 2020 in the strategy "From farm to fork" (https://ec.europa.eu/food/horizontal-topics/farm-fork-strategy_en). Ukraine's climate policy priorities should be adjusted in accordance with the European Green Deal and the new European Union policy, adapted to climate change and ensure the integration of climate policy priorities with the country's socio-economic development programs. The advantages of the European Green Deal for Ukraine lie in the transformation of the state's modern climate policy, aimed at achieving long-term and sustainable effects that will ensure the development and competitiveness of the national economy (Ivanyuta & Yakushenko, 2022).

Food security is significantly impacted by climate change. Global warming is leading to increased climate variability and extremes (Asseng et al., 2015; Trnka et al., 2015). Wheat's resilience to climate change has not improved and may even decline (Zhang et al., 2022). Global climate change is threatening for wheat productivity (Miedaner & Juroszek, 2021). Corn, rice and wheat yields are expected to decline by 25% by 2050. According to the United Nations, after 2050, grain yields will decrease even more significantly, while the world population could reach nine billion people (Shevchenko, 2017). Fluctuations in climatic conditions directly affect plant morphology, phenology, and physiology and indirectly affect productivity by altering soil biota, fertility, and water and nutrient availability (Bibi & Rahman, 2023).

Ukraine has strong potential to increase the production of grain crops, in particular winter wheat, which is facilitated by dynamically growing demand on world markets. Ukraine's share in total world production is stable: 13.1% of corn, 3.6–3.7% of wheat, 5.6% of barley, and 2.2% of oats (Cheremisina, 2021; Demyanyuk et al., 2023a). The sustainability of Ukrainian agriculture is formed under the influence of climatic conditions, based on the use of agricultural resource potential and innovative production technologies. Despite the fact that extreme climatic events in some years cause a significant decrease in yield, the agricultural producer can counter adverse weather conditions with a positive effect from land reclamation, the optimal structure of sown areas, the use of drought- and frost-resistant varieties of agricultural crops, and modern technologies for their cultivation (Yuzefovich et al., 2019). Due to the limited possibilities for expanding the area of growing crops, a significant increase in their productivity is necessary to ensure future food security in the current conditions of climate change. Increasing genetic yield potential is one of the key components of an integrated approach to improving crop productivity (Senapati et al., 2019).

An essential role in increasing wheat grain yield and quality is the creation of stable varieties with high adaptability and broad agroecological plasticity (Zhemla et al., 2020). The stability of the winter wheat harvest depends on the variety. However, the realization of the genetic potential of winter wheat variety directly depends on agrotechnology. So, new technologies are needed to fully use the potential of new varieties (Los & Dubovyk, 2022). Winter wheat varieties respond to several environmental factors, most clearly to climatic aspects, the agricultural value of the soil, and the level of agricultural intensification depending on the means and methods used by man (Bujak et al., 2013).

Drought stress is one of the significant constraints on grain yield (Khan et al., 2013). The higher temperatures expected with climate change and the possibility of more extreme temperatures will affect plant productivity. Pollination is one of the most sensitive phenological stages to temperature extremes in all species, and during this stage of development temperature extremes can strongly influence yield reduction (Hatfield & Prueger, 2015). However , research by Ishtiaq et al. (2022) shows that the cultivation of heat-resistant wheat varieties may lead to a 7–10% increase in yield over the next 50 years (2019–2068) compared to the last 40 years (1970–2010).

To obtain high and stable yields of winter wheat, modern technologies adapted to a specific variety and growing conditions are needed. Such technologies require constant improvement using the latest scientific developments (Ulich, 2014; Polovyi et al., 2018). It is also important to evaluate the influence of different cultivation techniques on the productivity and formation of its elements in modern winter wheat varieties.The purpose of this study was to examine the influence of cultivation technologies of different intensity on the realization of the genetic potential of winter wheat.

Materials and methods

Study area and data collection. Comprehensive research was conducted between 2016 and 2020 through a stationary multifactorial experiment at the Department of Grain Cereal Technologies, National Scientific Center "Institute of Agriculture of National Academy of Agrarian Sciences of Ukraine" (Fig. 1).

The results of the research on the impact of cultivation technologies on the yield and quality of winter wheat were illuminated in the article by Demyanyuk et al. (2023b). For a more detailed examination of the influence of cultivation technologies of varying intensities on the realization of the genetic potential of winter wheat, this article presents the results of morpho-physiological investigations.

The research was carried out on the dark gray podzolic coarse-ashy light loamy soil of Luvic Phaeozem. The humus content in the topsoil (according to Tyurin) is 1.7% (DSTU 4289:2004), the reaction of the soil solution is slightly acidic, the pH of the soil solution determined ionometrically was 5.5 (DSTU ISO 10390:2022). The soil contains 10.6 mg/kg of mineral nitrogen (ammonium nitrogen, DSTU 4729:2007; nitrate nitrogen, DSTU 4725:2007), 193.0 mg/kg of mobile phosphorus by Chirikov (DSTU 4115-2002) and 103.0 mg/kg of mobile potassium by Chirikov (DSTU 4115-2002).

Sampling and methods. Tillage for winter wheat was standard for the Forest-Steppe zone of Ukraine and included double ploughing with the AGD-2.5 disc harrow, cultivation with a KN 3.8 cultivator, pre-sowing cultivation with a Europak machine and rolling with a 3 KKSh-6 machine. Potassium and phosphorus fertilisers were applied as the main fertiliser under the basic tillage. Plant fertilisation was carried out at the 23rd, 30th, 45th stage of the U. Meier method (Meier, 2001) with nitrogenous mineral fertilisers. The research was conducted with winter wheat plants of the Kraevyd variety grown under different intensity of cultivation technologies. The cultivation technologies included the application of different doses of mineral fertilizers, the use of by-products of the predecessor, and an integrated plant protection system. The predecessor was peas.

Fertilization scheme in winter wheat cultivation technologies: treatment 1 – no fertilizer (control), treatment 2 (minimized resource-saving) – utilization of the by-products of the predecessor – background; treatment 3 (resource-saving 1) – background + $P_{45}K_{45}$ + N_{30} (23 BBCH) + N_{30} (30 BBCH); treatment 4 (resource-saving 2 with microfertilizers) – background + $P_{45}K_{45}$ + N_{30} (23 BBCH) + N_{30} (30 BBCH) + microfertilizer Bifoliar 0.5 L/ha (56–57 BBCH); treatment 5 (intensive 1) – background + $P_{90}K_{90}$ + N_{30} (23 BBCH) + N_{60} (30 BBCH) + N_{30} (45 BBCH); treatment 6 (intensive 2) – background + $P_{45}K_{45}$ + N_{30} (23 BBCH) + N_{60} (30 BBCH) + N_{30} (45 BBCH); treatment 7 (highly-intensive 1) – background + $P_{80}K_{100}$ + N_{80} (23 BBCH) + N_{100} (30 BBCH) + N_{60} (45 BBCH); treatment 8 (highly-intensive 2) – background + $P_{135}K_{135}$ + N_{60} (23 BBCH) + N_{75} (30 BBCH) + N_{45} (30 BBCH).

The plant protection system included protection of plants from diseases, pests and lodging and consisted of seed treatment (Vitavax 200 FF, 2.5 L/t) and two spray treatments of crops at 30 and 58–59 stages of the BBCH. The first treatment was carried out with a tank mixture containing the fungicide Alto Super 0.5 L/ha, the growth regulator Grum 1.5 L/ha with herbicides Axial (1.0 L/ha) and Calibr (50 g/ha), and the other involved the use of Amixtar Extra (0.75 L/ha).

Fig. 1. Study area: the map of Ukraine, Kyiv Region, Fastiv District with the location of the study area; a satellite image of the study agrolandscape in Google Earth, with the study sites (50.348178º N, 30.413010º E)

The stationary experiment was designed using the split-plot method. The size of the plot was 28 m^2, the replication of experiments – quadruple. The plots were placed systematically.

Winter wheat was sown at the optimal time for the Forest-Steppe zone. Weather conditions were taken into account when determining the sowing dates. The crop was sown to a depth of 3 cm using a SN-16A seeder in a continuous row method with a seeding rate of 4.5 million seeds per hectare.

Harvesting was carried out by direct harvesting with a SAMPO-130 combine at 92–99 stages of the BBCH. The grain harvest from each experiment variant was weighed, recalculated for 14% grain moisture and 100% purity. Accounting of by-products (pea straw) was also carried out by weighing in sections. Pea straw was taken out of the field in the experimental plots where the experimental design did not provide for the introduction of the predecessor's by-products.

At the 30, 34, 65 and 92 stages of BBCH, stem density counts of winter wheat were conducted according to the DSTU 7638:2014 (Cereal, leguminous and cereal crops. Methods of determining plant stand density).

The number of florets set in the growth cone, the number of fertile florets in the spike and the number of grains formed in the spike were determined using the method of biological control of sprouts (Kuperman, 1977) at stages 32, 34, 65, 75, 92, in accordance with the international system for the staging of the development of plants (BBCH), in the central ear and in the tillers' ear. The calculations were performed quintuply.

Climatic conditions. The formation of winter wheat yield was significantly influenced by weather conditions (in particular, temperature regime and the amount of precipitation) during the vegetation period, which defined the duration and conditions of the stages of organogenesis, in which these or those elements of productivity were formed (Table 1).

In general, for all five years of research, the weather conditions during the growing season were mainly favorable for the growth and development of winter wheat, but were characterized by an uneven distribution of precipitation and heat according to the stages of plant growth.

The duration of BBCH 1–29 of winter wheat during the years of research was close to or equal to the multi-year average value, except for 2020, in which their duration was reduced by 18 days. The sum of active temperatures in all years exceeded the long-term average values by 1.10–1.34 times, and in 2020 this excess was the highest, 1.46 times, and was accompanied by a deficit of precipitation. Their amount was only 27.9% of the norm or long-term average values. In other years, plants during this period had sufficient or even excess precipitation (153.3% of the norm in 2018).

The BBCH 30 of winter wheat lasted from 7 to 14 days with an average multi-year duration of 10 days and took place under a sufficient amount of heat, except for 2017, when the sum of active temperatures (>5 °C) during this period was 61.8% of their multi-year values, and stable lack of precipitation, except for 2019. Similar fluctuations in the duration of BBCH stages of growth were observed at BBCH 31–32. The precipitation deficit that continued from the previous stage contributed to a reduction in the duration of the stage by 3 days in 2019, and heavy precipitation, which exceeded the norm by 3.71 times during this period in 2016, extended this stage by 6 days. This period was characterized by a slight lack of heat compared to average multi-year data only in 2017 and 2018.

The following 33–36 of BBCH of winter wheat had an average level of variation in their duration by year, and the deviation from the average multi-year values for the years of research was within 2 days. This period was characterized by a lack of precipitation in 2017 and 2018, when its amount was 45.9% and 33.1% of the norm, and an excess in 2016, 2019, and 2020, exceeding the norm by 33.8%, 54.1%, 117.8%, respectively. The sum of active temperatures > 5 °C during this period in all years exceeded the long-term average values. The duration of the 37–59 stages of BBCH development of winter wheat was close to the long-term average values, with the exception of 2016 and 2020. In these years, the duration of development stages was extended by 2 and 7 days, respectively, due to precipitation 1.65 and 1.97 times higher than normal. In other years of research, only 7.4–32.6% of their average long-term amount fell during this period.

The flowering of winter wheat, or BBCH 60–69, during the years of research, did not differ in duration from the long-term average values and took place under conditions of little or no precipitation and a moderate amount of heat. The duration of BBCH 70–72 of on average over five years of research was 2 days shorter than the average multi-year values. This period took place in the conditions of a deficit of precipitations when their amount varied from 4.2% to 58.1% of the norm over the years. The sum of active temperatures >5 °C during this period, during the years of research, approached the average multi-year values and had a low level of variation. The period of pouring and ripening of grain in terms of duration and the sum of active temperatures >5 °C differed little from the average long-term values and took place in conditions of a lack of precipitation, which amounted to 27.8–71.3% of the norm, with the exception of 2018, when the amount of precipitation was 169.6% of the average multi-year values.

Statistical analysis was performed using the analysis of variance (ANOVA) (Statistica, version 6.0). The significance of differences between the samples was determined by Tukey's criterion, at $P < 0.05$. Results are given as average value ± standard deviation (x ± SD). The spike model was built using the Paint program. Results are expressed as means (x) ± standard deviation (SD).

Table 1
Meteorological conditions at the main BBCH stages of winter wheat and the duration of BBCH in the period 2016–2020 (x ± SD, n = 5)

Parameters	Year	BBCH stage								
		1–29	30	31–32	33–36	37–59	60–69	70–72	73–99	1–99
Duration of growth stages of winter wheat according to BBCH, days	2016	189	7	17	10	19	5	11	33	291
	2017	188	9	13	12	15	5	13	29	284
	2018	197	8	8	9	14	6	11	33	286
	2019	194	12	13	13	15	5	9	34	295
	2020	177	15	17	9	24	5	8	31	299
Average		189.0 ± 7.6	10.2 ± 3.3	13.6 ± 3.7	10.6 ± 1.8	17.4 ± 4.2	5.2 ± 0.5	10.4 ± 1.9	32.0 ± 2.1	291.0 ± 6.2
CV%		4.0	32.1	27.3	17.1	23.9	8.6	18.7	6.3	2.1
Precipitations, mm	2016	245.7	0.6	54.1	21	61	4.8	6.2	19.8	413.16
	2017	313.3	4.2	0	7.2	7.2	0	3.4	34.8	370.1
	2018	358.8	0	1.8	5.2	12.4	0	2.6	120.9	501.7
	2019	188.2	20.8	33.2	24.2	2.8	0.4	1.4	50.8	321.8
	2020	63.9	6	24	34.2	75	0.8	19.2	23.6	246.7
Average		234.0±115.1	6.3 ± 8.5	22.6 ± 22.5	18.4 ± 12.1	31.7 ± 33.7	1.2 ± 2.0	6.6 ± 7.3	50.0 ± 41.4	370.7 ± 95.8
CV%		49.2	134.0	100.1	66.1	106.4	170.0	111.0	82.9	25.9
Sum of active temperatures, >5°C	2016	523.4	111.1	193.4	150.9	288.5	90.3	183.7	757.3	2298.5
	2017	489.4	64.0	138.2	151.2	251.5	89.2	240.9	630.3	2054.7
	2018	504.8	113.3	132.4	195.6	235.1	124.5	220.9	684.2	2210.8
	2019	601.1	113.6	170.6	186.1	307.4	110.4	216.3	729.1	2434.6
	2020	657.5	122.0	192.0	120.6	285.3	113.6	200.8	702.2	2394.0
Average		555.2 ± 80.5	104.8 ± 42.5	165.3 ± 18.6	160.9 ± 31.6	273.6 ± 29.1	105.6 ± 15.4	212.5 ± 21.4	700.6 ±48.1	2278.5±129
CV%		12.9	22.1	17.5	18.8	10.8	14.6	10.2	6.9	6.7

Note: CV – coefficient of variation.

Results

Based on the results of morphophysiological studies conducted in 2016–2020, it was determined that in the central ear of the winter wheat variety Kraevyd at BBCH 32, 154–173 florets were formed, of which 94–109 were simultaneously developed flowers (Table 2). In the tiller spikes, far fewer florets were formed. Their total number ranged from 126–148 florets, including 79–100 synchronously developed florets. At BBCH 32, the total number of florets changed depending on the doses of applied fertilizers for different cultivation technologies. Thus, with high-intensity technology 1, there were 19 more florets in the central spike than in the control, with intensive technology – 14 more, and with energy-saving technology – 11 more florets. In the tiller spikes, the dependence of the initiated florets on the models of cultivation technologies was more evident. This excess compared to the control was 22, 18 and 14 flowers, respectively.

Table 2
Number of florets (grains) in the central spike and the tiller spikes of winter wheat variety Kraevyd at the main BBCH stages
under the cultivation technologies of different intensivity, average for 2016–2020 (x ± SD, n =5)

Treatment		The number of florets (grains) in an ear at the main BBCH stages, pcs				
		BBCH 32	BBCH 34	BBCH 65	BBCH 75	BBCH 92
Central spike	Without fertilisers (control)	153.5 ± 5.9^{a}	94.0 ± 4.1^{a}	45.5 ± 4.8^{a}	37.8 ± 3.2^{a}	37.2 ± 3.3^{a}
	Minimised resource-saving	157.3 ± 6.8^{ab}	97.1 ± 5.6^{a}	47.3 ± 5.1^{a}	43.3 ± 4.3^{a}	42.9 ± 5.2^{a}
	Resource-saving 1	165.3 ± 5.5^{b}	103.3 ± 5.3^{b}	56.2 ± 5.7^{b}	51.3 ± 5.1^{b}	51.0 ± 5.1^{b}
	Resource-saving 2 with microfertilisers	163.5 ± 7.5^{b}	101.8 ± 5.8^{ab}	63.0 ± 6.5^{b}	52.6 ± 5.0^{b}	52.1 ± 4.9^{b}
	Intensive 1	168.5 ± 5.3^{bc}	105.5 ± 4.9^{b}	64.1 ± 6.3^{b}	56.5 ± 6.3^{bc}	55.5 ± 5.0^{b}
	Intensive 2	164.5 ± 5.2^{b}	103.0 ± 3.7^{b}	62.3 ± 6.9^{b}	53.5 ± 5.6^{b}	53.3 ± 6.1^{b}
	Highly-intensive 1	173.0 ± 5.6^{c}	109.2 ± 4.4^{c}	68.5 ± 7.2^{c}	60.8 ± 5.5^{c}	60.0 ± 4.7^{c}
	Highly-intensive 2	170.5 ± 4.6^{c}	109.5 ± 3.8^{c}	65.8 ± 6.3^{bc}	58.5 ± 5.1^{c}	57.5 ± 4.2^{c}
Tiller spikes	Without fertilisers (control)	133.1 ± 7.9^{a}	78.5 ± 5.2^{a}	35.2 ± 4.1^{a}	20.8 ± 2.3^{a}	20.5 ± 2.2^{a}
	Minimised resource-saving	141.0 ± 9.5^{a}	87.0 ± 7.7^{b}	34.3 ± 4.6^{a}	24.5 ± 2.6^{a}	23.5 ± 2.4^{a}
	Resource-saving 1	150.2 ± 6.7^{b}	92.3 ± 4.3^{b}	46.8 ± 4.7^{b}	38.5 ± 3.9^{b}	37.5 ± 3.5^{b}
	Resource-saving 2 with microfertilisers	148.0 ± 7.9^{b}	91.5 ± 3.9^{b}	51.5 ± 5.3^{b}	39.0 ± 3.8^{b}	39.2 ± 4.1^{b}
	Intensive 1	155.3 ± 6.8^{c}	96.1 ± 2.4^{b}	54.8 ± 5.7^{c}	41.8 ± 4.3^{b}	41.3 ± 3.9^{b}
	Intensive 2	151.7 ± 6.5^{b}	93.3 ± 1.9^{b}	50.8 ± 2.5^{b}	45.3 ± 4.8^{c}	44.5 ± 4.7^{c}
	Highly-intensive 1	157.7 ± 7.2^{c}	100.3 ± 3.1^{c}	56.8 ± 6.1^{c}	47.3 ± 5.4^{c}	47.0 ± 4.8^{c}
	Highly-intensive 2	156.3 ± 5.9^{c}	98.5 ± 2.9^{c}	55.9 ± 5.8^{c}	48.1 ± 5.3^{c}	48.2 ± 5.3^{c}

Note: different letters mean significant differences between treatments at $P < 0.05$.

It was established that at the 65th stage in the central ear with improved nutrition conditions under resource-saving and intensive and highly intensive cultivation technologies, which involve the introduction of increasing doses of fertilizers, the number of fertile florets exceeded their number in the control by 10–23 florets. In the tiller spikes, their number increased by 12–22 flowers with 35 florets in the control, respectively. This regularity was preserved until the BBCH 92 in the main and tillers ears. According to the results of morphophysiological studies, it was established that the size of the reduction of flowers for the Kraevyd winter wheat variety on average for 2016–2020 was 65.3–75.4% of their total number at BBCH 32 in the central stems. For tiller spikelets, these losses were greater and ranged from 67.4–84.7%.

Based on the data from morphophysiological studies, the main periods during which a significant portion of the buds are reduced for a given variety are identified, and the magnitude of such reduction depends on the growing technology. It was established that, on average, for 2016–2020, 35.9–38.2% of initially formed florets at BBCH

32 in the central ear of winter wheat of the Kraevyd variety in the period from BBCH 32 to 34 were lost (Table 3). From BBCH 34 to 65, floret reduction ranged from 23.5% to 32.1% of all formed florets. In the period from BBCH 65 to 92, the size of floret reduction was significantly smaller and amounted to 2.7–6.9%.

Table 3
Reduction of florets (grains) in the central spike and tiller spike of winter wheat Kraevyd variety at the main stages of BBCH depending on the cultivation technology, the average for 2016–2020 (x ± SD, n =5)

Treatment		The number of florets lost during the period, pcs			
		BBCH 32–34	BBCH 34–65	BBCH 65–92	BBCH 32–92
Central spike	Without fertilisers (control)	59.5 ± 2.9^{a}	48.5 ± 5.3^{d}	8.3 ± 0.9^{b}	116.3 ± 3.8^{d}
	Minimised resource-saving	60.1 ± 3.1^{a}	50.4 ± 5.9^{d}	4.3 ± 0.6^{a}	114.8 ± 7.6^{c}
	Resource-saving 1	62.1 ± 1.2^{b}	47.0 ± 4.9^{c}	5.2 ± 0.5^{a}	114.3 ± 5.9^{c}
	Resource-saving 2 with microfertilisers	61.8 ± 2.6^{b}	38.8 ± 4.3^{a}	11.2 ± 1.1^{c}	111.8 ± 7.1^{a}
	Intensive 1	62.8 ± 1.1^{bc}	41.5 ± 4.4^{b}	8.5 ± 0.8^{b}	112.8 ± 2.9^{b}
	Intensive 2	61.5 ± 1.6^{b}	40.8 ± 3.8^{b}	9.1 ± 0.9^{bc}	111.4 ± 4.9^{a}
	Highly-intensive 1	63.8 ± 1.9^{c}	40.6 ± 3.9^{b}	8.5 ± 0.9^{b}	112.9 ± 3.1^{b}
	Highly-intensive 2	61.3 ± 1.8^{ab}	43.5 ± 4.7^{bc}	8.3 ± 0.8^{b}	113.1 ± 4.4^{b}
Tillers' spikes	Without fertilisers (control)	54.6 ± 5.1^{a}	43.5 ± 4.8^{b}	14.5 ± 1.7^{d}	112.6 ± 5.9^{c}
	Minimised resource-saving	54.0 ± 5.8^{a}	52.8 ± 5.3^{d}	10.8 ± 1.2c	117.6 ± 11.3^{d}
	Resource-saving 1	57.8 ± 5.7^{b}	45.5 ± 5.1^{c}	9.3 ± 0.9^{b}	112.6 ± 8.8^{c}
	Resource-saving 2 with microfertilisers	56.5 ± 5.8^{b}	40.4 ± 4.6^{a}	12.5 ± 1.3^{d}	109.4 ± 8.9^{b}
	Intensive 1	59.1 ± 6.4^{c}	41.3 ± 4.2^{a}	13.5 ± 1.4^{d}	113.9 ± 7.8^{c}
	Intensive 2	58.4 ± 5.9^{c}	42.5 ± 4.1^{ab}	6.3 ± 0.6^{a}	107.2 ± 8.7^{a}
	Highly-intensive 1	57.5 ± 5.5^{b}	43.5 ± 5.1^{b}	9.8 ± 1.1^{b}	110.8 ± 7.9^{b}
	Highly-intensive 2	57.8 ± 5.4^{b}	42.5 ± 4.8^{ab}	8.2 ± 0.8^{a}	108.5 ± 7.6^{b}

Note: see Table 2.

In the tiller spike, the percentage of reduced florets was higher compared to the central ear, and from BBCH 32 to 34, it was 36.5–40.9% of florets initially formed at BBCH 32, from BBCH 34 to 65, the reduction was 26.9–37.4%, from BBCH 65 to 92 – 4.2–10.9%.

As the doses of applied fertilizers increased from resource-saving to intensive and high-intensity cultivation technologies, the percentage of reduction of florets in spikes decreased. In particular, in the central ear under the energy-saving technologies by 7.1–7.9% for intensive technologies – by 8.5–9.3%, for highly intensive technologies – by 9.9–11.1% compared to the control. With resource-saving technologies, the reduction of flowers formed at the BBCH 32 was diminished by 9.6–10.7%, with highly-intensive technologies by 14.3–15.2% compared to the control.

Weather conditions at the beginning of the spring growing season in the years of research contributed to the intensive tillering of winter wheat. The density of winter wheat plants at BBCH 30 was 360–440 plant/m^2 (Table 4). The tillering ratio ranged from 3.5 to 5.4. At this stage, in the control (without fertilizers), the stem density of winter wheat was 1178 stem/m^2. The resource-saving technology, which involved the application of fertilizers in a dose of $N_{60}P_{45}K_{45}$, led to an increase in stem density by 1.32 times. With increasing doses of applied fertilizers to $N_{120}P_{90}K_{90}$ under intensive technology and to $N_{180}P_{135}K_{135}$ under highly-intensive technology 2, stem density increased by 1.45 times and 1.92 times, respectively, while both the total number of stems and the number of synchronously developed stems increased. A similar dependence of stem density on growing technology was maintained until the BBCH 92.

Table 4
Stem density dynamics of winter wheat in relation to cultivation technology, the average for 2016–2020 (stems/m^2, x ± SD, n = 5)

Treatment	Stem density, stems/m^2			
	BBCH 30	BBCH 34	BBCH 65	BBCH 92
Without fertilisers (control)	1178.5 ± 103.3^{a}	844.2 ± 94.4^{a}	532.3 ± 54.1^{a}	484.2 ± 20.7^{a}
Minimised resource-saving	1361.2 ± 120.7^{b}	942.5 ± 84.5^{a}	572.5 ± 59.3^{a}	526.5 ± 39.8^{a}
Resource-saving 1	1558.8 ± 54.4^{c}	1116.1 ± 124.8^{b}	690.2 ± 68.6^{b}	643.3 ± 24.9^{b}
Resource-saving 2 with microfertilisers	1665.5 ± 151.1^{c}	1164.5 ± 130.2^{b}	766.1 ± 58.6^{c}	682.2 ± 25.9^{c}
Intensive 1	1718.0 ± 145.1^{c}	1296.2 ± 115.9^{bc}	764.0 ± 68.4^{c}	695.0 ± 43.6^{c}
Intensive 2	1925.1 ± 165.4^{d}	1440.0 ± 128.8^{c}	760.5 ± 46.4^{c}	692.2 ± 16.4^{c}
Highly-intensive 1	2084.2 ± 216.3^{d}	1624.5 ± 145.3^{d}	890.2 ± 55.7^{d}	770.3 ± 43.1^{d}
Highly-intensive 2	2268.1 ± 189.5^{d}	1664.2 ± 167.5^{d}	860.0 ± 76.9^{d}	758.1 ± 56.3^{d}

Note: see Table 2.

During the growing season, there was a loss of stem density, which depended on agro-meteorological conditions and growing technology. The bulk of these losses occurred from BBCH 30 to 34 and from BBCH 34 to 65. The average loss for 2016–2020 for these periods was 22.1–30.1% and 23.9–35.5%, respectively, of the stem density at BBCH 30. Stem losses at BBCH from 65 to 92 were 3.1–5.8%. According to data from 2016–2020, the potential harvest of winter wheat of the Kraevyd variety, calculated for BBCH 65, varied from 10.4 t/ha under the minimized technology against 9.6 t/ha under control, to 15.8 t/ha under resource-saving and up to 23.2 t/ha for highly-intensive, which involved a three-fold increase in the dose of fertilizer compared to the resource-saving technology (Table 5). The degree of realization of the potential harvest at BBCH 65 of Kraevyd winter wheat ranged from 36.4% to 45.2%.

Discussion

As is known, winter wheat, like all flowering plants, goes through 12 successive stages of organogenesis or 99 stages of BBCH growth in its development. Each of the stages of development is characterized by the formation, differentiation, and growth of individual organs (Hilty et al., 2021; Celestina et al., 2023). At the same time, the need of plants for nutritional conditions, and supply of heat, light, and moisture changes (Kuperman, 1984; Slafer et al., 2023; Vadez et al., 2024). Plants in ontogenesis do not form their productivity potential immediately, but gradually, from stage to stage of the BBCH scale, from one stage of development to another. Indicators of potential and actual productivity are varietal, genetically determined traits, the implementation of which depends on nutritional and growing conditions (Kolyuchyy et al., 2007; Bapela et al., 2022; Paunescu et al., 2023).

In order to obtain a high yield, it is important that each ear contains the maximum number of well-developed grains, which depends on the number of set flowers in the growth cone (Calderini et al., 2021; Demyanyuk et al., 2023b).

The maximum number of florets in the ear is formed at the BBCH 31–32 stage. The BBCH 31–32 period determines their number, being genetically determined by the potential of the variety for this yield component. The magnitude of this period is determined by the average daily air temperature, moisture reserves in the soil, and the amount and volume of the precipitation over this period (Natrova & Smochek, 1983).

Table 5
Potential yield of winter wheat variety Kraevyd at the main growth stages of BBCH (x ± SD, n = 5)

Treatment	Potential yield, t/ha				Actual yield, t/ha	Realization of actual yield in relation to potential at BBCH, %			Contribution of ear potentials to potential yield at BBCH 92, %	
	BBCH 32	BBCH 34	BBCH 65	BBCH 75		BBCH 32	BBCH 34	BBCH 65	central ear	spikes of tillers
Without fertilisers (control)	55.5 ± 5.9^{a}	33.8 ± 3.6^{a}	9.3 ± 0.9^{a}	6.2 ± 0.7^{a}	4.2 ± 0.4^{a}	7.6 ± 0.7^{b}	12.5 ± 1.4^{b}	44.1 ± 4.9^{d}	62.9 ± 5.6^{d}	37.1 ± 3.3^{a}
Minimised resource-saving	64.5 ± 7.3^{a}	40.3 ± 3.92^{a}	10.0 ± 1.1^{a}	7.7 ± 0.8^{a}	4.6 ± 0.3^{a}	7.1 ± 0.6^{a}	11.4 ± 1.1^{a}	43.9 ± 4.8^{c}	58.8 ± 5.3^{c}	41.2 ± 3.7^{b}
Resource-saving 1	78.2 ± 8.2^{b}	48.34 ± 4.9^{b}	15.2 ± 1.4^{b}	12.6 ± 1.3^{b}	7.1 ± 0.4^{b}	9.1 ± 0.8^{d}	14.7 ± 1.3^{d}	45.2 ± 5.1^{d}	54.8 ± 4.9^{b}	45.2 ± 3.9^{c}
Resource-saving 2 with microfertilisers	81.8 ± 8.6^{b}	50.7 ± 5.7^{b}	18.9 ± 1.7^{b}	13.6 ± 1.4^{b}	7.4 ± 0.5^{b}	9.0 ± 0.8^{d}	14.6 ± 1.4^{d}	38.2 ± 3.4^{b}	48.2 ± 4.3^{a}	51.8 ± 4.7^{c}
Intensive 1	94.7 ± 10.2^{c}	58.9 ± 5.9^{c}	19.7 ± 1.9^{b}	14.9 ± 1.5^{c}	8.0 ± 0.3^{bc}	8.5 ± 0.7^{c}	13.6 ± 1.5^{c}	39.8 ± 3.6^{b}	51.1 ± 4.6^{b}	48.9 ± 4.4^{c}
Intensive 2	101.4 ± 10.9^{c}	62.6 ± 6.6^{c}	18.7 ± 1.8^{b}	15.1 ± 1.7^{c}	8.3 ± 0.4^{c}	8.2 ± 0.7^{c}	13.2 ± 1.2^{c}	43.5 ± 3.9^{c}	47.1 ± 4.2^{a}	52.9 ± 4.7^{d}
Highly-intensive 1	119.1 ± 12.1^{d}	75.6 ± 8.6^{d}	24.4 ± 2.2^{d}	18.2 ± 1.9^{d}	8.9 ± 0.4^{d}	7.5 ± 0.8^{b}	11.8 ± 1.2^{a}	36.4 ± 4.1^{a}	48.8 ± 4.4^{a}	51.2 ± 4.6^{c}
Highly-intensive 2	122.4 ± 12.4^{d}	76.9 ± 8.4^{d}	22.6 ± 2.1^{d}	17.6 ± 1.8^{d}	8.9 ± 0.3^{d}	7.3 ± 0.7^{b}	11.6 ± 1.1^{a}	38.4 ± 3.5^{b}	47.5 ± 4.2^{a}	52.5 ± 4.7^{d}

Note: see Table 2.

Analysis of data obtained at stage BBCH 32 indicates that the number of florets set in the spikelet varied depending on the doses of fertilizers applied under different growing technologies. In the ear of lateral shoots, the dependence of the number of laid flowers on the growing technology models was stronger.

An increase in the number of florets and grains in an ear of winter wheat with increasing doses of nitrogen applied during the period between the initiation of flower tubercles and flower differentiation was noted by Natrova & Smochek (1983). Grzebisz & Biber (2024) found that the nutritional management of winter wheat from the beginning of budding (BBCH 40) to the full flowering phase (BBCH 65) should take into account nitrogen (N). Any nutritional stress caused by a deficiency in the supply of nitrogen and nutrients that affect nitrogen uptake leads to a decrease in the number of fertile inflorescences and, consequently, to a decrease in the number of grains per ear. This effect is exacerbated by environmental stresses during this period (drought, extreme temperatures) and nutrient deficiencies, especially N (Zhao et al., 2021).

According to Shelepov et al. (2004) under optimal weather conditions, the difference in the rate of formation of the first two and subsequent flowers in spikelets can be reduced by enhanced organomineral plant nutrition. When applying fertilizers during the period of flower formation, it is possible to sharply increase the multi-flowering of spikelets and their graining. The number of fertile florets in the ear during the flowering period of winter wheat (BBCH 60–69) is an important indicator for the formation of ear productivity. Under cultivation technologies that involved the application of fertilizers, as a result of improved plant nutrition conditions, grain size and the number of grains in the ear increased. This pattern persisted until the BBCH 92 development in the ear of both orders. These cultivation methods increased the number of grains and ears in the spike. Due to the lack of fertilizer in the reference experiment, the number of grains per ear was significantly lower. As is known, some of the initiated flowers at BBCH 31–32 of winter wheat, lag behind in development and are reduced before reaching the BBCH 92.

According to morphophysiological studies, the main periods in which a significant part of the laid flowers for a given variety is reduced and the magnitude of such reduction depending on the cultivation technology were determined. With increasing doses of applied fertilizers from energy-saving to intensive and high-intensive cultivation technologies, the percentage of reduction of flowers of both orders decreased. The improvement of nutrition conditions had a greater effect on the reduction of the size of the reduction of flowers in the spikes of the tillers. High wheat grain yield is attributed to more efficient ears due to higher yield per ear due to increased biomass per stem after flowering (Ding et al., 2023). Therefore, the improvement of plant nutrition conditions under resource-saving, intensive, and highly intensive technologies led to increase in the number of flowers that reached the BBCH 92 (grains) both in the main and tillers ears.

Agronomic management of spikelet architecture can influence spikelet number and flower fertility (Luo et al., 2023). This is important for optimizing wheat yield and modern strategies for sustainable crop practices (Chen et al., 2020). Thus, it is possible to more fully realize the genetic potential of this yield element.

A more complete idea of the formation of the elements of ear productivity, the amount of their reduction, is provided by model schemes of potential and actual ear productivity.

AQ scheme model of the formation of the productivity of the central ear of winter wheat depending on the cultivation technology are shown at Figure 2. This model shows how the ear's potential changed from BBCH 32 to 92, the number of florets (grains) in the ear at different stages of development, and the actual grain size of the ear at BBCH 92 under different cultivation technologies (highly-intensive 1 and control (without fertilizers)). The construction of such a scheme model allows us to compare the nature of the processes of formation of ear productivity elements, establish the features of the decreased productivity elements, identify the effect of various factors on them.

The number of productive stems is one of the main indicators that determine the potential yield of winter wheat. It is known that the number of synchronously developed stems at BBCH 31–32, 37–46, and 92 has genetic determination. The synchronicity of stem development is formed under the influence of both genetic factors and environmental conditions (Kolyuchyy et al., 2007; Kiss et al., 2024). At the same time, by managing anthropogenic factors, it is possible to achieve the optimal structure of winter wheat sowing and increase its yield.

The formation of optimal density of productive stems is one of the key elements of highly productive agrophytocenoses and, according to many scientists, determines the level of crop yield by 50%. The optimal density of productive stems is considered to be such that, if exceeded, it reduces sowing productivity wheat (Feng et al., 2024). A number of experiments have shown that adjusting the seeding density is an effective agronomic measure to increase wheat yield per unit area (Zheng et al., 2017; Gao et al., 2021; Zheng et al., 2021). Optimizing the seeding density of wheat is mandatory for improving the population structure and regulating the quality of the stem, thus ensuring the achievement of high and stable wheat yields without significant lodging. At high seeding density of wheat, a decrease in grain mass was observed due to a significant increase in the number of spikelets per unit area, increased competition between individual plants, and a decrease in the number of grains per spike and grain mass (Liu et al., 2020). Optimal parameters of the main elements of yield can be obtained in two ways: by activating the formation of a new element or by weakening the quantitative reduction of the formed elements (Filip et al., 2023).

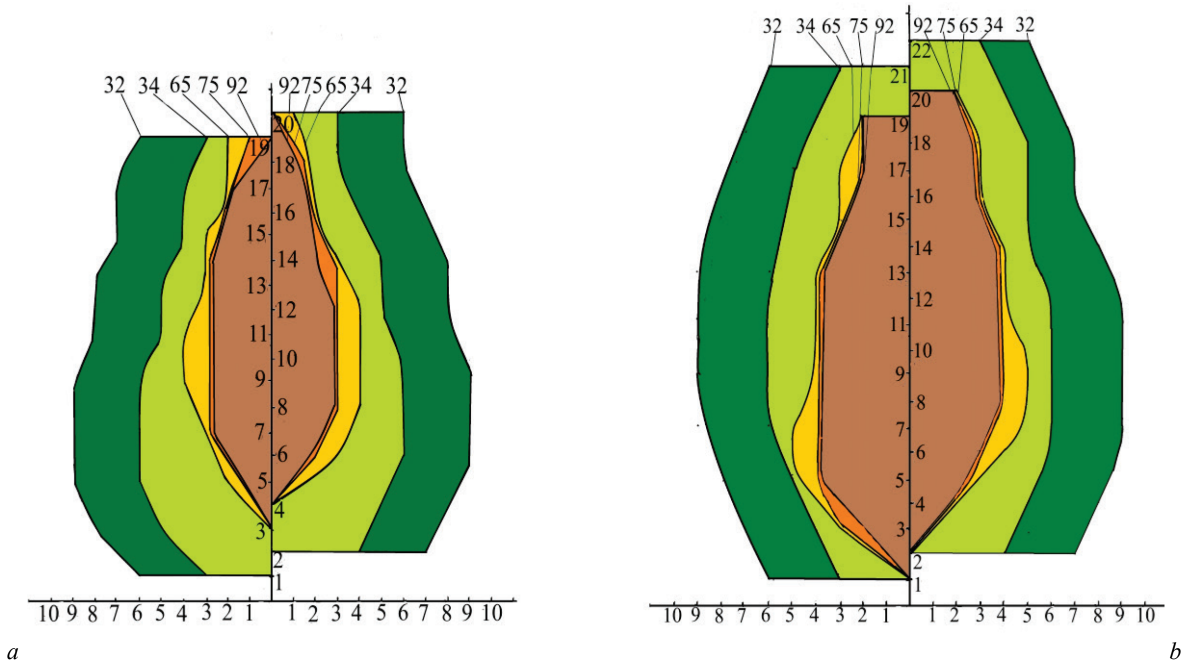

Fig. 2. Scheme model of formation of winter wheat ear's productivity under different cultivation technologies: *a* – without fertilisers (control), *b* – highly-intensive technology 1; on the X-axis – the number of florets (grains) in the spikelet; on the Y-axis – is the serial number of the spike; reduction of florets: dark green color – BBCH 32–34, light green (lettuce) – BBCH 34–65, yellow – BBCH 65–70, orange – BBCH 75–92, brown color – grain content of ears at BBCH 92

These processes were facilitated by the use of researched cultivation technologies of various intensities. Observation of the dynamics of stem density of winter wheat during the growing season showed that the stem density was determined by the stage of BBCH and the doses of applied fertilizers under cultivation technologies of different intensities.

The level of productive stems ranged from 33.4–41.3% of their number at BBCH 30. Intensification of treatment technology by improving plant nutrition conditions made it possible to preserve up to BBCH 92 1.59 times more productive stems with highly-intensive technology, and 1.43 times with intensive technology compared to the control.

Improving plant nutrition by applying fertilizers made it possible, to a certain extent, to compensate for the negative impact of weather conditions on the formation of individual elements of productivity (Chen et al., 2018; Macholdt et al., 2019; Hlisnikovský et al., 2023).

Based on the results of morphophysiological analysis of plants, calculations were made of the potential yield of winter wheat at the main stages of BBCH. They showed that the potential yield of winter wheat was determined by the stage of development and treatment technology (Table 5).

Analyzing the contribution of the potentials of the central ear and the tiller spikes to the formation of the crop at BBCH 92, it should be noted that in the control, the harvest of winter wheat of the Kraevyd variety was 61.9% formed by the potential of the central ear and 38.1% by the ears of the tillers. The use of highly-intensive technology made it possible to increase the share of tillers' ear potential in the harvest up to 52.5%.

The highly-intensive winter wheat cultivation technology, which included the application of P80K100N240 fertilizer on straw residues and integrated plant protection, ensured the highest grain yield of 8.93 t/ha on average over the 5-year period from 2016 to 2020. According to morphophysiological studies, such a productivity was provided by the number of the productive stems of 770 stem/m^2 and the average productivity of the ear of 1.42 g. The level of realization of the potential harvest at BBCH 65 stage was actually 36.4%, with the realization of productive stems 36.9% and 34.7% of the total number of florets preserved from BBCH 32 to 92.

Conclusions

Based on the data of plant condition monitoring, the duration of developmental stages according to the BBCH of winter wheat variety Kraevyd in relation to weather conditions in the northern part of the Forest-Steppe of Ukraine was determined.

The main regularities of formation of winter wheat productivity of the Kraevyd variety and its individual components depending on climatic conditions, biological potential of the variety and cultivation technologies were established.

The biological features and quantitative characteristics of flower set in the cones of stem growth of both (different) orders at the main stages of development according to the international scale of BBCH were determined. The periods and sizes of flower reduction and their dependence on the cultivation technology were noted, and a schematic model of the ear was constructed.

The dependence of winter wheat stem density on cultivation technologies and developmental stage is shown. The value of stem losses during the growing season and the degree of realization of productive stem under cultivation technologies of different intensity were determined. Based on the results obtained, the calculation of potential yields and the degree of their realization in the actual yield was carried out.

It was found that the cultivation of winter wheat variety Kraevyd under highly-intensive technology 1 created the conditions for increasing the realization of the genetic potential of the variety and the highest sowing productivity was obtained. The optimal parameters of productivity elements to ensure high yields were determined.

The results of the research are expected to reveal the genetically inherent reserves for increasing the crop productivity of the given winter wheat variety, to create optimal conditions for their manifestation through the application of cultivation techniques, and to take into account climate change. On the basis of the results obtained, cultivation techniques can be improved to ensure high grain yields, which will contribute to stabilising agricultural production and increasing food security.

Authors declare they have no conflict of interests with respect to this paper.

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