International Journal of Agriculture and Biosciences 2026 15(2): 840-849.
https://doi.org/10.47278/journal.ijab/2025.121

RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Effect of Precision Farming and Differential Nitrogen and Phosphorus Doses on Spring Wheat Yield in the Northern Kazakhstan Climatic Zone

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ABSTRACT

Our study investigates the effects of precision farming and varying nitrogen (N) and phosphorus (P) fertilizer doses on spring wheat yield in Kostanay, Kazakhstan. By using agrochemical analysis and productivity zones, this research aims to optimize fertilizer use for better crop yields and offers practical recommendations for sustainable farming in similar climates. The study was conducted in 2023 at Lugovoye Farm on 215ha, and N and P fertilizers were tested on spring wheat. The best results were achieved with a 75 kg/ha ammophos application, resulting in a 3.0kg/ha increase in yield. Higher doses in productive zones and lower doses in less productive areas also yielded positive results. The findings highlight the potential of precision agriculture to increase productivity, sustainability, and food security, particularly in developing regions, to support economic growth and poverty reduction.

Keywords: Fertilizer optimization; Spring wheat yield; Sustainable agriculture; Green agriculture; Agricultural planning

Article History
Article # 25-234
Received: 02-May-25
Revised: 12-Jun-25
Accepted: 12-Jul-25
Online First: 28-Jul-25

INTRODUCTION

The development of agriculture ensures global food security, especially with climate change and population growth putting increasing pressure on food production systems (Zafar et al., 2025). Precision agriculture an integrated system that applies digital technologies to monitor, analyze, and optimize agricultural operations has emerged as a promising solution for enhancing productivity, resource efficiency, and sustainability. Its relevance is particularly heightened by the degradation of soil health, loss of organic carbon, erosion, and the high cost of land treatment across large agricultural landscapes. However, the adoption of precision farming remains uneven, particularly in developing countries. Researchers have noted various problems with the introduction of precision farming in developing countries. First, these include the high initial costs associated with precision farming (there are not enough financial resources to purchase drones, sensors, automated equipment, and software necessary for data analysis, maintenance, and operation) (Baimuratov et al., 2021). Second, agricultural producers (especially farmers, including small private farms) lack technical knowledge in precision farming. The complexity of these systems requires specialized training, which is often lacking or unavailable in many developing regions. The convenient transfer of knowledge to farmers will make it easier for them to apply methods for differentiated fertilization via unmanned aerial vehicles (UAVs) and work with the normalized difference vegetation index (NDVI). Third, infrastructure constraints exist (in rural areas, reliable internet infrastructure, data storage hardware, and data processing and interpretation software are required) (Turganbayev et al., 2023).

Fourth, there is a need for a clear policy and framework to support the integration of digital technologies into agricultural practices. This includes policies related to subsidies, training programs, and the development of infrastructure and knowledge of industry participants. Addressing these challenges requires coordinated efforts involving governments, international organizations, and the private sector to provide the necessary resources, training,

Cite this Article as: Yskak A, Nugmanov A, Tulayev Y, Kuanyshbaev S, Somova S, Chashkov V, Paramonova T, Yermoldina G and Daribayeva S, 2026. Effect of precision farming and differential nitrogen and phosphorus doses on spring wheat yield in the Northern Kazakhstan climatic zone. International Journal of Agriculture and Biosciences 15(2): 840-849. https://doi.org/10.47278/journal.ijab/2025.121

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and support systems. North Kazakhstan was chosen as the focus of the study because its agriculture faces unique problems due to the sharply continental climate, characterized by cold winters with little snow and hot, dry summers. This leads to significant fluctuations in soil moisture and nutrient availability, which affect yield stability (Government of the Republic of Kazakhstan, 2018; Kim, 2023; Mutengwa et al., 2023). Previous studies have shown that the strategic use of fertilizers can significantly increase crop yields, but the effectiveness of such practices in the region remains insufficiently studied (Dulambayeva et al., 2023; Kashina et al., 2022).

Many studies have evaluated the impact of phosphorus (P) fertilizer quantities on crops, but research on how different P fertilizers affect crop yields is scarce (Bakhshandeh et al., 2017; Gallet et al., 2003; Khan et al., 2018; Sucunza et al., 2018). The effects of P fertilizers on crops and soils have been investigated under various conditions, such as with the incorporation of biochar (Bornø et al., 2018), straw (Fei et al., 2020; Hu et al., 2021), or humic acid (Izhar Shafi et al., 2020; Purwanto et al., 2021) or by partially replacing inorganic P with organic manure (Bi et al., 2020; Xin et al., 2017). Nitrogen (N) plays a significant role in the soil–plant P cycle. There is extensive N and P synergy in nature, necessitating an examination of how different P fertilizers impact N and P use efficiency (Liang et al., 2024). The selection of suitable P fertilizer types is crucial for improving their industrial structure, yet it is often neglected. As crops grow, biomass accumulates and differentiates into various organs, reflecting the differences in P supply. P deficiency during the flowering stage can result in fewer grains per ear, whereas deficiency during the filling stage can lead to a lower 1,000-grain weight.

Ammonium nitrate is popular because it provides both nitrate and ammonium forms of N that are readily available for plant uptake. This dual availability makes it an effective fertilizer for various crops, including wheat, as it supports rapid and sustained N uptake by plants, increasing growth and yield (FAO, 2003). Ammonium phosphate, particularly diammonium phosphate (DAP), is also extensively used because its high P content is crucial for root development and overall plant health. P from ammonium phosphate is readily available to plants, making it an excellent source for addressing P deficiencies in crops such as wheat. The widespread use of these fertilizers is supported by their effectiveness in improving crop yields and their ability to be easily incorporated into various soil types and agricultural systems. While some studies advocate higher doses to maximize yields, others emphasize the need for balanced fertilization strategies to prevent environmental degradation and improve nutrient efficiency (Effah et al., 2023; Yan et al., 2024). Studies have shown that higher doses improve yields only to a degree, and an additional increase ceases to result in significant benefits and can lead to problems with P runoff (Cui et al., 2022; Nikolajsen et al., 2020).

Though precision agriculture is becoming more and more popular worldwide as a way to raise crop output and sustainability, there is still a lot of research needed on how best to apply these technologies in underdeveloped countries. Among local farmers in northern Kazakhstan, the agricultural sector presents many difficulties, including variable soil fertility, erratic climatic conditions, and limited technological and financial resources. Although nitrogen and phosphorous fertilizers have clearly shown advantages in raising crop yields, their effective application remains a challenge, especially in terms of aligning them with the heterogeneous productivity zones observed in large-scale fields. Usually resulting in overuse and undernourishment in some areas, conventional/traditional fertilizer application techniques ignore these spatial variations (Ramazanova et al., 2023).

This results in suboptimal crop yields and also contributes to long-term soil degradation and environmental pollution through nutrient runoff. Furthermore, while studies have investigated the effects of different forms and doses of phosphorus fertilizers, few have systematically evaluated how these fertilizers perform in real field conditions when co-implemented in precision farming systems/techniques tailored to localized soil needs and soil types. This lack of field-based, region-specific research limits the development of evidence-based recommendations that can be realistically adopted by farmers, especially those in underdeveloped and developing settings. Compounding this issue is the limited access to advanced precision farming tools and the technical knowledge required to interpret data such as NDVI indices or carry out site-specific fertilization. Therefore, it is desperately necessary to close the knowledge and application gap between the daily reality of farming in areas like Kostanay and high-tech agricultural innovations. Given the region's strategic relevance for Kazakhstan's grain output and the larger objective of improving food security under the strain of climate variability, tackling this issue is especially vital. Therefore, the research issue revolves around the pressing need to maximize the use of generally available N and P fertilizers, especially ammonium nitrate and ammonium phosphate, through precision agriculture techniques suited to local conditions. The challenge entails not only the best fertilizer dosages but also how these should be distributed over production zones to maximize yield and resource economy (Gusev et al., 2022).

Our study aimed to evaluate the effects of precision farming combined with various N and P fertilizer doses on spring wheat yield in the Kostanay region of Kazakhstan. Using a differentiated approach to fertilization based on agrochemical analysis and productivity zones, this study aims to provide insight into optimizing fertilizer use to increase crop yields. The significance of this study is that it can offer practical recommendations for farmers in similar climates, contributing to sustainable farming methods and improving food security. Understanding the interaction between precision farming and fertilizer application can lead to more efficient use of resources and better adaptation strategies in the face of climate challenges.

By systematically assessing the impact of different fertilizer application rates, this study fills the existing gap and supports the development of adapted agronomic methods that maximize crop yields while maintaining environmental health.

MATERIALS & METHODS

Study Design

The study was conducted in 2023 at Lugovoye Farm, Kostanay region (coordinates 52°42′19″ N, 63°09′20″ E). During the reporting period, we established a production experiment on 215 ha. In the course of practical fieldwork, we studied the effectiveness of N and P fertilizers on spring wheat.

Climate

The climate in the research area is sharply continental, with cold winters with little snow and hot, dry summers. Prolonged cold weather in spring, earlier temperature decreases in autumn, and late summer precipitation are typical for the region and distinguish it from other arid regions (for example, the Volga region, Russia). High exposure to sunlight, a sharp temperature difference during the day and night, low humidity, low clouds and frequent winds cause intense moisture evaporation, exceeding the amount of precipitation by 2–5 times. The end of May is especially dry, as is the case in June, when spring grains are in the tillering and stem elongation stages. Before precipitation, plants must expend rapidly disappearing moisture reserves accumulated in the soil as a result of winter precipitation. All the climatic factors vary greatly in different years in terms of intensity and time of manifestation.

According to long-term data, the annual precipitation norm in the area where the experiments were conducted is 340 mm. Precipitation during the warm period (April--October) accounts for 71.2% of the annual total, with most precipitation falling in the second half of the summer. The total precipitation for the period from October to September was as follows: in 2021, it was 322.6 mm, which is 94.9% of the annual norm; in 2022, it was 291.9 mm, or 85.8% of the annual norm; and in 2023, it was 384.2 mm, or 113% of the annual norm.

Notably, in May 2021, the average daily air temperature exceeded the long-term average by 6.3°C, whereas in the other months of the warm period that year, it was close to the long-term average. In April 2022, the temperature exceeded the long-term average by 4.5°C, which, combined with the precipitation deficit during this period, contributed to an earlier start of sowing operations. However, in the remaining months of the warm period in 2022, temperatures remained close to long-term averages. In April 2023, the temperature exceeded the long-term average by 2.7°C, and a significant temperature increase was also observed in May (exceeding long-term averages by 2.6°C). This, combined with a precipitation deficit, raised concerns among farmers in the region and led to an earlier start of sowing (similar to the conditions in 2022). The entire month of July was also hot, with temperatures exceeding the long-term averages by 3.1°C, which, along with the precipitation deficit, significantly reduced crop yields for early sowing dates.

Experimental Design

A randomized complete block design (RCBD) was used to test the effects of different nitrogen (N) and phosphorus (P) fertilizer doses on the spring wheat yield of Chelyaba 75. The experiment included four treatments: 60, 75, and 90kg/ha pure N and a control group with no fertilizer application. Each treatment was replicated three times across the experimental sites within a single experimental area of 215ha with high plant productivity and low availability of nutrients in the soil.

Soil Sampling

To assess the initial state of the soil at the production site, samples were taken to determine the main mineral nutrient contents before sowing. We checked the contents of nitrate N ($N{-}NO_3$), mobile P (P_2O_5), exchangeable potassium (K2O), and mobile sulfur (S) and the content of organic matter (humus) in the 0-20cm soil layer. Using the Qoldau.kz website, we created a grid along the contours of the fields, which were broken down into elementary plots. The soil sample selection was carried out via a mobile sampler, following the technical specifications of the coordinate system.

The task map for differentiated sowing and fertilizer application for the experiment was developed in QGIS 3.26.2-Buenos Aires, which is based on the productivity zone map from the OneSoil service. On the basis of the data from the agrochemical survey of the fields in QGIS 3.6, maps of the availability of humus, mobile P, exchangeable K_2O, S, and nitrate N were created. For this purpose, differentiated coloring styles based on logical rules were applied to the properties of each vector layer with elementary sections of farm fields, according to the degree of nutrient availability in the soil. In the course of practical work in the field, we studied the effectiveness of N and P fertilizers, ammonium nitrate (N 33%) and ammophos (P 46%), on spring wheat. The analysis of productivity zones for fields in recent years has been carried out, and a map of productivity zones has been compiled (Fig. 1). The different zones are color-coded to reflect areas of varying productivity potential. The scheme of the experiment used to study the effectiveness of the differentiated use of ammophos applied at sowing on spring wheat is shown in Fig. 2. Spring wheat sowing was carried out via the differential application of mineral fertilizers on the basis of agrochemical analysis. The map (Fig. 3) displays how fertilizer was applied on the basis of the productivity zones identified earlier.

Precision Farming Tools and Technology

Precision farming tools, including UAV-based remote sensing and normalized difference vegetation index (NDVI) mapping, were employed to assess crop health and optimize fertilizer application. The Geoscan 101 UAV equipped with a Sony A6000 multispectral camera captured field imagery throughout the growing season, and the NDVI data were analyzed via QGIS software to identify productivity zones for differentiated fertilizer application. The UAV recorded 1,214 shooting positions and connected 267,298 points for analysis. The vegetation index was

Fig. 1: Productivity zones of fields intended for the cultivation of spring wheat.

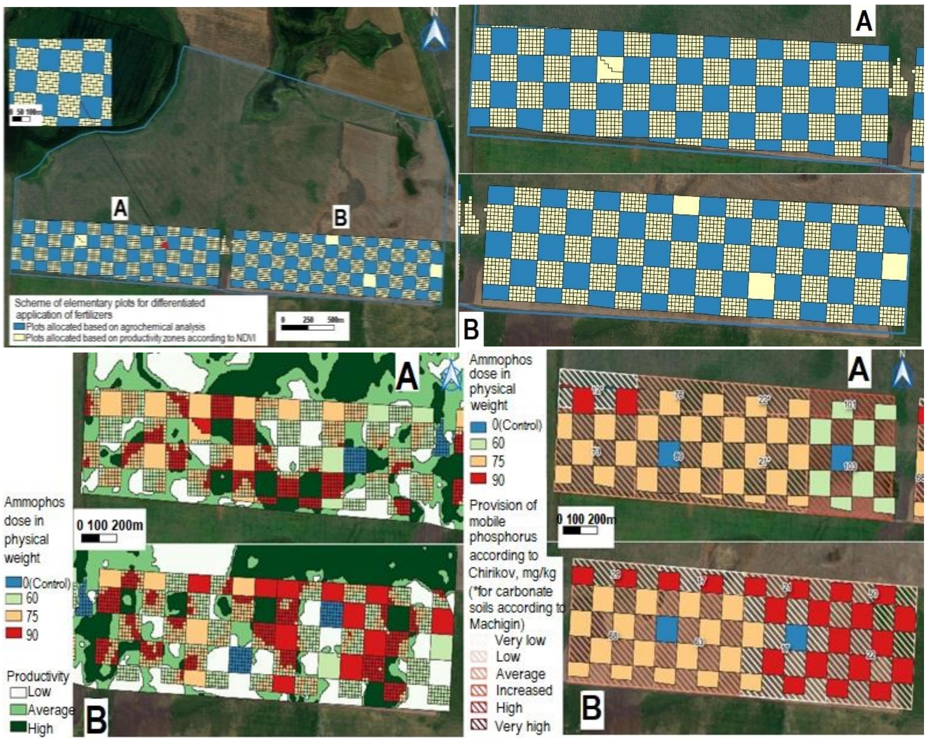


Fig. 2: Scheme of the experiment based on agrochemical analysis and analysis of productivity zones. Area A – plots designated on the basis of agrochemical analysis; Area B – plots designated on the basis of productivity zones according to the NDVI.

Fig. 3: The task map for the different applications of N fertilizers.

monitored in the fields (Fig. 4 and 5). The index peaked on July 25. Fig. 4 provides a visual representation of crop growth, with the peak NDVI values indicating the optimal growth stage of the crop. Fig. 5 visually compares the growth parameters of spring wheat across different nitrogen doses. As a result of remote monitoring of the vegetation index, we noted that the peak index changes in the fields occurred on July 25. However, on July 25, there were clouds over this field. In early August, we also carried out intermediate morphometric calculations of the physical weights of spring wheat with various dosages of mineral fertilizers.

Fig. 4: Field images taken between July 22 and 25, field 1, spring wheat.

Fig. 5: Images of the field taken between July 22 and 30.

Observations and Accounts of the Experiment

During the growing season, changes in the dynamics of the NDVI were monitored.

The index was measured at three key phases of wheat growth:

- Tillering stage (early May)
- Stem elongation stage (late June)
- Grain-filling stage (late July)

These measurements were taken via UAV-based remote sensing, which captured normalized difference vegetation index (NDVI) data every two weeks throughout the growing season. In accordance with the NDVI, arrays of plots that were located mainly in the same productivity zone and where there was a difference in NDVI coloration between the options for manual sampling were identified. The monitoring of spring wheat crops via aerial photography with a Geoscan 101 UAV equipped with a Sony A6000 multispectral camera and subsequent route studies, which were based on the NDVI, allowed us to identify areas with high weed infestations quickly.

Biological Yield

The biological yield was recorded in predetermined coordinates with an accuracy of +/-3 m in the center of the plots following the scheme of the experiment. Sampling was carried out from an area of 1 m^2 at each point. The following accounts and observations were carried out:

Agronomic parameter calculation via information and analytical system tools (calculation of the growing season of the crops);

Phenological observations via remote sensing, the portable devices GreenSeeker and N-tester, and visual estimation. The date of sowing, the onset of the main phases of the development of the crops, maturation, and harvesting were recorded. Agrometeorological observations were carried out independently via the readings of the Caipos automatic weather station and according to the Kostanay Agrometeorological Station. The average daily air temperature and the sum of the effective temperatures were measured. During the growing season, the amount of precipitation was recorded. We performed ground-based accounting of field germination and plant density and identification of problem areas via remote monitoring tools. The determination of nitrate N ($_{N\text{–}NO_3}$) and mobile P (P_2O_5) concentrations was performed according to the Chirikov or Machigin methods, depending on the soil type in the 0--20 cm soil layers before sowing, with reference to the coordinate system. An accurate positioning system was used during the pre-sowing treatment. Sampling of plant sheaves was performed to determine the yield and productivity of the plants. Yield accounting was performed with geo-linking in the field sections. Grain sampling was performed to determine quality indicators.

Statistical Analysis Methods

We carried out accumulation, correction, systematization of initial information, and visualization of the results in the QGIS 3.26.2-Buenos Aires and Microsoft Office Excel 2016 spreadsheets. Quantitative indicators with a normal distribution were described via the arithmetic mean (M), standard deviation (SD), and boundaries of the 95% confidence interval (95% CI). In the absence of a normal distribution, quantitative data were described using the median (Me) and the lower and upper quartiles (Q1–Q3).

RESULTS

Remote sensing data revealed an upward shift in the vegetation index at the end of April and on May 1, 2021, indicating the early and widespread emergence of overwintering weed species. Ground-based field inspections confirmed this observation, enabling timely chemical weed control approximately 10 days earlier than the long-term regional average. This early intervention effectively preserved productive moisture in the root zone and minimized nutrient depletion, thereby enhancing initial crop development (Fig. 6). Agrochemical analyses

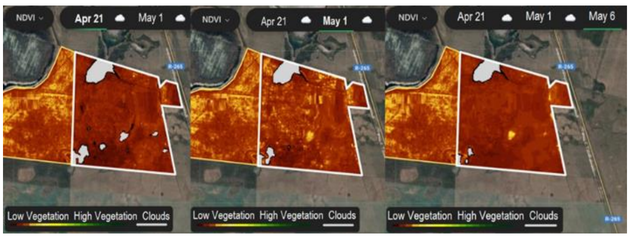


Fig. 6: Monitoring of the weed infestation index to control weeds in a timely manner during presowing treatment*; *The date when the image was taken is indicated at the top, and the reflected number on the contour of the field is the date of the last available image.

Table 1: The basic nutrient content in the 0--20 cm soil layer

Field/plot	N-NO_3	Availability	P_2O_5	Availability	K_2O	Availability	pH	Degree of acidity	S	Availability	Humus, %	Content
1	2	3	4	5	6	7	8	9	10	11	12	13
11704-1-1	8.5	low	68	average	298	very high	8.14	slightly alkaline	2.5	very low	2.44	low
11704-2-1	4.8	very low	63	average	300	very high	7.95	slightly alkaline	2.8	very low	3.46	low
11704-3-1	7.6	low	17	very low	226	very high	7.35	neutral	3.4	low	2.66	low
11704-4-1	5.2	low	22	low	262	very high	7.12	neutral	2.1	very low	2.63	low
11704-1-2	4.8	very low	29	low	218	very high	7.55	slightly alkaline	1.8	very low	3.75	low
11704-2-2	5.4	low	17	very low	254	very high	8.07	slightly alkaline	2.8	very low	2.26	low
11704-3-2	5.2	low	21	low	370	very high	7.10	neutral	1.4	very low	2.88	low
11704-4-2	5.5	low	50	average	278	very high	7.25	neutral	9.7	increased	2.55	low
11704-1-3	5.0	low	45	low	239	very high	7.65	slightly alkaline	1.6	very low	2.36	low
11704-2-3	4.9	very low	102	increased	351	very high	7.79	slightly alkaline	1.8	very low	3.37	low
11704-3-3	5.8	low	70	average	360	very high	7.54	slightly alkaline	1.4	very low	2.96	low
11704-4-3	9.8	low	18	very low	399	very high	7.12	neutral	2.1	very low	3.26	low
11704-1-4	4.6	very low	52	average	290	very high	7.90	slightly alkaline	1.3	very low	2.02	low
11704-2-4	4.8	very low	45	low	236	very high	7.92	slightly alkaline	1.2	very low	1.92	very low
11704-3-4	6.4	low	57	average	320	very high	7.28	neutral	1.8	very low	3.00	low
field 14, plot 1	≤2.8	very low	103	increased	390	very high	7.76	slightly alkaline	3.4	low	3.33	low
field 14, plot 2	≤2.8	very low	101	increased	402	very high	7.73	slightly alkaline	7.0	average	3.72	low
field 14, plot 3	≤2.8	very low	70	average	341	very high	7.19	neutral	1.4	very low	3.20	low
field 14, plot 4	≤2.8	very low	58	average	312	very high	7.22	neutral	1.2	very low	2.73	low
field 14, plot 5	≤2.8	very low	59	average	290	very high	7.20	neutral	3.5	low	2.88	low
field 14, plot 6	3.4	very low	21*	average	445*	very high	7.68	slightly alkaline	1.5	very low	3.49	low
field 14, plot 7	3.3	very low	22*	average	492*	very high	7.94	slightly alkaline	6.5	average	3.39	low
field 14, plot 8	≤2.8	very low	70	average	450	very high	7.61	slightly alkaline	2.7	very low	3.24	low
field 14, plot 9	≤2.8	very low	89	average	449	very high	7.24	neutral	2.2	very low	3.26	low
field 14, plot 10	3.1	very low	76	average	324	very high	7.16	neutral	1.1	very low	3.24	low
field 14, plot 11	2.9	very low	61	average	352	very high	7.20	neutral	1.9	very low	2.91	low
field 14, plot 12	≤2.8	very low	73	average	351	very high	6.98	neutral	4.1	low	3.01	low
field 14, plot 13	3.3	very low	12*	low	467*	very high	7.65	slightly alkaline	4.1	low	3.25	low

*The Machigin method was used in the marked areas for the agrochemical analysis.

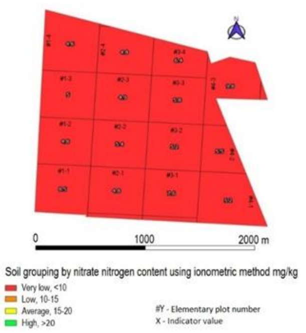
Table 2: N content in plant leaves and vegetation indices

Variant	Reading GreenSeeker	N content, %	N-tester readings
Ammonium nitrate			
Plot 753 (control)	0.29	3.21	645
Plot 784 (75kg)	0.54	3.60	646
Plot 530 (control)	0.43	3.21	639
Plot 517 (60kg)	0.48	3.44	691
Plot 597 (75kg)	0.51	3.38	694
Plot 623 (90kg)	0.46	3.33	631
Ammophos			
Plot 8550 (control)	0.36	3.09	541
Plot 662 (60kg)	0.38	3.15	622
Plot 4099 (75kg)	0.40	3.16	663
Plot 6479 (90kg)	0.46	3.92	655
Plot 1789 (control)	0.32	2.56	585
Plot 1886 (60kg)	0.35	3.42	627
Plot 8674 (75kg)	0.39	3.44	648
Plot 6183 (90kg)	0.46	3.26	621

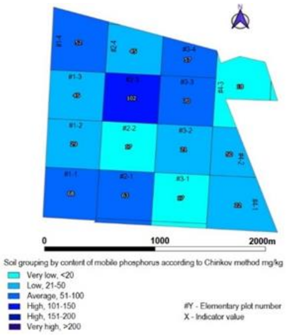
Table 3: The yield structure of spring wheat plants

Variant	Productive tillering capacity	Number of grains in an ear, units	Yield, c/ha	Weight of 1,000 seeds, g
1	2	3	4	5
Ammonium nitrate				
Plot 753 (control)	1.60	21.2	8.77	44.8
Plot 784 (75kg)	1.48	24.4	11.64	43.9
Plot 530 (control)	1.46	18.7	13.47	44.8
Plot 517 (60kg)	1.64	19.4	13.58	44.5
Plot 597 (75kg)	1.60	21.7	15.77	43.0
Plot 623 (90kg)	1.52	18.5	14.38	42.6
Ammophos				
Plot 8550 (control)	1.12	19.5	9.36	45.3
Plot 662 (60kg)	1.25	18.8	12.09	43.1
Plot 4099 (75kg)	1.56	22.0	15.05	43.1
Plot 6479 (90kg)	1.28	26.1	11.68	43.9
Plot 1789 (control)	1.16	15.7	7.50	43.8
Plot 1886 (60kg)	1.52	19.1	12.87	44.1
Plot 8674 (75kg)	1.56	28.5	14.71	44.6
Plot 6183 (90kg)	1.20	27.0	12.69	40.8

conducted during the 2021 growing season (Table 1) showed that 33% of the studied fields had low mobile phosphorus (P) availability, and all fields demonstrated low nitrate nitrogen (N) content. Based on these results, digital maps of nutrient availability—including humus, mobile phosphorus, exchangeable potassium, sulfur, and nitrate nitrogen—were generated for the "Lugovoye" farm using QGIS 3.6 software. Logical rule-based color schemes were applied to vector layers for each elementary field plot, reflecting spatial variability in soil nutrient levels (Fig. 7). A comparative analysis was conducted using two parameters: nitrogen content in wheat leaves and vegetation index values, supplemented by structural yield component assessments (Table 2 and 3). All fertilizer-treated plots demonstrated superior vegetative performance and yield attributes relative to untreated controls. Spatial yield data were collected from 37,536 georeferenced points using yield-mapping harvesters, and median values (Me) were used for analysis due to the non-normal distribution of several parameters (Fig. 8). For the final evaluation, the data from each elementary plot were aggregated according to the respective experimental variant (Fig. 9). Results showed that in unfertilized plots, wheat yield positively correlated with both soil phosphorus availability (as measured by P_2O_5 content) and mapped productivity zones. However, the application of 60kg/ha of ammophos in areas with high P availability yielded no significant increase in productivity relative to the control. In contrast, a dose of 75kg/ha ammophos led to notable yield gains. In soils with moderate phosphorus availability, the average yield increase was 3.0 centners per hectare (c/ha). In low-phosphorus soils, the same dose resulted in a 3.5 c/ha increase. Interestingly, a higher dose of 90 kg/ha provided a smaller gain of 2.6c/ha, suggesting diminishing returns at elevated P rates in low-P soils. These findings suggest that 75kg/ha of ammophos is the optimal rate under both low and medium phosphorus conditions, when determined through agrochemical survey data. When ammophos application was based on mapped



Nitrate N content map
Field N2LXS2021-6229-01-11704



Mobile P content map
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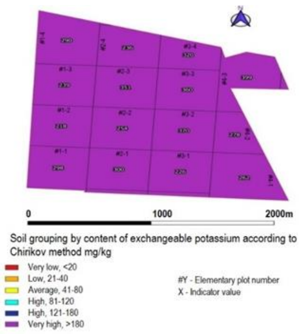
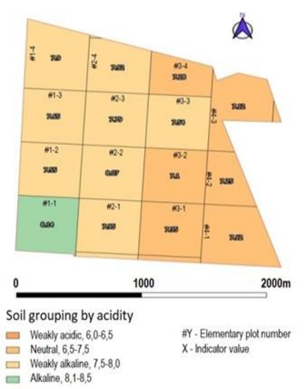
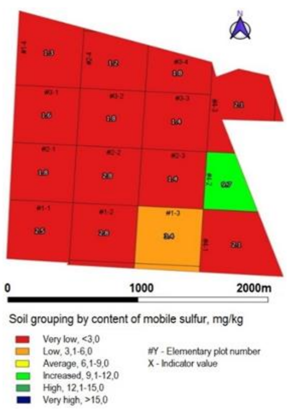


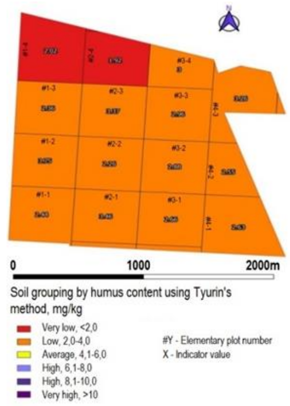
Exchangeable K content map
Field N2LXS2021-6229-01-11704



Map of the pH of the soil environment
Field N2LXS2021-6229-01-11704



Mobile S content map
Field N2LXS2021-6229-01-11704



Humus content map
Field N2LXS2021-6229-01-11704

Fig. 7: The results of agrochemical studies.

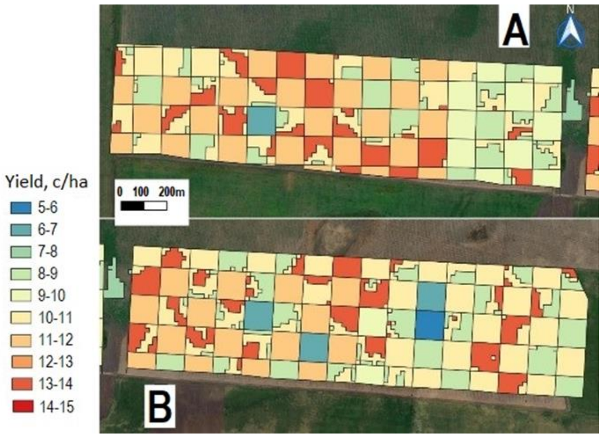


Fig. 8: The average yield of spring wheat in the experimental plot, Lugovoye Farm: Area A – plots designated on the basis of agrochemical analysis; Area B – plots designated on the basis of productivity zones according to the NDVI.

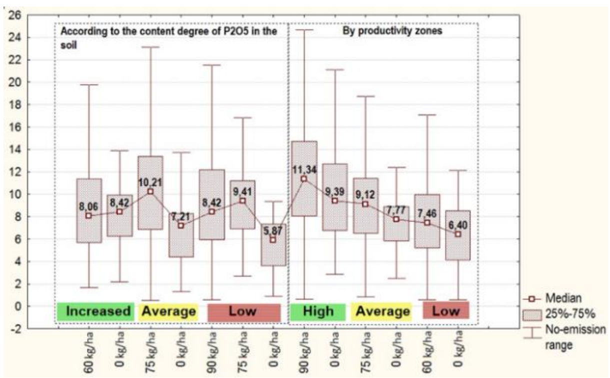


Fig. 9: The yield of spring wheat with different applications of ammophos during sowing (winter wheat yield for different differentiated ammophos application approaches).

productivity zones, a nearly linear relationship was observed: in each zone, fertilization led to yield improvements that enabled the crop to approach the productivity of the next higher zone. This further validated the effectiveness of spatially informed, variable-rate fertilizer applications. Fig. 10 and 11 illustrate the morphometric performance of spring wheat under different nitrogen (Fig. 10) and phosphorus (Fig. 11) fertilizer rates during the grain-filling (milk ripening) stage. Measurements included plant height, stem density, and ear development, and collectively confirmed that both N and P fertilization had significant positive effects on these growth traits. Harvesting was carried out using John Deere combine

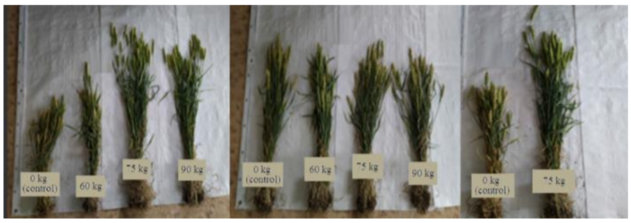


Fig. 10: N fertilizers on spring wheat.

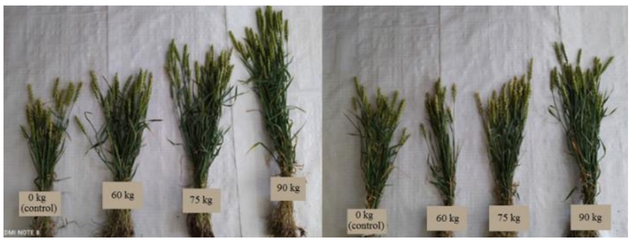


Fig. 11: P fertilizers on spring wheat.

harvesters equipped with GPS-based yield monitoring systems, enabling high-resolution spatial yield data collection. Overall, the highest yield response to phosphorus fertilization was observed with 75kg/ha of ammophos applied to soils with moderate P availability, leading to a mean yield gain of 3.0c/ha. This outcome underscores the value of site-specific fertilization strategies based on agrochemical mapping in maximizing wheat productivity while maintaining input efficiency.

DISCUSSION

Our study allowed us to draw several theoretical and practical conclusions. First, using Earth remote sensing (ERS) and glyphosate-containing preparations during pre-sowing treatments is an important component of conservation agriculture. A qualitative assessment of weed infestations allows protection equipment and money to be saved. Today, vegetation index monitoring is associated with many agrotechnical operations. These include pre-sowing treatments, seedling monitoring, care of fallow fields, and crop vegetation. This practice aligns with the studies of Perekopskiy et al. (2023) and Fedoniuk et al. (2025) who evaluated the effectiveness of Earth remote sensing in pre-sowing treatments and also its application in ascertaining weed infestation and identifying 'hotspots' for weed proliferation. The data obtained by remote monitoring indicated that upward changes in the vegetation index in the field occurred in the first decade of May and confirmed the presence of perennial weeds and fallen grains. Aligning with the studies of Roslim et al. (2021) and Huang et al. (2025), who highlighted the effectiveness of weed mapping using satellite technology to ensure precise application of herbicides while taking factors such as drift into consideration. The results obtained further reinforces the advantages of precision farming, precisely remote sensing as it gives farmers the opportunity to make prompt decisions using precise data. With respect to the development of precision farming methods at the Lugovoye farm, it is necessary to pay attention to variable rate technology (VRT), sensors, and the global positioning system (GPS). VRT can significantly increase nutrient efficiency when fertilizers are applied at the right rate, at the right time, and at the right place. This approach minimizes nutrient losses and improves fertilizer absorption by crops. A previous study (Raza et al., 2023) demonstrated that precision farming tools optimize N and P application, leading to increased yields and reduced environmental impact (Cui et al., 2022). A previous study (Raza et al., 2023) revealed that precision farming technologies, including soil sensors and GPS-guided equipment, help to accurately assess soil fertility and adjust fertilizer application rates (Vrchota et al., 2022). An important step, considering sustainable development principles, is to use precision farming methods to reduce greenhouse gas emissions from agricultural soils. Studies have shown that optimized management through precision farming can reduce emissions, contributing to more sustainable farming practices (Yan et al., 2024). Second, our results confirmed that one of the main factors constraining crop yields was low nutrient availability in the soil. The application of fertilizers can compensate for nutrient deficiency (Vrchota et al., 2022). The effectiveness of this agricultural approach depends on the compliance of the doses with the nutrient content in the soil. Interestingly, the data for Table 1 indicates low to very low nutrient levels from 0-20cm and very high potassium levels. These data also indicate the possibility of nutrient leaching and in such scenario the application of fertilizers could prove counterproductive. Taking into consideration, Wang et al. (2021) study, which highlighted that chemical and organic fertilizer additions increased total nitrogen leaching loss. A very high potassium level can also inhibit magnesium and calcium uptake leading to secondary deficiencies. Future research should consider testing for leaching possibilities and long-term application of organic matter/manure can be used to restore leached soil before fertilizer application (Wang et al., 2021). Compared with the control treatment, in the experimental plots with increased availability of P_2O_5, an ammophos dose of 60kg/ha did not significantly increase the yield. With an average availability of mobile P in the soil, an ammophos dose of 75kg/ha increased the average yield by 3.0 c/ha, and in the plots with low availability, the increase from the same dose was 3.5c/ha. A 90kg/ha ammophos dose in the plots with low P availability provided an average increase of 2.6c/ha. Thus, with the differentiated application of ammophos on the basis of agrochemical survey data, the greatest relative increase was provided by an ammophos dose of 75 kg/ha in the plots with low and average mobile P contents in the soil. This result aligns with the study of Kulikova et al. (2020) who also concluded that the greatest relative increase after applying ammophos was between 70-80kg/ha.

An analysis of the yield results obtained when P fertilizers were applied on the basis of the analysis of productivity zones revealed that at a physical weight of 90kg, an average increase of 2.0c/ha was obtained in the high-productivity zone. At an ammophos dose of 75kg/ha in physical weight, in the plots with average productivity, the increase was 1.4 c/ha. The use of ammophos at a dose of 60 kg in physical weight in the plots with low productivity allowed for an increase of 1.1c/ha.

Third, our results and the results obtained by other researchers should be used to improve the skills of farmers and specialists at small private farms, especially in developing countries, where such systems are often not widely used. It is crucial to provide farmers with the knowledge and skills necessary to use these technologies effectively. For example, in Kazakhstan, public authorities play a key role in agricultural training programs. The experiment was conducted on a single farm in northern Kazakhstan, which limits the generalizability of the findings to other regions with different climates, soils, and environmental conditions. While the sharply continental climate of northern Kazakhstan provides unique insights, results may not fully translate to regions with milder or more humid conditions and may be limited to Central Asian countries and semi-arid regions. However, the use of precision farming techniques and agrochemical analysis helps ensure that the findings are applicable to similar climates and farming conditions in northern Kazakhstan, making the results valuable for regional adaptation and optimization of fertilizer use. Another limitation is the constraint to one planting season, which does not provide sufficient information for year-to-year variability in weather patterns, soil nutrient dynamics, and crop responses. Long-term studies are essential to validate the consistency and sustainability of the proposed fertilizer regimes and precision farming strategies. Although the study employed advanced tools such as UAV-based NDVI mapping and agrochemical analysis for precision fertilization, the accessibility and cost of such technologies remain a barrier for widespread adoption by small-scale or resource-limited farmers, especially in developing regions, and support from the government and private equities is needed to make precision farming a reality. In addition, future studies should focus on other fertilizers to provide a broad perspective. This study showed how precision farming methods combined with site-specific fertilizer application can increase spring wheat yields in northern Kazakhstan. The findings demonstrate how well moderate fertilizer dosages—specifically, 75kg/ha of ammophos—improve productivity in a given area. Even though the results provide insightful information for sustainable farming methods, more studies in a variety of settings and growing seasons are necessary to improve these tactics and increase their applicability.

Conclusion

This study explored the effects of precision farming combined with varying doses of nitrogen (N) and phosphorus (P) fertilizers on the yield of spring wheat in northern Kazakhstan. The key findings indicate that through the use of agrochemical analysis and productivity zone mapping, the targeted application of 75kg/ha ammonium phosphate provided the best results, increasing crop yield by 3.0c/ha in regions with moderate phosphorus availability. These findings emphasize the importance of adapting fertilizer application to specific field conditions to maximize yield and minimize environmental impact. Moreover, this study underscores the potential of precision farming to improve the efficiency of fertilizer use, reduce costs and reduce environmental risks such as nutrient runoff. By developing precision agriculture, developing countries can increase agricultural productivity, sustainability, and food security, contributing to economic growth and poverty reduction. This additional information will help highlight the importance of agricultural methods for achieving sustainable and efficient agricultural production.

DECLARATIONS

Funding: This research was carried out within the framework of the project BR24992785 "Organization and implementation of comprehensive research to ensure sustainable development of the agro-industrial complex of the Kostanay region with the creation of a research and technology center".

Acknowledgement: The authors would like to express their sincere gratitude to the editorial board and the anonymous reviewers of the International Journal of Agriculture and Biosciences for their constructive comments and valuable recommendations that significantly improved the quality of this manuscript.

Conflict of Interest: Authors declare no conflict of interest.

Data Availability: Data will be available at request.

Ethics Statement: This study did not involve any human participants or animal subjects. All field trials and data collection procedures were conducted in accordance with institutional and national guidelines for agronomic research in Kazakhstan.

Author's Contribution: Conceptualization, ST, SS and AJ; Data curation, AN and VCh; Investigation, TP; Methodology, AY, ST, SS and TP; Project administration, YuT; Resources, SK and AJ; Supervision, YuT; Validation, AJ; Visualization, SK, VCh and TP; Writing – original draft, AY, SK, VCh, TP and AJ; Writing – review & editing, AN, YuT, ST.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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