EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(5), 146–162
https://doi.org/10.12912/27197050/203075
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Received: 2025.02.28
Accepted: 2025.03.25
Published: 2025.04.01

Agroecological aspects of zonal application of fertilizers and pesticides in wheat cultivation in the Forest-Steppe of Ukraine

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ABSTRACT

The article examines the efficiency of wheat cultivation in the Forest-Steppe zone of Ukraine in the Vinnytsia, Kyiv, Poltava, Sumy, Ternopil, Kharkiv, Khmelnytskyi, Cherkasy, and Chernivtsi regions, during 2020–2024. It was determined that the total contribution of the Forest-Steppe region to winter wheat cultivation accounts for 40.5% of the total wheat area in Ukraine as of 2024, or 36.4% on average over the observation years. The highest wheat yields were recorded in Khmelnytskyi (5.85 t/ha), Ternopil (5.50 t/ha), Sumy (5.19 t/ha), Cherkasy (5.15 t/ha), and Vinnytsia (5.00 t/ha) regions. It was also determined that regions with higher wheat yields had greater nitrogen uptake, especially in Ternopil (182.5 kg/ha) and Khmelnytskyi (194.3 kg/ha) regions. The highest phosphorus removal was observed in Ternopil (72.7 kg/ha) and Khmelnytskyi (77.4 kg/ha) regions. The highest potassium uptake was recorded in Cherkasy (107.8 kg/ha), Sumy (108.1 kg/ha), Ternopil (115.0 kg/ha), and Khmelnytskyi (122.5 kg/ha) regions. This indicates a deficient balance of nitrogen, phosphorus, and potassium, with wheat plants depleting soil reserves to meet their nutrient demands. On average, in the Forest-Steppe of Ukraine, nitrogen losses amount to 84.6 kg/ha, phosphorus losses to 52.0 kg/ha, and potassium losses to 90.6 kg/ha. Across Ukraine as a whole, over the past five years, the negative balance of these nutrients has been better by 12.4 kg/ha for nitrogen, 9.1 kg/ha for phosphorus, and 12.4 kg/ha for potassium. The highest fungicide application rates were recorded in Vinnytsia (352 g/ha), Sumy (360 g/ha), Kyiv (377 g/ha), and Khmelnytskyi (387 g/ha) regions. The highest herbicide usage was observed in Ternopil (161 g/ha), Kyiv (173 g/ha), Chernivtsi (187 g/ha), and Khmelnytskyi (188 g/ha) regions, while the lowest was in Poltava (81 g/ha) region. The highest insecticide load on agroecosystems was recorded in Ternopil (108 g/ha) and Khmelnytskyi (95 g/ha) regions, while the lowest application was observed in Poltava (53 g/ha), Chernivtsi (56 g/ha), and Kharkiv (58 g/ha) regions. The highest application of growth regulators was identified in Kyiv (83 g/ha), Vinnytsia (98 g/ha), Khmelnytskyi (102 g/ha), and Ternopil (104 g/ha) regions. The lowest application rates were recorded in Poltava (31 g/ha) and Kharkiv (20 g/ha) regions.

Keywords: nitrogen, phosphorus, potassium, fungicides, insecticides, herbicides, growth regulators.

INTRODUCTION

Wheat is one of the most widespread and important cereal crops in the world, as its high nutritional value and versatility play a crucial role in global food security (FAO, 2023; FAO, 2021). However, wheat cultivation technology must be adapted to local growing conditions, such as weather patterns, abiotic and biotic stresses, and soil fertility (Zargar et al., 2017). A higher crop yield can be achieved when plants are in good physiological condition and experience optimal growth and development, ensured by all essential nutrients (Lollato, 2019; Bakalova et al., 2019).

Currently, grain crops dominate Ukraine's agricultural sector, as they are grown on approximately 11 million hectares out of 22 million hectares of total sown areas. Moreover, grain exports are a crucial component of the country's foreign economic activity (Tsilurik et al., 2017). Thus, cereal crops hold a leading position not only in Ukraine's agroecosystems in general but also in the Forest-Steppe zone, which is particularly favorable for grain cultivation due to a balance of sufficient thermal resources and moisture availability. Additionally, the region features fertile soils capable of supporting the needs of most traditional crops grown in Ukraine.

Among all cereal crops, winter wheat accounts for 82.7% of the total sown areas, as it can efficiently utilize the autumn-winter period of Ukraine's Forest-Steppe zone and resume vegetation early in spring, benefiting from the absence of resource deficits. This enables it to take full advantage of stored winter moisture and dominate agrocenoses without competition from weeds. As of 2023, winter wheat covers 71.6% of the total grain area, while spring wheat serves primarily as an insurance crop, ensuring production continuity in case of winter wheat losses. Each year, spring wheat is sown on approximately 200,000 hectares (Prysiazhniuk et al., 2024; Kalenska & Hordyna, 2022).

Fertilizers and pesticides are indispensable in modern agricultural practices, as they improve crop productivity and help preserve yields (Fan et al., 2023; Rehman et al., 2019; Subedi et al., 2023). However, excessive chemical use can harm soil health and the environment, making it unsustainable for long-term agricultural systems (Carvalho, 2006; Eijsackers & Maboeta, 2023; Wan et al., 2013).

It is believed that reducing fertilizer and pesticide use could lower yields, so farmers tend to apply these inputs in amounts that maximize output while minimizing costs (Rezaei et al., 2019; Fei et al., 2021). Additionally, there is a perspective that supplementary fertilizers and pesticides can replace certain costly yet less effective cultivation techniques by enhancing plant growth processes (Addison, 2016), especially under adverse weather conditions (Erdinc et al., 2018; Qi et al., 2018). It is also well known that farmers often prioritize the application of fertilizers and pesticides on more profitable crops, not necessarily those with the highest yields, but those that guarantee a better market price and economic return (Abadi, 2018; Colaço & Bramley, 2018; Mutua-Mutuku et al., 2017).

On the other hand, reducing fertilizer and pesticide use without replacing them with eco-friendly alternatives could increase production costs. A partial yield loss may discourage farmers from growing cereals, which are already not among the most economically profitable crops. Furthermore, lower fertilizer use may push agriculture toward extensive farming practices and reduced sown areas in intensively cultivated regions, potentially leading to a global decrease in cereal production and grain shortages (Sinha et al., 2022).

Among all wheat cultivation techniques, crop protection is one of the most complex technological processes (Pisarenko et al., 2021). The effectiveness of these protective measures depends on proper pesticide selection and correct application methods (Gamajunova et al., 2022). It is crucial to monitor harmful biota and adapt crop protection measures according to the agroecological state of the fields (Liskovskyi et al., 2020).

Among root system diseases, root rots are particularly common, leading to yield losses of up to 30% (Bakay et al., 2019; Slobodianyk et al., 2022). Wheat plants and grains are also damaged by leafhoppers, cereal flies, aphids, and grain beetles (Fedorenko et al., 2021). Additionally, various weed species, particularly grasses, can reduce wheat yields by up to 60% if left unmanaged (Storchous, 2019). The diversity of pests and diseases necessitates strong crop protection strategies, incorporating fungicides, insecticides, and herbicides.

Thus, to address the challenges of agricultural intensification, which has improved human well-being but also led to environmental consequences, modern sustainable farming practices and precision/organic agriculture technologies are being implemented (Muhie, 2022; Rebouh et al., 2023; Winkler et al., 2023; He et al., 2021). However, achieving high wheat yields through environmentally friendly technologies remains a topic of ongoing discussion, as organic farming systems typically produce lower yields than conventional methods. Therefore, the objective of this study is to identify the specific features of wheat cultivation across different regions of Ukraine, promoting more rational use of agrochemicals and pesticides.

MATERIALS AND METHODS

The study was conducted in the Vinnytsia, Kyiv, Poltava, Sumy, Ternopil, Kharkiv, Khmelnytskyi, Cherkasy, and Chernivtsi regions of Ukraine, all of which belong to the Forest-Steppe zone.

Weather conditions

The climate across all studied regions in Ukraine's Forest-Steppe zone is moderately continental. However, differences in long-term climatic indicators and annual weather variations must be analyzed in more detail, as they significantly affect wheat productivity.

Vinnytsia region

Average annual temperature (7–9 °C), annual precipitation (550–650 mm). Coldest month – January (-4 – -6 °C), warmest month – July (19–22 °C). Maximum precipitation in May–July, minimum precipitation in January–February.

Winter 2020 had moderate air temperatures and average precipitation. Spring was close to normal, with periodic rainfall that supported proper winter crop development. Summer was hot, especially in July and August, with drought periods. Autumn temperatures were close to the multi-year averages, with sufficient rainfall. Winter 2021 had below-average temperatures with moderate snowfall, ensuring proper soil moisture. Spring saw a gradual temperature increase with adequate precipitation. Summer recorded extremely high temperatures, particularly in June and July, with a precipitation deficit, leading to potential plant stress. Autumn temperatures were within the norm, with sufficient rainfall for winter crop preparation and soil moisture accumulation.

Winter 2022 featured moderate temperatures and average snowfall, providing proper soil moisture. Spring had average temperatures with periodic rainfall, supporting normal winter crop development. However, summer saw temperature increases, especially in July and August, with drought periods potentially affecting yield. Autumn temperatures remained close to multi-year averages, with sufficient precipitation for soil preparation.

Winter 2023 had lower-than-average temperatures with moderate snowfall. Spring was marked by a gradual temperature rise and sufficient precipitation, aiding vegetation. Summer saw extreme heat, particularly in June and July, with precipitation shortages. Autumn temperatures were within normal limits, with adequate precipitation.

Winter 2024 featured moderate temperatures and average snowfall. Spring had average temperatures with periodic rainfall, ensuring normal winter crop development. Summer had high temperatures, especially in July and August, with drought periods. Autumn temperatures were close to long-term averages, with sufficient precipitation.

Kyiv region

Average annual temperature (7–9 °C), annual precipitation (550–650 mm). Coldest month – January (-4 – -6 °C), warmest month – s July (19–22 °C). Maximum precipitation in June–July, minimum precipitation in February–March.

Spring and summer 2020 were warmer than average, with periods of extreme heat. Spring was humid, supporting crop sowing, while summer had uneven rainfall, including drought periods, affecting yields. A warm 2021 year with record summer heat. The annual temperature exceeded the norm. Spring was humid, supporting winter crop development. However, summer drought intensified, reducing yields. Intense storms with hail caused crop damage.

Hot summer 2022, mild winter. Spring was relatively dry, complicating sowing. Summer precipitation was uneven, with drought periods. Thunderstorms and strong winds damaged crops and infrastructure. Warm 2023 year with record summer heat. Winter was mild, with minor frosts. Spring was humid, favoring winter crops. Summer rainfall was uneven, with drought periods. Intense storms and hail caused significant crop damage.

Overall, a warm 2024 year with abnormally high summer temperatures. Winter was mild, with minor frosts. Spring was humid, promoting winter crop growth. Summer drought significantly reduced agricultural yields.

Poltava region

Average annual temperature (7–9 °C) and annual precipitation (450–550 mm). Coldest month – January (-5 – -7 °C), warmest month – (20–22 °C). Maximum precipitation in June–July, minimum precipitation in February–March.

Spring and summer 2020 were warmer than average, with periods of extreme heat. Rainfall was uneven. Spring was humid, aiding sowing, but summer had drought periods, reducing yield. Storms and strong winds occurred. A warm 2021 year with record summer heat. Spring was humid, favoring winter crop growth, but summer drought intensified, reducing yields.

Hot summer 2022, mild winter. Spring was dry, complicating sowing. Summer precipitation was uneven, with drought periods. Extreme summer 2023 heat. Winter was mild, with minimal frosts. Spring was humid, while summer had uneven rainfall, including drought periods. Severe drought – only 267 mm of precipitation 2024, which is 51% of the multi-year average (524 mm). Monthly temperatures exceeded the norm except in May. Soil surface temperatures reached 61–67 °C in summer.

Sumy region

Average annual temperature (6–8 °C), annual precipitation (500–600 mm). Coldest month – January (-6 – -8 °C), warmest month – July (19–21 °C). Maximum precipitation in June–July, minimum precipitation in February–March.

Winter 2020 was cold with regular snowfall. Spring was moderately warm, with a gradual temperature increase and sufficient precipitation, ensuring an early vegetation start. Summer temperatures rose to average values, with occasional peaks but no ext reme anomalies. Precipitation was unevenly distributed. Autumn saw a gradual temperature decline with variable precipitation, supporting normal crop maturation.

Cold winter 2021 with prolonged frosts and heavy snowfall. Spring had gradual warming but included dry spells, affecting plant growth. Summer was hot, with moisture shortages, creating stressful conditions for crops. Autumn temperatures were higher than normal, with uneven precipitation distribution.

Mild winter 2022 with weaker frosts and less snowfall. Spring had stable vegetation start, with moderate temperatures and sufficient rainfall. Summer saw rising temperatures with clear drought periods. Autumn was warm but dry, with lower-than-normal precipitation, reducing soil moisture accumulation. Warmer-than-usual winter 2023, while spring had an early and rapid temperature increase. Summer was extremely hot with significant drought, leading to severe water stress for plants. Autumn remained warm, with below-normal precipitation, affecting soil moisture retention.

Ternopil region

Average annual temperature (7–9 °C), annual precipitation (550–700 mm). Coldest month – January (-4 – -6 °C), warmest month – July (18–21 °C). Maximum precipitation in May–July, minimum precipitation in January–February.

Moderately cold winter 2020 with normal snowfall. Spring was favorable, with gradual warming and sufficient precipitation, promoting early vegetation growth. Summer was warm, with occasional heat waves, but precipitation remained evenly distributed. Autumn was moderately cool, with steady cooling and stable precipitation levels.

Colder-than-average winter 2021 with heavy snowfall. Spring arrived early, with temperature fluctuations and rainy periods, providing good soil moisture. Summer saw rising temperatures and some drought periods, creating localized dry conditions. Autumn was warm but had uneven precipitation distribution, slightly affecting winter crop development.

Warmer-than-normal winter 2022 with stable temperatures and typical precipitation levels. Spring was favorable for crop growth, with sufficient soil moisture. Summer was warm, with occasional heat waves, and precipitation was evenly distributed. Autumn had moderate temperatures and adequate rainfall, supporting a normal end to the vegetation cycle.

Mildly cold winter 2023 with regular precipitation. Spring came early, bringing a warm period with occasional rainfall. Summer was extremely hot with a strong precipitation deficit, resulting in drought conditions. Autumn was warm but had insufficient rainfall, limiting soil moisture accumulation.

Mild winter 2024 with moderate temperatures and typical precipitation. Spring had unstable temperature swings and uneven rainfall. Summer was marked by record-high temperatures and a significant precipitation deficit, leading to severe drought conditions. Autumn was warm and dry, with low soil moisture levels before winter.

Kharkiv region

Average annual temperature (6–8 °C), annual precipitation (450–550 mm). Coldest month – January (-6 – -8 °C), warmest month – July (20–22 °C). Maximum precipitation in June–July, minimum precipitation in January–March.

Typical winter 2020 cold periods with regular snowfall, ensuring proper soil moisture. Spring saw moderate warming, gradual temperature increases, and occasional rainfall, facilitating good crop development. Summer was warm, with occasional heat waves, but precipitation was uneven, leading to localized droughts. Autumn had a gradual temperature decline, with sufficient soil moisture for winter preparation. Colder-than-normal winter 2021 with intense snowfall. Spring had sharp temperature fluctuations and irregular precipitation. Summer was hot, with prolonged heat periods and drought, causing water stress for crops. Autumn was warmer than usual but had irregular rainfall patterns, alternating between excessive and deficient moisture periods.

Moderate winter 2022 temperatures with sufficient snowfall. Stable spring onset, with regular precipitation and gradual warming, supporting healthy plant growth. Summer had above-average temperatures with periods of low rainfall, leading to drought conditions. Autumn saw gradually declining temperatures and periodic rainfall, ensuring proper soil moisture accumulation before winter.

Cold winter 2023 with intense snowfall. Spring began early, with a sharp temperature rise, followed by alternating cool and warm periods with sporadic rainfall. Summer was extremely hot with a severe precipitation deficit, leading to crop stress and reduced yields. Autumn was warm but had uneven precipitation, with alternating wet and dry periods.

Mild winter 2024 with moderate temperatures and regular precipitation. Spring saw frequent daily temperature fluctuations and uneven rainfall distribution. Summer experienced record-high temperatures with a severe precipitation deficit, leading to widespread drought and crop losses. Autumn was warm but dry, with inadequate moisture levels for soil replenishment before winter.

Khmelnytskyi region

Average annual temperature: (7–9 °C), annual precipitation (550–700 mm). Coldest month – January (-4 – -6 °C), warmest month – July (18–21 °C). Maximum precipitation in May–July, minimum precipitation in January–February.

Moderately cold winter 2020 with regular precipitation. Spring brought gradual warming and stable rainfall, ensuring an early start to vegetation. Summer was warm with occasional heat waves, and precipitation was uneven, sometimes leading to localized moisture deficits. Gradual cooling in autumn, with stable precipitation levels, supported normal crop maturation.

Slightly colder-than-normal winter 2021 with intense precipitation. Early spring warming was interrupted by dry periods, delaying seed germination and plant growth. Summer saw higher-than-average temperatures with heatwaves and precipitation deficits. Autumn was moderately warm, with irregular precipitation – some periods were wet, others dry.

Moderate winter 2022 with stable temperatures and near-average precipitation. Spring had gradual warming and sufficient rainfall, fostering active plant growth. Summer was warm but had dry periods due to insufficient precipitation. Autumn temperatures were near normal, and precipitation supported proper soil moisture accumulation.

Typical winter 2023 with adequate snowfall, but cold spells affected winter crop survival. Spring started early, with a rapid temperature rise and fluctuations in precipitation. Summer was extremely hot with a significant drought, causing dry conditions for crops. Autumn was warm, but precipitation was unstable – some periods were excessively wet, while others faced moisture deficits.

Mild winter 2024 with moderate temperatures and regular precipitation. Spring had strong temperature fluctuations and uneven rainfall. Summer was excessively hot with severe precipitation deficits, creating drought and stress for crops. Autumn was warm but dry, with below-normal precipitation, affecting winter crop development and soil moisture retention.

Cherkasy region

Average annual temperature (7–9 °C), annual precipitation (500–600 mm). Coldest month – January (-4 – -6 °C), warmest month – July (19–22 °C). Maximum precipitation in May–July, minimum precipitation in February–March.

Winter 2020 was near the long-term average, with moderate temperatures and regular precipitation. Spring warming was gradual, with stable rainfall, ensuring an early vegetation start. Summer was warm with heatwaves and uneven precipitation, sometimes leading to moisture deficits. Moderate autumn cooling, with sufficient precipitation, allowed normal crop maturation.

Slightly cooler-than-average winter 2021 with increased precipitation. Early spring warming was accompanied by dry spells. Summer had high temperatures, frequent heatwaves, and significant precipitation deficits. Autumn temperatures gradually declined, but precipitation remained irregular.

Mild winter 2022 with stable temperatures and normal precipitation. Spring had sufficient rainfall and gradual warming. Summer was warm with moderate temperature increases, and precipitation remained close to normal, aiding crop development. Moderate autumn cooling with stable precipitation ensured proper soil moisture accumulation before winter.

Typical winter 2023 with regular precipitation but occasional cold spells. Early spring had a rapid temperature increase and uneven precipitation. Summer was extremely hot with a strong precipitation deficit, leading to dry conditions. Autumn was warm with irregular precipitation – some periods had excessive moisture, while others faced drought.

Winter 2024 conditions were near the long-term average. Spring had significant temperature fluctuations and uneven precipitation. All summer months were excessively warm with severe drought conditions, while autumn was warm and dry, with below-normal precipitation.

Chernivtsi region

Average annual temperature (7–9 °C), annual precipitation: 650–850 mm. Coldest month – January (-3 – -5 °C), warmest month – July (18–22 °C). Maximum precipitation in May–June, minimum precipitation in January–February.

Moderately cold winter 2020 with regular precipitation. Gradual spring warming and sufficient rainfall ensured an active start to the vegetation period. Summer was warm with occasional heatwaves, while precipitation was uneven, leading to short dry periods. Gradual autumn cooling, with adequate precipitation, allowed proper crop growth and maturation.

Winter 2021 was slightly colder than the previous year, with increased snowfall. Early spring warming brought unstable weather and short-term precipitation deficits. Summer was hot, with prolonged heatwaves and insufficient rainfall. Autumn was warm with irregular precipitation distribution, alternating between wet and dry periods.

Mild winter 2022 with moderate snowfall. Gradual spring warming and regular precipitation provided optimal conditions for agricultural activities. Summer was warm with occasional heatwaves, but overall precipitation levels remained near normal. Moderate autumn cooling, with sufficient precipitation, helped prepare winter crops for dormancy.

Near-average winter 2023 with regular snowfall, but occasional severe frost periods. Spring had an early start with rapid temperature increases, while precipitation distribution was uneven. Summer was extremely hot with prolonged droughts, causing significant moisture shortages. Autumn was warm with inconsistent precipitation levels, including both excessive rainfall and dry spells.

Moderate winter 2024 temperatures with near-average precipitation. Spring had unstable weather with sharp temperature fluctuations and irregular precipitation. Summer was hot with significant precipitation deficits, causing widespread drought. Autumn remained warm with below-normal precipitation, limiting soil moisture accumulation before winter.

Soil conditions

Vinnytsia region

Podzolized chernozems cover about 60% of the region's territory. Gray forest soils are common in the northern and central parts, with medium humus content but high acidity, requiring liming. Sod-podzolic soils, found in the north, are less fertile, have a light mechanical composition, and require cultivation. Meadow and marshy soils occur along river valleys.

Kyiv region

Gray and dark gray forest soils are the most widespread. Podzolized chernozems, found mainly in the south, are highly fertile, rich in humus, and retain moisture well. Sod-podzolic soils, located in the north, have a light mechanical composition, are less fertile, and require fertilization. Meadow and marshy soils are found in river floodplains (Dnieper, Desna, Teteriv).

Poltava region

Typical chernozems are the dominant soil type, covering about 70% of the region and containing 5–6% humus. Podzolized chernozems, found in the north, have moderate humus content and require organic and mineral fertilizers. Gray and dark gray forest soils, common on the right bank of the Dnieper, have medium fertility but high acidity. Meadow and marshy soils are found along river valleys.

Sumy region

Gray and dark gray forest soils cover a significant part of the region, especially in the central areas. Podzolized chernozems, found in the south, contain 4–5% humus. Sod-podzolic soils, prevalent in the north, are less fertile. Meadow and marshy soils are found in the floodplains of the Desna, Seim, and Psel rivers.

Ternopil region

Podzolized chernozems are the most widespread, highly fertile, and contain 3–5% humus. Gray and dark gray forest soils are found in the north and central parts, while brown forest soils are typical in the west. Meadow and marshy soils are concentrated in the river valleys of the Dniester, Seret, and Zbruch rivers.

Kharkiv region

Ordinary and podzolized chernozems dominate, covering over 60% of the region, being highly fertile, rich in humus (4–6%), and excellent for moisture retention, making them ideal for agriculture. Gray and dark gray forest soils are found mainly in the north and west. Sod-podzolic soils are common in the north, while meadow and marshy soils are found in the floodplains of the Siverskyi Donets and Oskil rivers.

Khmelnytskyi region

Podzolized chernozems are the most prevalent, containing 3–5% humus. Gray and dark gray forest soils are also widely distributed. Brown forest soils, found in the west, are less fertile. Meadow and marshy soils are present in the floodplains of the Dniester and Southern Bug rivers.

Cherkasy region

Podzolized and typical chernozems are dominant, containing 4–6% humus. Gray and dark gray forest soils are found mainly in the north. Sod-podzolic soils are present in wooded areas, while meadow and marshy soils are located in the floodplains of the Dnieper and Ros rivers.

Chernivtsi region

Gray and dark gray forest soils cover a significant portion of the region, especially in foothill areas. Podzolized chernozems, found in lowland areas, contain 4–5% humus. Brown forest soils dominate the Carpathian foothills and mountainous zones. Meadow and marshy soils are present in the floodplains of the Prut, Dniester, and Seret rivers.

Statistical analysis

Statistical analysis was performed using the ANOVA method using the Statistica 12 software (Prysiazhniuk et al, 2016).

RESULTS AND DISCUSSION

Traditionally, large areas of land for wheat cultivation are characteristic of Kharkiv, Vinnytsia, Poltava, Khmelnytskyi, Kyiv, Cherkasy, and Sumy regions. The total contribution of the region in terms of winter wheat cultivation area accounts for 40.5% of the total wheat-growing area in Ukraine as of 2024, or 36.4% on average over the observation years (Figure 1).

Apart from the large areas of wheat cultivation in the Forest-Steppe zone of Ukraine, higher yield levels are observed both in individual regions and on average for the entire area. The yield

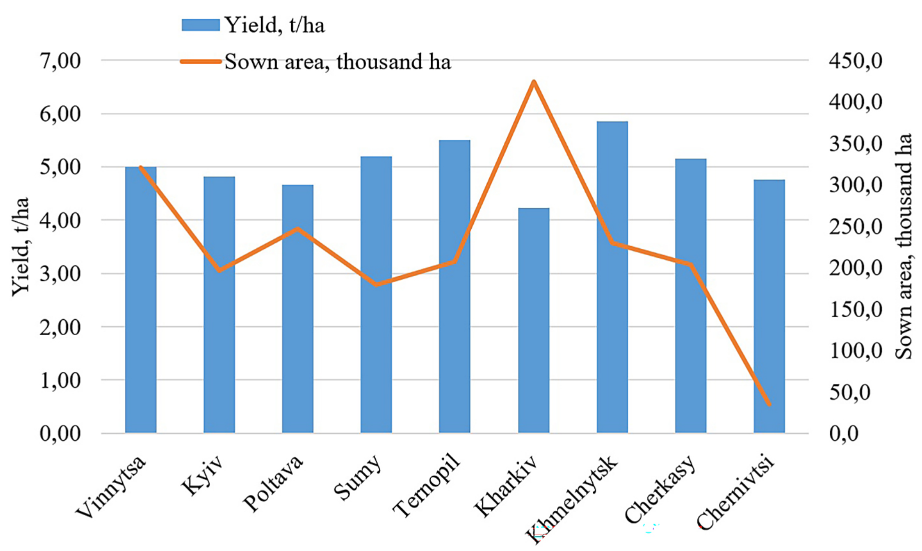

Figure 1. Average areas and wheat yields by regions of the Forest-Steppe of Ukraine, for 2020–2024

advantage over the national average ranges from 0.62 to 0.89 t/ha.

The complexity of the impact of cultivation conditions in the Forest-Steppe region of Ukraine lies in the fact that in certain years, limiting factors emerge, leading to significantly lower yields compared to the national average. This was observed in Chernivtsi in 2020 and in Kharkiv in 2022, 2023, and 2024. Therefore, the study of agroclimatic factors affecting the zonal distribution of cereal crops needs deeper research.

Another important element determining the efficiency of wheat cultivation and its environmental sustainability is the use of fertilizers. Across Ukraine, relatively low levels of organic fertilizers are applied, despite wheat being a crop that currently receives minimal organic fertilization. However, scientific studies show that the application of 25–30 t/ha of manure compensates for the depletion of macro- and micronutrients at a yield level of 6.0 t/ha.

It was also found that Kyiv region consistently applies higher amounts of organic fertilizers, whereas Chernivtsi, Vinnytsia, and Sumy regions have the lowest rates. Regarding organic fertilizers, despite seasonal fluctuations in their quantity, there is a general trend of maintaining similar application volumes, which indirectly indicates resource limitations across different regions.

Mineral fertilizers, on the other hand, are available for purchase and use in all regions of the Forest-Steppe zone of Ukraine. However, the trend in nitrogen fertilizer application shows a gradual decline in usage year by year, with the most significant reduction starting in 2022. The average nitrogen fertilizer use in the Forest-Steppe zone was 70 kg/ha in 2022, 82.6 kg/ha in 2021, and 85.9 kg/ha in 2020.

Only in Vinnytsia, Sumy, Ternopil, and Cherkasy regions, nitrogen application increased by 31.9 kg/ha, 11.7 kg/ha, 6.3 kg/ha, and 10.5 kg/ha, respectively, compared to the previous year.

In 2023, the war and declining grain purchase prices further affected mineral fertilizer use, so only Kyiv and Ternopil regions maintained their previous year's nitrogen application levels.

A similar decline was observed in the use of phosphorus mineral fertilizers. However, on average, in 2020, 2021, and 2022, farmers in the Forest-Steppe zone applied 15 kg/ha of phosphorus, while in 2023 and 2024, the rate dropped to approximately 10 kg/ha. Within the regions, a significant decrease in phosphorus fertilization below 10 kg/ha was recorded in Kyiv, Poltava, Kharkiv, and Cherkasy regions over the past two years.

Unlike nitrogen and phosphorus fertilizers, the use of potassium fertilizers remained relatively stable until 2022, with a downward trend similar to phosphorus application. The average potassium fertilizer application in the region was 13 kg/ha in 2020, 2021, and 2022, while in 2023 and 2024, it dropped to 10 kg/ha.

Traditionally, a high level of potassium fertilizer use is observed in farms located in Sumy and Ternopil regions, while the lowest potassium application is recorded in Poltava, Kharkiv, and Chernivtsi regions. This may be due to the soil nutrient levels in these areas.

However, as seen from the average exchangeable potassium content in the region's soils, Chernivtsi has the lowest levels of potassium in the entire Forest-Steppe zone of Ukraine.

Overall, the volumes of mineral fertilizer application align with classical studies, which indicate that in most soils of the Forest-Steppe zone: 38.0% have very low and 54.0% have low levels of hydrolyzable nitrogen, 37.0% have medium levels and 37.4% have increased levels of available phosphorus, 41.5% have increased levels and 28.5% have high levels of potassium. On average, farmers in the Forest-Steppe zone apply 79.3 kg/ha of nitrogen, 13.0 kg/ha of phosphorus, and 11.1 kg/ha of potassium.

These findings indicate the need for a balanced fertilization approach to maintain wheat productivity and soil fertility in the region.

Given the importance of the impact of mineral fertilizers on wheat yield formation, we will analyze whether they determined the level of obtained yield (Figure 2).

As we can see from the obtained regression equations, their accuracy is insufficient to assert that the application of these specific amounts of organic and mineral fertilizers effectively increases wheat yield. This is due not only to the low doses of fertilizers applied but also to the lack of a model experiment that includes variants with zero fertilization. Similarly, low correlation coefficients were obtained when comparing wheat yield levels with organic matter reserves and macroelements in the soil (Figure 3).

Unlike the previous analysis, wheat yield shows a slight but statistically significant dependence on the organic matter content in the soil. However, the rest of the factors do not have a significant influence.

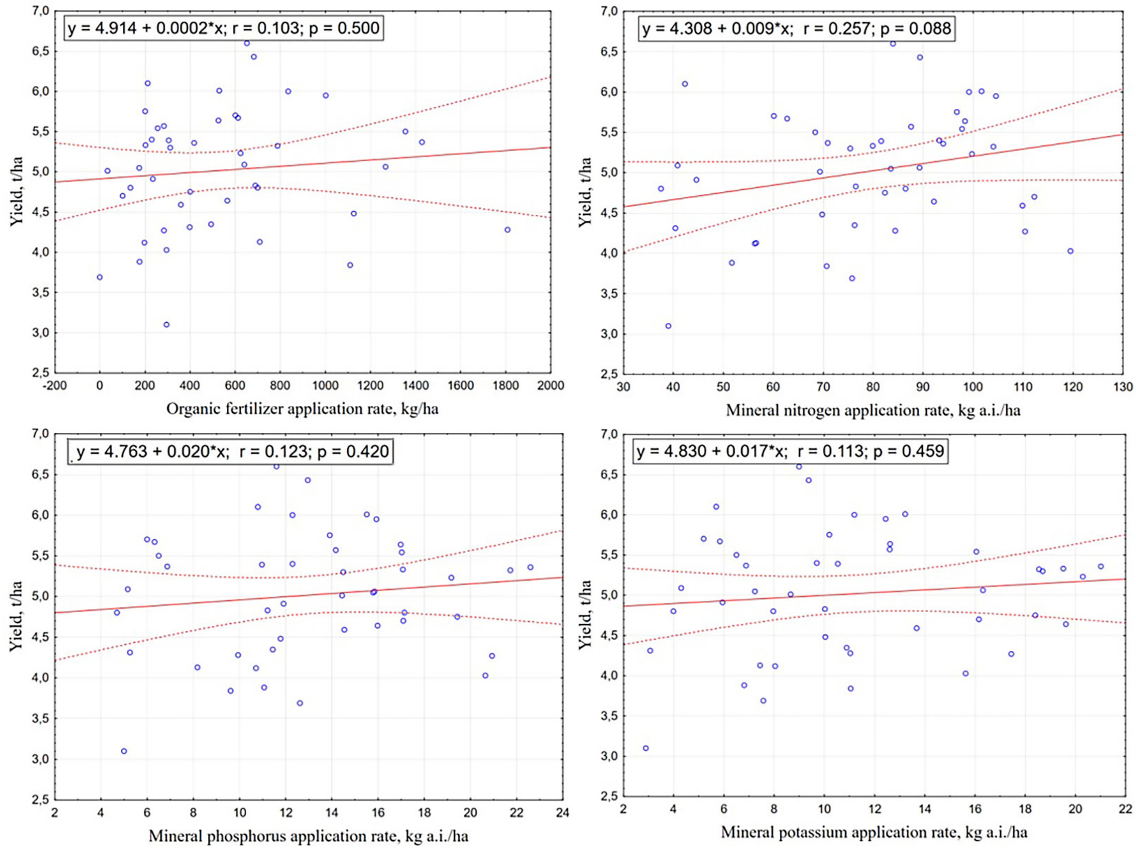

Figure 2. Dependence of wheat yield on the rates of application of organic and mineral fertilizers

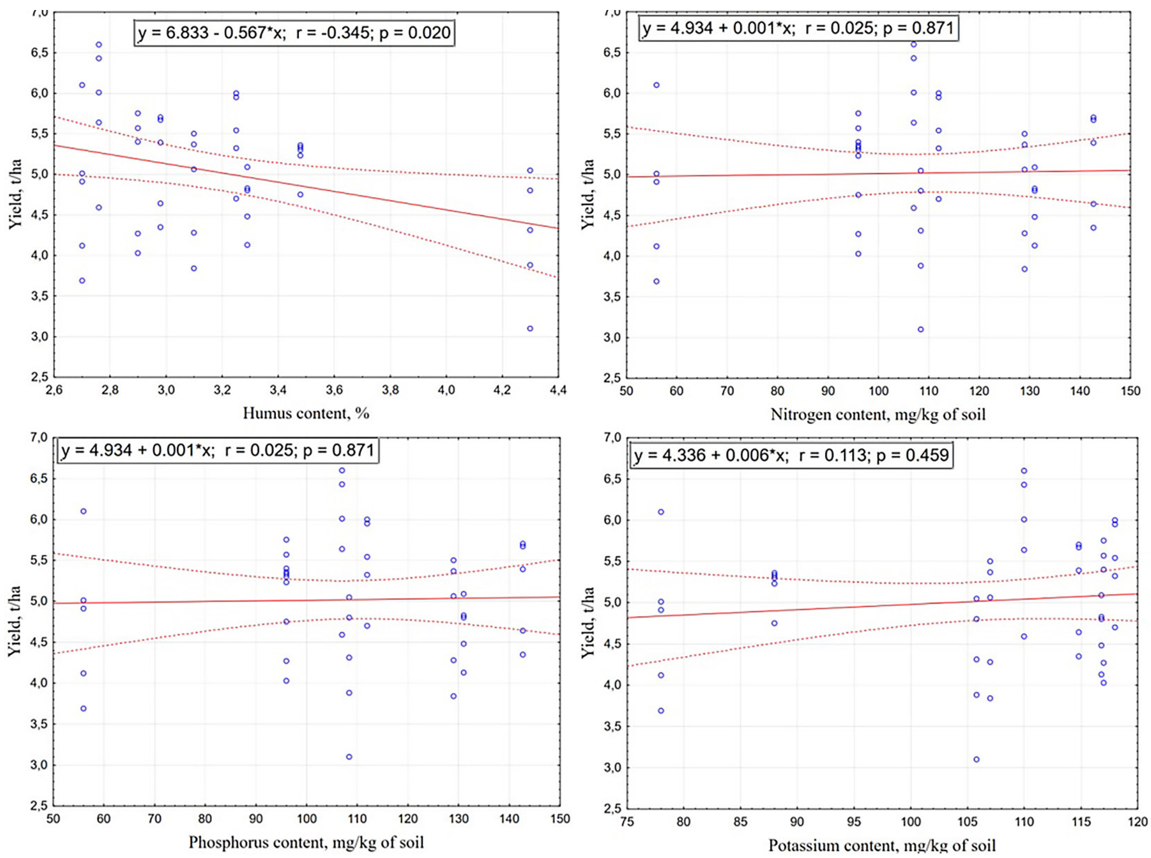

Figure 3. Dependence of wheat yield on the content of humus and macroelements in the soil

Thus, the growth and development of cereal crops in the Forest-Steppe zone of Ukraine is influenced by a combination of soil and climatic factors, as well as cultivation technologies, making each element a crucial component in achieving high crop productivity.

Therefore, we will analyze the impact of the deviation significance coefficient of precipitation amounts during the growing season on wheat yield (Figure 4), as the primary limiting factor for effective growth and development of plants in the Forest-Steppe zone of Ukraine.

As shown, the obtained relationship between wheat yield and the deviation significance coefficient of precipitation demonstrates that under modern moisture conditions, an increase in this indicator beyond the average values typical for the Forest-Steppe zone results in a significant yield increase overall. This confirms the importance of considering weather elements in achieving the maximum efficiency of any crop cultivation and optimizing the influence of environmental factors. Equally important is the understanding of nutrient balance in the crop production process. It should be noted that wheat is not the most fertilizer-intensive crop in crop rotations. Therefore, over an entire crop rotation cycle, agricultural enterprises may maintain a neutral or even positive nutrient balance.

However, the primary goal of sustainable agriculture is to ensure the return of sufficient nutrients to the soil. Since an operational nutrient deficit during certain phases of crop rotation increases the need for higher doses of mineral fertilizers, this automatically leads to greater losses of biogenic elements due to leaching, microbial degradation, or fixation in an immobile form by soil minerals.

Overall, it can be stated that all nutrient element balances were negative during wheat cultivation, meaning that nutrient depletion from the soil exceeded inputs from organic and mineral fertilizers (Tables 1–3).

Moreover, a negative nutrient balance does not necessarily indicate a high yield in a particular region. Even with moderate yields, inefficient fertilizer application or low application rates can lead to imbalanced soil nutrition. For example, the greatest nitrogen losses from the soil were observed in Poltava, Khmelnytskyi, Cherkasy, and Chernivtsi regions, averaging 94.7, 94.8, 93.8, and 99.8 kg/ha over the years, respectively. In contrast, in Vinnytsia region, wheat fields absorbed 63.4 kg/ha of nitrogen from the soil annually, which was the lowest both in the Forest-Steppe region and compared to the Ukrainian average, by 8.8 kg/ha.

Regarding phosphorus uptake from the soil, the highest depletion rates were recorded in Ternopil, Khmelnytskyi, and Cherkasy regions, with negative balances of 54.4, 61.7, and 56.6 kg/ha, respectively. On average, wheat cultivation in Ukraine resulted in an annual phosphorus loss of 42.9 kg/ha, whereas the best figures were observed in Kharkiv region, where phosphorus depletion exceeded the national average by 1.5 kg/ha.

In general, despite the high availability of phosphorus in the soils of the Forest-Steppe region and its significant reserves, it is not a

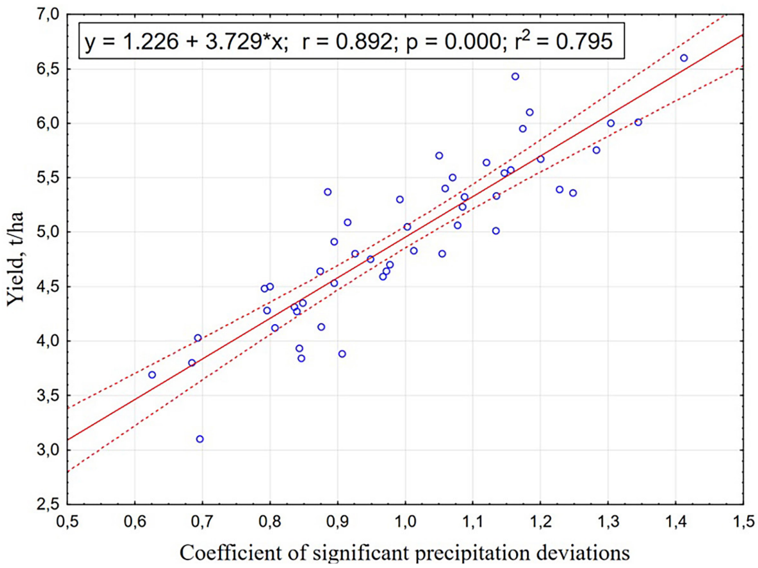

Figure 4. The influence of the coefficient of significant of precipitation deviations on wheat yield

Table 1. Nitrogen balance for wheat cultivation on average in Ukraine and regions of the Forest-Steppe zone, 2020–2024, kg/ha

Region	Year				
	2024	2023	2022	2021	2020
Ukraine	-98.78	-97.54	-56.66	-68.94	-39.14
Vinnytsa	-83.48	-94.03	-10.49	-100.37	-28.74
Kyiv	-105.95	-101.09	-49.03	-76.41	-47.42
Poltava	-117.07	-125.76	-74.60	-84.22	-72.04
Sumy	-97.58	-96.87	-78.68	-77.14	-69.22
Ternopil	-94.22	-88.90	-65.52	-89.26	-41.98
Kharkiv	-61.61	-101.41	-73.99	-75.99	-81.84
Khmelnytskyi	-130.09	-121.68	-82.95	-100.01	-39.43
Cherkasy	-124.60	-123.31	-56.33	-100.08	-64.44
Chernivtsi	-157.53	-117.98	-77.11	-100.81	-45.72

Table 2. Phosphorus balance for wheat cultivation on average in Ukraine and regions of the Forest-Steppe zone, 2020–2024, kg/ha

Region	Year				
	2024	2023	2022	2021	2020
Ukraine	-48.12	-55.24	-37.15	-42.65	-31.38
Vinnytsa	-55.86	-65.62	-32.23	-59.08	-32.92
Kyiv	-60.11	-64.30	-38.70	-48.18	-40.24
Poltava	-54.64	-64.09	-44.99	-51.19	-42.66
Sumy	-52.18	-56.61	-47.67	-42.64	-46.10
Ternopil	-61.98	-64.38	-47.09	-55.90	-42.72
Kharkiv	-33.72	-53.73	-40.11	-46.27	-48.32
Khmelnytskyi	-70.77	-74.83	-56.75	-62.99	-43.23
Cherkasy	-65.04	-71.07	-44.35	-59.84	-42.92
Chernivtsi	-66.31	-55.85	-43.60	-52.00	-34.53

Table 3. Potassium balance for wheat cultivation on average in Ukraine and regions of the Forest-Steppe zone, 2020–2024, kg/ha

Region	Year				
	2024	2023	2022	2021	2020
Ukraine	-86.64	-90.43	-65.51	-87.37	-60.77
Vinnytsa	-103.14	-111.52	-63.77	-109.01	-63.51
Kyiv	-101.69	-99.35	-59.64	-88.10	-60.98
Poltava	-93.32	-100.68	-71.50	-92.78	-69.94
Sumy	-91.53	-93.22	-84.44	-84.34	-77.20
Ternopil	-110.70	-108.74	-83.89	-105.06	-74.22
Kharkiv	-60.89	-86.69	-70.29	-97.48	-89.48
Khmelnytskyi	-126.68	-123.98	-97.84	-116.66	-73.03
Cherkasy	-111.75	-111.71	-70.46	-106.96	-70.36
Chernivtsi	-122.05	-97.61	-73.77	-102.05	-63.86

critical limiting factor for plant growth and development. However, substantial annual losses lead to irreversible declines in soil fertility and gradual degradation of high-quality topsoil. The highest exchangeable potassium losses from the soil, due to wheat uptake, were observed in

Ternopil and Khmelnytskyi regions—96.5 and 107.6 kg/ha, respectively. Conversely, wheat plants in Kharkiv and Kyiv regions absorbed the least potassium, at 81.0 and 82.0 kg/ha, respectively.Pesticides, including fungicides, insecticides, and herbicides, significantly influence plant growth, development, and agroecosystem stability. Therefore, in the context of biological crop production technologies, it is crucial to analyze changes in the amount of these chemicals applied per hectare (Tables 4–6).

Different regions use different pesticide formulations, making it difficult to identify clear patterns from the data. However, the quantity of chemical inputs is crucial when aiming to reduce environmental impact and limit the intensification of chemical-based technologies without compromising yield and product quality.

It is important to highlight that 2022 was a critical year in terms of fungicide, herbicide, insecticide, and growth regulator use, which was directly linked to the war and low wheat procurement prices. As a result, farmers significantly reduced their use of these chemicals. However, such trends were less pronounced for mineral fertilizers, as these are usually purchased before the start of the growing season and were already available on farms when the war began.

In all other years, fungicide application on wheat fields remained stable, averaging 323 g/ha in the Forest-Steppe region, which is approximately 100 g/ha more than the Ukrainian average.

The highest fungicide use was recorded in Vinnytsia (352 g/ha), Sumy (360 g/ha), Kyiv (377 g/ha), and Khmelnytskyi (387 g/ha) regions, while the lowest use of this pesticide class was observed in Kharkiv region (224 g/ha).

Regarding herbicide application, farms in the Forest-Steppe region of Ukraine use an average of 143 g/ha, which is in line with the national average.

Table 4. Average fungicide application rates for wheat cultivation in Ukraine and regions of the Forest-Steppe zone, 2020–2024, kg/ha

Region	Year				
	2024	2023	2022	2021	2020
Ukraine	0.272	0.250	0.143	0.293	0.267
Vinnytsa	0.389	0.342	0.127	0.436	0.469
Kyiv	0.443	0.371	0.112	0.515	0.444
Poltava	0.339	0.329	0.082	0.348	0.313
Sumy	0.420	0.372	0.101	0.468	0.439
Ternopil	0.338	0.313	0.189	0.362	0.362
Kharkiv	0.240	0.224	0.143	0.256	0.257
Khmelnytskyi	0.435	0.411	0.186	0.458	0.444
Cherkasy	0.385	0.364	0.143	0.406	0.398
Chernivtsi	0.274	0.256	0.251	0.291	0.292

Table 5. Average herbicide application rates for wheat cultivation in Ukraine and regions of the Forest-Steppe zone, 2020–2024, kg/ha

Region	Year				
	2024	2023	2022	2021	2020
Ukraine	0.162	0.136	0.054	0.188	0.179
Vinnytsa	0.117	0.116	0.082	0.118	0.200
Kyiv	0.195	0.156	0.062	0.233	0.221
Poltava	0.089	0.092	0.046	0.086	0.092
Sumy	0.123	0.114	0.070	0.132	0.163
Ternopil	0.180	0.167	0.066	0.193	0.200
Kharkiv	0.132	0.109	0.056	0.154	0.157
Khmelnytskyi	0.197	0.190	0.088	0.204	0.259
Cherkasy	0.138	0.106	0.063	0.170	0.169
Chernivtsi	0.230	0.160	0.047	0.300	0.197

Table 6. Average insecticide application rates for wheat cultivation in Ukraine and regions of the Forest-Steppe zone, 2020–2024, kg/ha

Region	Year				
	2024	2023	2022	2021	2020
Ukraine	0.066	0.065	0.050	0.068	0.067
Vinnytsa	0.075	0.063	0.091	0.088	0.077
Kyiv	0.069	0.058	0.061	0.080	0.075
Poltava	0.060	0.053	0.021	0.067	0.064
Sumy	0.081	0.069	0.076	0.093	0.090
Ternopil	0.115	0.166	0.129	0.064	0.064
Kharkiv	0.061	0.053	0.031	0.068	0.080
Khmelnytskyi	0.087	0.103	0.160	0.070	0.056
Cherkasy	0.069	0.065	0.073	0.073	0.126
Chernivtsi	0.044	0.052	0.101	0.037	0.045

The highest herbicide use was recorded in Ternopil (161 g/ha), Kyiv (173 g/ha), Chernivtsi (187 g/ha), and Khmelnytskyi (188 g/ha) regions, while the lowest application was observed in Poltava region (81 g/ha).

Insecticide protection of wheat crops against pests is slightly higher than the Ukrainian average. In the Forest-Steppe region, 76 g/ha of insecticides are applied on average, whereas across Ukraine, the usage is 12 g/ha lower.

The highest insecticide loads on agroecosystems were recorded in Ternopil (108 g/ha) and Khmelnytskyi (95 g/ha) regions, while the lowest were in Poltava (53 g/ha), Chernivtsi (56 g/ha), and Kharkiv (58 g/ha) regions.

This pattern of pesticide use is typical for the Forest-Steppe region, as fluctuating moisture levels and vigorous plant development create favorable conditions for the active spread of diseases and pests. Meanwhile, weeds compete for available space in all soil-climatic zones of Ukraine, leading to similar insecticide application rates across different regions.

Among all agrochemical inputs, growth regulators and accompanying plant stimulants are desirable because they are often biologically active substances of natural origin and do not significantly pollute the environment. Their positive effects include increased yields and improved crop quality.

Thus, analyzing the use of plant growth regulators helps to evaluate their efficiency in wheat production technologies (Table 7). In the Forest-Steppe region, an average of 69 g/ha of growth regulators is applied, which is 31 g/ha more than the Ukrainian average. The highest usage was recorded in Kyiv (83 g/ha), Vinnytsia (98 g/ha), Khmelnytskyi (102 g/ha), and Ternopil (104 g/ha) regions, while the lowest was in Poltava (31 g/ha) and Kharkiv (20 g/ha) regions. It is also important to note that pesticide and growth

Table 7. Average of growth regulators application rates for in wheat cultivation in Ukraine and regions of the Forest-Steppe zone, 2020–2024, kg/ha

Region	Year				
	2024	2023	2022	2021	2020
Ukraine	0.047	0.045	0.002	0.049	0.044
Vinnytsa	0.117	0.097	0.002	0.136	0.136
Kyiv	0.100	0.068	0.000	0.133	0.112
Poltava	0.043	0.037	0.000	0.049	0.025
Sumy	0.070	0.062	0.000	0.078	0.074
Ternopil	0.124	0.097	0.000	0.150	0.149
Kharkiv	0.028	0.028	0.000	0.028	0.018
Khmelnytskyi	0.133	0.107	0.000	0.158	0.112
Cherkasy	0.059	0.039	0.015	0.079	0.059
Chernivtsi	0.082	0.047	0.005	0.117	0.121

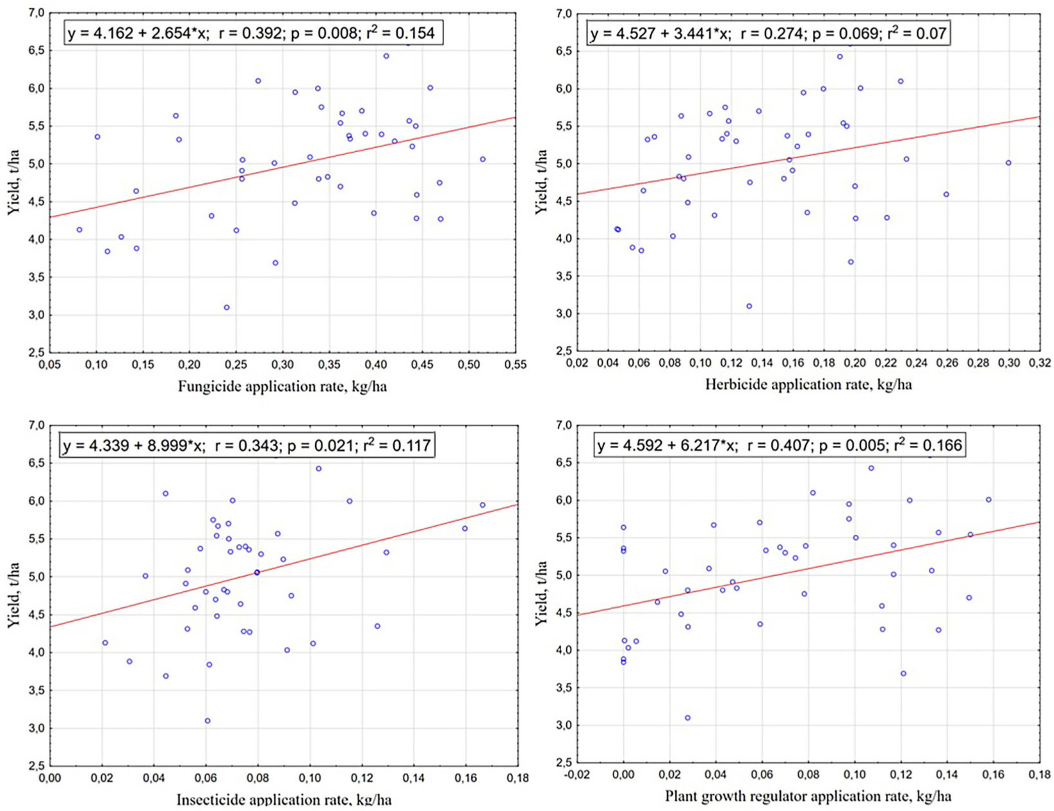

Figure 5. The impact of pesticide and growth regulator application rates on wheat yield

regulator use did not show significant fluctuations over the study period, except for 2022, when their application dropped sharply due to the war and low wheat prices. However, in 2023, there was a recovery in application levels, reaching pre-war 2021 levels in 2024.

Furthermore, significant correlations were found between wheat yield and the application rates of fungicides, insecticides, and growth regulators (Fig. 5), highlighting their role as key elements of an effective wheat production technology.

Previous scientific studies have demonstrated that the long-term and extensive use of pesticides has serious ecological and agricultural consequences (Baysal & Silme, 2018).

Therefore, it is essential to create conditions for soil health restoration, natural pest regulation, and biodiversity conservation, while ensuring the sustainability of grain production (del Portillo et al., 2022; Garrison et al., 2014; Crotty et al., 2015).

Research also indicates that eco-friendly farming practices in wheat production contribute to high and stable yields. This is achieved not only through the optimization of plant nutrition but also by ensuring that crops are grown in favorable climatic zones (Chhibber & Ravichandran, 2024).

CONCLUSIONS

It was determined that the average wheat cultivation area in the Kharkiv, Vinnytsia, Poltava, Khmelnytskyi, Ternopil, Cherkasy, Kyiv, and Sumy regions is 424, 320, 247, 230, 207, 204, 196, and 180 thousand hectares, respectively. The total share of the Forest-Steppe region in winter wheat cultivation accounts for 40.5% of the total wheat area in Ukraine as of 2024 or 36.4% on average over the years of observation. The highest wheat yields over the study years were recorded in Khmelnytskyi, Ternopil, Sumy, Cherkasy, and Vinnytsia regions, reaching 5.85, 5.50, 5.19, 5.15, and 5.00 t/ha, respectively.

The analysis of organic and mineral fertilizer application on wheat yield formation revealed that the observed relationships do not accurately define fertilization as the key factor. This is due to insufficient application rates of organic and mineral fertilizers, which fail to meet crop demands. In regions where higher yields were recorded, greater nitrogen uptake was also observed, particularly in Ternopil (182.5 kg/ha) and Khmelnytskyi (194.3 kg/ha) regions. Phosphorus depletion was the highest in Ternopil

(72.7 kg/ha) and Khmelnytskyi (77.4 kg/ha) regions. The highest potassium uptake was recorded in Cherkasy (107.8 kg/ha), Sumy (108.1 kg/ha), Ternopil (115.0 kg/ha), and Khmelnytskyi (122.5 kg/ha) regions.

It was determined that the overall nitrogen, phosphorus, and potassium balance remains deficient, with wheat plants depleting soil reserves of these elements to meet their nutrient needs. On average, in the Forest-Steppe of Ukraine, nitrogen losses amount to 84.6 kg/ha, phosphorus losses to 52.0 kg/ha, and potassium losses to 90.6 kg/ha.

In contrast, across Ukraine as a whole, over the past five years, the negative balance of these elements has been 12.4 kg/ha better for nitrogen, 9.1 kg/ha better for phosphorus, and 12.4 kg/ha better for potassium. The highest nitrogen losses were observed in Poltava (94.7 kg/ha), Khmelnytskyi (94.8 kg/ha), Cherkasy (93.8 kg/ha), and Chernivtsi (99.8 kg/ha) regions. For phosphorus depletion, the leading regions were Ternopil (54.4 kg/ha), Khmelnytskyi (61.7 kg/ha), and Cherkasy (56.6 kg/ha) regions. The greatest exchangeable potassium losses were recorded in Ternopil (96.5 kg/ha) and Khmelnytskyi (107.6 kg/ha) regions. The highest fungicide application rates were recorded in Vinnytsia (352 g/ha), Sumy (360 g/ha), Kyiv (377 g/ha), and Khmelnytskyi (387 g/ha) regions. The highest herbicide usage was observed in Ternopil (161 g/ha), Kyiv (173 g/ha), Chernivtsi (187 g/ha), and Khmelnytskyi (188 g/ha) regions, while the lowest was in Poltava (81 g/ha) region. The highest insecticide load on agroecosystems was recorded in Ternopil (108 g/ha) and Khmelnytskyi (95 g/ha) regions, while the lowest application was observed in Poltava (53 g/ha), Chernivtsi (56 g/ha), and Kharkiv (58 g/ha) regions. The highest application of growth regulators was identified in Kyiv (83 g/ha), Vinnytsia (98 g/ha), Khmelnytskyi (102 g/ha), and Ternopil (104 g/ha) regions. The lowest application rates were recorded in Poltava (31 g/ha) and Kharkiv (20 g/ha) regions.

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