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Spatial variability of soil properties and its influence on maize yield formation in precision farming systems of the Ukrainian Polissia

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Abstract.

Spatial heterogeneity of soil properties is one of the key factors determining crop productivity and the efficiency of resource use in modern agricultural systems. This issue is particularly relevant for the Polissia region, where soils are characterized by significant variability in agrophysical and physico-mechanical fertility indicators (structure, soil hardness & compaction), organic matter content, acidity (pH levels), and nutrient availability. Conventional uniform management practices often fail to account for this variability, resulting in inefficient fertilizer use and reduced economic returns. The aim of this study was to determine the patterns of grain maize (*Zea mays* L.) productivity formation under conditions of spatial soil heterogeneity within a precision farming system. The research was conducted under the implementation of precision farming technologies at a high-tech agricultural enterprise located within the Vysokivska rural territorial hromada of the Zhytomyr district, Zhytomyr region. The spatial variability of soil cover properties and maize yields was assessed by integrating yield map data obtained from combine harvester monitoring systems, soil agrochemical analysis results, and satellite-based vegetation indices characterizing crop development dynamics throughout the growing season. Spatial data processing and visualization were performed using digital farm management platforms,

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specifically Cropwise Operations Center and John Deere Operations Center, which facilitate the accumulation, analysis, and integration of agronomic and geospatial data within a precision agriculture framework. Geostatistical and GIS-based methods were employed to delineate management zones and evaluate the interrelationships between soil parameters and maize productivity. All target plots are situated within the Haplic Albeluvisols (Light Grey Forest Soils) soil association, with minor inclusions of Haplic Phaeozems (Dark grey forest soils) and Haplic Chernozems, which is characteristic of this particular sub-region of the Ukrainian Polissia. Geostatistical and GIS-based methods were used to identify management zones and assess relationships between soil parameters and maize productivity. The results demonstrated significant spatial variability of yield within the field, which was strongly associated with differences in soil fertility indicators, particularly humus content, soil acidity, and nutrient availability. The findings confirm the importance of site-specific management practices in conditions of heterogeneous soil cover. Implementation of precision agriculture tools enables optimization of fertilizer application and improved resource use efficiency, thereby enhancing the sustainability and economic performance of maize production systems in the Polissia region.

Keywords:

precision agriculture
spatial variability
soil heterogeneity
yield mapping
maize for grain
maize productivity
GIS analysis

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Spatial variability of soil properties is one of the most important factors determining crop productivity and resource use efficiency in modern agricultural systems [1, 2, 3]. Agricultural fields are rarely homogeneous, and variations in soil texture, organic matter content, nutrient availability, and topography often lead to substantial differences in crop growth and yield formation within relatively small areas [4, 5, 6]. Ignoring this variability when applying uniform agronomic practices can result in inefficient use of fertilizers, reduced productivity, and increased environmental risks [7, 8, 9].

Precision agriculture technologies provide new opportunities for identifying and managing within-field variability through the integration of geospatial data, yield monitoring systems, remote sensing, and digital farm management platforms. Yield maps generated during harvesting, together with soil property data and vegetation indices derived from satellite imagery, enable the identification of spatial patterns of crop productivity and the delineation of management zones within agricultural fields [10, 11, 12].

Maize (*Zea mays* L.) is one of the most important cereal crops globally and plays a significant role in the agricultural economy of Ukraine. However, maize productivity is highly sensitive to soil fertility conditions and spatial heterogeneity of soil properties [13]. In regions such as the Ukrainian Polissia, where soils are characterized by relatively low natural fertility and high spatial variability, understanding the relationships between soil properties and crop productivity is particularly important for improving the efficiency of crop production systems [14, 15, 1].

Recent studies have demonstrated that the integration of yield monitoring data with geostatistical and remote sensing approaches allows researchers to quantify spatial variability of crop productivity and to develop site-specific management strategies [16, 17, 18]. Methods such as spatial autocorrelation analysis, semivariogram modeling, and kriging interpolation have been widely applied to analyze spatial patterns of soil properties and crop yields in precision agriculture systems [19, 20, 21].

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Despite the increasing adoption of precision farming technologies in Ukraine, studies investigating the influence of soil spatial heterogeneity on maize productivity under local agroecological conditions remain limited [14, 15]. Therefore, research aimed at understanding spatial relationships between soil properties and crop productivity is essential for the development of efficient site-specific crop management strategies [2, 3, 5].

Therefore, the objective of this study was to analyze the spatial variability of grain maize productivity and its relationship with soil properties under precision farming conditions in the Zhytomyr region of Ukraine.

Materials and Methods

The research was conducted in a commercial agricultural field located within the territory of the Vysokivska rural territorial community in Zhytomyr district, Zhytomyr region, Ukraine. The study area is situated in the Polissia natural zone, which is characterized by a moderately continental climate, relatively high annual precipitation, and soils with generally low natural fertility. The dominant soil cover within the experimental plots is represented by an association of Light Grey Forest Soils (Haplic Albeluvisols), with minor inclusions of Dark Grey Forest Soils (Haplic Phaeozems) and Haplic Chernozems formed on light loamy parent material. These soils are typically characterized by moderate acidity, relatively low organic matter (humus) content, and significant spatial variability in nutrient availability.

The total area of the analyzed field was approximately 677 ha.

Soil samples were collected using a 5-hectare grid-based sampling design commonly applied in precision agriculture systems. Sampling points were distributed across the field to capture spatial variability of soil properties.

Laboratory analyses were conducted to determine the following soil parameters: soil pH, humus content, available phosphorus (P_2O_5), exchangeable potassium (K_2O), mineral nitrogen (N_2O). Standard agrochemical methods were used for soil analysis.

Maize grain yield data were obtained from a combine harvester equipped with a yield monitoring system and GPS

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receiver. The system recorded grain yield and geographical coordinates at regular spatial intervals during harvesting. Raw yield data were pre-processed to remove erroneous observations associated with harvester acceleration, deceleration, turning areas, and sensor delays. Outliers were identified and removed using statistical filtering procedures based on threshold values and spatial consistency of the dataset. After filtering, the cleaned yield data were interpolated using geostatistical methods to generate a continuous yield surface of the field. The resulting yield map was used to analyze spatial variability of crop productivity and to identify stable productivity zones within the field.

Satellite imagery from the Sentinel-2 platform was used to calculate vegetation indices during the maize growing season. The normalized difference vegetation index (NDVI) was calculated using multispectral satellite imagery to evaluate spatial variability of crop growth and biomass development.

Basic statistical parameters were calculated for soil properties and maize yield: mean, standard deviation (SD), coefficient of variation (CV). The coefficient of variation was used to evaluate the degree of spatial variability:

$$CV = (SD / Mean) \times 100$$

One-way ANOVA was applied to test the significance of yield differences between productivity zones identified within the field. Statistical analyses were conducted using Statistica 10.0 and GIS-based spatial analysis tools.

Results and Discussion

The selection of field plots for the study was based on the criterion of a single soil type or their genetic similarity (i.e., comparable levels of soil fertility), as well as the cultivation of the same maize variety or hybrid within each field during a given year. Despite these constraints, descriptive statistical analysis revealed substantial spatial variability in soil fertility indicators within the selected study fields. The coefficient of variation ranged from low variability for soil pH to moderate variability for humus content and nutrient availability. The

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highest spatial variability was recorded for soil penetration resistance, particularly in the 5–15 cm soil layer. A high level of spatial variability was also observed for available phosphorus, indicating considerable heterogeneity in nutrient distribution within the field.

Analysis of maize yield monitoring data for the 2023–2025 growing seasons revealed substantial differences in crop productivity depending on hybrid genetics and annual agroclimatic conditions. The highest yield level was recorded in 2025, when the hybrid Amarok (Ukrainian breeding program, VNIS) was cultivated, with an average grain yield of $9.98 \pm 1.47 \text{ t ha}^{-1}$. Slightly lower productivity was observed in 2023, when the hybrid RAGT MAXXATAK produced an average yield of $8.27 \pm 0.65 \text{ t ha}^{-1}$. The lowest yield was recorded in 2024 for the hybrid P8816 (Pioneer brand), with an average productivity of $6.77 \pm 0.95 \text{ t ha}^{-1}$.

At the same time, the results indicated considerable spatial variability in maize productivity within the selected field area. Variance analysis showed that the combined effect of hybrid genetics and annual weather conditions accounted for approximately 62% of the total yield variability, while the contribution of spatial heterogeneity of soil conditions reached 32% (Fig. 1).

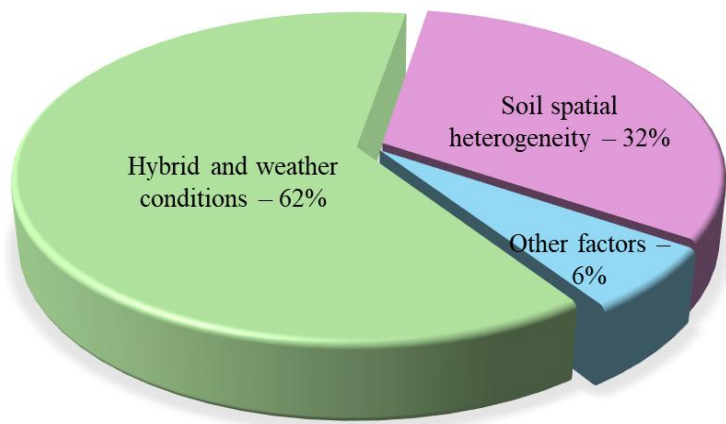


Figure 1
Relative contribution of genetic, environmental, and soil heterogeneity factors to maize yield variability during the 2023–2025 growing seasons

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The cleaned yield monitoring dataset demonstrated varying levels of within-field yield variability across the study years. Specifically, the coefficient of variation (CV) was 7.8% in 2023, 14.0% in 2024, and 14.7% in 2025, indicating moderate spatial variability of crop productivity within the analyzed fields. Such levels of yield variability are typical for agricultural landscapes of the Ukrainian Polissia, where soils are characterized by pronounced spatial heterogeneity and mosaic distribution of fertility indicators.

At the next stage of the research, an important objective was to evaluate the feasibility of implementing precision agriculture practices that account for spatial variability in crop productivity when making management decisions regarding variable-rate seeding and variable-rate application of liquid complex fertilizers. Such an approach aims to improve the overall efficiency of maize production technology by optimizing input use according to the spatial distribution of soil fertility within the field. For this purpose, a specific field with a total area of 125.3 ha was selected for detailed analysis. The field was characterized by pronounced within-field variability in soil fertility indicators and crop productivity. Soil conditions were analyzed based on laboratory results of soil samples collected from 25 elementary field plots, followed by visualization and spatial analysis of the obtained data using analytical tools available within the Cropwise Operations Center digital platform.

Spatial interpolation of yield data revealed distinct patterns of productivity distribution across the field, confirming the significant influence of soil fertility gradients on maize yield formation. Areas consistently characterized by higher yields corresponded to zones with improved soil fertility indicators, particularly higher soil organic matter content and greater availability of essential plant nutrients. The generated yield map clearly demonstrated spatial clustering of productivity levels, confirming that yield variability was associated with spatially structured environmental factors rather than random fluctuations. Visualization and preliminary statistical analysis of the dataset were performed using analytical tools available in the John Deere Operations Center digital platform.

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Correlation analysis revealed positive relationships between maize yield and several soil fertility indicators. The strongest relationship was observed between crop yield and soil organic matter content ($R^2 = 0.69$). Areas characterized by higher humus content generally demonstrated increased crop productivity. Moderate correlations were also identified between maize yield and available phosphorus ($R^2 = 0.56$) as well as exchangeable potassium ($R^2 = 0.49$). Further statistical analysis using descriptive statistics and analysis of variance (ANOVA) confirmed statistically significant differences between mean yield values among the identified productivity zones at a significance level of $p < 0.05$.

The analysis of global spatial autocorrelation using Moran's I revealed statistically significant spatial autocorrelation of maize yield values across the study field. This indicates that yield variability was not random but was driven by spatially structured environmental factors, particularly soil properties. These findings confirmed the presence of spatial clustering within the dataset and provided a scientific basis for the delineation of management zones. The identification of such zones supports the implementation of precision agriculture technologies, including variable-rate seeding and site-specific fertilizer application, taking into account the spatial patterns of crop productivity. The adoption of these practices can substantially improve resource-use efficiency and enhance the sustainability of maize production systems.

The practical implementation of precision agriculture practices based on the delineation of productivity zones allowed evaluation of the effectiveness of site-specific crop management for maize production. Based on the analysis of spatial variability of yield and soil fertility indicators, productivity zone maps were developed and used to implement a variable-rate seeding system combined with site-specific application of liquid complex fertilizers.

The implementation of this approach resulted in a measurable increase in maize productivity. In 2023, the average yield increased from 7.6 to 8.38 t ha⁻¹, corresponding to a 10.3% yield improvement across the cultivated area. In

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2024, the application of the same site-specific management strategy increased the average yield from 7.3 to 8.10 t ha⁻¹, representing a 10.9% increase in productivity.

The obtained results indicate that adapting agronomic practices to spatial variability in soil fertility significantly enhances crop performance. The greatest productivity gains were observed in zones previously characterized by moderate yield limitations, where optimized seeding density and targeted nutrient supply improved plant development and yield formation. In contrast, high-productivity zones benefited mainly from optimized resource allocation and more efficient input use.

These findings demonstrate that site-specific crop management based on productivity zones can substantially improve yield stability and resource-use efficiency, particularly in agricultural landscapes characterized by heterogeneous soil conditions.

Conclusions.

The results of this study confirmed the presence of pronounced spatial variability of soil properties and maize productivity under conditions of heterogeneous soil cover within the studied agricultural landscape. Even within fields selected based on similar soil types and comparable fertility levels, substantial within-field variability in key soil fertility indicators and crop productivity was observed.

The analysis of yield monitoring data for the 2023–2025 growing seasons demonstrated significant differences in maize productivity depending on hybrid genetics and annual weather conditions. The highest average yield was recorded in 2025 for the Amarok hybrid (9.98 ± 1.47 t ha⁻¹), while lower productivity levels were observed in 2023 (8.27 ± 0.65 t ha⁻¹) and 2024 (6.77 ± 0.95 t ha⁻¹). At the same time, spatial variability of yield within fields remained substantial, with coefficients of variation ranging from 7.8% to 14.7%, indicating low to moderate variability typical of agroecosystems in the Polissia region.

Variance partitioning analysis revealed that hybrid genetics and weather conditions accounted for approximately 62% of the total variability in maize yield, whereas spatial heterogeneity of soil conditions contributed about 32%. These

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results emphasize the significant role of soil-related factors in shaping spatial yield patterns under field conditions.

Spatial interpolation of yield data and geostatistical analysis confirmed the presence of clear productivity gradients across the field. Areas with consistently higher maize productivity were associated with zones characterized by improved soil fertility parameters, particularly higher soil organic matter content and greater nutrient availability. Correlation analysis further demonstrated strong relationships between maize yield and soil fertility indicators, with the highest correlation observed between yield and soil organic matter content ($R^2 = 0.69$), followed by available phosphorus ($R^2 = 0.56$) and exchangeable potassium ($R^2 = 0.49$).

The analysis of spatial autocorrelation using Moran's I confirmed that the observed yield variability had a structured spatial pattern rather than a random distribution. This finding provides a scientific basis for delineating management zones within the field.

The identification of spatially homogeneous management zones creates favorable conditions for the implementation of precision agriculture technologies, including variable-rate seeding and site-specific fertilizer application. Such approaches allow producers to adapt crop management practices to spatial differences in soil fertility, thereby improving input-use efficiency and enhancing the sustainability of maize production systems.

The results of this study confirm the significant influence of spatial soil heterogeneity on maize productivity under precision farming conditions. Geostatistical and spatial analyses revealed clear productivity gradients associated with soil fertility parameters, particularly soil organic matter and nutrient availability.

The delineation of management zones provided a reliable basis for the implementation of site-specific agronomic practices. The application of variable-rate seeding and fertilization resulted in yield increases of 10.3% in 2023 and 10.9% in 2024, demonstrating the practical effectiveness of precision agriculture technologies in commercial production systems.

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Overall, the integration of yield monitoring data, soil fertility assessment, and spatial statistical analysis proved to be an effective framework for supporting data-driven crop management decisions. The application of this approach allows producers to better adapt agronomic practices to field heterogeneity, thereby improving productivity, optimizing input use, and enhancing the sustainability of maize production systems.

The obtained results highlight the high potential of precision agriculture technologies for improving the productivity and sustainability of maize production systems in the heterogeneous soil landscapes of the Polissia region.

Future research should focus on multi-year datasets and the integration of additional spatial data sources (e.g., remote sensing indices and topographic variables) to further improve the stability and accuracy of management zone delineation and to enhance the effectiveness of site-specific crop management strategies.

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