A Comparison of Precise Fertilization Prescription Rates to a Conventional Approach Based on the Open Source GIS Software

Modeliranje karte za preciznu gnojidbu korištenjem GIS programa otvorenoga koda

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SUMMARY

Fertilization is one of the most important components of precision agriculture, ensuring high and stable crop yields. The process of spatial interpolation of soil sample data is recognized as a reliable method of determining the prescription rates for precise fertilization. However, the application of a free open-source geographic information system (GIS) software was often overlooked in the process. In this study, a method of precise fertilization prescription map creation was developed using an open-source GIS software to enable a wider and cheaper availability of its application. The study area covered three independent locations in Osijek-Baranja County. A method was developed for the fertilization of sugar beet with phosphorous pentoxide, but its application is universal with regard to the crop type. An ordinary kriging was determined as an optimal interpolation method for spatial interpolation, with the mean RMSE of 1.8754 and R^2 of 0.6955. By comparing the precision fertilization prescription rates to a conventional approach, the differences of 4.1 kg ha^{-1} for Location 1, 15.8 kg ha^{-1} for Location 2, and 11.2 kg ha^{-1} for Location 3 were observed. These values indicate a general deficit in soil phosphorous pentoxide, and precise fertilization could ensure its optimal content in the future sowing seasons.

Keywords: precision agriculture, spatial interpolation, kriging, SAGA GIS, geostatistics

INTRODUCTION

Precision agriculture is based on the newly developed computerized machine systems of programmed exploitation potential, using a smaller number of high-reliability machines and high technological aids (Zhang and Kovacs, 2012). The application of agronomical inputs is based on a variable rate technology, allowing for the application of a necessary amount on every part of an agricultural parcel (Seelan et al., 2003). Contrary to a conventional approach based on a homogenous application of agronomical inputs over an entire agricultural area, this results in the balanced and optimal conditions in the field subsequent to the performance of agrotechnical operations. Even though precision agriculture requires a considerable investment at the beginning of its implementation, it allows for the long-term benefits with regard to the financial gains to the farmer (Tozer, 2009). It is also beneficial to environment protec-

tion due to a generally lower amount of pesticides and mineral fertilizers applied, which are one of the primary sources of heavy metals and toxic organic compounds in the agricultural land in Croatia (Radočaj et al., 2020a). Fertilization in precision agriculture is one of the important factors in agricultural production, as quality fertilization is a requirement for stable crop yields. The fertilization prescription maps should therefore be based on the physiochemical soil analysis data, and the calculation of a required amount must take profitability, specific plant species needs, and soil fertility potential into account. Most of the newer agricultural machinery contains the built-in precision farming systems, allowing for an easy integration of prescription maps create in the GIS envi-

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ronment in their controllers. This fact greatly facilitates the implementation of precision agriculture in practice, even for the smaller farms and companies. Spatial interpolation is an established procedure for the development of prescription maps in precision agriculture, enabling the prediction of a soil nutrient status using a limited soil sample number (Reyes et al., 2015). Spatial interpolation methods imply two subsets, i.e., the geostatistical and deterministic methods, which generally differ by their spatial prediction principle (Robinson and Metternicht, 2006). Geostatistical methods perform a prediction based on the quantification of spatial autocorrelation and fitting of an optimal mathematical model, selected according to the spatial input value properties. Deterministic methods utilize the simpler and universal mathematical prediction functions, most frequently with a limited number of modifiable interpolation parameters. Both groups of interpolation methods are highly applicable for a prediction of soil parameters within an agricultural field, as their performance depends on the quantity and value distribution of input soil sample data. Several free exemplars of the open-source geographic information system (GIS) software have been developed in the past decades, allowing for a global availability concerning the spatial interpolation of soil properties and the creation of prescription maps (Conrad et al., 2015). These functionalities are completely free and could reduce the cost of precise fertilization by avoiding the purchase of expensive commercial GIS and farming software.

This study's hypothesis was that a precise fertilization approach would produce a variable rate prescription considering the present soil heterogeneity, causing differences in prescription rates if compared to a conventional fertilization approach. Therefore, this study aimed to propose and evaluate a method for the creation of a prescription map for precise fertilization applying an optimal interpolation method. This was performed while utilizing a free GIS open-source software exclusively, as an alternative to the expensive commercial programs. The model was designed for a universal application regarding the crop type. It was evaluated for a precise sugar beet fertilization with phosphorous pentoxide (P_2O_5), which represents a typical situation for the implementation of precise fertilization.

MATERIAL AND METHODS

In recent studies, the soil properties and an overall land suitability for the cultivation of various crop types in Osijek-Baranja County have demonstrated a moderate to high variability (Šiljeg et al., 2020; Radočaj et al., 2021). These observations have indicated a possibility of better agricultural land management both on a macro- and on a microlevel. Osijek-Baranja County is a historically important agricultural part of Croatia, covering approximately 14% of the country's total cultivated agricultural area, based on the most recent official data (Croatian Bureau of Statistics, 2018). The study area consisted of three subsets in Osijek-Baranja County, created by grouping the neighboring agricultural parcels, each of them forming a location with the distinctive statistical properties (Table 1). These subsets formed the study area within Osijek-Baranja County: Location 1 (45° 32' N, 18° 45' E), Location 2 (45° 52' N, 18° 43' E), and Location 3 (45° 45' N, 17° 58› E) (Figure 1). The soil samples having random sampling locations were obtained from Osijek-Baranja County's Department for Agriculture and Economy database. The survey area and soil sample characteristics are illustrated using descriptive statistics in Table 1. Location 1 covered the largest area, Location 2 had the lowest mean P_2O_5 value, while Location 3 had the highest. The sampling density in all three areas was approximately equal, averaging 4.24 samples per hectare. The coefficients of variation in all areas indicate a moderate variability in the sample values.

Table 1. Descriptive statistics of input soil samples

Tablica 1. Deskriptivna statistika ulaznih vrijednosti uzoraka tla

| Property *Svojstvo*	Location 1 *Lokacija 1*	Location 2 *Lokacija 2*	Location 3 *Lokacija 3*
Sample count *Broj uzoraka*	198	51	47
Location area *Površina područja*	816 ha	206 ha	214 ha
Average area per sample *Prosječna površina po uzorku*	4.12 ha	4.04 ha	4.55 ha
Mean (mg 100 g^{-1}) *Aritmetička sredina (mg 100 g^{-1})*	22.3	11.4	24.8
Value range (mg 100 g^{-1}) *Raspon vrijednosti (mg 100 g^{-1})*	34.6	24.8	39.6
Coefficient of variation *Koeficijent varijacije*	41.1%	46.9%	42.1%
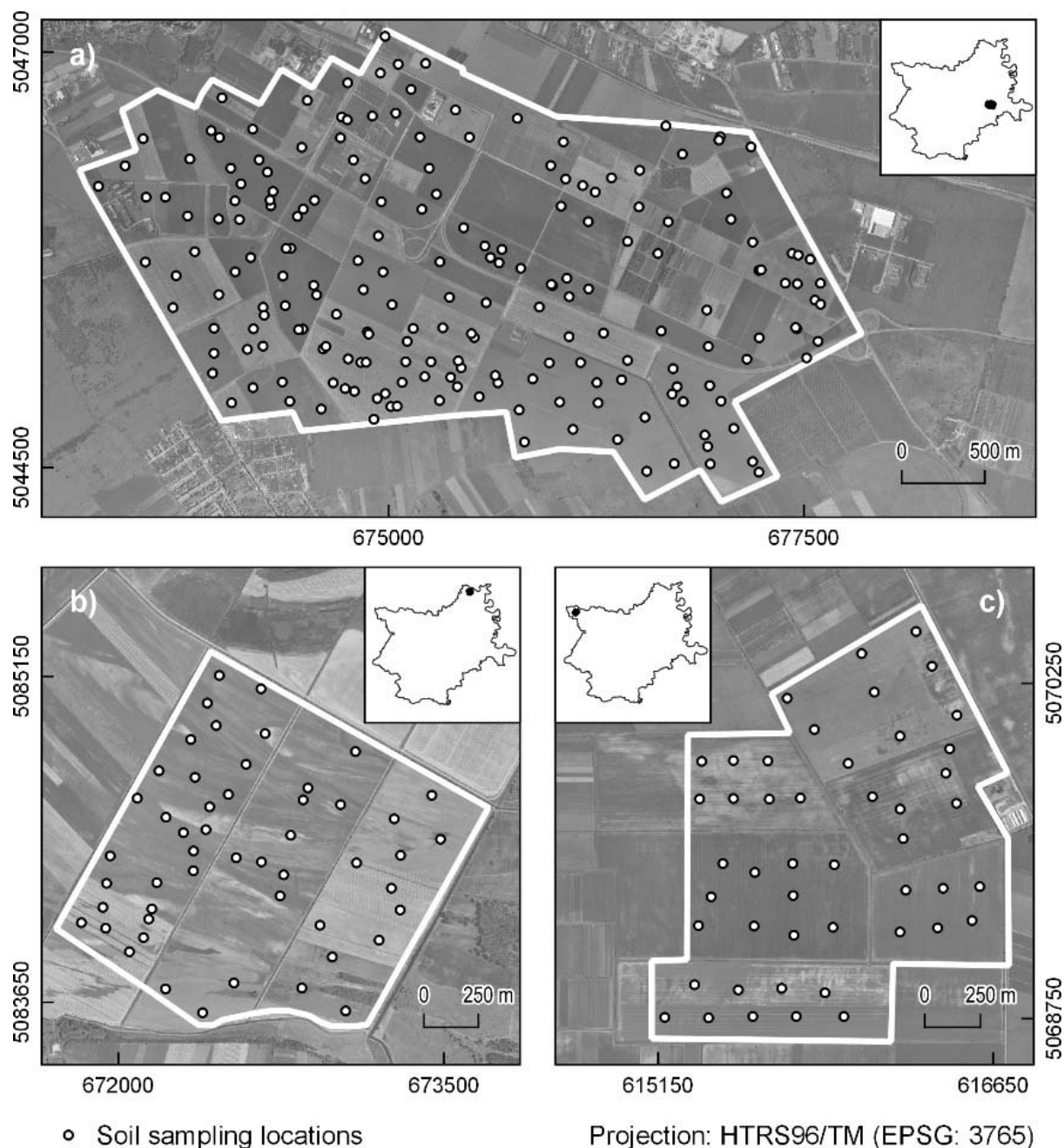
Figure 1. Study area with three subsets: a) Location 1, b) Location 2, and c) Location 3

Slika 1. Područje istraživanja s trima podskupinama: a) lokacija 1, b) lokacija 2, c) lokacija 3

The evaluated spatial interpolation methods consisted of a geostatistical ordinary kriging method and two deterministic methods, i.e., of an inverse distance weighted and of an angular distance weighted. These methods produced a high interpolation accuracy and are detailly explained in the similar studies (Robinson and Metternicht, 2006). A determination of interpolation parameters was performed based on the examination of normal distribution and input data stationarity. These values are also the basic prerequisites for kriging interpolation (Jurišić et al., 2020). In this study, the

examination of normal input value distribution was performed using the Shapiro-Wilk normality test in *R v4.0.3*, *RStudio v1.3*. The evaluation of stationarity as a measure of local variability between the adjacent samples was performed by an interpretation of Thiessen polygon properties (Radočaj et al., 2021). The Thiessen polygons contained all points geometrically closest to a particular input soil sample. A weight coefficient modeling within an ordinary kriging was performed using a semivariogram, calculated as a distance function of all sample pairs. A mathematical model which has produced the

best semivariogram fitting according to the highest coefficient of determination (R^2) was selected for interpolation. The linear, Gaussian, spherical and exponential mathematical models were evaluated in the process. A logarithmic transformation was performed as a preprocess to an ordinary kriging in cases of a skewed distribution of input sample data. The number of lags during an ordinary kriging interpolation was 22, each covering a 118-meter distance. An inverse distance weighted and an angular distance weighted were performed using an inverse-distance-to-a-power weighting function, with a weighting power of 2. A cross-validation using the leave-one-out procedure was performed for the sake of an accuracy assessment of interpolation results pertaining to all evaluated spatial interpolation methods. A root-mean-square-error ($RMSE$) and R^2 were selected for an interpolation accuracy assessment, with the lower $RMSE$ and higher R^2 values indicating a higher interpolation accuracy. A spatial resolution of interpolation results was set to 50 m, which were georeferenced in the Croatian Terrestrial Reference System (HTRS96/TM). All spatial calculations were performed in a GIS environment using an open-source *SAGA GIS v7.4.0* software (Conrad et al., 2015). An interpolated data visualization

and the export to the ESRI Shapefile vector format were performed using an open-source *QGIS v3.10* software.

A prescription map for precise fertilization of P_2O_5 for sugar beet was created according to the existing instructions for sugar beet cultivation in the research area proposed by Jurišić (2008) (Table 2). Prescription rates were calculated as a difference between a necessary P_2O_5 soil content and its current soil quantity, determined by spatial interpolation. These values were grouped using the stepwise classification to match the defined P_2O_5 presence classes. This procedure meets a requirement of forming the relatively homogenous zones in precision agriculture (Seelan et al., 2003), as six zones were utilized in the study. Prescription rates for a conventional fertilization were calculated as a difference between the same necessary P_2O_5 soil content as in the precise fertilization approach and the average of all input soil sample values per location. This resulted in a single value per location, designated for a homogenous fertilizer application. The differences in the prescribed fertilization rates per location were determined individually, calculated as a difference between the total prescribed P_2O_5 rates in precise fertilization ($Total_{prec}$) and a conventional approach ($Total_{conv}$).

Table 2. Recommendation of P_2O_5 fertilization for sugar beet according to the present P_2O_5 soil content (Jurišić, 2008)

Tablica 2. Preporuka za aplikaciju P_2O_5 za šećernu repu u odnosu na postojeću sadržaj P_2O_5 u tlu (Jurišić, 2008.)

P_2O_5 presence classes *Klase prisutnosti P_2O_5*	P_2O_5 soil content (mg 100 g^{-1}) *Sadržaj P_2O_5 u tlu (mg 100 g^{-1})*	Necessary P_2O_5 fertilization (kg ha^{-1}) *Potrebna količina P_2O_5 (kg ha^{-1})*
O (very low / *vrlo nisko*)	< 5	240
A (low / *nisko*)	6–10	180
B (moderate / *umjereno*)	11–17	140
C (high / *visoko*)	18–25	90
D (very high / *vrlo visoko*)	26–35	60
E (extremely high /*ekstremno visoko*)	36 >	0

RESULTS AND DISCUSSION

Based on the Shapiro-Wilk test, it was determined that the P_2O_5 samples for all locations do not possess a normal distribution (Table 3). Since the examined samples do not meet a normal distribution condition, a logarithmic transformation was performed as a pre-process to an ordinary kriging. The Thiessen polygons indicated moderate stationarity at Location 1, a high stationarity at Location 2, and a moderately high stationarity 3 was observed, with the exception of a high P_2O_5 concentration, in its eastern part (Fig. 2). Using the same normal distribution and stationarity tests, Hasan et al. (2014) found that the adjustment of kriging parameters, depending on the tests performed in this study, allowed for an increase in interpolation accuracy. The Thiessen

polygons might cause a bias in stationarity evaluation, as they primarily depend on an observer's visual interpretation (Radočaj et al., 2021).

Table 3. Shapiro-Wilk normality test results

Tablica 3. Rezultati Shapiro-Wilkova testa normalne razdiobe

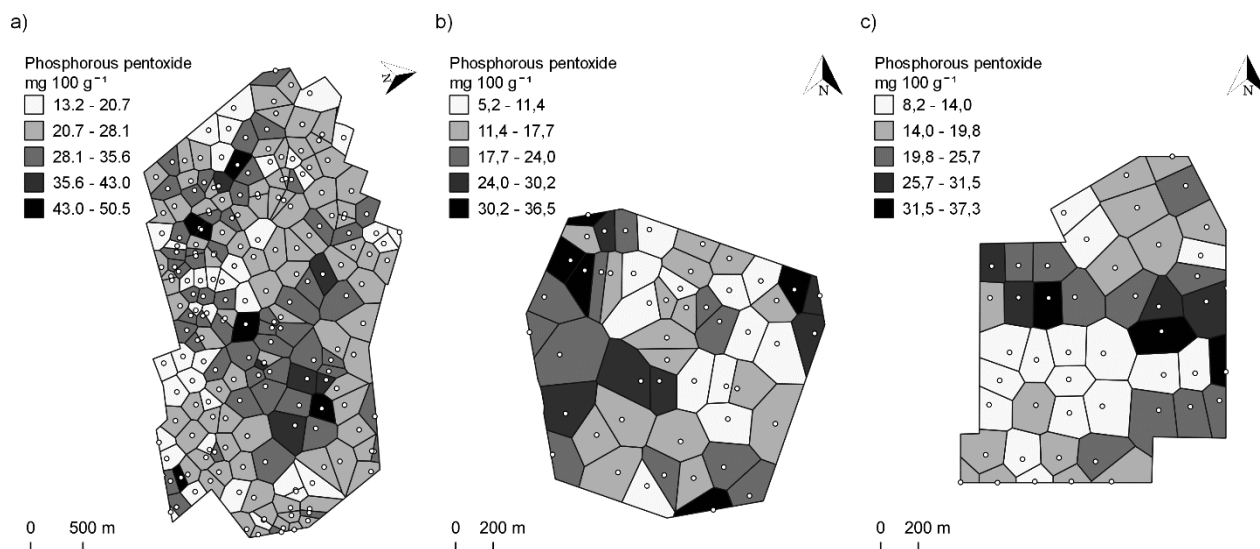| Location *Lokacija*	Shapiro-Wilk test results *Rezultati Shapiro-Wilkova testa*	
	W	P
1	0.9395	< 0.0001
2	0.8974	0.0004
3	0.8813	0.0002

Figure 2. The Thiessen polygons for: a) Location 1, b) Location 2, and c) Location 3
Slika 2. Thiessenovi poligoni za: a) lokaciju 1, b) lokaciju 2 i c) lokaciju 3

A spherical model was selected as a mathematical interpolation model due to the highest level of semi-variogram correlation. An Ordinary kriging produced the highest *RMSE* and R^2 values for all locations and was therefore determined as the most accurate interpolation method for these input samples (Table 4). It produced a mean *RMSE* of 1.8754 and an R^2 of 0.6955, which were influenced by the slightly lower interpolation accuracy values on Location 2. An angular distance weighted produced the second-highest interpolation accuracy for all study locations, followed by an inverse distance weighted. Both deterministic methods produced much better results on Location 1 when compared to the other two locations, which were mutually distinctive, primarily regarding a soil sample count. An ordinary kriging outperformed the deterministic interpolation methods in the similar studies as well (Dai et al., 2014), but the deterministic methods are commonly a more suitable option in cases of a low input data density, normality, or stationarity (Radočaj et al., 2020b).

Table 4. Interpolation accuracy of P_2O_5 per a tested interpolation method
Tablica 4. Točnost interpolacije P_2O_5 za ispitane metode interpolacije

Location *Lokacija*	Ordinary kriging *Obični kriging*		Inverse distance weighted *Metoda inverzne udaljenosti*		Angular distance weighted *Metoda kutne udaljenosti*	
	RMSE	R^2	RMSE	R^2	RMSE	R^2
1	1.6334	0.7332	2.4180	0.6933	2.4205	0.7056
2	2.0537	0.6307	2.1082	0.3997	2.1068	0.4448
3	1.9391	0.7227	2.6268	0.5701	2.6285	0.5995

The highest P_2O_5 values on Location 1 were identified in the central and northern part, peaking at 30.8 mg 100 g^{-1}, while these values decreased toward the borders at the southwest (Fig. 3). Location 2 had the lowest P_2O_5 values compared to the other locations, primarily due to the low values at the central part. On Location 3, the relatively high P_2O_5 values were observed in the entire area, with minor exceptions in the eastern borderline part. Standard deviations of the interpolated P_2O_5 values in all three cases indicate that the most accurate interpolated area is the one near the samples, while this accuracy decreases in proportion to a distance from the samples. Therefore, the highest standard deviations were observed at the borders of each location.
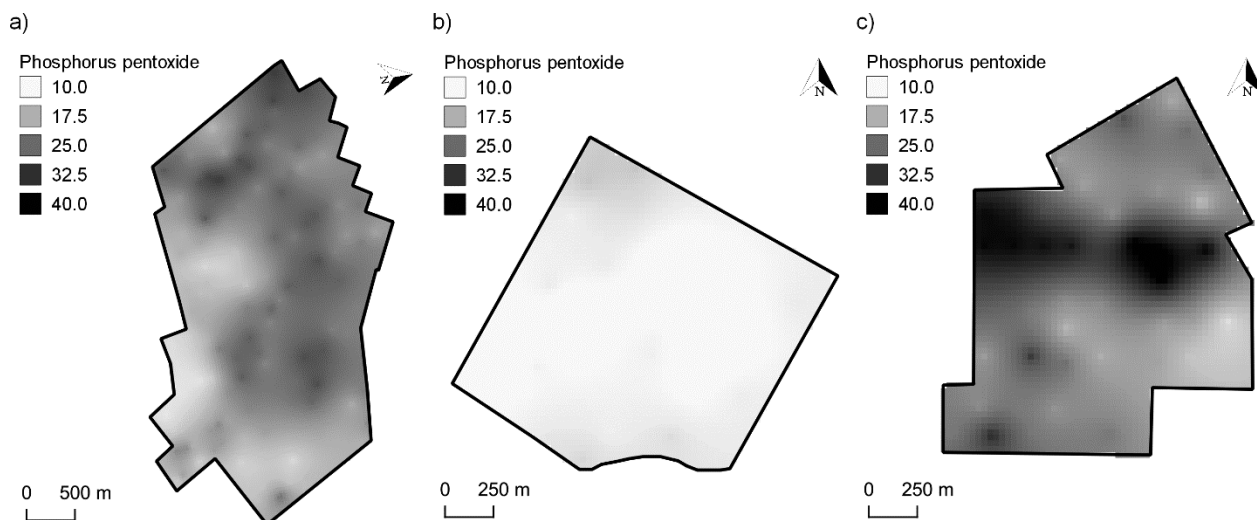
Figure 3. Interpolation result of an ordinary kriging for: a) Location 1, b) Location 2, and c) Location 3
Slika 3. Rezultat interpolacije primjenom običnoga kriginga za: a) lokaciju 1, b) lokaciju 2 i c) lokaciju 3

The mean P_2O_5 values of all samples per location were applied for the calculation of P_2O_5 recommendations concerning conventional fertilization. Conventional fertilization's prescription rates amounted to 90 kg ha^{-1} for Location 1, 140 kg ha^{-1} for Location 2, and 90 kg ha^{-1} for Location 3 (Table 5). The difference in prescription rates for a precise and conventional fertilization amounted to 4.1 kg ha^{-1} for Location 1, 15.8 kg ha^{-1} for Location 2, and 11.2 kg ha^{-1} for Location 3. The larger differences were observed proportionally for a higher variability of the existent soil P_2O_5 values. Contrary to a common situation of a lesser quantity of necessary fertilizer in a precise fertilization approach (Tozer, 2009), the prescription rates for the Locations 1 and 2 exceeded those of a conventional approach. A larger amount of fertilizer required on these locations is present in the areas with the very low or with the extremely low existing P_2O_5 values. This situation is expected to occur in cases of an existent soilborne P_2O_5 deficit, as a larger fertilizer quantity sets soil P_2O_5 to an optimal level for sugar beet cultivation, regardless of the amount of fertilizer applied, if compared to a conventional fertilization. By applying a larger amount of fertilizer within a precise fertilization system in case of a seasonal soilborne nutrient deficiency, the better conditions are being created for a crop growth and for the long-term fertilizer savings in the future sowing seasons (Zhang and Kovacs, 2012).

Table 5. Recommendation of P_2O_5 fertilization for sugar beet per study location
Tablica 5. Preporuka za aplikaciju P_2O_5 za šećernu repu po lokaciji istraživanja

Location *Lokacija*	Precise fertilization P_2O_5 rates (ha) *Količina aplikacije P_2O_5 (ha)*					Total$_{prec}$ (kg)	Total$_{conv}$ (kg)	Difference (kg) *Razlika (kg)*
	0 kg ha^{-1}	60 kg ha^{-1}	90 kg ha^{-1}	140 kg ha^{-1}	180 kg ha^{-1}			
1	/	154.0	503.0	158.6	/	76,714	73,404	3,310
2	/	/	/	124.6	81.2	32,060	28,812	3,248
3	16.7	53.8	129.2	14.4	/	16,872	19,269	−2,397

According to the modeled fertilization maps, the need for P_2O_5 is maximal and uniform throughout Location 2, with only two zones for precise fertilization (Fig. 4). The precise fertilization prescription rates at Locations 1 and 3 contain large variations, with four zones nearly equally distributed in them. The creation of management zones in precise fertilization could be upgraded by adopting the unsupervised classification. It was successfully applied for the delineation of soil C/N management zones in the study area by Radočaj et al. (2021) and could severely reduce a possibility of operator's subjective error in the formation of prescription rates zones.
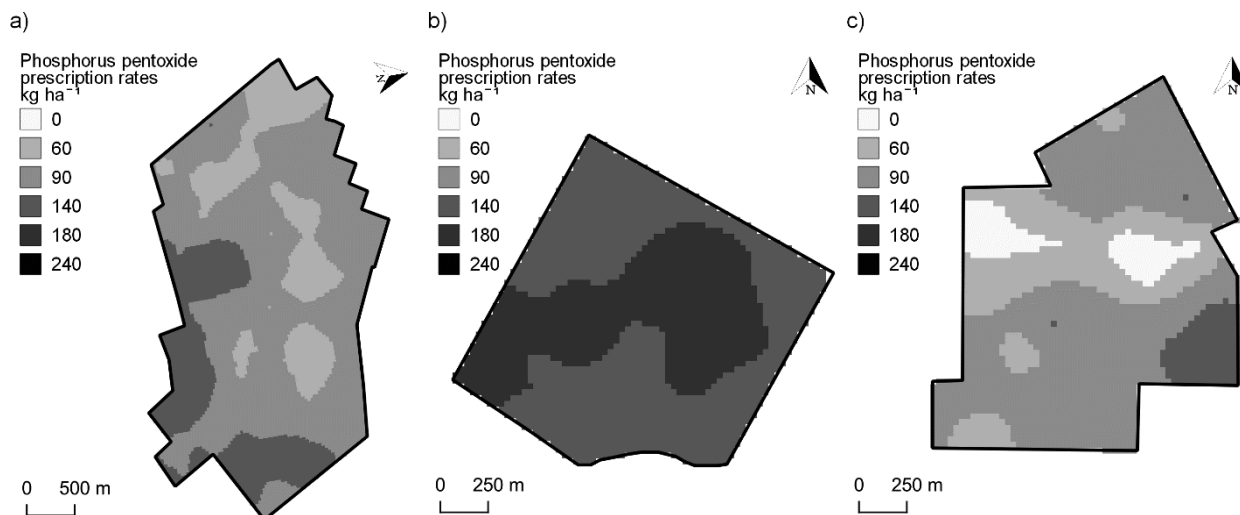
Figure 4. Recommended prescription rates of P_2O_5 for a) Location 1, b) Location 2, and c) Location 3

Slika 4. Preporučene količine aplikacije P_2O_5 za a) lokaciju 1, b) lokaciju 2 i c) lokaciju 3

CONCLUSION

The application of the free open-source *SAGA GIS* and *QGIS* software allowed for the obtainment of necessary results for the creation of prescription maps in precise fertilization. This primarily refers to the evaluation of spatial interpolation methods, which had a major impact on the final prescription rates. An ordinary kriging produced a superior interpolation accuracy on all three study locations, compared to the two deterministic interpolation methods, an inverse distance weighted and an angular distance weighted, respectively. The application of ordinary kriging for a prescription map creation also enabled the operator to control the interpolation parameters, in contrast to the commercial solutions where this procedure is often simplified or inaccessible. The proposed model resulted in the higher precise fertilization prescription rates when compared to a conventional approach on two out of three study locations. The differences in precise and conventional fertilization prescription rates of 4.1 kg ha^{-1}, 15.8 kg ha^{-1}, and 11.2 kg ha^{-1} for the Locations 1, 2, and 3, respectively, have confirmed the study hypothesis. In accordance with the principle of precise fertilization, the application of the recommended P_2O_5 values would enable an optimal amount of phosphorus for sugar beet cultivation, as opposed to a conventional fertilization, after which there would still be a significant P_2O_5 deficit in the soil. By applying the proposed amount of fertilizer with a higher nutrient deficit in the soil, a basis is created for a lesser application of fertilizer in the future sowing seasons if compared to a conventional fertilization. The developed model supports a precise fertilization regardless of the soil element or the crop type. The accessibility of creating a fertilization map in the vector ESRI Shapefile format enables the efficient connection between the GIS analysts and tractor operators in the process of precise fertilization.

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MODELIRANJE KARTE ZA PRECIZNU GNOJIDBU KORIŠTENJEM GIS PROGRAMA OTVORENOGA KODA

SAŽETAK

Gnojidba je jedna od najvažnijih sastavnica precizne poljoprivrede koja osigurava visoke i stabilne prinose usjeva. Proces prostorne interpolacije podataka uzorka tla prepoznat je kao pouzdana metoda određivanja stope aplikacije u preciznoj gnojidbi. Međutim, primjeni besplatnih softvera geografskoga informacijskog sustava (GIS) otvorenoga koda često nije dana dovoljna pozornost. U ovome je istraživanju razvijena metoda modeliranja karte za preciznu gnojidbu korištenjem GIS softvera otvorenoga koda kako bi se omogućila šira i jeftinija dostupnost njezine primjene. Područje ispitivanja obuhvaćalo je tri neovisne lokacije u Osječko-baranjskoj županiji. Razvijena je metoda za preciznu gnojidbu šećerne repe za fosforov pentoksid, no njezina primjena je univerzalna bez obzira na vrstu usjeva. Obični kriging određen je kao optimalna metoda interpolacije, sa srednjim vrijednostima RMSE-a od 1,8754 i R² od 0,6955. Usporedbom modeliranih vrijednosti precizne gnojidbe s konvencionalnim pristupom uočene su razlike od 4,1 kg ha⁻¹ za lokaciju 1, 15,8 kg ha⁻¹ za lokaciju 2 i 11,2 kg ha⁻¹ za lokaciju 3. Te vrijednosti ukazuju na deficit fosforova pentoksida u tlu, a precizna gnojidba mogla bi osigurati njegov optimalan sadržaj u budućim sezonama sjetve.

Ključne riječi: precizna poljoprivreda, prostorna interpolacija, kriging, SAGA GIS, geostatistika