Cropland suitability determination for maize (Zea mays L.) using multilevel GIS-based multicriteria analysis in continental Croatia

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Cropland suitability determination for maize (*Zea mays* L.) using multilevel GIS-based multicriteria analysis in continental Croatia

Određivanje pogodnosti poljoprivrednog zemljišta za uzgoj kukuruza (*Zea mays* L.) primjenom višerazinske GIS multikriterijske analize u kontinentalnoj Hrvatskoj

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ABSTRACT

Previous research in continental Croatia indicated that cropland suitability levels are highly variable and existing natural resources could be better utilized. To overcome this issue, a method of multilevel Geographic information system (GIS)-based multicriteria analysis based on Analytic hierarchy process (AHP) for maize cropland suitability determination was proposed and evaluated. Free spatial data and free open-source software were implemented in the research in 250 m spatial resolution. The effects of air temperature, precipitation, soil and topography were modelled with the multilevel approach to avoid inconsistency in pairwise comparison due to criteria count. The maize suitability index (MSI) was calculated using the weighted linear combination, with higher values indicating proportionally higher suitability. According to the results of the AHP method, the weight consistency ratio was lower than the borderline value (0.042 < 0.100). Soil type and mean air temperature in June had the most impact on the suitability result, with 14.3% and 13.6% influence, respectively. The highest MSI values were achieved along the Sava River, especially in the proximity of Sisak and Nova Gradiška, resulting up to 3.9 of the possible 5.0. The sensitivity analysis of criteria indicated precipitation data in May, July and August particularly impactful in continental Croatia, while mean air temperature in September had very low variability of the suitability and was the least impactful on calculated MSI values.

Keywords: AHP, open-source software, sensitivity analysis, land management, corn

SAŽETAK

Prethodna istraživanja u kontinentalnoj Hrvatskoj pokazala su da su razine pogodnosti poljoprivrednog zemljišta vrlo promjenjive i da bi se postojeći prirodni resursi mogli iskoristiti na bolji način. Da bi se prevladalo ovo pitanje, predložena je i evaluirana metoda višerazinske GIS multikriterijske analize temeljena na analitičkom hijerarhijskom procesu (AHP) za utvrđivanje pogodnosti poljoprivrednog zemljišta za uzgoj kukuruza. Istraživanje je temeljeno na besplatnim prostornim podacima i besplatnom GIS softveru otvorenog koda s prostornom razlučivost od 250 m. Kriteriji temperature zraka, oborina, tla i topografije modelirani su višerazinskim pristupom kako bi se izbjegla nedosljednost u usporedbi parova kriterija. Indeks pogodnosti područja za uzgoj kukuruza (MSI) izračunat je primjenom težinske linearne kombinacije, pri čemu veće vrijednosti proporcionalno ukazuju na veću pogodnost. Prema rezultatima AHP metode, omjer konzistencije težina bio je niži od granične vrijednosti (0,042 <0,100). Vrsta tla i srednja temperatura zraka u lipnju najviše su utjecali na rezultat pogodnosti, s 14,3%, odnosno 13,6% utjecaja. Najveće MSI vrijednosti postignute su uz rijeku Savu, posebno u okolici Siska i Nove Gradiške, rezultirajući s 3,9 of mogućih 5,0. Analiza osjetljivosti kriterija ukazala je da su podaci o oborinama u svibnju, srpnju i kolovozu bili posebno utjecajni u kontinentalnoj Hrvatskoj, dok je srednja temperatura zraka u rujnu imala vrlo nisku varijabilnost pogodnosti i najmanje je utjecala na izračunate MSI vrijednosti.

Ključne riječi: AHP, programi otvorenog koda, analiza osjetljivosti, upravljanje zemljištem, kukuruz

INTRODUCTION

Maize (*Zea mays* L.) is traditionally considered a fundamental part of many crop rotations in Croatia, also being among the most frequently cultivated and important crops globally (Kljak et al., 2020). The majority of the agroecological criteria important for maize cultivation can be spatially modelled, especially using the free global spatial data sources, which allows its suitability modelling (López-Blanco et al., 2018). This fact encouraged the application of Geographic information system (GIS) and multicriteria analysis in land suitability calculations for the cultivation of maize (Ramamurthy et al., 2020), as well as for many other crops (Radočaj et al., 2020; Šiljeg et al., 2020). The recent effects of climate changes caused significant yield decreases on areas previously considered suitable (Jayathilaka et al., 2012). Therefore, the same authors recommended updating the crop suitability calculations using GIS-based multicriteria analysis.

Since the founding of the Republic of Croatia, maize has been the agricultural crop with the largest production. In 2017, 1,560 thousand tons of maize were produced at the country level, averaging at 6.3 tons per hectare (Croatian Bureau of Statistics, 2018a). Jurišić (2008) stated that maize can produce extremely high yield, peaking at 25 tons per hectare in optimal conditions. By comparing the current maize production in Croatia with the maximum possible value, possibilities for further improvement of agricultural maize production are obvious. The average producer price of maize in 2017 was 1,021.95 HRK per ton (Croatian Bureau of Statistics, 2018b), which combined with total maize yield in the same year amounts to 1.59 billion HRK of total income. By adjusting agricultural land management plans to adapt to climate changes, potentially 16 million HRK for each 1% in maize yield increase could be obtained in future years. Previous research in continental Croatia noted a high variability of cropland suitability, which indicates a possibility of a more efficient land management planning considering the suitability values per crop type (Jurišić et al. 2020; Radočaj et al. 2020; Šiljeg et al., 2020). Land-use management and planning in various economies worldwide benefited from maize land suitability determination due to its general heterogeneity and susceptibility to temporal changes (Pilevar et al., 2020; Ramamurthy et al., 2020).

The common vegetative period of maize types in continental Croatia ranges from April to September. Continental Croatia is characterized by a moderately warm and rainy climate according to the Köppen classification. Besides the sufficient soil humidity at the time of sowing, maize germination and emergence requires optimal air temperatures ranging from 15 °C to 20 °C (Jurišić, 2008). Soil water reserves before sowing are crucial for the subsequent growth and development of maize (Iqbal et al., 2010). However, a large amount of precipitation in a short period is detrimental to maize development. Mean air temperatures from 18 °C to 20 °C are the most favourable during vegetative growth stages (Jurišić, 2008). Reproductive development stages are characterized by the risk of drought as a result of high air temperatures and poor nutrition due to lack of soil nitrogen. In the late stages of maturity, temperatures higher than average are favoured by maize, as well as slightly drier weather with less precipitation (Wei et al., 2020). Criteria regarding air temperature were modelled for the full maize vegetative period from April to March, while precipitation was modelled using a narrower range (May to August).

The primary aim of this study is to develop and evaluate the model of land suitability calculation for maize cultivation using GIS-based multicriteria analysis in continental Croatia. The purpose of created suitability maps was aimed for aid in decision-making for agricultural land management. The secondary aim of the study is to enable global applicability of the model, by using predominantly free spatial data for suitability calculations.

MATERIALS AND METHODS

Continental Croatia is a predominantly agricultural area, with CORINE 2018 Land Cover class of agricultural areas covering 54% of the study area (Figure 1).

According to defined agroecological parameters, six criteria groups were selected (Table 1). These criteria were modelled in GIS environment from open data sources WorldClim2 (Fick and Hijmans, 2017) for the air temperature and precipitation criteria and Shuttle Radar Topography Mission (SRTM) 1-arc second global digital elevation model was used for the topography criteria. Air temperature is divided to minimum air temperatures (Tmin) and mean air temperatures (Tmean), according to maize requirements for the specific month. Total soil nitrogen and soil type were interpolated from the Ministry of Environment and Energy of the Republic of Croatia (MEE) soil samples. Soil Type criterion was reclassified to Food and Agriculture Organization (FAO) specifications to suitable (S1, S2, S3) and non-suitable (N1, N2) classes. Soil, climate and topography criteria groups are a basis for cropland suitability calculation studies due to their measurability and availability of accurate data (Pilevar et al., 2020; Ramamurthy et al., 2020; Radočaj et al., 2020). These are the dominant factors that influence cropland suitability on a macro-level but do not include agricultural activities on a micro-level which are rarely well-documented. These activities typically consist of land cultivation systems, existence and intensity of the irrigation systems, fertilization and crop protection system. However, land-use planning and management should include cropland suitability recommendations that are based on natural conditions which cannot be altered, as micro-level activities can be modified from season to season (Jurišić et al., 2020).

Soil sample values were interpolated using ordinary kriging, which is the most commonly applied geostatistical interpolation method and is regarded as more accurate than deterministic methods in most cases (Radočaj et al., 2021). Its most important segments and prediction principle is thoroughly explained in Oliver and Webster (2014). All criteria were converted to 250 m spatial resolution in pre-processing (Figure 2). The Croatian Terrestrial Reference System (HTRS96/TM) was selected for georeferencing the criteria. WorldClim2 rasters were downscaled using the bilinear interpolation method, which produced the highest downscaling performance using the same dataset in a study by Peng et al. (2019). These authors achieved even higher quality of downscaled WorldClim data compared to the lower-resolution dataset, according to accuracy assessment using the ground-truth observations from weather stations. Open-source GIS software was exclusively used in this study

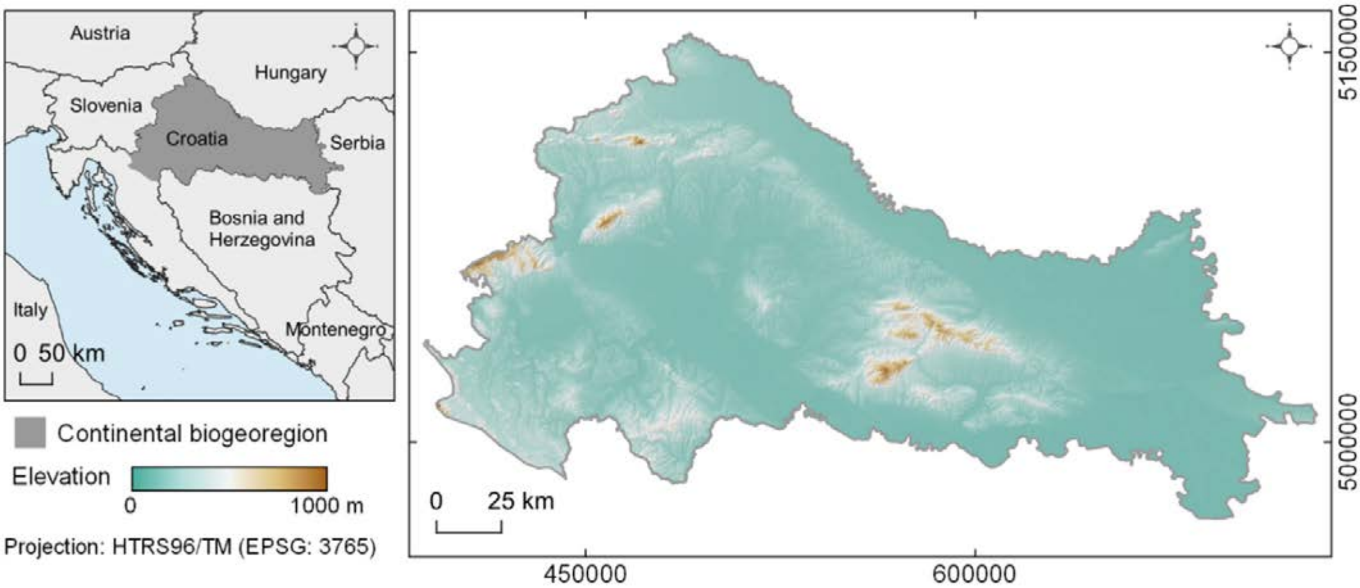

Figure 1. The spatial extent of continental Croatia

Table 1. The selected criteria for maize cropland suitability calculation

Criteria name	Description	Source	Unit
Air Temperature	Minimum and mean monthly air temperatures	WorldClim2	°C
Precipitation	Average total monthly precipitation	WorldClim2	mm
Soil Type	General agricultural suitability classes	MEE	/
Total Nitrogen	Total soil nitrogen at soil depth 0-30 cm	MEE	%
Solar Irradiation	Total solar irradiation based on the relief	SRTM	kWh m^{-2}
Flow Accumulation	Total area of flow accumulation from neighbouring upslope area	SRTM	pixels

to enable applicability of the proposed suitability model: SAGA GIS v7.4.0 for pre-processing and calculations, with QGIS v3.10 for suitability mapping.

Standardization enabled the integration of vector and raster layers within the multicriteria analysis through the definition of a unique numerical interval. This procedure allowed integration of both quantitative (Air Temperature, Precipitation, Total Nitrogen, Solar Irradiation, Flow Accumulation) and qualitative criteria (Soil Type) for the suitability calculation. A [1,5] number interval was selected for the standardization, which was successfully applied in Plaščak et al. (2019). All elements of the input layers (pixel values for rasters) were assigned new values within the set numerical interval, so that a higher value indicates greater suitability of the criteria to the final result. Standardization was performed by the stepwise classification method. The advantage of the stepwise classification over the simple linear stretching method of the input values is the resistance to the extremely low or high values, which typically occur in the topographic criteria (Radočaj et al., 2020). It is implemented by specifying five classes, assigning limit values to each class, and then assigning new values within a specified interval. The classification method enables a large subjective influence of the user, which also makes it possible to transfer a larger amount of professional knowledge to the result of multicriteria analysis.

The determination of criteria weights was performed using the Analytic hierarchy process (AHP) method, which is a reliable choice as a crop suitability calculation technique due to its flexibility and comprehensiveness (Musakwa, 2018). The calculation of criteria weights was based on the pairwise comparison of all combinations of selected factors, designating the values of 1 (equally important) to 9 (extremely more important), according to their relative importance (Saaty, 2008). The consistency of these comparisons was checked using the Consistency Ratio (CR), depending on the Consistency Index (CI) and the number of compared criteria expressed with the Random Consistency Index (RI) (Saaty, 2008) (Table 2).

The CR ratio below 0.10 indicates a consistent pairwise comparison for further processing. CI and CR were calculated according to equations (1) and (2), respectively:

$$CI = (\lambda - n) / (n - 1) \tag{1}$$

$$CR = CI / RI \tag{2}$$

where n is the number of criteria and λ is the value representing consistency vectors. Multilevel weight determination using AHP was selected according to the specifications by Saaty and Ozdemir (2003), which state that the optimal criteria count for AHP weight determination is five to nine factors. Therefore, air temperature and precipitation criteria were grouped for the pairwise comparison with other criteria in the first level and then the criteria inside these groups were compared in the second processing level. The individual weights of the criteria in these groups were calculated by the multiplication of air temperature or precipitation group weights with the impact of individual criteria within the group.

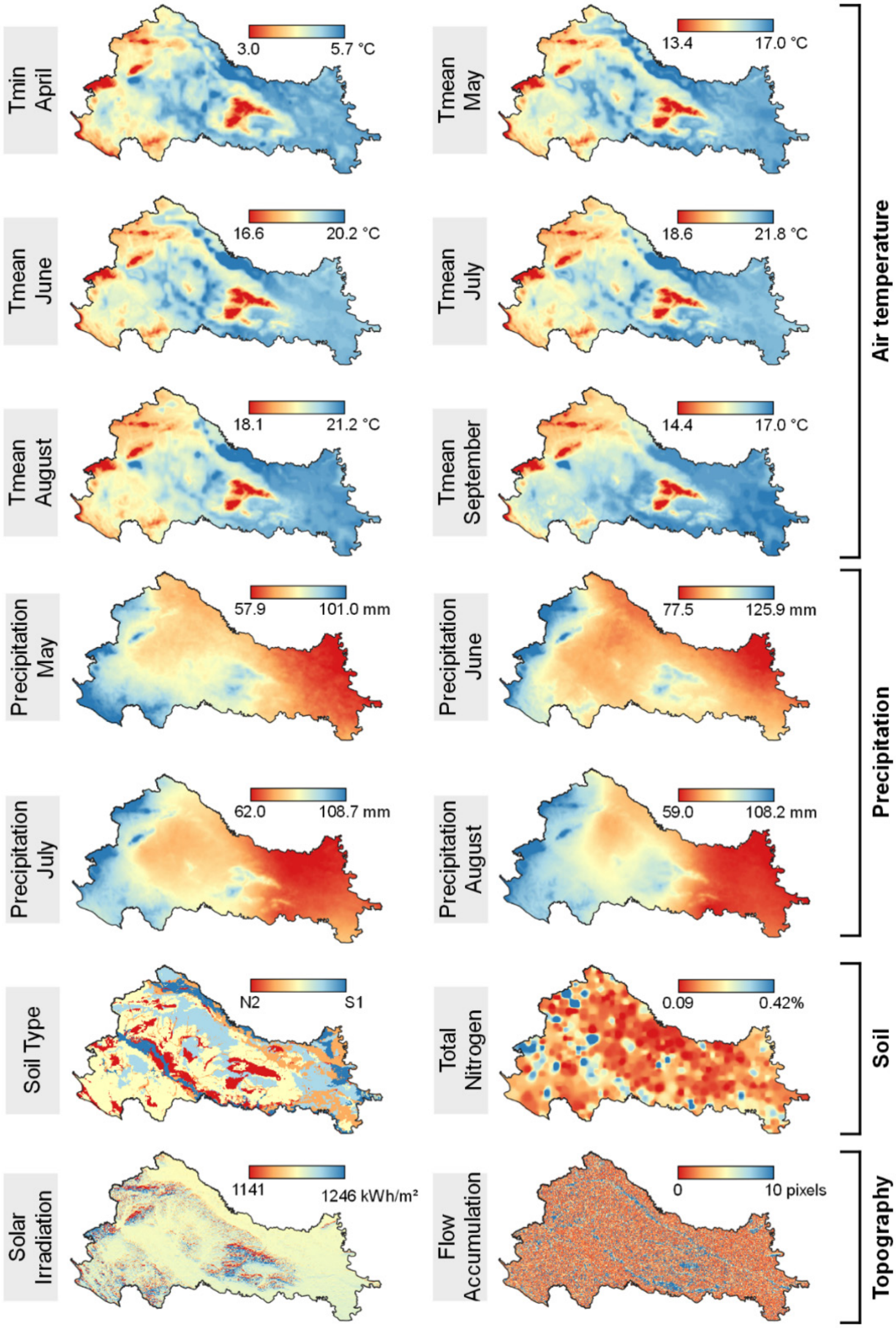

Figure 2. Input values of the selected criteria

Table 2. Random Consistency Index (RI) according to Saaty (2008)

Number of criteria	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.24	1.41	1.45	1.49

Standardized criteria values and their respective weights from AHP were aggregated using the weighted linear combination method. A maize suitability index (MSI) values were calculated as a result, representing the cropland suitability levels for maize cultivation. Possible MSI values range from 1 to 5, proportionally indicating higher suitability. MSI was calculated according to the equation (3):

$$MSI = \sum X_i w_i \tag{3}$$

where X represents standardized values and w represents criteria weights for the criteria i. Sensitivity analysis of individual criteria impact on suitability result was performed according to the frequencies of standardized values per criteria. Frequencies were calculated into five classes with the number intervals of [0,1], [1,2], [2,3], [3,4] and [4,5]. A nearly equal distribution of frequencies designated a highly variable criterion, which had a notable impact on the final suitability results. Frequencies that were dominantly distributed on only two or fewer frequency classes indicate a high homogeneity of the particular criterion, which carries a low information value to the suitability result. The recommendations for criteria selection for crop suitability analyses in the study area were given, since a highly skewed distribution of criteria values indicates a necessity for its modification or replacement.

RESULTS AND DISCUSSION

Standardized criteria values were displayed in Table 3. Mean air temperature for July and August, as well as precipitation were standardized equally for two months due to very similar maize requirements of these criteria in the selected period.

Pairwise comparisons and calculated criteria weights within the AHP are shown in Table 4. Performed comparisons resulted in CR of 0.042, indicating a consistent pairwise comparison. Climate criteria had the highest combined weight, having a 70.3% impact on the final suitability result. The relative impact of the criteria monthly components of the Air temperatures and Precipitation criteria was assessed as shown in Table 5. Climate values in June and July were the most impactful, with the 50% and 65% relative impact for Air temperatures and Precipitation, respectively.

Standardized criteria values and their respective weights determined using AHP were aggregated for the MSI calculation as shown in Eq. (4). The display of the spatial distribution of MSI in the study area showed the largest cropland suitability for maize cultivation along the Sava river, most notably in the proximity of Sisak and Nova Gradiška (Figure 3). The maximum calculated MSI values of 3.9 resulted in these areas, with the slightly lower suitability values near the Drava river in the north and the south-western part of the study area in Vukovar-Srijem County. The suitability range covered 46% of the possible [1,5] number interval, which is a similar value compared with the previous cropland suitability analyses in the study area (Plaščak et al., 2019; Jurišić et al., 2020).

$$MSI = Tmin_{April} \cdot 0.057 + Tmean_{May} \cdot 0.057 + Tmean_{June} \cdot 0.091 + Tmean_{July} \cdot 0.136 + Tmean_{August} \cdot 0.057 + Tmean_{September} \cdot 0.057 + Precipitation_{May} \cdot 0.043 + Precipitation_{June} \cdot 0.074 + Precipitation_{July} \cdot 0.088 + Precipitation_{August} \cdot 0.043 + Soil\ Type \cdot 0.143 + Total\ Nitrogen \cdot 0.067 + Solar\ Irradiation \cdot 0.045 + Flow\ Accumulation \cdot 0.042$$

Standardized values of air temperature criteria generally resulted in value distribution close to normal, with a low count of very high suitability pixels (Figure 4). Tmean for September was an exception, as it dominantly covered very low and low suitability, with no pixels having values of 4 and 5. Precipitation criteria for May, July and August resulted in a value distribution over all five classes, while the same values for June had a skewed distribution over high and very high suitability classes. Therefore, Tmean in September and Precipitation in June should be additionally examined and possibly modified in additional iterations after their calibration using ground-truth data. All soil and topography criteria had standardized values over all five suitability classes. This process is increasingly important in the borderline areas for the cultivation of a particular crop type. Plaščak et al. (2019) noted a low variability of a terrain elevation for the calculation of hazel cultivation suitability, which also had an impact on the variability of total solar irradiation. This implies a necessity for the evaluation of multiple standardization methods for the calculation of cropland suitability, most notably linear scaling, stepwise standardization and fuzzy standardization (Radočaj et al., 2020).

The accuracy assessment of the obtained results can be performed with known vector data on agricultural plots on which maize was cultivated in the previous year

Table 3. Standardized values according to input value intervals per criterion

Criteria	Standardized values				
	1	2	3	4	5
Tmin (April)	< 3.75	3.75 – 4.5	4.5 – 5.25	5.25 – 6	6 >
Tmean (May)	< 14	14 – 15.5	15.5 – 16.5	16.5 – 18	18 >
Tmean (June)	< 17.5	17.5 – 18.5	18.5 – 19.5	19.5 – 21	21 >
Tmean (July and August)	< 19	19 – 20	20 – 21	21 – 22	22 >
Tmean (September)	< 17.5	17.5 – 18.5	18.5 – 19.5	19.5 – 21	21 >
Precipitation (May, June)	< 60	60 – 70, 110 >	70 – 80	95 – 110	80 – 95
Precipitation (July, August)	< 70	70 – 80	80 – 90	90 – 105	105 >
Soil Type	N2	N1	S3	S2	S1
Total Nitrogen	< 0.15	0.15 – 0.17	0.17 – 0.19	0.19 – 0.21	0.21 >
Solar Irradiation (April to September)	< 1100	1100 – 1175	1175 – 1200	1200 – 1225	1225 >
Flow Accumulation	< 2, 40 >	2 – 5	5 – 10	10 – 20	20 – 40

Table 4. Pairwise comparison matrix within the AHP method

	AT	PR	ST	TN	SI	FA	Weight
AT	1	3	4	7	7	8	0.455
PR	1/3	1	2	5	6	6	0.248
ST	1/4	1/2	1	3	3	4	0.143
TN	1/7	1/3	1/3	1	2	2	0.067
SI	1/7	1/3	1/3	1/2	1	1	0.045
FA	1/8	1/4	1/4	1/2	1	1	0.042
Σ	1.994	5.033	7.917	17.000	20.000	22.000	1.000

AT: Air temperatures, PR: Precipitation, ST: Soil type, TN: Total nitrogen, SI: Solar irradiation, FA: Flow accumulation

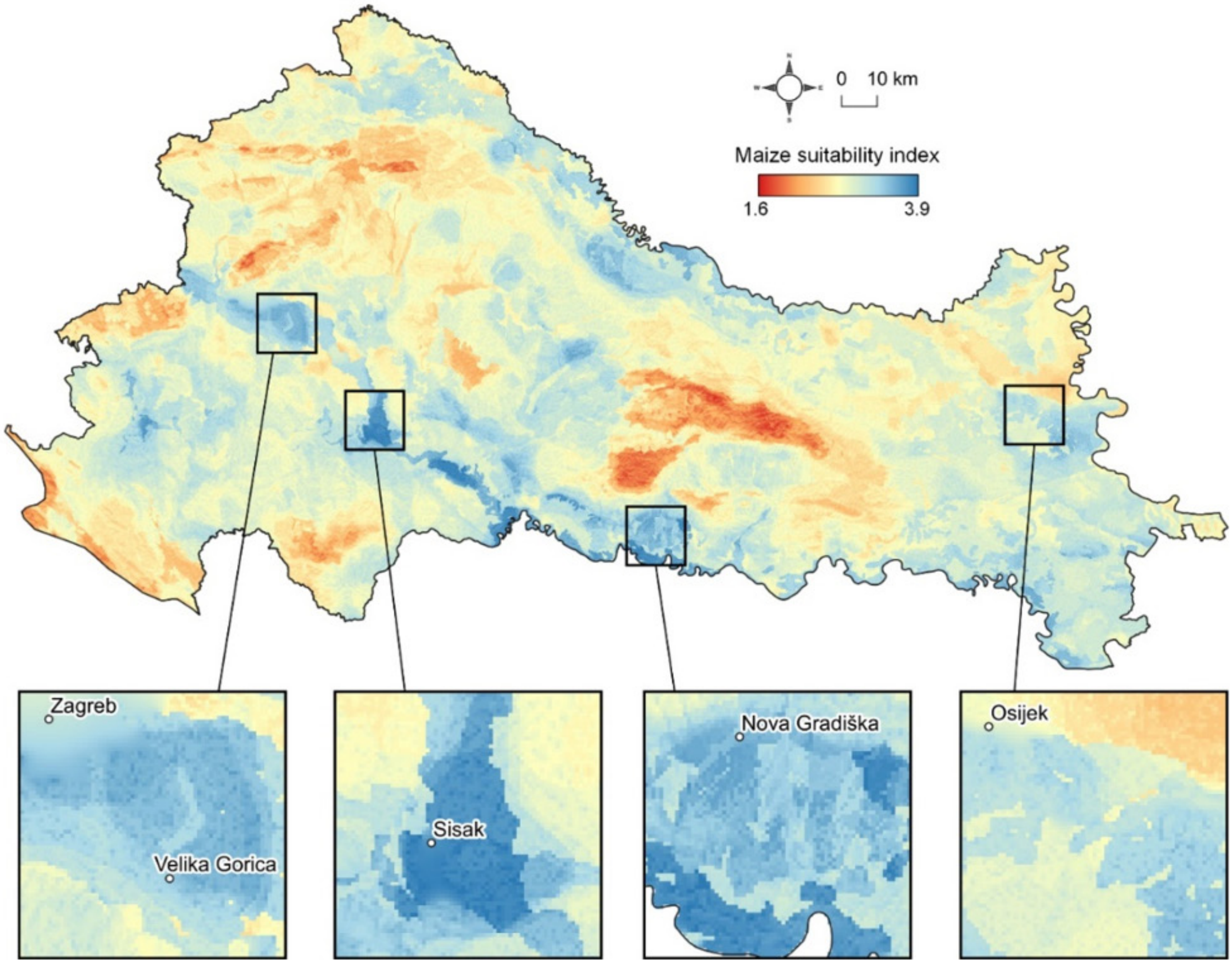

Figure 3. Cropland suitability map for maize cultivation in continental Croatia

Table 5. Determination of individual weights of monthly climate criteria

Criteria name	Month	Criteria weight	Relative impact (%)	Individual weight
Air temperatures	April		12.5	0.057
	May		12.5	0.057
	June		20.0	0.091
	July	0.455	30.0	0.136
	August		12.5	0.057
	September		12.5	0.057
Precipitation	May		17.5	0.043
	June		30.0	0.074
	July	0.248	35.0	0.088
	August			0.043

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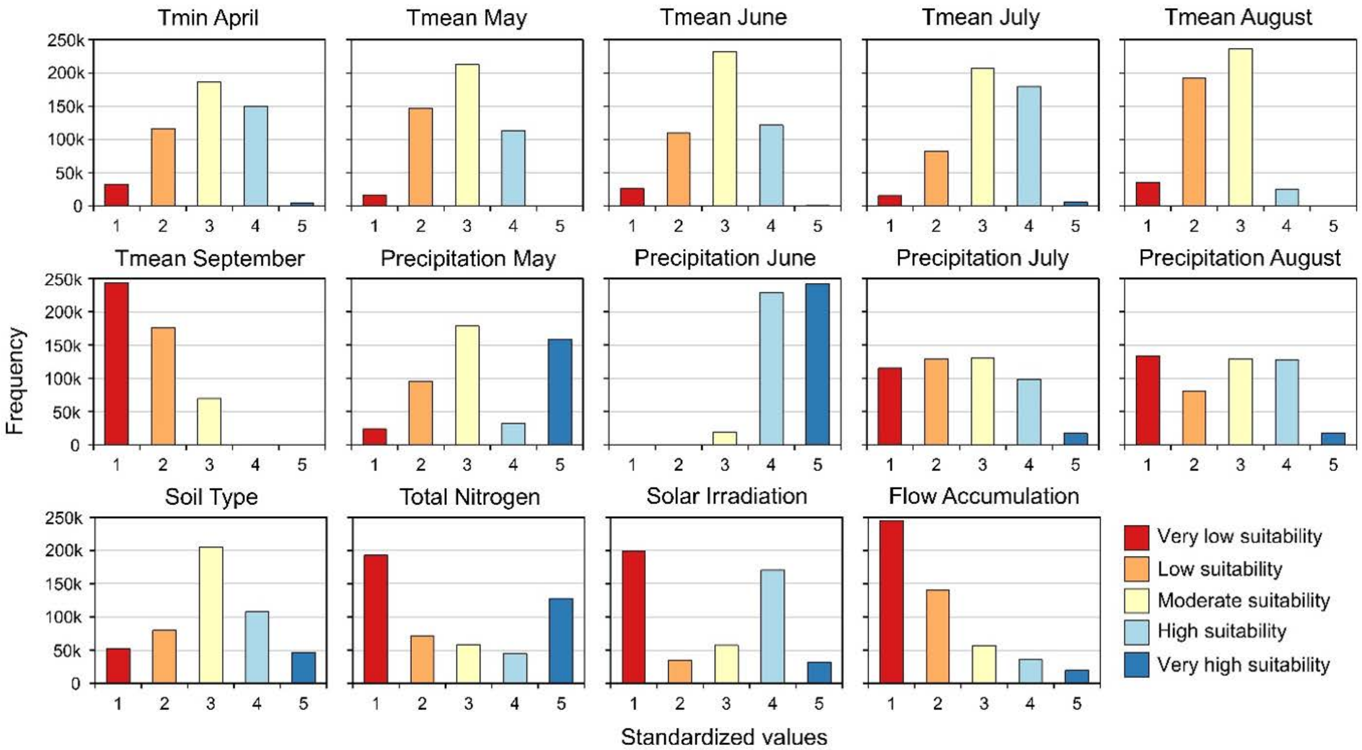

Figure 4. Sensitivity analysis of standardized values of criteria used in the analysis

(Šiljeg et al., 2020). The most important attributes in the process include yield, soil tillage, and fertilization data. By observing the correlation between the values of cropland suitability for maize cultivation from multicriteria analysis and the yield in the same area, it would be possible to express the quality and reliability of the used procedure and the obtained results (Dedeoğlu and Dengiz, 2019).

CONCLUSIONS

Cropland suitability results for maize cultivation using the GIS-based multicriteria analysis calculated in this survey were intended to aid in better agricultural land management in the study area. The application of free open-source GIS software and free spatial datasets allow the global accessibility to this methodology. This removes the cost-related obstacles in performing such analyses, making this methodology available to anyone with the required knowledge in the world. However, the calculation is based on macro-level conditions which include climate, soil, and topography criteria, without considering land cultivation, irrigation, fertilization, and crop protection systems on a micro-level, which is the current limitation of this method.

The area by the Sava river was detected as the most suitable area for maize cultivation in continental Croatia and could benefit from additional subsidies for farmers in terms of higher yield and crop quality. The applied multilevel procedure of determining criteria weights using AHP allowed pairwise comparison with the optimal criteria count. Consequentially, this prevented redundancy of criteria and the subjective inaccuracies during the pairwise comparison. Two criteria were detected as redundant during the sensitivity analysis, indicating that this procedure could lead to more reliable results in the future iterations of the suitability analysis.

The lack of reliable ground-truth data for the accuracy assessment still remains the main restriction of the GIS-based multicriteria analysis for cropland suitability calculation in continental Croatia. The available georeferenced yield data, as well as the sowing and fertilization information, should be more available with technological advancements in the future and could present a cornerstone of similar future studies.

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