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Agroecological assessment of maize suitability in the Polissia and Forest-Steppe of Ukraine under future climate projections

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Abstract. Climate change is profoundly altering the spatial structure of agricultural land use, particularly in regions such as Polissia and the Forest-Steppe of Ukraine. These areas, characterised by distinct climatic and edaphic conditions, are increasingly vulnerable to shifts in temperature, precipitation patterns, and the frequency of extreme weather events. This study presents a comprehensive spatial modelling approach to assess the historical and projected suitability of maize cultivation in these agroecological zones under four Shared Socioeconomic Pathways (SSP126, SSP245, SSP370, SSP585) across three time horizons (2021–2040, 2041–2060, and 2061–2080). Using a combination of 19 bioclimatic variables from the WorldClim and CMIP6 datasets and 9 soil predictors derived from SoilGrids, the analysis integrates historical yield data from the CROPGRIDS database to construct a multivariate linear regression model with Box-Cox transformation. The results indicate that in the historical period, maize distribution was primarily constrained by low winter temperatures, excessive annual precipitation, and high soil nitrogen levels, while optimal temperature and moisture conditions during the growing season significantly enhanced suitability. Soil compaction was found to be a critical limiting factor, underscoring the importance of soil physical properties for root development. Under future climate scenarios, short-term warming is projected to facilitate a northward expansion of suitable areas. However, in the medium and long term, a consistent reduction in the spatial extent of favourable zones is observed, particularly in the northern Polissia region. The SSP585 scenario, representing high emissions and rapid socioeconomic development, results in the most substantial decline in maize suitability, whereas SSP126 maintains relative stability in central Forest-Steppe areas. Analysis of variance (ANOVA) and non-parametric tests confirm that time (period) is the dominant driver of variability in projected maize areas, while SSP scenarios and their interaction play secondary roles. Delta maps of projected change relative to historical baselines reveal pronounced spatial and temporal heterogeneity. While early periods may exhibit local gains, especially under mild scenarios, losses increasingly dominate in subsequent decades, with more intense warming accelerating the contraction of suitable areas. The generated spatial maps and scenario-specific forecasts provide valuable insights for adaptive agricultural planning. These tools enable the identification of stable, transitional, and vulnerable zones and support the development of region-specific strategies such as adjusting crop rotations, investing in irrigation, and selecting climate-resilient varieties. The study highlights the need for integrated approaches that consider both climatic and edaphic variability in the context of global change. Future research should expand on these findings by incorporating socioeconomic variables, land use practices, and farmer-level adaptation strategies. Overall, this work establishes a scientific foundation for enhancing the climate resilience of maize production systems and informs evidence-based policy development for sustainable agriculture in Ukraine.

Keywords: crop suitability modelling; edaphic limitations; temperature–precipitation interactions; spatial regression; agroecological zoning; shared socioeconomic pathways; Eastern European agriculture; land-use adaptation.

Introduction

In the context of growing climate pressure on the agricultural sector, spatial forecasting of changes in crop yields is becoming particularly relevant (Zymaroieva et al., 2021). Concurrently, fluctuations in temperature, variations in precipitation levels and their distribution, an escalation in the frequency of extreme weather events, soil depletion, and diminished availability of water resources are engendering novel constraints on agricultural production (Vogel et al., 2016). The development of spatial models is imperative in order to capture the regional specifics of natural conditions and predict possible scenarios of agricultural landscape transformation, in order to respond to these challenges effectively (Gustafson & Parker, 1992). Such models are based on a combination of data on climate change, soil characteristics, topography, and land use patterns, which allows the assessment of the current potential of regions and the prediction of the dynamics of their changes (Zymaroieva & Zhukov, 2020). A critical component is socioeconomic development scenarios that consider future levels of greenhouse gas emissions, urbanisation rates, demographic shifts, and land use practices (Riahi et al., 2017). Integrating such scenarios with geospatial modelling opens up opportunities to identify areas with increased potential for adaptation to new conditions and areas where it is advisable to introduce alternative crops or adaptive technologies. Spatial yield forecasting is emerging as a pivotal instrument in the realm of agricultural planning, facilitating early risk assessment, optimisation of crop structure, enhancement of resource efficiency, and preservation of agroecosystem stability. This approach provides a scientific basis for developing a climate-oriented agricultural policy and implementing sustainable agricultural models in the face of global change (Kabir et al., 2024).

Maize is a leading crop due to its combination of agro-environmental, nutritional and economic benefits, making it a key element of sustainable agriculture (Fiorini et al., 2020). As a source of high-quality vegetable protein, maize provides a critical part of the diet for people and livestock, which is especially important amid the global growth in demand for high-protein foods (Braimoh & Vlek, 2006). Due to its ability to absorb nutrients efficiently and produce high yields in a wide range of agro-climatic conditions, this crop is strategically vital for food security (Zymaroieva et al., 2019). Despite the absence of symbiotic fixation of atmospheric nitrogen (unlike legumes), maize is characterised by high fertiliser use efficiency, which leads to a lower need for mineral fertilisers and helps optimise agronomic practices. Furthermore, the residual biomass following harvesting has been shown to enrich the soil with organic matter, thereby improving its structure and increasing biological activity (Ambrosio et al., 2017). This makes maize an essential component of crop rotations, providing high economic returns, and creating favourable conditions for subsequent crops. Maize also exhibits relatively high plasticity to climatic conditions, demonstrating the ability to adapt to dry periods (Zhang et al., 2023). This is particularly relevant for regions with risky farming, such as Southeast Europe. In the context of climate change, its potential is growing as it can now be cultivated in previously marginal areas, making it a promising crop for adaptation and climate risk mitigation strategies (Markos et al., 2023). Within the socioeconomic framework, the cultivation of maize has been demonstrated to facilitate the development of local agricultural enterprises, promote diversification of agricultural production, and enhance autonomy in relation to imported feed sources. Maize is a highly technologically suitable crop for processing, and as such, it plays a significant role in the production of bioenergy, bioethanol, starch, and other industrial products (Zymaroieva, 2019). Given the growing demand for organic and environmentally friendly products, maize is gaining importance as a crop that combines environmental sustainability with high productivity. Maize is not only a highly productive crop, but also an essential element of ecosystem services, the adaptive potential of agricultural systems, and a tool for strengthening the climate resilience of agriculture. Its agronomic versatility, economic feasibility, and environmental significance form the basis for further integration of this crop into adaptive scenarios for the development of the agricultural sector (Xu et al., 2024).

Maize cultivation depends on various environmental factors, primarily climate and soil conditions, that determine its adaptive potential in a particular region (Allakonon & Akponikpè, 2022). This crop is susceptible to the environment, which results in strict requirements for temperature, moisture, and physical and chemical properties of the soil (Riffaldi et al., 1994). One of the main climatic constraints is low temperatures in winter, especially the minimum values in the coldest month of the year, which form the northern limit of maize distribution and can cause damage to plants in the early stages of growth. An excessive increase in temperature during flowering and grain formation can cause sterility of flowers, reduced fertilisation and, as a result, reduced yields (Kettler et al., 2022). The soil water regime is equally critical: in the early stages of growth, maize has an increased need for moisture, but is sensitive to water stagnation and waterlogging, which provoke the development of root pathogens. The level of precipitation in the wettest quarter of the year plays a special role, as does the supply of moisture during the growing season, when productive organs are formed. Soil parameters, including structure, acidity, humus and nitrogen content, and density, significantly impact the growth, development, and productivity of maize (Garello et al., 2023). Deep, well-aerated loamy soils with a neutral or slightly acidic reaction, high fertility, and drainage properties are considered the most favourable. Compaction of the soil profile, excessive acidity or salinity significantly impair plants' physiological processes, reduce nutrient absorption efficiency, and create stressful conditions for crop development (Vanhees et al., 2021). The combined effects of these factors result in the formation of an agroecological niche conducive to the sustainable cultivation of maize. In view of the fact that climate change is a phenomenon that is not going to cease any time soon, even minor shifts in temperature or hydrothermal conditions may significantly affect the spatial potential of this crop. It is therefore essential that traditional farming areas are reviewed and that agricultural technologies are adapted to new conditions.

Maize is considered a pivotal crop in the context of contemporary agriculture, a position attributable to a combination of factors. Primarily, it is distinguished by its capacity to yield substantial quantities, a quality that is widely acknowledged. Additionally, it is recognised for its high nutritional value, a trait that is particularly salient in food production. Another considerable attribute of maize is its capacity to adapt to diverse agro-climatic conditions, a quality that enhances its resilience and utility in agricultural systems (Klopfenstein et al., 2013). It provides a significant share of vegetable protein and energy in human nutrition and is a fundamental element of the feed base for livestock. Its well-developed root system facilitates efficient water and nutrient absorption, which ensures relative resistance to drought and efficiency in using soil resources. Maize is well integrated into crop rotations, enriching the agricultural system with crop residues that contribute to improved soil structure and increased organic matter content (Zong et al., 2024). The high cover index also reduces the risk of erosion, preserves soil moisture and improves the microclimate of the field. Combined with the flexibility of technological approaches, maize is a valuable crop in times of climate instability (Zhang et al., 2022). In the socioeconomic context, maize contributes to food security, diversification of agricultural production, and support for small farmers. Its growing role in ensuring the stability of agroecosystems and food systems underscores the strategic importance of the crop in the face of climate change (Tanumihardjo et al., 2020).

Climate change is significantly altering the spatial structure of agricultural land use, putting forward new requirements for adapting agrarian systems to environmental change (Donmez et al., 2024). In view of the indisputable evidence for rising average annual temperatures, shifting seasonality of precipitation, and increasing frequency of climate extremes, it is imperative to analyse the responses of crops to these challenges (Harrison et al., 2011). Maize is of pivotal significance in the context of ensuring productivity, sustainability, and ecological balance within agricultural systems, considering its status as a staple crop in the global agricultural context. Its agro-ecological efficiency is determined by high yields, adaptability to different soil types, and the ability to form a deep root system that ensures efficient use of moisture. Maize remains sensitive to changes in thermal conditions and humidity, especially during critical phases of development (Wu et al., 2024). The spatial specifics of growing this crop, both in retrospect and under forecast scenarios, remain insufficiently studied in the regional context, particularly within the Polissia and Forest-Steppe regions of Ukraine, which are zones with different climatic conditions, soil characteristics, and risk of degradation processes (Zymaroieva et al., 2021). Existing assessments often do not consider regional spatial specificity and variability of environmental constraints in the context of future climate scenarios. In this regard, the study aims to spatially model territories' historical and projected suitability for maize cultivation based on bioclimatic and soil factors, considering different climate change trajectories according to global socioeconomic scenarios. This approach makes it possible to identify the leading environmental determinants of crop productivity, assess the spatial and temporal dynamics of changes in suitable areas, and form a scientifically sound basis for adaptive agricultural planning under conditions of climate uncertainty.

The study aims to spatially model the suitability of the Polissia and Forest-Steppe areas of Ukraine for maize cultivation in the historical period and under the conditions of projected climate change, taking into account bioclimatic and soil factors and by different scenarios of global socioeconomic change (Shared Socioeconomic Pathways, SSP). The study aims to identify the key environmental determinants that determine the agroecological efficiency of maize, analyse the spatial and temporal dynamics of changes in suitable areas, and form a scientific basis for adaptive agricultural planning in the face of climate change.

Materials and methods

The historical values of maize harvested areas were obtained from the global CROPGRIDS v1.08 dataset (Tang et al., 2024), which provides a spatially consistent yield map for 173 crops as of 2020 at a resolution of 0.05°. This set is built by hybridising a previous MRF study (Monfreda et al., 2008), integrating the latest satellite and statistical sources (including FAOSTAT), and ranking them according to quality criteria for each country and crop. Nineteen bioclimatic variables (BIO1–BIO19) were employed in the yield modelling to account for climatic conditions. These variables were derived from the WorldClim v2.1 dataset, which has a spatial resolution of 2.5 minutes of arc (~5 km). The variables under consideration are derived from monthly temperature and precipitation values, and characterise annual averages, seasonality, and extreme conditions that are ecologically important for crop growth. Following the completion of the download process, the bioclimatic rasters were subjected to a cropping procedure to conform to the topographical features of the study area. Subsequently, they were masked to align with the delineated boundaries of agricultural land. Then, they were aligned with the yield layer using bilinear interpolation and resampled to match the spatial resolution. To characterise soil conditions affecting crop productivity, nine soil predictors were used, obtained from the global SoilGrids dataset (via the soil_world function), for the soil layer at a 5–15 cm depth. The following list comprises the variables that were included in the study: bulk density of soil (bdod), coarse particle content (cfvo), clay content (clay), total nitrogen (nitrogen), calculated organic carbon (ocd), acidity (phh2o), and proportions of sand (sand), silt (silt), and organic carbon (soc).

Each variable was subjected to a series of processing steps. Initially, each variable was cropped to correspond with the contour of the study area. Following this, the variables were masked. Then, the variables were brought to a single yield layer coordinate system using bilinear interpolation. Finally, the variables were resampled to a common spatial resolution. The data about the OCS variable (organic carbon in stocks) was not utilised to avoid the potential for excessive collinearity with other indicators of organic matter. The amalgamation of all historical variables utilised as input predictors for the yield modelling resulted in a singular raster layer stack. This included the maize harvest area mask, 19 bioclimatic variables (Bio1–Bio19), and the nine soil variables described in the previous subsections. Before the amalgamation of the layers, a meticulous examination was conducted to ascertain the congruence of the coordinate projection (CRS), the spatial extent, and the resolution of all constituent layers. This rigorous procedure was undertaken to ensure the validity and integrity of the subsequent analysis. This approach enabled us to avoid spatial inconsistencies and ensure all variables in space were aligned with pixel-by-pixel precision.

To prevent multicollinearity among a multitude of bioclimatic variables and to avoid the dimensionality of the climate space, principal components analysis (PCA) was executed based on standardised values of the BIO1–BIO19 variables. For analysis purposes, only those pixels with finite values for all variables were considered, and only those with variance greater than zero were included in the analysis. Four principal components with eigenvalues (λ) > one were selected for further study according to the Kaiser criterion. From each element, the variable with the most significant contribution to the load was identified and used as an independent climate predictor (primary_vars). To eliminate the collinearity of other bioclimatic variables with these key predictors, regression residuals were calculated for each relative to primary_vars. The residual variables (indexed by _resid) retained unique information uncorrelated with the principal components and were incorporated into the model as orthogonalised climate predictors.

After the orthogonalisation of the climate variables, a subset of pixels was formed for which all the necessary data were available (idx indices). The corresponding values of soil variables were extracted from the soil_hist layer for these pixels. To prepare the final predictor matrix for building the yield model, the following data were combined: harvested area as a response variable, selected key bioclimatic variables (primary climatic variables), regression residuals for other climatic predictors (orthogonalised variables), and the complete set of soil variables. The resultant table, predictor_df, comprises a series of rows corresponding to individual pixels within the designated study area, with the columns representing the various predictors employed in the statistical modelling process.

Given the positively skewed distribution of the response variable (harvested area) and its zero values, a Box-Cox transformation was implemented before modelling to stabilise the variance and approach a normal distribution. Initially, a minimal positive number, designated as ε, was added to all values. This number was calculated as half of the minimum positive value of harvested area. This ensured the correctness of the logarithmic transformation if the parameter λ approaches zero. The optimal value of the parameter λ for the Box-Cox transformation was determined by maximising log-likelihood within the interval [-2, 2]. Depending on its value, either a power or a logarithmic transformation was used. A multivariate linear model was constructed based on the transformed response variable (harv_bc) and the matrix of predictors (primary_vars, orthogonalised bioclimatic variables, and soil indicators). The estimation of the model indicated significant relationships between environmental conditions and the spatial distribution of maize yields in the baseline period.

A hierarchical clustering method was implemented to mitigate the impact of multicollinearity among predictors, with the correlation structure of variables being utilised as the basis for this process (Kayode Ayinde & Nwosu, 2021). In the initial phase of the study, the standardisation of all predictors was conducted utilising the formula: z = (x – mean(x)). The data were reduced to a dimensionless scale with a mean of 0 and a standard deviation of 1, i.e. / sd(x). Subsequently, a matrix of pairwise correlations among all variables (except the response variable) was constructed using the Pearson's coefficient. The symmetric distance between the variables was calculated using the following matrix: 1 - |r|, where r denotes the absolute value of the correlation. The resulting distance matrix was then utilised for hierarchical clustering of variables, employing the average linkage method. The number of clusters was determined empirically (e.g., k = 12), considering the dendrogram structure. In the study context, a single variable was selected from each cluster. This selection was based on the premise that the variable in question exhibited the lowest average correlation with other variables within the cluster. This formed a set of representative predictors included in the final linear regression model. This approach was adopted to minimise the information overlap between variables and thereby reduce the risk of unstable estimates of regression coefficients, a characteristic of excessive multicollinearity.

The projected climate data from the CMIP6 (CNRM-CM6-1 model) for four socioeconomic scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) were utilised to estimate spatial changes in yields in the future period 2061–2080 (Riahi et al., 2017). The climate variables (bioclimatic predictors bio1-bio19) were retrieved from the CMIP6 global database at 2.5 min resolution and adjusted to the projection, resolution, and spatial resolution of the historical farmland mask using the project() and resample() methods with bilinear interpolation. The soil parameters were assumed to remain constant over time; therefore, the values from the historical dataset (soil_hist) were incorporated into the forecast stack. The residuals were calculated by regressing additional climate variables (other_clim) on the main set of predictors (primary_vars) to reduce multicollinearity among bioclimatic variables. In conjunction with the primary bioclimatic and soil predictors, the resulting residuals were amalgamated into the predictors_fut matrix. For each combination of SSP × time interval (2021–2040, 2041–2060, 2061–2080), yields were predicted using a previously developed linear regression model that incorporated the Box-Cox transformation. The estimated parameter λ was used to perform the inverse transformation. Negative values that could arise due to numerical errors were replaced with zero. The creation of spatial raster maps of the predicted yield (harvarea_ssp*_*.tif) and delta maps of yield changes relative to the historical period (delta_ssp*_*.tif) was based on the predicted values. A two-colour blue-white-red scale centred on zero was utilised to visualise the gradients of changes. The values of the expected yields and their differences were also added to the final xy_df dataframe with geographic pixel coordinates for further analysis and mapping products.

Results

Within the Ukraine's Polissia and Forest–Steppe regions, the spatial distribution of maize share among crops in the historical period was determined according to the synergistic influence of several bioclimatic and soil factors (N = 11,803; R_{adj}^2 = 0.55). According to the results of a linear regression with a Box–Cox–transformed dependent variable and after eliminating multicollinearity of predictors, it was found that the most substantial adverse effect was the average temperature of the coldest month (bio11; β = –0.38 ± 0.01; t = –47.95; P < 0.001), indicating a decrease in the share of maize in mild winters (Table 1).

Table 1
Results of the linear regression of the dependent variable (Box-Cox transformed yield) on the selected predictors after removing grouped multicollinearity (N = 11,803; R_{adj}^2 = 0.55). The standardised regression coefficients (β) and standard errors (SE) are presented in the format β ± SE

Predictor	*β* ± SE	t	P–value
(Intercept)	0.02 ± 0.01	3.97	<0.001
Precipitation in the wettest quarter (bio18)	0.06 ± 0.01	9.46	<0.001
Average temperature of the coldest month (bio11)	–0.38 ± 0.01	–47.95	<0.001
Average daily temperature range (bio2)	0.05 ± 0.01	6.35	<0.001
Temperature of the wettest quarter (bio8)	0.16 ± 0.01	20.34	<0.001
Minimum temperature of the coldest month (bio6)	0.08 ± 0.01	11.97	<0.001
Temperature of the driest quarter (bio9)	0.01 ± 0.01	1.70	0.09
Annual precipitation (bio12)	–0.28 ± 0.01	–28.70	<0.001
Precipitation of the wettest month (bio13)	–0.01 ± 0.01	–1.49	0.14
Precipitation of the driest month (bio14)	0.10 ± 0.01	11.91	<0.001
Precipitation in the wettest quarter (bio16)	0.14 ± 0.01	18.18	<0.001
Soil density (bdod)	0.47 ± 0.01	47.28	<0.001
Total nitrogen content in the soil (nitrogen)	–0.16 ± 0.01	–20.40	<0.001

The same direction of influence was found for annual precipitation (bio12; β = –0.28 ± 0.01; t = –28.70; P < 0.001) and total soil nitrogen (nitrogen; β = –0.16 ± 0.01; t = –20.40; P < 0.001), which reflects the limiting role of excessive moisture and high soil nitrogen availability for the establishment of maize crops. Precipitation in the coldest quarter also had a negative impact (bio19; β = –0.01 ± 0.01; t = –1.49; P = 0.140), but this variable did not reach statistical significance. Among the bioclimatic factors with a positive effect on the specific area of maize were precipitation in the wettest quarter (bio16; β = 0.14 ± 0.01; t = 18.18; P < 0.001), temperature in the wettest quarter (bio8; β = 0.16 ± 0.01; t = 20.34; P < 0.001), and the average daily temperature range (bio2; β = 0.05 ± 0.01; t = 6.35; P < 0.001), which indicates the importance of sufficient water supply and thermal amplitude during the growing season. The effects of the minimum temperature of the coldest month (bio6; β = 0.08 ± 0.01; t =

11.97; $P < 0.001$) and precipitation of the driest quarter (bio14; $\beta = 0.10 \pm 0.01$; $t = 11.91$; $P < 0.001$) were less pronounced, but also positive. The temperature of the driest quarter (bio9; $\beta = 0.01 \pm 0.01$; $t = 1.70$; $P = 0.093$) also did not show a statistically significant effect. Among the soil indicators, soil density (bdod; $\beta = 0.47 \pm 0.02$; $t = 47.28$; $P < 0.001$) was the key negative factor, which underlines the preference of maize for soils with better water–air conditions, since high density radically affects its ability to develop the root system. In the historical context, the distribution of areas favourable for maize cultivation was determined by a combination of thermal limitations of the winter period, hydrothermal precipitation regimes and fundamental physical and chemical properties of soils, which together formed favourable or restrictive conditions for its cultivation.

The forecast of spatial variability of maize share within Polissia and Forest–Steppe of Ukraine under different climate scenarios (SSP126, SSP245, SSP370, SSP585) and three time windows (2021–2040, 2041–2060, 2061–2080) shows a precise combination of stable geographical patterns and gradual changes with intensification of climate change (Fig. 1).

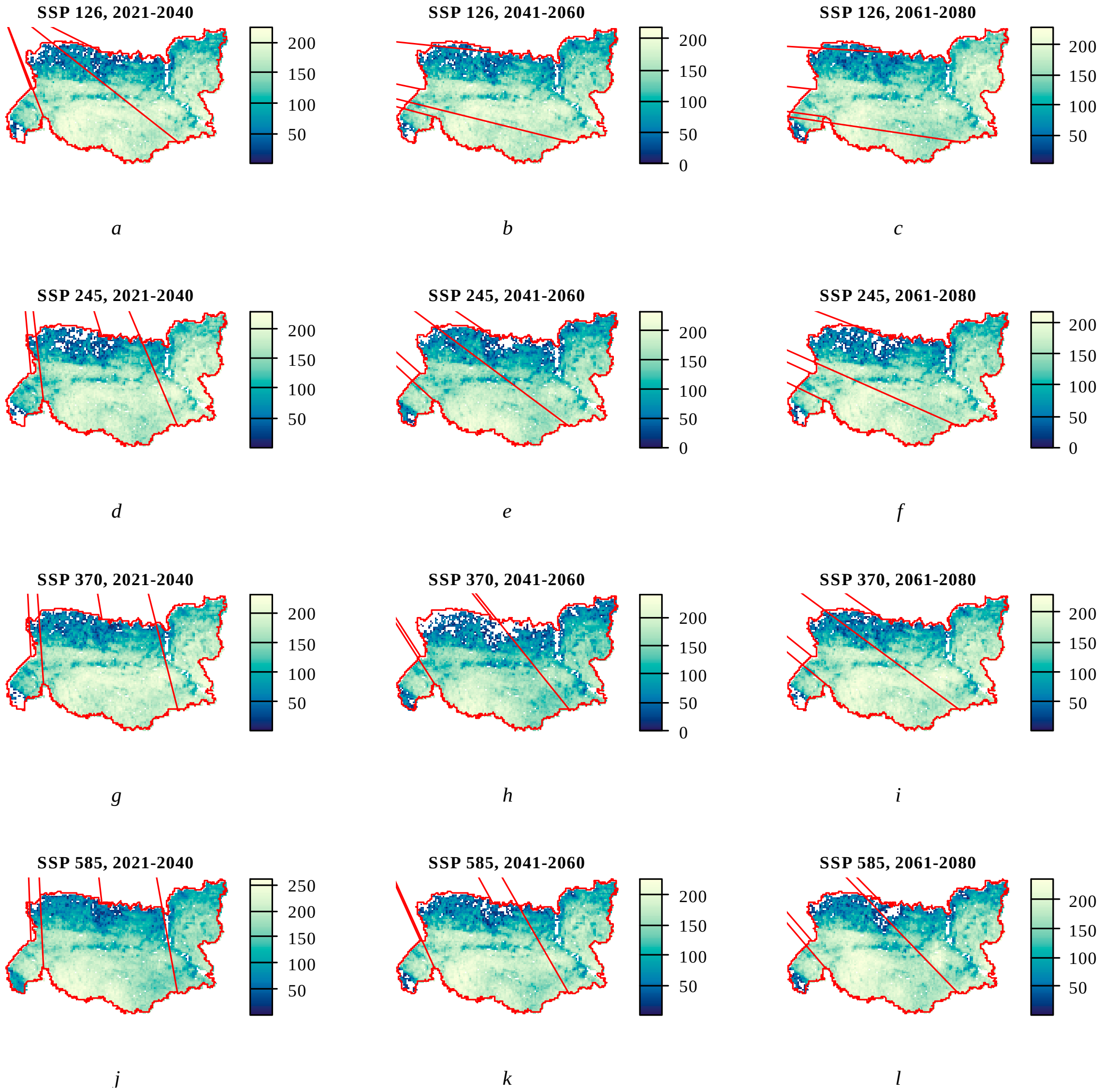

Fig. 1. Projected changes in the maize area under different scenarios of future societal development used for modelling climate change in combination with varying levels of SSP greenhouse gas impacts in 2021–2080: the maps show the spatial variability of the maize yields (in hectares per pixel) within the studied region of Ukraine for three time periods (2021–2040, 2041–2060, 2061–2080) and four socio-economic development scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5); these SSP scenarios represent distinct trajectories of societal development combined with differing levels of greenhouse gas emissions, reflecting potential outcomes of climate change impacts on the crop production: *a* is the SSP1–2.6 scenario for 2021–2040; *b* is the SSP1–2.6 scenario for 2041–2060; *c* is the SSP1–2.6 scenario for 2061–2080; *d* is the SSP2–4.5 scenario for 2021–2040; *e* is the SSP2–4.5 scenario for 2041–2060; *f* is the SSP2–4.5 scenario for 2061–2080; *g* is the SSP3–7.0 scenario for 2021–2040; *h* is the SSP3–7.0 scenario for 2041–2060; *i* is the SSP3–7.0 scenario for 2061–2080; *j* is the SSP5–8.5 scenario for 2021–2040; *k* is the SSP5–8.5 scenario for 2041–2060; *l* is the SSP5–8.5 scenario for 2061–2080

In all the scenarios, the spatial distribution retains maximum values in the central and southeastern regions of the Forest–Steppe and minimum values in the northern part of Polissia. Under the SSP126 scenario (minimal climate change), the overall picture is almost unchanged throughout the projection period. However, there is a slight decrease in the intensity of the Box–Cox–transformed share of maize: from a maximum of ≈ 224 in the first window to ≈ 217 in the middle and ≈ 228 in the late window (sharp fluctuations are explained by the specifics of the Box–Cox transformation of threshold values). In the SSP245 scenario, which assumes a moderate increase in emissions, a noticeable decrease in spatial contrast is recorded already in the middle window (2041–2060): the maximum values fall from ≈ 229 in 2021–2040 to ≈ 218 in the last window, and the boundaries of the "high suitability" zones are shrinking to the central regions of the Forest–Steppe. The SSP370 scenario is characterised by a peak in transformed values in the first window (max ≈ 230), followed by a decrease to ≈ 228 in 2061–2080. At the same time, the map becomes more fragmented: clear zones of decline extend to the northern regions of Polissia, indicating an increase in water stress in the conditions of the north with elevated temperatures. The most significant spatial changes are observed in the SSP585 scenario: the maximum Box–Cox values in 2021–2040 reach ≈ 262, after which they gradually decrease to ≈ 227 (2041–2060) and ≈ 236 (2061–2080). The maps demonstrate the growing dominance of low-value areas, especially in the northern and central Polissia and southern Forest–Steppe regions. Under all the scenarios, the primary geographic hotspots for maize production in the central forest and steppe regions are maintained. At the same time, the northern Polissia region appears to be the most vulnerable to climate change. The most stable conditions are projected to have the lowest human impact on climate (SSP126), and the most significant reduction in maize area is projected in scenarios with higher intensity of change (SSP370, SSP585).

The delta maps of the projected change in the Box–Cox–transformed share of maize area relative to the historical background show a distinct spatial and temporal heterogeneity depending on climate scenarios and time intervals. In the mildest SSP126 scenario, the short–term window of 2021–2040 is characterised by local gains of up to ≈+178 Box–Cox units, but already in the middle period (2041–2060) negative deviations prevail (minimum ≈–158; maximum ≈+163), and by the end of the century (2061–2080) losses are concentrated mainly in the northern and north-eastern regions with a minimum of about –120 and isolated local maximums of ≈+182 (Fig. 2).

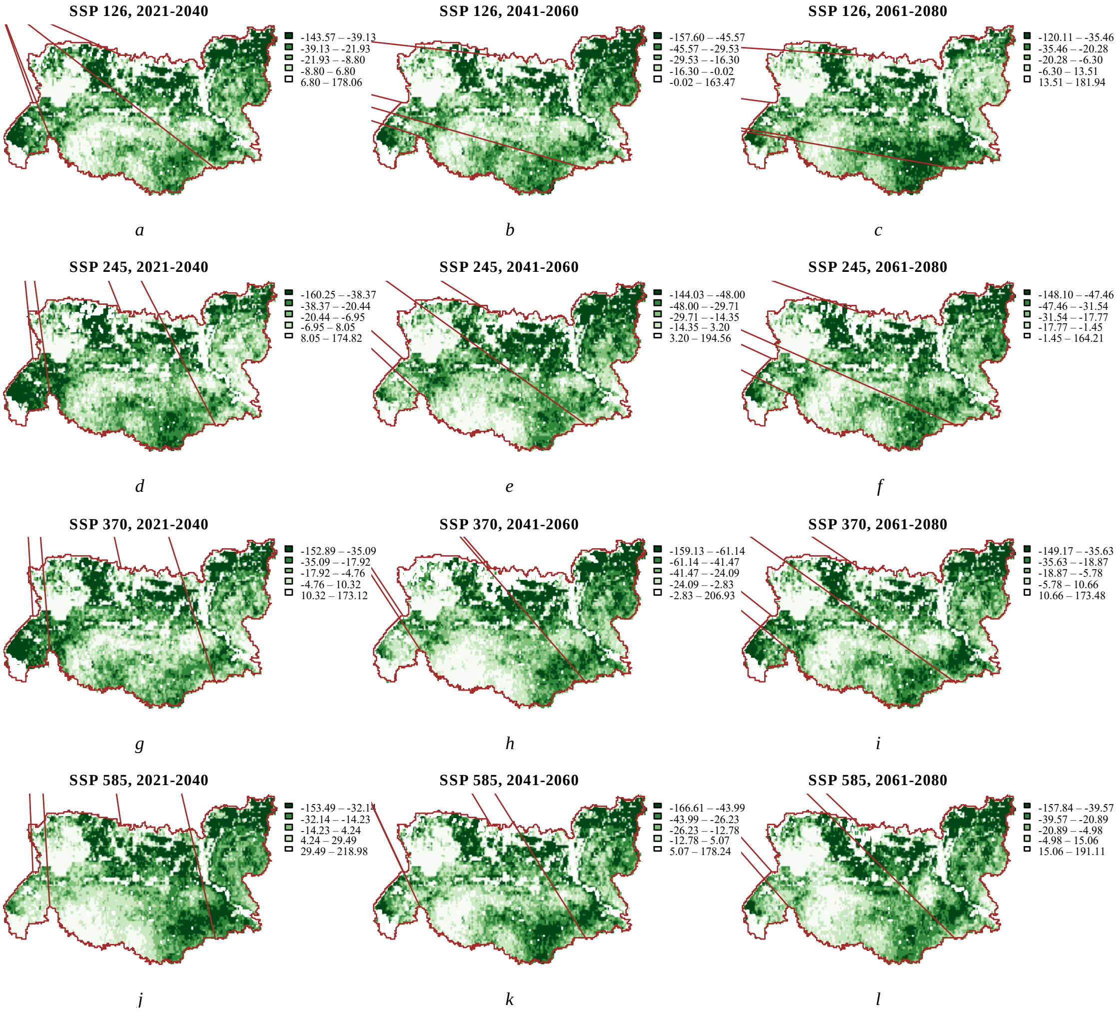

Fig. 2. Projected changes in the maize area compared with the historical levels (delta) under different SSP scenarios during 2021–2080: values reflect the difference between projected and baseline areas; positive values (lighter shades) indicate an area expansion, while negative values (darker shades) indicate a reduction; the boundaries of the study region are marked in red; these SSP scenarios represent distinct trajectories of societal development combined with differing levels of greenhouse gas emissions, reflecting potential outcomes of climate change impacts on the crop production: *a* is the SSP1–2.6 scenario for 2021–2040; *b* is the SSP1–2.6 scenario for 2041–2060; *c* is the SSP1–2.6 scenario for 2061–2080; *d* is the SSP2–4.5 scenario for 2021–2040; *e* is the SSP2–4.5 scenario for 2041–2060; *f* is the SSP2–4.5 scenario for 2061–2080; *g* is the SSP3–7.0 scenario for 2021–2040; *h* is the SSP3–7.0 scenario for 2041–2060; *i* is the SSP3–7.0 scenario for 2061–2080; *j* is the SSP5–8.5 scenario for 2021–2040; *k* is the SSP5–8.5 scenario for 2041–2060; *l* is the SSP5–8.5 scenario for 2061–2080

The SSP245 scenario in the early window also shows increases (up to ≈+175) along with significant subsidence (up to ≈–160), but in the middle window, the positive zones almost disappear, and in 2061–2080, the deltas remain negative in Polissia (minimum ≈– –148; maximum ≈+164). Under the SSP370 medium–intensity change scenario, local growth peaks in 2021–2040 (max ≈+173; min ≈–153), after which spatial losses increase (2041–2060: min ≈–159; max ≈+207) and by the end of the century cover almost the entire northern strip (2061–2080: min ≈–149; max ≈+173). The deepest negative deltas are characteristic of SSP585: although in 2021–2040 there are still local increases of up to ≈+219, in the middle window the growth zones practically disappear (min ≈–167; max ≈+178), and in 2061–2080 the losses are widespread (min ≈–158; max ≈+191). Thus, regardless of the scenario, favourable growth in maize area is possible only in the short term and locally. By contrast, negative deltas dominate in the medium and long term, increasing with climate change, which highlights the crop's high sensitivity to future conditions and the need for adaptive measures, especially in the northern regions of Polissia.

The forecast of the temporal dynamics of the area under maize indicates an apparent decrease in its share in the agricultural landscape of Polissia and the Forest-Steppe of Ukraine during the 21st century under all four climate scenarios (SSP126, SSP245, SSP370, SSP585, Table 2). The scatterplots (Fig. 3) clearly show that each scenario's median Box-Cox-transformed share of the occupied area decreases from the historical period to 2021–2040, and declines even further in 2041–2060 and 2061–2080. The smallest decline is seen in the mildest scenario, SSP126, while the medium and high intensification scenarios (SSP370, SSP585) show the sharpest declines, with significant downward shifts in the medians already in the second and third periods. The period 2021–2040 is characterised by only moderate deviations or even partial preservation of the level of historical areas, while in 2041–2060 and 2061–2080, negative changes dominate.

The non-parametric Kruskal-Wallis test and Dunn's post-hoc analysis confirm that the differences among all time windows within each SSP scenario are statistically significant ($P < 0.001$; groups are distinguished by letters above the boxes, Fig. 3). The analysis of variance (ANOVA; Table 2) showed that the primary source of variation in the projected share of areas is the period factor ($\eta^2 = 0.30$), while the climate scenario also has a considerable but less significant effect ($\eta^2 = 0.07$). The interaction of SSP × period contributes to the overall variance ($\eta^2 = 0.05$), indicating that the speed and depth of the reduction in maize area slightly differ among the scenarios over time. In summary, the consistent results of the visual and statistical analyses indicate a steady downward trend in maize area in the second half of the century, with the most sensitive decrease under more severe climate change and a clear manifestation of temporal trends as a key driver of the process.

Table 2
Results of the analysis of variance (ANOVA) of the impact of socioeconomic development (SED) scenarios, periods and their interaction on the change in the projected share of agricultural land under maize cultivation (the degrees of freedom, sum of squares, mean squares, F-statistics, P-value, and the proportion of variance (η^2) explained by each source of variation are presented

Source of variation	Degrees of freedom	Sum of squares	Middle square	F-statistics	P-value	η^2 (proportion of variance)
SSP	4	2249140	562285	233.8	<0.001	0.006
Period	2	3089042	1544521	642.2	<0.001	0.008
SSP × Period	6	1253249	208875	86.8	<0.001	0.003
Remains	150137	361092660	2405	–	–	0.982

Discussion

The study of the spatial distribution of maize in Polissia and the Forest-Steppe of Ukraine in the historical period demonstrated that a combination of climatic and soil conditions determined its distribution. Among climatic factors, temperature exerted the most powerful influence during the growing season. Maize spread was favoured by the average temperature of the warmest quarter of the year, while the average temperature of the wettest quarter further increased the agroclimatic suitability of the areas in which maize was cultivated. By contrast, high annual precipitation and mild winters with high average temperatures in the coldest month significantly limited the share of maize crops. This is explained by the risk of stagnant soil moisture and reduced plant reproductive capacity during cold periods. Soil analysis demonstrated that the key negative factor was the increased content of total nitrogen. Maize requires symbiotic nitrogen fixation, which is decreased in nitrogen-saturated soils. This may reduce its competitiveness in the crop structure. Higher soil profile densities have been observed to minimise water permeability and aeration, which hinders root development and limits the crop's distribution. The historical spatial distribution of maize is the result of a complex interplay between optimal temperature and moisture during the growth period, and the physical and chemical properties of soils that determine the availability of water and nutrients. These findings provide a solid basis for the development of adaptive maize cultivation strategies that consider average climatic conditions and local soil characteristics.

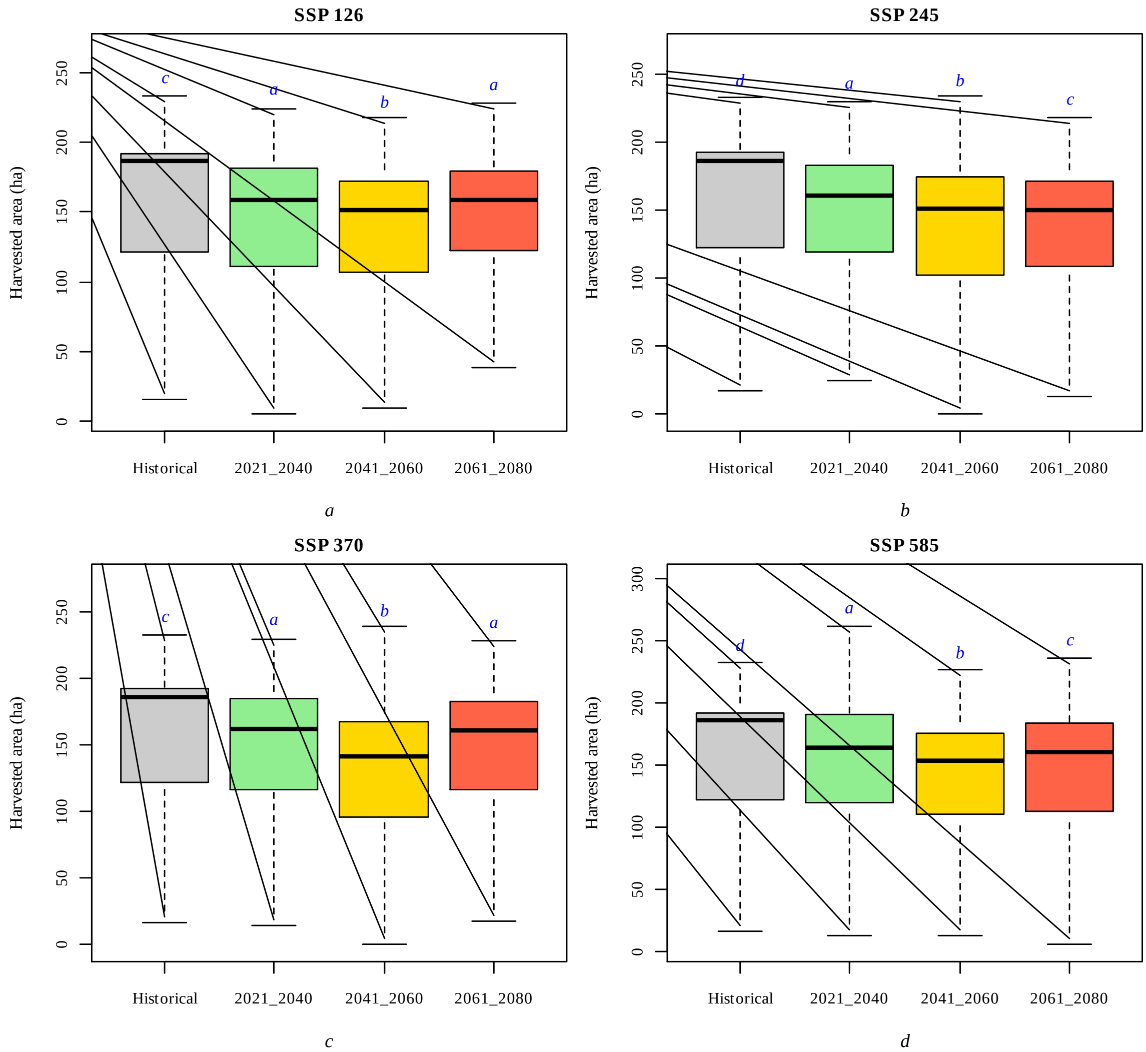

Fig. 3. Scatterplots of the harvested area (ha) under four SSP scenarios (SSP126, SSP245, SSP370, SSP585) in different periods: historical period (baseline), 2021–2040, 2041–2060, and 2061–2080; different letters above the boxes indicate statistically significant differences between periods within each SSP according to Dunn's test (with Bonferroni correction, $P < 0.05$); the central line indicates the median, the box, the interquartile range, the whiskers, and the limits of the 1.5 interquartile range; the central line indicates the median; the box represents the interquartile range; whiskers extend to 1.5 times the interquartile range: *a* is the SSP1–2.6; *b* is the SSP2–4.5; *c* is the SSP3–7.0; *d* is the SSP5–8.5

The research indicates that the projected climate change under the Shared Socioeconomic Pathways scenarios will significantly transform the spatial distribution of favourable conditions for maize cultivation in Polissia and the Forest-Steppe of Ukraine. In the short term, until 2040, rising average annual temperatures and a lengthier growing season will promote the expansion of suitable areas to the north, where previously cold conditions imposed limitations on the development of the crop. Concurrently, in the central and southern regions of the Forest-Steppe, heterogeneous dynamics are to be expected. Maintaining or slightly increasing favourable parameters is only possible under a moderate emissions growth scenario. Conversely, more intense scenarios will lead to the fragmentation of optimal agroclimatic zones even in the first period. In the medium term (2041–2060), the spatial expansion of the zones of suitability is replaced by a tendency towards their reduction. This is due to a gradual increase in the frequency of summer droughts and uneven seasonal distribution of precipitation, which lead to a loss of agroclimatic suitability in the western and northern regions. In the context of the moderate scenario, this decline does not yet reach a critical level.

The phenomenon is primarily concentrated in specific regions. Under the medium and high scenarios, there is an increase in the number of regions that demonstrate negative deviations from the historical background. In the long term, 2061–2080, the spatial contours of favourable conditions will remain clearly defined only in the central Forest-Steppe zone, while in Polissia, there will be a general decline in suitability, with almost complete disappearance of optimal sites in the northern regions. The magnitude of the decline grows with the severity of climate change, with the most profound negative changes observed under the intensive carbon emissions growth scenario. The spatial response to weather extremes appears uneven: short-term warming leads to a temporary recovery, but a deep decline in maize area prevails in the medium and long term. The SSP climate scenarios present a multifaceted depiction of the spatial transformation of agroclimatic conditions, wherein the shift in the northern boundaries of suitability is accompanied by the fragmentation and gradual contraction of optimal agro-soil zones.

The projected spatial distribution of areas suitable for maize cultivateon is subject to change over time. In the short term (2040), most scenarios demonstrate an expansion of the suitable areas in the north, owing to warming and a lengthier growing season. Conversely, in the medium term (2041–2060), and especially in the long term (2061–2080), these areas are projected to decrease. The second component is constituted by the climate scenarios themselves, which determine the depth and pace of these changes. The mildest scenario, involving low carbon emissions, maintains relative stability of agroclimatic conditions in the centre of the Forest-Steppe for a greater duration. Conversely, scenarios with increasing emissions lead to more pronounced fragmentation and loss of suitable areas, primarily in Polissia. Finally, their interaction demonstrates that spatial patterns respond to the combination of time and scenario unevenly: short-term warming under severe climate change may yield local benefits, but in the medium and long term, loss of the overall area occurs much faster under high scenarios, while under moderate scenarios, losses occur later and have a smaller spatial extent.

The study's practical outcomes are the detailed maps delineating the spatial distribution and projected changes in the areas conducive to maize cultivation in Polissia and the Forest-Steppe of Ukraine. These maps facilitate the identification of areas characterised by consistently favourable, conditionally stable, and risky agroclimatic characteristics. The resulting models facilitate the determination of optimal regions for expanding or reducing crop areas by agricultural producers and regional authorities. They also enable the adjustment of crop rotations to future climate scenarios and the selection of appropriate agricultural technologies (irrigation, mulching, and variety selection). The practical tools that are available for use include: The following four points are to be considered: firstly, maps of short-, medium- and long-term land suitability; secondly, an assessment of the sensitivity of individual sub-regions to climate fluctuations; thirdly, spatial recommendations for zonal placement of maize in the face of moderate and intense warming; and fourthly, analytical data for integration into decision support systems in the agricultural sector and the development of targeted state support programmes. The findings of this study provide a scientific foundation for the formulation of adaptive strategies for maize cultivation in a changing climate.

The potential for future research lies in the refinement of spatial suitability models, with the aim of incorporating the interactive effects of climate and soil factors, as well as socioeconomic determinants. These determinants include land use patterns, access to agricultural technologies, irrigation systems, and maize subsidy policies. Firstly, it is advisable to integrate spatial models of agroclimatic suitability with dynamic environmental and agronomic simulations to assess interannual yield variability, taking into account biotic factors (pests, diseases) and adaptation practices (sowing dates, seeding rates, tillage). Secondly, in order to comprehend how climate signals are translated into practical decisions by farmers, it is necessary to consider the socioeconomic determinants of land use, which include ownership structure, the availability of inputs such as irrigation and machinery, market incentives, and policy support programmes. Thirdly, it is imperative to develop a multi-scale approach, whereby regional results are matched to local fields and soil conditions, thus facilitating the development of targeted recommendations for individual communities and farms. The fourth step in this process is to experimentally validate the predictive mapping models through field trials with different maize varieties, including those with increased tolerance to drought and temperature extremes. Finally, the integration of climate scenarios with scenarios of changing socioeconomic conditions (e.g., investments in irrigation or the green transition) is anticipated to facilitate the modelling of joint trajectories of the agri-food sector. Such an integrated approach will provide a solid basis for adaptive planning and increased resilience of maize production in the face of an uncertain climate future.

Conclusion

The present study found that the spatial distribution of maize in the historical period in Polissia and the Forest-Steppe of Ukraine is determined by a combination of thermal and hydrothermal factors (temperature of the warmest and wettest quarters, annual precipitation) and soil properties (total nitrogen content and profile density). Projections of short-term warming indicate new suitable areas in the northern regions. Nevertheless, medium, and long-term climate scenarios consistently suggest a steady decline in the area suitable for maize cultivation, particularly in the northern regions of Polissia and the western parts of the Forest-Steppe. The predominant factor driving this change is the temporal element, with the intensity of climate change under the various scenarios serving merely to modulate the depth and speed of this process. Given the potential impacts of climate change, it is essential to develop strategies to ensure the sustainability of maize production. These strategies must take into account the heterogeneity of climatic conditions and soil characteristics on regional levels.

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