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Agro-ecological forecasting of rapeseed (*Brassica napus*) suitability in Ukraine under climate change scenarios

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Abstract. Climate change poses increasing challenges to agricultural sustainability, particularly for crops such as rapeseed that are sensitive to thermal and hydrological conditions. The present study provides a spatially explicit forecast of rapeseed agro-ecological suitability across Ukraine under different climate change scenarios (SSP1–2.6, SSP2–4.5, and SSP5–8.5) and time frames (2021–2040, 2041–2060, 2081–2100). The utilisation of machine learning-based regression models, calibrated with historical yield data and a suite of bioclimatic and edaphic predictors, enabled the development of high-resolution suitability maps and the estimation of potential shifts in favourable cultivation areas. The analysis indicated a progressive decline in stable high-suitability zones, particularly under pessimistic emission pathways. The analysis identified thermal conditions, particularly the minimum temperature of the coldest month and the mean temperature of the wettest quarter, as leading climatic constraints. Furthermore, excessive moisture or heat stress during sensitive growth phases was identified as a further limiting factor. The soil characteristics of drainage class, granulometric composition, and organic matter content provided more stable spatial reference points of rapeseed compliance. However, regional interactions with climatic factors significantly modified the local outcomes. The findings indicate that the future spatial distribution of rapeseed suitability will be shaped by a complex interplay between scenario severity and temporal scale, resulting in spatial fragmentation and heightened regional contrasts. It is predicted that areas currently well-suited for cultivation may become marginal or unsuitable by the end of the century, particularly in southern and eastern regions. Under the most severe scenario (SSP5–8.5), favourable zones exhibit a substantial contraction and a north-westward shift, thereby narrowing the ecological niche of rapeseed. Conversely, under SSP1–2.6, certain regions may maintain or even expand their suitability in the short term, although long-term stability remains questionable. A comparison with recent studies from other European and temperate regions confirms the broader applicability of these trends. Our findings are consistent with previous research indicating that the combined effect of warming trends and precipitation variability will lead to increased instability in crop performance, unless adaptive strategies are implemented. The spatial projections are also in close correspondence with observed historical shifts in cultivation patterns, thus providing further validation for the modelling approach. The novelty of this study lies in its combined use of spatial regression forecasting, climate scenario modelling, and agro-ecological zoning to deliver actionable insights for regional planning and crop adaptation. The proposed methodology integrates climatic gradients, soil heterogeneity, and temporal uncertainty, thereby enabling more robust decision-making under future climate conditions. The approach facilitates not only the identification of climate-resilient zones but also the quantification of long-term transformation trajectories, rendering it a valuable tool for policymakers, agronomists, and land-use planners. In view of the projected spatial instability and narrowing of optimal growing zones, the development of targeted adaptation strategies is imperative for sustaining rapeseed production in Ukraine under accelerating environmental change. Such strategies may include cultivar selection, modified sowing dates, water management, and crop diversification.

Keywords: climate change; spatial pattern; temporal dynamic; landscape; soil cover.

Introduction

Climate pressure is one of the most potent factors determining the functioning of the agricultural sector, affecting both crop productivity and the stability of production systems (Zymarioieva et al., 2022). Changes in the temperature regime, transformation of the seasonal rhythm, and an increase in the frequency of extreme weather events change the duration and sequence of vegetation phases, disrupt traditional agronomic cycles, and reduce natural resource use efficiency (Stefanovska et al., 2025). An increase in average temperatures can accelerate plant development, but at the same time shorten the period of biomass accumulation, which often leads to lower yields (Kunakh et al., 2022). Excessive heat during critical growth phases, especially during flowering and seed formation, causes stress reactions, which impede fertilisation and the formation of generative organs. In addition to temperature changes, increasingly uneven and unpredictable precipitation is becoming a significant risk to the sustainability of agricultural production. In regions where water availability is limited, droughts or prolonged dry spells can destroy crops and cause soil erosion, while intense but short-term precipitation can also have a nega-

tive impact on soil structure (Panagos et al., 2016). Changes in snow cover, fewer frosty days and shorter winter periods also significantly impact winter crops, changing the conditions for hardening, overwintering, and the start of the spring growing season (Schneider et al., 2013). Climate pressure also indirectly affects the agricultural economy through increased yield volatility, the need to upgrade technologies, and higher costs for irrigation, crop protection, and fertiliser application (Beringer et al., 2011). Climate change exacerbates regional inequalities in agricultural productivity, causing a shift in traditional crop growing areas, fragmentation of farming landscapes, and the need to adapt to new environmental conditions (Lesk et al., 2016). Climate pressures are transforming the agricultural sector's biophysical and socio-economic foundations, creating new challenges for food security, regional planning and agricultural sustainability in a global context (Bach et al., 2020).

Rapeseed (*Brassica napus* L.) is multifunctional in modern agricultural production, combining high economic value with agroecological feasibility (Jankowski et al., 2015). First and foremost, it is one of the leading oilseeds, providing vegetable oil for food and technical use, including biofuel production (Supit et al., 2010). Due to its high content of

fat and valuable proteins, rapeseed is in demand as a raw material for the feed industry, particularly in the form of rapeseed meal (Sojka et al., 1991). From an agronomic point of view, rapeseed is an essential element of crop rotation, especially in intensive farming systems (Ahmadi et al., 2025). It improves soil structure due to its developed root system, promotes biological loosening of the soil profile, and increases its aeration and water permeability. Rapeseed residues increase the soil's organic matter content, positively impacting agrochemical parameters and subsequent crops in the crop rotation (Yang et al., 2020). Rapeseed is also of phytosanitary importance, as it reduces the risk of soil damage from diseases common to cereals and interrupts the pest development cycle (Borzykh et al., 2024). Due to its high adaptability to different climatic conditions, rapeseed is a promising crop for expanding sown areas in the context of climate change (Jannat et al., 2022). Its winter forms can make effective use of winter and spring moisture, demonstrating higher productivity than their spring counterparts in moderate moisture conditions. However, the crop is sensitive to extreme weather events, such as droughts, early frosts or sharp temperature fluctuations, which can significantly reduce yields (Klatt et al., 2021). Rapeseed is both an indicator and a victim of climate variability, making it a key target for research on adapting agrosystems to global environmental change. Rapeseed is a strategic crop for food and energy security and an essential component of sustainable agriculture that combines productivity, ecological functionality and adaptive potential (Palmieri et al., 2014).

The distribution and level of favourable conditions for growing rapeseed are determined by several key environmental factors, dominated by climate and soil parameters (Svanes et al., 2020). One of the leading climate factors is temperature, particularly the average temperature of the coldest month, which directly affects the crop's ability to overwinter successfully (Li et al., 2022). Extremely severe winters can lead to the freezing of winter crops, while excessively mild winters disrupt the hardening process of plants and increase the risk of pathogens (Kornychuk & Yurchuk, 2023). The minimum temperature during the germination period and the intensity of spring warming, which determines the start of the growing season, are also critical. The amount and distribution of precipitation also play an essential role. Rapeseed is sensitive to both drought and excessive moisture (Li et al., 2022). Conditions with a uniform water supply during the growing season, particularly during the flowering and pod formation phases, are optimal. Excessive precipitation in some months can lead to diseases and deterioration of seed quality, while moisture deficit during the budding or seed filling phase significantly reduces yields (Bilibio et al., 2011). Other important climatic characteristics include temperature seasonality, daily fluctuations, the temperature of the wettest quarter, and the amount of precipitation during the driest periods. These indicators form the thermal and hydrological balance, which determines the intensity of growth, biomass accumulation, and the completion of crop ontogeny. Soil factors are equally important (Wang et al., 2025). Rapeseed requires well-drained, structurally stable soils with medium to high fertility. High soil density restricts root development, impairs aeration and retains moisture, negatively affecting productivity. Excessive levels of total nitrogen or organic matter can cause disproportionate vegetative growth, lodging, and an increased risk of fungal infections (Jin et al., 2019). The pH level is also essential: rapeseed grows better on slightly acidic or neutral soils (Vigovskis et al., 2016). Areas suitable for growing rapeseed are formed within territories that have an optimal combination of temperature, a uniform moisture supply, favourable soil characteristics, and an absence of stressful extremes. This ensures stable agro-ecological compliance for the crop (Königer et al., 2021).

In addition to its productive function, rapeseed cultivation significantly contributes to the maintenance of ecosystem services, including climate regulation, soil quality improvement, biodiversity preservation, and energy sustainability (Mohamed et al., 2025). Thanks to its deep and extensive root system, rapeseed effectively structures the soil, enhances its aeration and water permeability, and reduces the risks of surface runoff and erosion, which is particularly important for sloped and degraded areas (Ma et al., 2019). Post-harvest rapeseed residues have been demonstrated to contribute to the accumulation of organic matter, thereby forming a stable humus balance and activating soil biota (Yang et al., 2020). From an ecological perspective, rapeseed is a vital honey crop that supports pollinator populations during periods when the scarcity of flowering vegetation limits access to nectar and pollen. This is pivotal in preserving the functional diversity of pollinators, thereby ensuring the productivity of other crops (Budrys et al., 2025). Rapeseed can function as a component of phytosanitary management, as it has been observed to disrupt the

developmental cycles of certain soil-dwelling pests and pathogens, thereby reducing the necessity for chemical protection measures. In the context of climate change, the cultivation of rapeseed has the potential to contribute to the mitigation of greenhouse gas emissions, particularly if the crop is utilised for biofuel production (Flénet, 2012). The utilisation of rapeseed as a renewable energy source has been demonstrated to assist in the reduction of reliance on fossil fuels, thereby facilitating the development of more sustainable agro-energy systems. The expansion of the area under rapeseed as part of a scientifically based crop rotation contributes to an overall increase in ecosystem productivity and resilience of agricultural landscapes to environmental stresses (Amiri et al., 2019). In general terms, rapeseed represents a vital component of agricultural practices, providing sustenance and energy resources while fulfilling a variety of regulatory, supportive and service functions that are indispensable for maintaining ecological equilibrium within agricultural regions.

Climate change is significantly transforming the spatial structure of agricultural land use, causing both a redistribution of agrarian production zones and a change in the functional load on agricultural landscapes (Meusburger et al., 2012). Rising average annual temperatures, an increase in the frequency of extreme weather events, and a shift in the seasonal rhythm of vegetation are changing the suitability of areas for growing certain crops (Opdam & Wascher, 2004). In regions that have previously experienced limitations due to excessive humidity or short growing seasons, conditions may temporarily improve, encouraging the expansion of acreage. At the same time, traditionally productive areas may lose their agro-ecological potential due to increased heat stress, lack of moisture or increased risk of soil erosion (Moriando et al., 2011). These changes lead to a vertical and horizontal shift in crop boundaries, the emergence of new crops in previously unsuitable regions, and the withdrawal of some land from circulation due to a loss of agricultural production efficiency (Turker & Kok, 2013). There is also increased fragmentation of farm landscapes and mosaic land use, which complicates planning and increases the risk of localised production failures (Mantyka-Pringle et al., 2012). Climate change is also affecting the agricultural sector's infrastructure. There is a growing need for irrigation systems, land reservations for buffer or compensatory use, and differentiation of crop rotations depending on local conditions (Bailey et al., 2015). On a global scale, there is a trend towards a shift in intensive farming zones towards temperate latitudes, accompanied by a redistribution of capital, changes in rural employment, and the need to revise agro-policy priorities (Novakovska et al., 2025). Climate transformations are shaping a new configuration of the spatial organisation of agricultural land use, which requires adaptive management, integration of climate risks into agrarian planning, and introduction of flexible land use models (Fritz et al., 2010).

Despite the growing attention to climate-driven transformations of agricultural landscapes, the issue of predicting the impact of global climate change on the spatial dynamics of conditions favourable for rapeseed cultivation remains insufficiently studied, especially at the regional scale and considering different socio-economic scenarios. In this context, the study aims to quantify and map the current and projected zones of agro-ecological suitability for rapeseed in Ukraine, using integrated climate and soil predictors, and to analyse the impact of alternative climate change scenarios on the spatial and temporal sustainability of these zones in the short, medium, and long term.

Materials and methods

The historical values of rapeseed harvested areas were obtained from the global dataset CROPGRIDS v1.08 (Tang et al., 2024), which provides a spatially consistent yield map for 173 crops as of 2020 with 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. In order to account for climatic conditions, 19 bioclimatic variables (BIO1–BIO19) were used in the yield modelling. 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. After downloading, the bioclimatic rasters were subjected to a cropping operation along the contour of the study region. Subsequently, they were masked to align with the boundaries delineated for agricultural land. The data was then brought to the same coordinate system as the yield

layer using bilinear interpolation, and resampled to the exact spatial resolution. Nine soil predictors were utilised to characterise soil conditions that affect crop productivity, obtained from the global SoilGrids dataset (via the `soil_world` function) for the soil layer at a depth of 5–15 cm. The list of variables included in the study was as follows: 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. Thereafter, 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 OCS variable (organic carbon in stocks) was not utilised in order to circumvent excessive collinearity with other indicators of organic matter. The amalgamation of all historical variables utilised as input predictors for the yield modelling process resulted in the formation of a singular raster layer stack. This included the rapeseed harvest area mask, 19 bioclimatic variables (`bio1`–`bio19`) and the nine soil variables described in the previous sections. Prior to the amalgamation of layers, a comprehensive evaluation of the coordinate projection (CRS), spatial extent, and resolution of each layer was conducted to ensure the integrity of the subsequent analysis. This approach enabled us to circumvent spatial inconsistencies and ensure the alignment of all variables in space, achieving pixel-by-pixel precision.

Principal components analysis (PCA) was performed based on the standardised values of the `BIO1`–`BIO19` variables. This was done in order to avoid the problem of multicollinearity between numerous bioclimatic variables and to reduce the dimensionality of the climate space. For the purposes of the study, only those pixels with finite values for all variables were considered, and only those with variance greater than zero were used. In accordance with the Kaiser criterion, four principal components with eigenvalues (λ) > one were selected for further analysis. The element from which the variable with the most significant contribution to the load was identified was then used as an independent climate predictor (`primary_vars`). In order to eliminate the collinearity of other bioclimatic variables with these key predictors, regression residuals were calculated relative to `primary_vars`. The residual variables (indexed by `_resid`) retained unique information that was uncorrelated with the principal components and were incorporated into the model as orthogonalized climate predictors. Subsequent to 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 the soil variables were extracted from the `soil_hist` layer for these pixels. In order 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 soil variables. The resultant table, `predictor_df`, has been arranged such that each row corresponds to one pixel of the study area, with the columns corresponding to the predictors utilised for statistical modelling. Given the distribution of the response variable—the area of crop harvesting—which is positively skewed and contains zero values, a Box–Cox transformation was performed prior to modeling to stabilize the variance and approximate a normal distribution. Initially, a minimal positive number, designated as ϵ , was appended to all values. This number was calculated as half of the minimum positive value of `harvarea`. 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 the 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 on the basis of 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 rapeseed yields in the baseline period.

To reduce the impact of multicollinearity between predictors, a hierarchical clustering method based on the correlation structure of variables was applied (Kayode Ayinde & Nwosu, 2021). In the initial phase of the study, the standardisation of all predictors was conducted utilising the formula: $z = (x - \text{mean}(x)) / \text{sd}(x)$. The data were reduced to a dimensionless scale with a mean of 0 and a standard deviation of 1, i.e. $z = (x - \text{mean}(x)) / \text{sd}(x)$. Pearson's coefficient was then used to construct a matrix of pairwise correlations

between all variables (with the exception of the response variable). In accordance with the matrix provided, the symmetric distance between the variables was calculated as $1 - |r|$, where r denotes the absolute value of the correlation. The resulting distance matrix was then utilised for the purpose of hierarchical clustering of variables, employing the average linkage method. The number of clusters was determined empirically (e.g., $k = 12$), with consideration given to the structure of the dendrogram. In this study, a single variable was selected from each cluster, with the cluster exhibiting the lowest average correlation with other variables within the same cluster being selected. This formed a set of representative predictors included in the final linear regression model. This approach was adopted in order to minimise the information overlap between variables and thereby reduce the risk of unstable regression coefficient estimates, a characteristic of excessive multicollinearity.

In order to estimate spatial changes in yields in the future period 2061–2080, CMIP6 projected climate data (CNRM–CM6–1 model) for four socio-economic scenarios (SSP1–2.6, SSP2–4.5, SSP3–7.0, SSP5–8.5) were used (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 be constant over time; therefore, the values from the historical dataset (`soil_hist`) were appended to the forecast stack. In order to reduce multicollinearity between bioclimatic variables, the residuals were calculated by regressing additional climate variables (`other_clim`) on the main set of predictors (`primary_vars`). The resulting residuals and the primary bioclimatic and soil predictors were amalgamated into the predictors_fut matrix. For each combination of SSP $\times$ 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 inverse transformation was conducted in accordance with the estimated parameter λ . Negative values that might have arisen due to numerical errors were replaced with zero. The predicted values were used to create spatial raster maps of the expected yield (`harvarea_ssp*_.tif`) and delta maps of yield changes relative to the historical period (`delta_ssp*_.tif`). A two-colour blue-white-red scale centred on zero was utilised to visualise the gradients of changes. The values of the predicted 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 Polissia and Forest-Steppe regions of Ukraine, the spatial distribution of rapeseed areas in the historical period was formed under the influence of the combined action of bioclimatic and soil factors that determined the agro-ecological suitability of this crop to local conditions ($N = 11,803$; $\text{Rad}j^2 = 0.50$) (Table 1).

The results of linear regression with standardised coefficients and Box–Cox transformation revealed that the leading limiting factor was the average temperature of the coldest month (`bio11`; $\beta = -0.33 \pm 0.01$), indicating a decrease in the proportion of rapeseed in mild winters, which can disrupt the natural dormant period or promote the development of pathogens. Annual precipitation (`bio12`; $\beta = -0.26 \pm 0.01$) is a significant negative predictor, reflecting the crop's vulnerability to excessive moisture and associated risks, including tuber rot and reduced yield quality. An adverse effect was also found for the temperature of the driest quarter (`bio9`; $\beta = -0.17 \pm 0.01$), likely due to the increased risk of overheating and aridity during the active growing season. Excessive precipitation in the wettest month (`bio13`; $\beta = -0.03 \pm 0.01$) also had a limiting effect, indicating the importance of uniform rather than peak water supply. The content of total nitrogen in the soil (`nitrogen`; $\beta = -0.27 \pm 0.01$) was negatively correlated with the proportion of area, which may be due to disproportionate vegetative growth in excessively rich soils. The strongest soil constraint was high soil density (`bdod`; $\beta = -0.24 \pm 0.01$), which hinders tuber development due to poor aeration and water permeability. Precipitation in the wettest quarter (`bio18`; $\beta = 0.13 \pm 0.01$) was favourable for rapeseed, providing an adequate water supply at critical growth stages. A positive effect was also found for the temperature of the wettest quarter (`bio8`; $\beta = 0.12 \pm 0.01$), the average daily temperature range (`bio2`; $\beta = 0.18 \pm 0.01$), the minimum temperature of the coldest month (`bio6`; $\beta = 0.10 \pm 0.01$), and precipitation of the driest month (`bio14`; $\beta = 0.13 \pm 0.01$), which together indicates the importance of a moderate thermal

regime, the absence of extreme frosts and the provision of moisture to the crop even in dry periods. The historical spread of rapeseed was shaped by a combination of thermal, hydrological, and soil factors that created the most favourable conditions in well-drained soils with moderate water supply, mild winters, and a pronounced seasonal thermal amplitude. The results obtained provide a basis for further scenario modelling of land suitability dynamics in the context of global climate change.

Spatial forecasting of growing conditions for rapeseed within the Polissia and Forest-Steppe regions of Ukraine reveals apparent regional differences and dynamics closely related to the intensity of climate change (Fig. 1). All scenarios show a stable zone of high agro-ecological suitability in the central part of the Forest-Steppe, which acts as a "core of favourability". This zone retains high values of the transformed index even in the face of increasing climate risks, indicating a relative resilience to environmental change. By contrast, the north of Polissia is characterised by consistently low suitability, which will further decline in the future, especially under intensive scenarios.

Modelling under the SSP126 scenario shows relative moderation of changes: the maximum values of the index decrease only slightly over the century, and the spatial distribution of favourable areas remains almost unchanged. This allows us to consider this scenario the most favourable in maintaining stable growing conditions. In the SSP245 scenario, there is an evident narrowing of the high suitability areas, manifested in both a decrease in maximum values and a reduction in the area with optimal condi-

tions. At the same time, border areas with unstable potential are expanding, particularly in the northwest and southeast of the region.

Table 1

Results of the linear regression of the dependent variable (Box-Cox transformed yield) on the selected predictors after removing grouped multicollinearity ($N = 11,803$; $\text{Radj}^2 = 0.50$). The standardised regression coefficients (β) and standard errors (SE) are presented in the format $\beta \pm \text{SE}$

Predictor	$\beta \pm \text{SE}$	t	P
(Intercept)	0.01 ± 0.01	2.33	0.020
Precipitation of the wettest quarter (bio18)	0.13 ± 0.01	17.62	< 0.001
Average temperature of the coldest month (bio11)	-0.33 ± 0.01	-39.81	< 0.001
Average daily temperature range (bio2)	0.18 ± 0.01	22.30	< 0.001
Temperature of the wettest quarter (bio8)	0.01 ± 0.01	0.90	0.367
Minimum temperature of the coldest month (bio6)	0.24 ± 0.01	33.75	< 0.001
Temperature of the driest quarter (bio9)	0.01 ± 0.01	1.85	0.064
Annual precipitation (bio12)	-0.17 ± 0.01	-15.87	< 0.001
Precipitation of the wettest month (bio13)	0.07 ± 0.01	10.74	< 0.001
Precipitation of the driest month (bio14)	0.06 ± 0.01	7.21	< 0.001
Precipitation of the wettest quarter (bio16)	0.04 ± 0.01	4.35	< 0.001
Soil density (bdod)	0.44 ± 0.01	42.53	< 0.001
Total nitrogen content in the soil (nitrogen)	-0.27 ± 0.01	-31.90	< 0.001

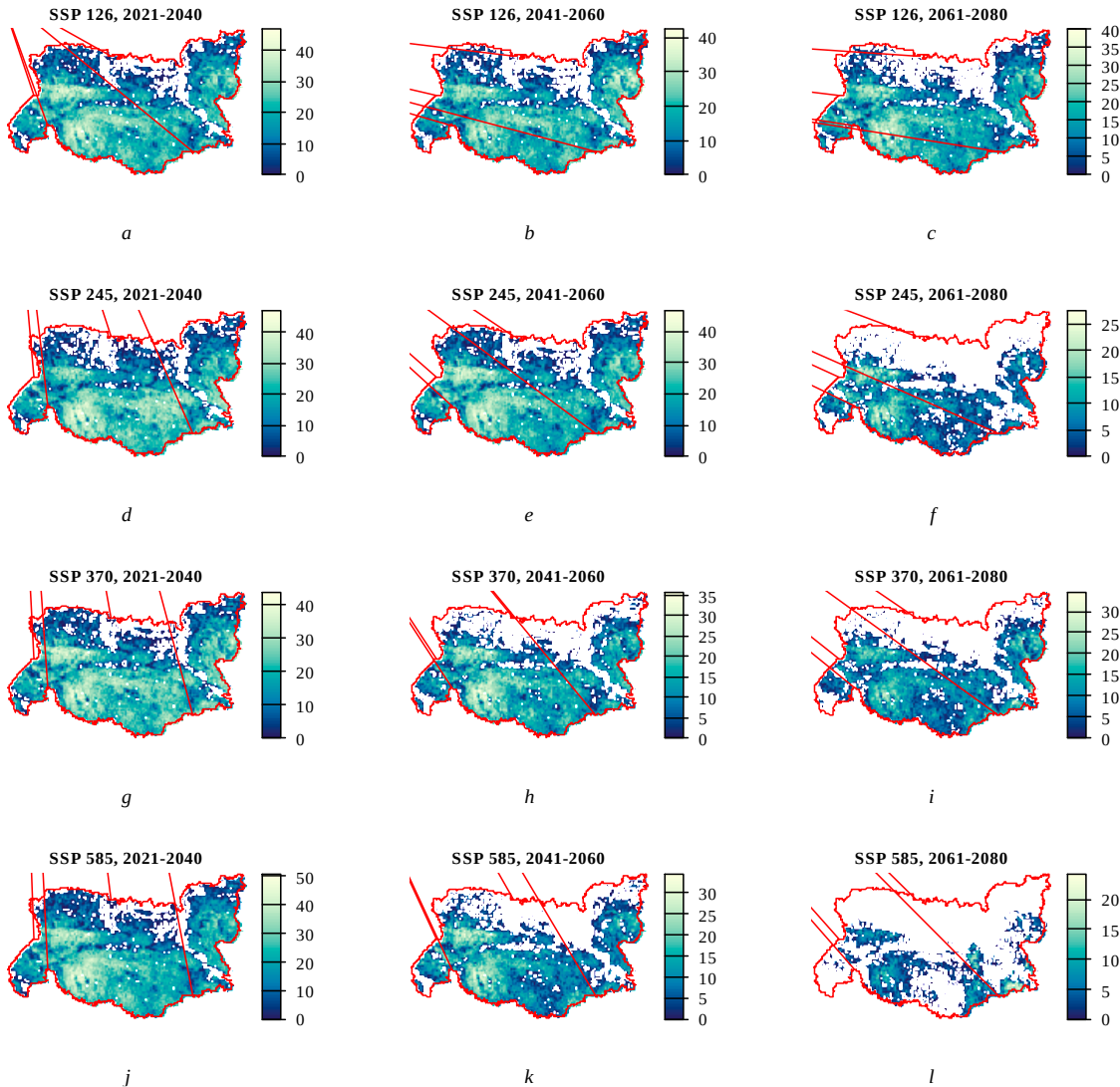


Fig. 1. Projected changes in rapeseed area under different scenarios of future societal development used to model climate change, combined with varying levels of SSP greenhouse gas impacts in 2021–2080: the maps show the spatial variability of rapeseed yields (in hectares per pixel) within the studied 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 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 more ambitious SSP370 scenario shows an increasing fragmentation of conditions: instead of coherent ecologically suitable regions, mosaic structures are formed with isolated pockets of favourable conditions surrounded by areas with moderately unfavourable characteristics. This indicates an increase in spatial heterogeneity, which complicates planning and increases risks for producers. The most critical changes are recorded in the SSP585 scenario: by the end of the century, a large part of the territory loses its favourable properties, and potential for rapeseed cultivation is concentrated in limited areas with residual environmental stability. As climate change intensifies, there is a clear trend of reduction in areas with a high level of agro-ecological compliance and an increase in the share of areas with marginal or unstable conditions. This indicates a decli-

ne in the spatial reliability of rapeseed cultivation and requires a rethinking of agricultural planning: a shift to adaptive practices, including breeding more resistant varieties, developing irrigation infrastructure, and introducing technologies that can compensate for the risks of reduced productivity in the face of climate turbulence.

The analysis of delta maps of projected changes in the transformed share of rapeseed area compared with the historical background (Fig. 2) indicates an increasing instability of agro-ecological compliance under climate change. Spatial changes have a distinct scenario and temporal gradient: while in the short-term horizon (2021–2040) some areas of the central Forest-Steppe still show local increases, in the medium and long term, negative shifts prevail, covering most of Polissia and a part of the Forest-Steppe.

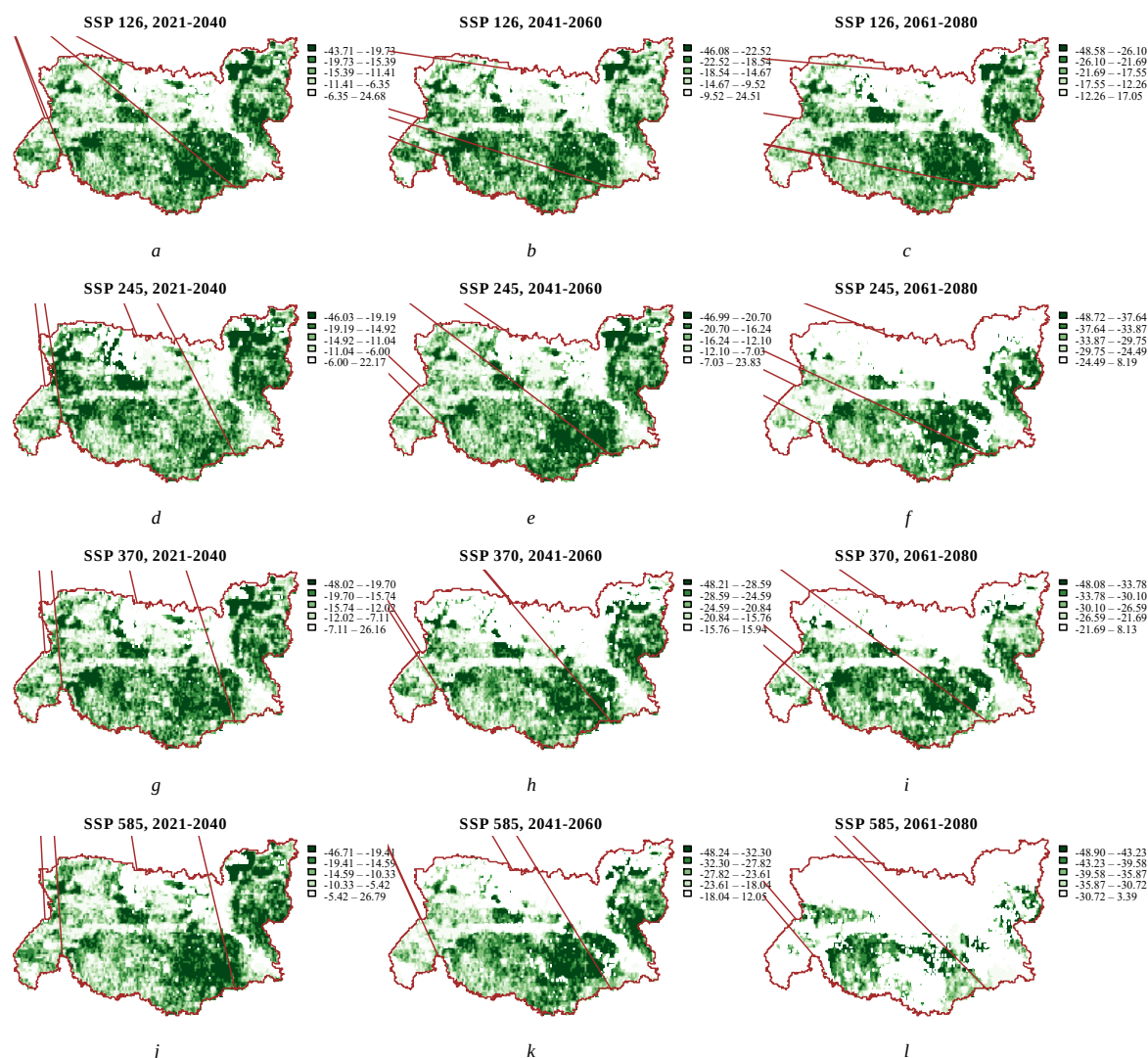


Fig. 2. Projected changes in rapeseed area compared to historical levels (delta) under different SSP scenarios during 2021–2080: values reflect the difference between projected and baseline areas; positive values (lighter shades) indicate an area expansion, while negative values (darker shades) indicate a reduction; the boundaries of the study region are marked in red: *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

Under the SSP126 scenario—which assumes the slowest rate of climate change—positive changes in the first time window reach +24.7 Box-Cox units and are concentrated in the Forest-Steppe zone. By 2041–2060, signs of degradation are already detected, with a maximum loss of –46.1 Box-Cox units. At the end of the century, the negative deltas increase, reaching –48.6, while the growth potential is reduced to +17.0. This indicates the exhaustion of the possibilities of natural compensation for the impact of climate stress, even under the most optimistic scenario.

The SSP245 scenario shows a similar spatial pattern, but with more contrasting deviations. In the first period, the increases do not exceed +22.2, while the minimum values reach –46.0. In the second time interval, the negative deltas deepen to –47.0, reducing the share of areas with positive dynamics. In 2061–2080, the maximum decreases to +8.2, and

the decline reaches –48.7, indicating a rapid loss of favourable conditions even under a relatively moderate climate scenario. Under SSP370, the first period shows a slightly wider amplitude: gains of up to +26.2 and losses of up to –48.0. However, in 2041–2060, the picture changes significantly: both positive and negative values decrease, signalling the formation of mosaic patterns with pockets of instability. In 2061–2080, the losses become almost systemic (at least –48.1), and positive changes are limited to only +8.1, confirming the tendency towards fragmentation of productive zones.

The SSP585 scenario, which envisages the most intense climate transformations, demonstrates the most critical changes. Despite the maximum short-term increase of +26.8 in 2021–2040, the positive signal is already weakening to +12.1 in the medium term, and losses are deepening

to -48.2. In 2061–2080, the zone of positive change almost disappears, and the minimum values reach -48.9, indicating a structural decline in the suitability in most areas. All scenarios show a natural decrease in the regions with positive changes and the spread of areas with negative dynamics. The gradual depletion of the natural resilience potential is most noticeable in northern Polissia and north-eastern Forest-Steppe, where the increasing frequency and depth of negative deltas indicate a particular vulnerability to climate change. Such spatial and temporal destabilisation creates a justified need for adaptation of agricultural production, including changes in the spatial structure of crops, the introduction of adaptive rapeseed varieties and a revision of the zonal distribution of crops in response to new climate realities. The results of the analysis of variance (ANOVA) indicate a statistically significant impact of all three factors studied (the type of climate scenario (SSP), periods, and their interaction) on the change in the share of agricultural land suitable for rapeseed cultivation (Table 2).

Table 2

Results of the analysis of variance (ANOVA) of the impact of socio-economic development (SED) scenarios, periods, and their interaction on the change in the projected share of agricultural land under rapeseed 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	Mean square	F-statistic	P-value	η^2 (proportion of variance)
SSP	4	2158298	539575	6089.4	<0.001	0.149
Period	2	1281680	640840	7232.2	<0.001	0.089
SSP × Period	6	376423	62737	708.0	<0.001	0.026
Residuals	120239	10654328	89	—	—	0.736

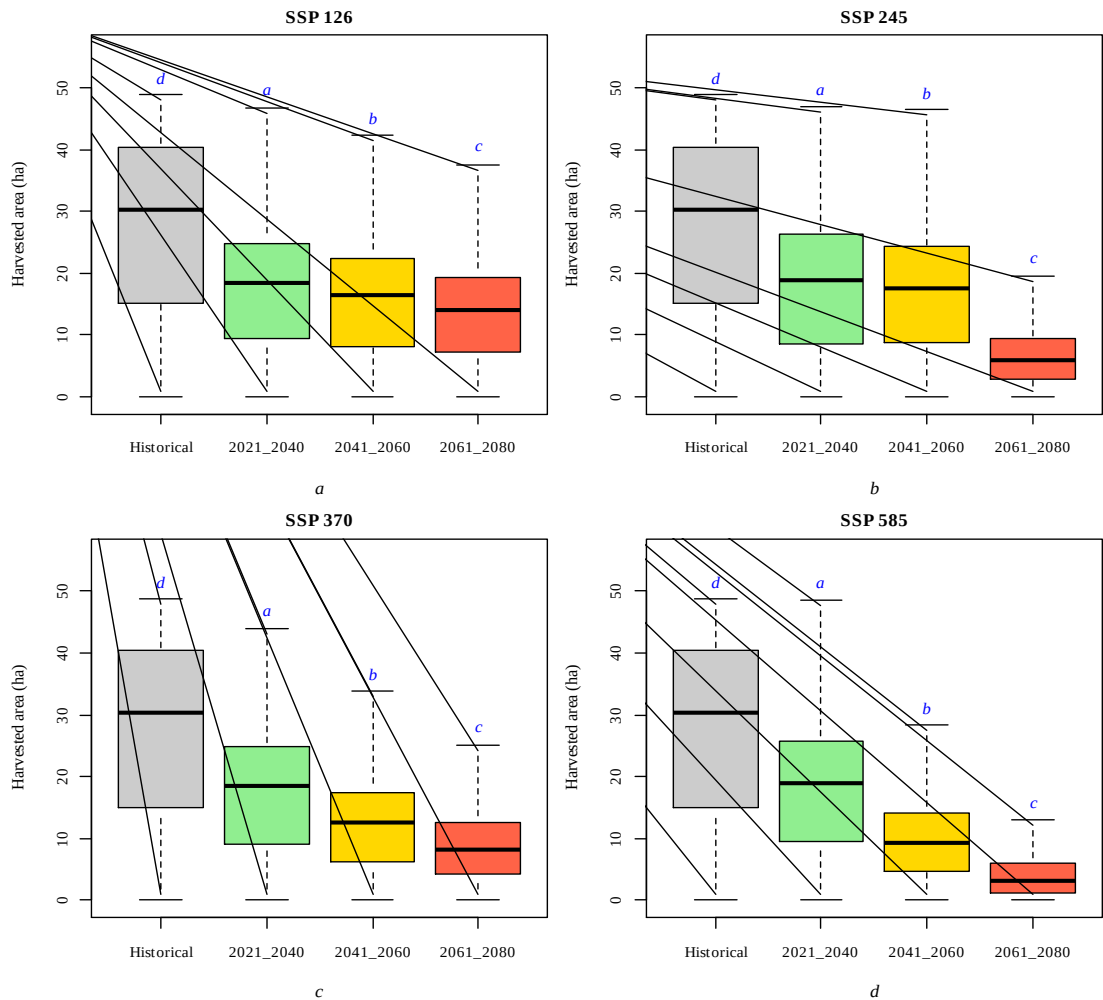


Fig. 3. Scatterplots of harvested area (ha) under four SSP scenarios (SSP126, SSP245, SSP370, SSP585) in different periods: historical period (baseline), 2021–2040, 2041–2060, and 2061–2080: different letters above the boxes indicate statistically significant differences between periods within each SSP according to Dunn's test (with Bonferroni correction, $P < 0.05$); the central line indicates the median; the box indicates the interquartile range; the whiskers indicate the limits of the 1.5 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 statistically significant differences between periods and scenarios (indicated by different letters above the blocks) confirm the high sensitivity of agro-ecological suitability to both factors. The decreasing median values and decreasing amplitude of variations in later periods indicate a narrowing of the adaptation window and an exacerbation of spatial degra-

The most crucial factor was time ($\eta^2 = 0.236$), which indicates the critical importance of chronological dynamics in climate change. The type of climate scenario also had a significant impact ($\eta^2 = 0.149$), demonstrating that the future agro-ecological situation mainly depends on the overall trajectory of global socio-economic development. The interaction between scenarios and periods (SSP × Period) provided a minor but statistically significant contribution to the variance ($\eta^2 = 0.026$), indicating the complexity of forecasting when both factors are considered simultaneously.

The graphical representation of the results (Fig. 3) demonstrates a consistent decrease in the Box-Cox-transformed values of the suitability of areas for rapeseed cultivation under all scenarios from the short-term horizon (2021–2040) to the long-term horizon (2061–2080). The most significant decrease was projected under SSP370 and SSP585, which reflects the increase in negative climate pressure under more intense warming scenarios.

The combination of temporal changes, scenario uncertainty, and their interaction creates a complex configuration of risks for sustainable rapeseed production. It requires adaptive planning, differentiation of varieties by region, and revision of crop structures in the medium and long term.

Discussion

During the historical period, the spatial distribution of rapeseed areas in Polissia and the Forest-Steppe of Ukraine was formed under the influence of a combination of climatic and soil characteristics, which determined this crop's agro-ecological suitability to local environmental conditions. Our findings are consistent with those of previous research highlighting the dominant role of climatic and edaphic factors in defining land suitability for rapeseed cultivation (Budak et al., 2024). Both studies emphasize the critical importance of temperature regimes and water balance during the growing season, as well as the negative impact of excessive moisture or heat stress during key developmental phases of the crop. Despite methodological differences—regression-based forecasting under climate change scenarios in our study and a multi-criteria assessment using fuzzy logic in Budak et al. (2024)—both approaches reveal similar spatial patterns: stable cores of agro-ecological suitability surrounded by zones of reduced or marginal potential. This congruence confirms the generalisability of the identified patterns and underscores the applicability of such models across diverse climatic regions to inform adaptation strategies in agriculture under environmental change.

Our findings confirm the leading role of winter temperature parameters in determining the agro-ecological suitability of rapeseed cultivation in northern and central Ukraine (Kornychuk & Yurchuk, 2023). In particular, the average and minimum temperatures of the coldest month (BIO1 and BIO6) were identified as the most influential predictors, showing a strong positive relationship with the relative area under rapeseed. This highlights the vulnerability of winter rapeseed to cold stress during overwintering and explains the spatial distribution of cultivation areas, which are concentrated in regions with milder winters. These results align with the crop's known sensitivity to frost damage and emphasise the importance of incorporating detailed winter thermal indicators in suitability modeling. Consequently, adaptation strategies for future climate scenarios should pay particular attention to shifts in winter temperature minima, as they represent a key limiting factor for maintaining stable production areas in continental climates. Areas with moderately mild winters created conditions for stable growth of winter rape, while excessively harsh temperatures limited its spread.

Precipitation, especially its distribution throughout the year, also played an important role. The present study's findings on precipitation-related factors are consistent with those reported by Li et al., (2022), who emphasised that both total rainfall and its intra-annual distribution are crucial in the development and optimisation of rapeseed yield. The findings of the study demonstrate that rainfall scarcity during the early growth stages of the plants, in conjunction with excess moisture during the flowering stage, can have a substantial impact on the potential yield of the crop. This observation lends support to the hypothesis that water availability, particularly during critical phenophases, should be incorporated explicitly into spatial suitability modelling and future agro-climatic scenario planning. Rapeseed is sensitive to excessive moisture, especially during germination and flowering (Nabloussi et al., 2019), which explains the negative impact of annual precipitation and peak values in the wettest months. On the contrary, a uniform moisture supply during the growing season, particularly in the wettest quarter, contributed to higher yields by ensuring an optimal water balance at critical stages of crop development. The thermal regime during the spring vegetation renewal and crop maturation also played a significant role. These findings are consistent with those of the recent field-based research (Verdejo & Calderini, 2025), which demonstrated that thermal conditions during early grain filling, especially the 0–15 and 15–30 day windows after flowering, have a decisive effect on both yield quantity and quality in rapeseed. This phenomenon corresponds to the spring vegetative renewal and crop maturation phases observed in temperate climates. The elevated temperatures experienced during these phases exerted a significant influence on the number and composition of the grains, underscoring the pivotal role of spring thermal conditions in determining the final yield outcomes in the context of climate change scenarios. The positive impact of the average daily temperature range indicates a favourable adaptation of rapeseed to moderately contrasting thermal conditions that stimulate photosynthetic activity and biomass accumulation.

Soil characteristics formed a more stable basis for rapeseed agro-ecological compliance. The relatively stable influence of soil characteristics on rapeseed suitability observed in our study is consistent with previous regional assessments (Zymaroieva et al., 2020), which emphasise that soil fertility, drainage, and texture form a resilient foundation for rapeseed

production in the Right-Bank Forest-Steppe zone. In contrast to the climate-related variables, which fluctuate across years and scenarios, edaphic conditions remain largely stable and thus constitute a critical constant in agro-ecological zoning and long-term planning. The correlation between soil density and crop yield was found to be positive, suggesting that regions with high productivity may benefit from favourable water retention and soil structure. Concurrently, the deleterious effects of elevated total nitrogen may be associated with excessive vegetative mass, which can result in lodging and heightened susceptibility to fungal diseases, particularly under the conditions of unstable moisture. The historical spatial distribution of rapeseed reflects the balance between thermal conditions, uniformity of moisture supply, and physical and chemical characteristics of soils. This aligns with the findings of Zymaroieva et al. (2020), who demonstrated that rapeseed suitability in the Right-Bank Forest-Steppe zone is shaped by the interaction of temperature requirements, intra-seasonal moisture distribution, and the physical and chemical properties of soils. The spatial stability of edaphic conditions, coupled with the sensitivity of rapeseed to thermal and hydrological variability, provides a consistent explanation for the crop's historical agro-ecological zoning in this region. Areas with moderately mild winters, stable precipitation throughout the year, and well-structured soils with a reduced tendency to waterlogging and lodging were the most favourable for growing rapeseed. This configuration of factors defined the core of sustainable land use for rapeseed within the central Forest-Steppe, which became the basis for further predictive modelling of changes in suitability under climate change.

Changes in the climate conditions in the forecast period will significantly transform the spatial configuration of areas favourable for rapeseed cultivation, causing both a narrowing of stable agro-ecological compliance zones and an increase in regional contrasts. Our projection that climate changes will fundamentally reconfigure the spatial suitability for rapeseed, compressing historically stable cultivation zones and amplifying regional disparities, is consistent with the recent findings from Jannat et al. (2022). These demonstrate that warming trends enhance growing conditions but undermine maturity, while rainfall variability and temperature shifts produce diverse regional impacts across major rapeseed-producing areas. Together, this evidence highlights the need to integrate climatic heterogeneity into spatial planning for future rapeseed cultivation under changing environmental conditions. The modelling results show a clear trend towards a reduction in areas with positive dynamics and an increase in areas with unfavourable conditions, which is most pronounced in the medium and long term. Even under the most optimistic development scenario (SSP126), the natural ability to compensate for climate stress is gradually being exhausted, indicating a general decline in the adaptive potential of agricultural landscapes.

The most resilient are the central parts of the Forest-Steppe, which retain relatively high transformed yields due to moderate thermal conditions and relative uniformity of precipitation. Conversely, the northern Polissia and north-eastern regions are progressively experiencing a loss of their favourable characteristics. A structural decline in the agro-ecological compliance is predicted in these areas, indicating increased vulnerability to climate change. Under scenarios with more intense climate change (SSP370, SSP585), spatial patterns are mosaic-like, with alternating areas of residual favourability and regions with boundary conditions. This indicates an increase in the fragmentation of agriculturally suitable space and the complication of conditions for large-scale planning of crop production. Climate transformations are leading to a reduction in the area ideal for rapeseed and an increase in the spatial instability of this suitability. In the long term, this will require adaptation of agricultural practices: transition to regionally differentiated variety updating, introduction of technologies that compensate for growing aridity and heat stress, and revision of crop placement by the changed climate corridors of favourability.

In the short term (2021–2040), the rapeseed growing conditions may temporarily improve in some regions, primarily the central and south-eastern Forest-Steppe. This is due to a moderate increase in temperature and a partial reduction in winter risks, which creates more favourable conditions for winter crops. Under the SSP126 scenario, which assumes the least climate change, local increases in transformed yields (up to +24.7 Box–Cox units) are observed in the first time window, indicating an expansion of the agro-ecological compliance zone in certain areas. However, such improvements are primarily local and temporary. In the medium and long term (after 2040), the projections indicated a tendency towards depletion of the agro-ecological suitability even in those areas due to increased heat stress, water imbalance, and increased climate

instability. Under the more ambitious climate change scenarios (SSP370, SSP585), the positive effects are completely levelled by the middle of the century, and in some regions they even change to negative ones. Although there may be temporary improvements in rapeseed growing conditions in some areas, these trends are unstable and must be interpreted cautiously. They can create windows of opportunity for short-term expansion, but do not guarantee a long-term positive effect without adaptive agricultural management.

As a result of global climate change, the worst forecasts for rapeseed growing conditions are recorded within the northern Polissia and north-eastern Forest-Steppe regions of Ukraine. These areas show the most profound negative changes in transformed yields under all future scenarios, especially under intense warming trajectories such as SSP370 and SSP585. In these regions, a systemic decline in agro-ecological suitability is predicted, manifested in the form of a steady decline in the index to extremely low values, signalling the actual loss of favourable conditions for the crop. The main reasons for this degradation are a combination of several negative factors: increased summer heat stress, unstable winter temperatures that disrupt wintering processes, and increased spatial and seasonal rainfall irregularities. In these areas, the water balance is disrupted at critical stages of rapeseed development, and soil conditions are insufficient to compensate for climate risks. The projected reduction in suitable areas in the northern region is of agro-ecological and socio-economic importance, as it requires a reorientation of the crop structure, the use of adaptive varieties or even the removal of the crop from circulation in certain areas. These changes point to the need for strategic agricultural planning that considers the growing regional vulnerability to climate change.

Time, climate change scenarios, and their interaction have a significant and interrelated impact on conditions favourable for rapeseed cultivation, which is manifested in a progressive reduction of agro-ecological compliance and increased spatial instability. This is manifested in a steady decline of agro-ecological compliance and increasing spatial heterogeneity of favourable zones. Similar dynamics were reported by Cheng et al. (2023), who showed that the interaction between time horizons and emission pathways (SSP2–4.5 vs. SSP5–8.5) explained a large proportion of the variability in crop productivity and spatial resilience. Their findings confirm that climate-induced transformations are not uniform but instead lead to regional amplification of risks, whereby formerly stable production zones become fragmented and less reliable. This convergence of evidence underlines the importance of incorporating both temporal and scenario-based dimensions into agro-climatic forecasting frameworks. The most crucial factor is time: during each subsequent period (from 2021–2040 to 2061–2080), a consistent reduction in areas with high suitability is recorded, which indicates the cumulative effect of climate change. Changes in the temperature regime, including an increase in average annual temperatures and the frequency of extreme events, are gradually pushing large parts of the region beyond optimal conditions for rapeseed, especially in the northern and eastern areas. The socio-economic development scenarios (SSPs), which determine the intensity of climate change, also have a clear impact: the more ambitious the scenario (e.g. SSP370 or SSP585), the faster and more profound the degradation of conditions. This is attributable to the fact that rising greenhouse gases and global temperatures have a detrimental effect on water shortages, shift vegetation phases, and destabilise the seasonal climate rhythm, which are critical for winter crops. Conversely, under the SSP126 scenario, where the rate of warming is reduced, a relative stability is sustained in key growing areas, at least in the short term. The interaction between scenario and time is statistically significant, although less potent than the main effects, and indicates that the rate of degradation of conditions is not linear, but depends on a specific combination of time dynamics and climate pathway. Under moderate scenarios, adverse changes may accumulate gradually, allowing for adaptation; however, in more severe scenarios, there is a sudden loss of favourability in the medium term. This phenomenon elucidates the reason why certain regions that initially possess potential during the initial forecast period subsequently experience a substantial decline in agricultural suitability, signifying an escalation in risk and a reduction in the adaptation window. The interaction of these factors gives rise to a complex risk configuration, which necessitates scenario-dependent agricultural planning and flexible mechanisms for adapting to climate challenges.

The relatively low explanatory power of factors such as time, types of climate change scenario, and their interaction on the variability of conditions favourable to rapeseed production is explained by the complex

nature of agro-ecological suitability, which is shaped by climate and a range of local biophysical characteristics. While climatic factors have been shown to exert a significant influence on the dynamics of suitability, their effects are frequently modulated by factors such as spatially stable yet heterogeneous soil properties, orography, historical land use, and even agricultural practices, which are not typically encompassed within the scope of scenario modelling. Despite their extensive coverage of global trends, climate scenarios do not take into account all regional or micro-climatic nuances that can be crucial at the level of a particular pixel or farm. The precise temperature or precipitation levels in disparate regions may exert divergent effects on crops, depending on factors such as the hydrological regime, soil type, or drainage availability. It is important to note that even substantial alterations to the scenario do not invariably result in directly proportional changes in suitability, due to the buffering role of local conditions. The proportion of variance explained by these factors is reduced by the complex interplay of linear and non-linear effects, seasonal compensatory mechanisms (e.g. cooler springs can partially offset warm winters), and the potential insensitivity of the crop to specific boundary changes. This suggests that climate, while important, is only one building block in the multidimensional construct of agro-ecological fit, and its isolated impact has limited explanatory power without considering a wider range of spatially stable factors or factors that are difficult to predict.

The results obtained are of great practical importance for the strategic planning of agricultural production during climate instability. Firstly, the identification of areas with high, moderate, and low suitability for rapeseed cultivation allows for a reasonable reorientation of the structure of sown areas. This can minimise the risks of crop losses in vulnerable regions and optimise the use of resources in more stable agricultural landscapes. Secondly, the predictive scenarios of spatial dynamics of suitability provide a basis for adaptive agricultural planning, particularly for introducing new, climate-tolerant varieties, developing irrigation or drainage infrastructure, and selecting optimal sowing dates. Thirdly, the results can be used at the level of agricultural policy to identify priority regions for state support, agricultural risk insurance, and the development of localised climate change adaptation programmes. It is evident that the resulting models and suitability maps have the potential to be integrated into geographic information systems. This integration would facilitate the creation of digital platforms, thereby enabling agricultural producers, consultants, and regional authorities to make decisions in a timely manner. This has been demonstrated to engender enhanced reliability, flexibility, and resilience within the farming sector when confronted with medium- and long-term climate challenges.

The potential for further research lies in the deepening of the spatial and temporal analysis of the interaction of climatic, soil, and anthropogenic factors that determine the agro-ecological suitability of areas for rapeseed cultivation. A pivotal area of concern is the integration of land use change scenarios, encompassing urbanisation, soil degradation, and alterations in the composition of agricultural landscapes. These factors have the potential to substantially modify the effects of climate change. In addition, it is recommended that technological advancements in the agricultural sector, such as precision farming, advanced irrigation systems, and adaptive agricultural practices, be taken into consideration when formulating projections within the context of potential adaptation. A bioclimatic model, enriched with phenological observations and experimental data on the resistance of current and future rapeseed varieties to heat and water stress, deserves special attention. This will facilitate a more precise evaluation of the crop's potential beyond the confines of present scenarios. Another promising area of research is the study of the impact of extreme climatic events, such as spring frosts, summer heat waves, and prolonged droughts. These events are often not considered in average climate variables but can be critical for crop production. Finally, a significant challenge is to devise dynamic, interactive suitability maps. These maps must facilitate the expeditious updating of forecasts using novel data. Moreover, they must ensure the malleable utilisation of results in agricultural decision support systems across various levels – from the farm to the national climate change adaptation strategy.

Conclusion

The study found that the spatial distribution of areas suitable for rapeseed cultivation in Ukraine is influenced by a combination of climatic and soil factors, with winter temperature, moisture uniformity, and the physical and chemical properties of soils playing a predominant role. Forecast

modelling based on climate change scenarios (CCS) indicates a gradual reduction in agro-ecological compliance zones in the medium and long term, accompanied by increased spatial fragmentation and vulnerability, particularly in the northern regions. While some areas may experience short-term improvements, these changes are localised and volatile. The duration of the scenario, its intensity, and their interaction have a statistically significant yet limited impact on explaining spatial variability, underscoring the importance of considering regional specificities. The findings hold practical value for adaptive agricultural planning, risk forecasting, and the development of climate-resilient farming systems. Additionally, they identify areas for further research aimed at enhancing the accuracy of suitability assessments and developing effective adaptation scenarios.

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