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Agroecological Determinants of Potato Spatiotemporal Yield Variation at the Landscape Level in the Central and Northern Ukraine

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Abstract

Global food security largely depends on the crop yield increase, so the study of the yield-limiting factors of potato (the second bread) is a pressing issue today. This study determines the contribution of the agroecological factors, namely, bioclimatic variables, soil indicators, and factors of landscape diversity, to the variation in potato yields. Conducted in Polissya and Forest-steppe zones of Ukraine during 1991–2017, this study has not only addressed the relationship between ecological determinants and potato yields, but also considered crop yields as a dynamic system. The dynamics of potato yields from the mid-1990s to the present is described by a log-logistic model. There are statistically significant regression dependencies between potato yield parameters and agroecological factors. Potato yield is dependent on the diversity of landscape cover. The relationship between yield parameters and landscape-ecological diversity is non-linear, which determines the presence of optimal landscape structure for the highest potato yields. Among climatic factors, the continental climate is of the greatest importance for potato yield. The high sensitivity of potato yield parameters to soil indices was found, and mostly the soil texture components (silt content), which largely determines the potato yield spatial variation.

Keywords

Yield; Ecological factors; Spatiotemporal variation; Potato

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Introduction

Potato production is the fourth largest in the world and the largest among non-grain crops since it is 'the second bread' in many countries, including Ukraine (FAO, 2019, Jennings *et al.*, 2020). Potatoes have been cultivated in Ukraine since the 18th century, but the crop was adapted slowly to the Ukrainian climate until the end of the 19th century (Hamkalo, 2005). Although Ukraine is one of the world's top five potato producers in terms of gross production, the average yield per hectare is lower than in developed countries (FAO, 2019). This can be explained by the influence of economic and agrotechnological factors (Zymaroieva *et al.*, 2020; Zymaroieva and Zhukov, 2020). Nevertheless, there are ecological drivers of potato yield dynamics (Haverkort and Struik, 2015; Stol *et al.*, 1991), but their contribution to long-term variation of potato yield within the country needs clarification.

The most influential environmental factors determining crop yields are climate and soil properties (Schmidhuber and Tubiello, 2007; Ray *et al.*, 2015; Feller *et al.*, 2012; Lal, 2020). Climate drivers affect crop yields on the physiological level by regulation of the transpiration, photosynthesis, and respiration processes. The interaction of the meteorological factors with the crop responses is rather complex (Pereira *et al.*, 2008).

In the experiments conducted on potato, it was shown that environmental factors such as rainfall (soil moisture) and temperature have a significant effect on its growth and yield (Diacono *et al.*, 2012). Fluctuations in potato yield are determined both by the influence of weather conditions on the photosynthetic productivity of plants, and the influence of the same conditions on the spread of infectious diseases and pest outbreaks (Quiroz *et al.*, 2018; Lakshman et al., 2020). According to the study of Zhao *et al.* (2016), the key climatic factors limiting potato yields in northern China over the past 30 years at a regional scale were diurnal temperature range, precipitation, radiation, and evapotranspiration. Moreover, the effects of climate change on potato yield are regionally diverse (Haverkort and Struik, 2015), this determines the relevance of present research.

There is a strong correlation between potato yield and soil nutrient factors (Wang *et al.,* 2019). The soil structure, which defines water relations in agricultural systems, is also an important driver of potato yield variation (Redulla *et al.*, 2002). Although, the impact of soil indicators on crop yields is a well-studied issue, yet the spatial aspect of yield variation depending on soil properties needs to be investigated. There is strong evidence of a sustained impact of biodiversity on crop yields both in the natural ecosystems (Hooper *et al.*, 2005) and in agroecosystems (Picasso *et al.,* 2008). Land-use diversity has an important role in ensuring higher yields and, as a result, resilient agricultural returns (Abson *et al.,* 2013). However, the relationship between crop yields and biodiversity at the landscape level is insufficiently explored.

The aim of this study is to establish the contribution of the agroecological factors, namely, bioclimatic variables, soil indicators and factors of landscape diversity in the variation of potato yield in the central and northern Ukraine during 1991-2017.

Methodology

Yield data and study area

Potato yield data were obtained from the State Statistics Service of Ukraine[1]. The time series datasets include averages of the crop annual yields in 206 administrative districts of 10 regions of Ukraine during the period 1991–2017. The data represent the mean values of the yields based on the spatial criterion without differentiating soil water availability and fertility, irrigation management, cultivar, and crop cycle. The research area is located in two environmental zones: the Central European Mixed Forests ecoregion

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[1] http://www.ukrstat.gov.ua/

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(Polissia) and East European Forest Steppe ecoregion (Forest-steppe zone). Twenty-seven years' data series of the potato yields were available for 10 administrative regions (Cherkasy, Chernihiv, Khmel'nyts'kyy, Kyiv, L'viv, Rivne, Ternopil', Vinnytsya, Volyn andZhytomyr) (Figure 1) (Zymaroieva *et al.,* 2020).
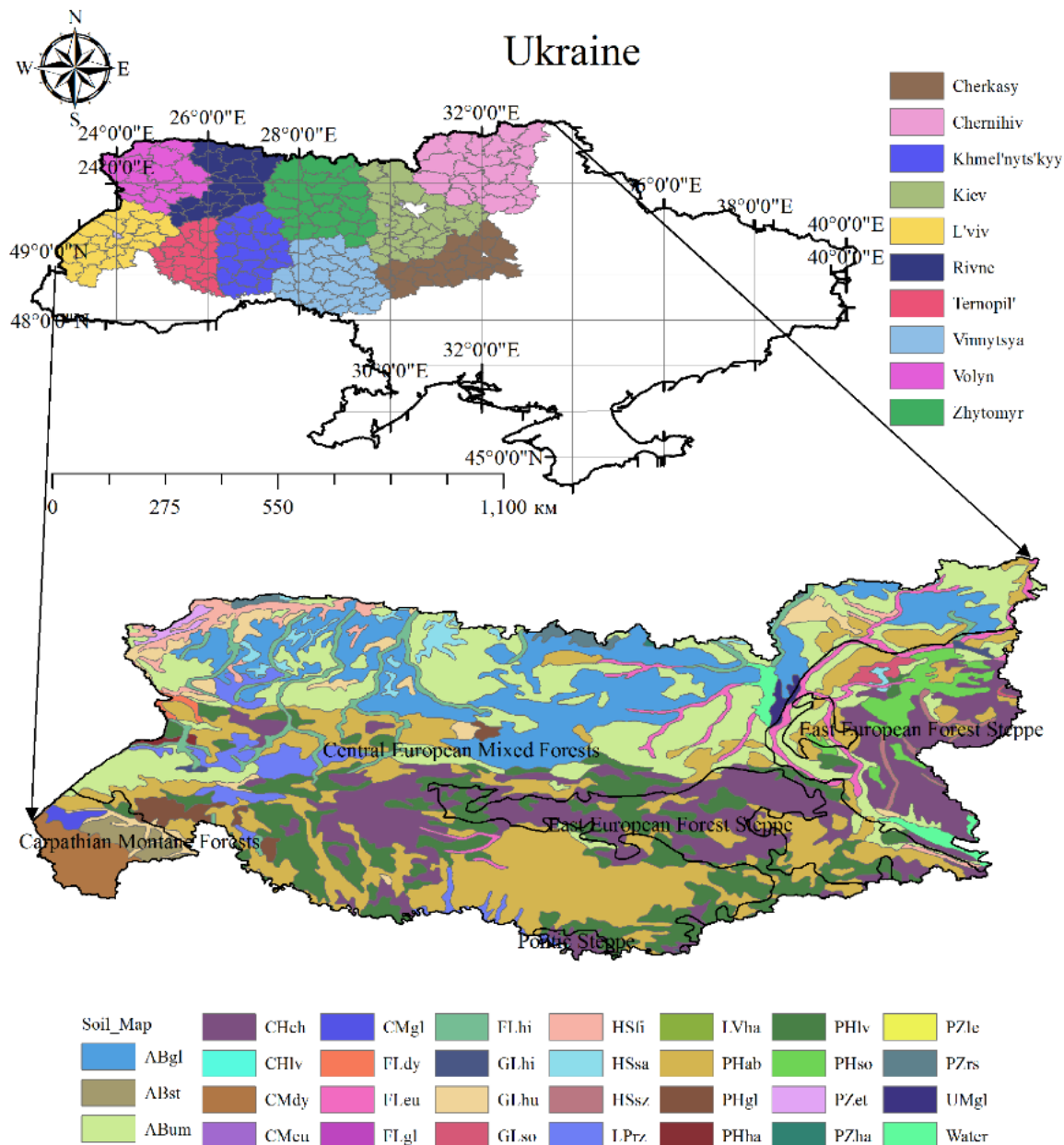

Figure 1: Map of 10 administrative region in Ukraine, Ecoregions and soil map.
Legends: Soil classification according World Reference Base for Soil Resources: ABgl –Albeluvisols Gleyic; ABst – Albeluvisols Stagnic; ABum –Albeluvisols Umbric; CHch –Chernozems Chernic; CHlv – Chernozems Luvic; CMdy – Cambisols Dystric; CMeu –Cambisols Eutric; CMgl – Cambisols Gleyic; FLdy – Fluvisols Dystric; FLeu – Fluvisols Eutric; FLgl – Gleyic Fluvisols; FLhi – Fluvisols Histic; GLhi – Gleysols Histic; GLhu – Gleysols Humic; GLso – Gleysols Sodic; HSfi – Histosols Fibric; HSsa – Histosols Sapric; HSsz – Histosols Salic; LPrz – Leptosols Rendzic; LVha – Haplic Luvisols; PHab – Phaeozems Albic; PHgl – Phaeozems Gleyic; PHha – Phaeozems Haplic; PHlv – Phaeozems Luvic; PHso – Phaeozems Sodic; PZet – Podzols Entic; PZha – Podzols Haplic; PZle – Leptic Podzols; PZrs – Podzols Rustic

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Yield dynamics model and its characteristic points

In this work, not just the relationship between ecological determinants and yield is studied, but crop yields are also considered as a dynamic system, which is characterized by changes in time and space. The choice of the model is explained by its statistical reliability and significant explanatory ability, which allows meaningful interpretation of crop yield data. The symmetrical four-parameter log-logistic model was used to describe the potato yield dynamics:

$$Y = c + \frac{d-c}{1+exp\ (b(\log(x)+\log\ (ED50)))},\qquad(1)$$

where x represents years (1 – 1991, 2 – 1992, …); y is the response (crop yield); c shows the lower response limit (the lowest yield level); d is the upper limit (the plateau level of yields) when x approaches infinity; b is a slope of the response curve near the inflection point when x acquires ED50 (the time it takes to reach a half increase between the lower and upper limits). Hence, the log-logistic model has characteristic points that can be used as parameters of the variation of the yield (Figure 2): Lower limit indicates the lowest level of yields during the study period; slope – a slope of the trend curve, which shows the rate of yield change over time; ED50 – the time that is required to achieve half of the maximum yield level and at the same time the point with the highest rate of yield growth; upper limit – the highest level of productivity which, at the present level of agricultural technology development, is determined precisely by the biotic potential of the territory.
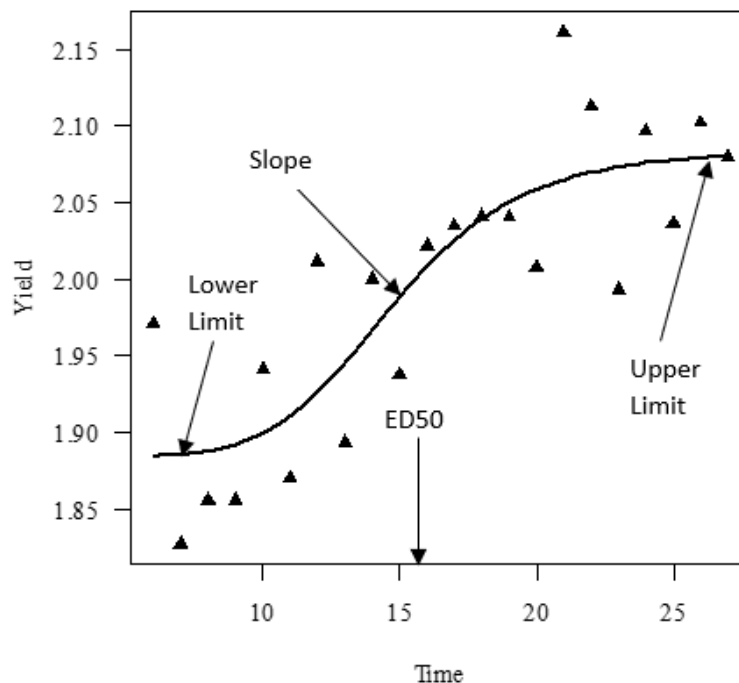

Figure 2: Typical dynamics of the potato yields during 1991–2017 and its approximation by the logistic model. The abscissa axis – years (1 – 1991, 2 – 1992, …, 2017), the ordinate axis is the potato yield, dt ha^{-1}.

These characteristics of the potato yield dynamics were calculated for each administrative district and used as an integral quantitative indicator of the crop yield variation at a given point in space over a certain period of time (Kunah *et al.,* 2018; Zhukov *et al.,* 2018). The symmetrical four-parameter log-logistic model was used calculated by means of the *drm* function from the *drc* package (Ritz *et al.,* 2015) for a language and environment for statistical computing *R* (R Core Team, 2020).

Climatic and soil characteristics

Bioclimatic data were applied according to the WorldClim version 2 database[2] (Fick and Hijmans, 2017). Climatic information is presented in the form of raster maps with a resolution of 1 km, which is sufficient for the study purpose. The bioclimatic variables represent ecologically significant aspects of annual temperature and precipitation changes. 19 bioclimatic variables were used for analysis (Zymaroieva *et al.,* 2021). The Box-Cox transformation to convert abnormal dependent variables to normal form was used (Osman *et al.,* 2014), which was implemented using the AID library for the statistical computing environment R (R Core Team, 2020).

The principal components analysis was used to reduce the dimensionality of climate matrices and soil properties. General linear models were used to test the significance of the influence of climate and soil variables on yield parameters. The principal components analysis of climate variables allowed to identify four main components, the eigenvalues of which are greater than one and which together explain 92.5% of the variability of climate variables (Zymaroieva *et al.*, 2021). Spatial variation of soil properties and soil classification were obtained from the SoilGrids database[3] (Hengl *et al.,* 2017; Zhukov *et al.,* 2017). To analyze the impact of soil factors on potato yields, the indicators such as soil organic carbon (SOC), pH, bulk density, sand, clay or silt content for different soil layers were used. As a result of the principal components analysis of soil variables, 6 principal components were identified with eigenvalues higher than one and which together explain 98.5% of the total variance of soil indicators (Zymaroieva *et al.,* 2021). Statistical analysis was performed using Statistica 10 software.

Landscape diversity indices

The 300 m GlobCover Landscape Type Map, based on the two-month MEdium Resolution Imaging Spectrometer (MERIS) (Ottlé *et al.*, 2013; Fritz *et al.*, 2015; Tsendbazar *et al.*, 2015; Pérez-Hoyos *et al.*, 2017), was used as a basis for creating a landscape diversity map. The landscape diversity was evaluated using the Shannon diversity index (Dušek and Popelková, 2017; Kunah *et al.*, 2018; Zhukov *et al.,* 2015). The diversity index was calculated for each focal pixel and the eight adjacent ones. Calculations were made using the Corridor Designer toolbox works in ArcGIS 10.1 (Majka *et al.,* 2007).

Along with landscape diversity, the distance between objects is important (McGarigal *et al.,* 2002; McGarigal *et al.,* 2012; Koshelev *et al.,* 2020). Natural protected areas (NPA) affect the productivity of the surrounding landscapes. Therefore, the distance to NPA was considered as a measure that reflects this influence (Chape *et al.,* 2005; Fedonyuk *et al.,* 2020). The distance between natural protected areas (NPA) and each pixel of the studied area was calculated. The average value of this index within administrative areas was used as a marker of the naturalness of the territory. Data about natural protected areas was obtained from https://opengeo.intetics.com.ua/osm/pa/ in the form of a shape-file. The distance was calculated using ArcGIS 10.1.

Results and discussion

Statistically significant regression dependences ($p < 0.05$) between agroecological predictors and potato yield parameters in the studied region of Ukraine were established (Table 1).

Table 1: Regression dependence of potato yield parameters on climatic and soil variables, as well as indicators of landscape diversity*

Predictors	Slope. $R_{adj}^2 = 0.26$	Lower Limit. $R_{adj}^2 = 0.57$	Upper Limit. $R_{adj}^2 = 0.54$	ED50. $R_{adj}^2 = 0.32$
Shannon (H)	–	-0.79 ± 0.27	-1.20 ± 0.28	1.18 ± 0.34

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[2] http://worldclim.org/version2

[3] https://soilgrids.org

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Predictors	Slope. $R_{adj}^2 = 0.26$	Lower Limit. $R_{adj}^2 = 0.57$	Upper Limit. $R_{adj}^2 = 0.54$	ED50. $R_{adj}^2 = 0.32$
H^2	–	0.94±0.28	1.28±0.30	–0.98±0.36
Distance (D)	–0.74±0.24	–	–	1.10±0.23
D^2	0.63±0.23	–	–	–1.14±0.22
Climate 1	–	–0.85±0.13	–0.78±0.14	–
Climate 2	0.26±0.10	0.20±0.08	–	–
Climate 3	–	–	–	–
Climate 4	–0.26±0.08	–	–0.13±0.06	–
Soil 1	–	0.23±0.10	–	–
Soil 2	–	–0.12±0.06	–0.19±0.06	–
Soil 3	0.28±0.09	–	–	–
Soil 4	–0.33±0.12	–0.65±0.09	–0.60±0.10	–
Soil 5	0.28±0.09	0.35±0.07	0.33±0.07	–
Soil 6	–	–	–	–

Note: Standardized regression coefficients are statistically significant for p <0.05
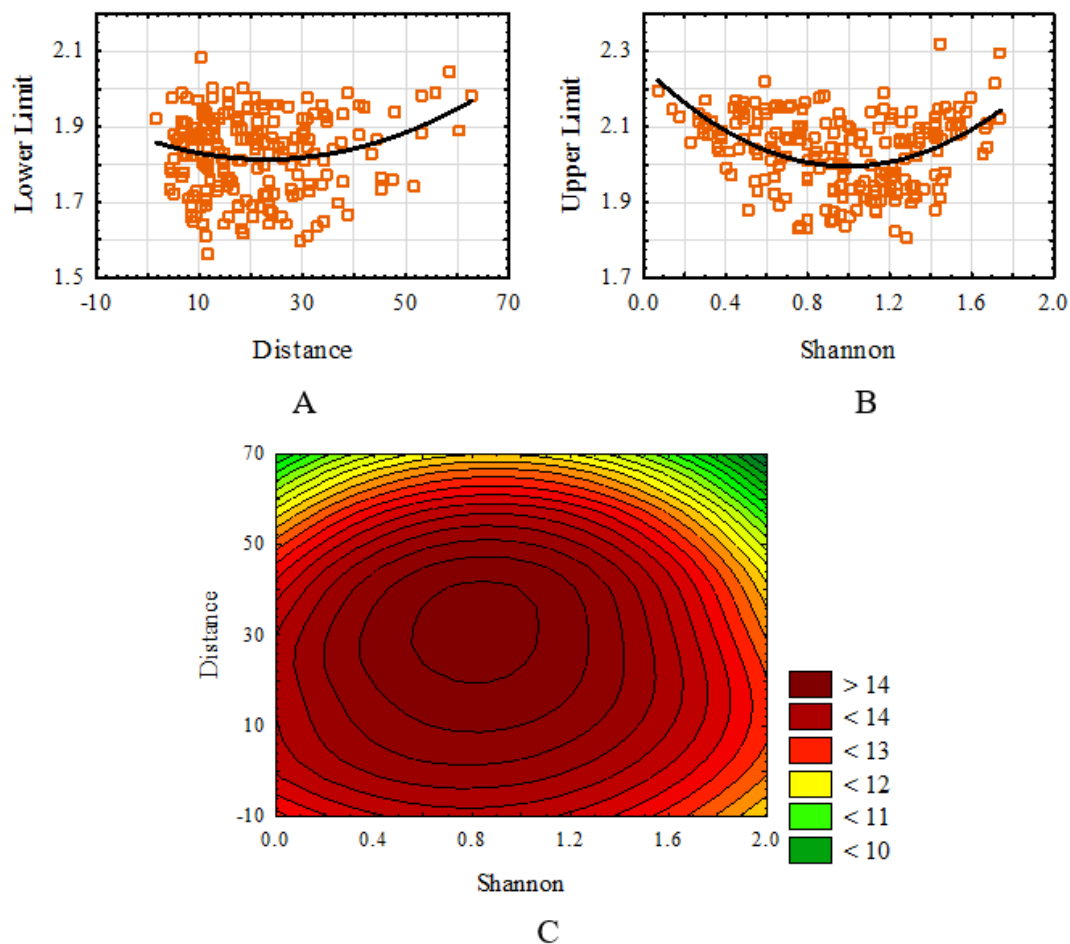

Figure 3: The dependence of the minimum level of potato yield on the average distance of the administrative district from the nearest natural protected area (Distance) (A), the maximum level of yield from the landscape diversity (Shannon) (B), and the dependence of ED50 on the landscape diversity and the distance NPA (C)

Notably, the level of landscape diversity plays an important role in varying potato yields (Table 1). Thus, the growth rate of potato yield is characterized by a nonlinear dependence on the distance to the NPA (Figure 3, A). The maximum and minimum potato yields are significantly affected by the diversity of landscape cover (Table 1, Figure 3, B). The lowest, highest yield levels and the slope of the trend model variate regularly with the changes both in the landscape-ecological diversity marked by the Shannon index changes and the distance to the nearest NPA. The pattern is non-linear, which indicates the presence of the optimal ratio of diversity in which there is the smallest decrease in crop yield ("largest" lowest yield) and the highest level of maximum yield. Similarly, there is an optimal value of the diversity and density of NPA for the highest slope of the model (the highest rate of yield increasing over time).

It is obvious that crop yield positively correlated with landscape diversity and density of NPA within units with a low level of these indicators. Nevertheless, under conditions of high landscape diversity and density of NPA potato yield decreases due to the predominance of the landscape cover types that are unfavorable for agriculture because of low soil fertility.

The value of the yield parameter ED50 by 32% is determined solely by landscape diversity (Table 1). The influence of landscape-ecological diversity and distance to natural protected areas on ED50 is shown in Figure 3, C. The symmetrical configuration of the figure indicates an independent influence of the landscape diversity and NPA density at the time of reaching half of potato yield maximum level. The western regions of the study area characterized by the largest values of ED50 (Figure 4).
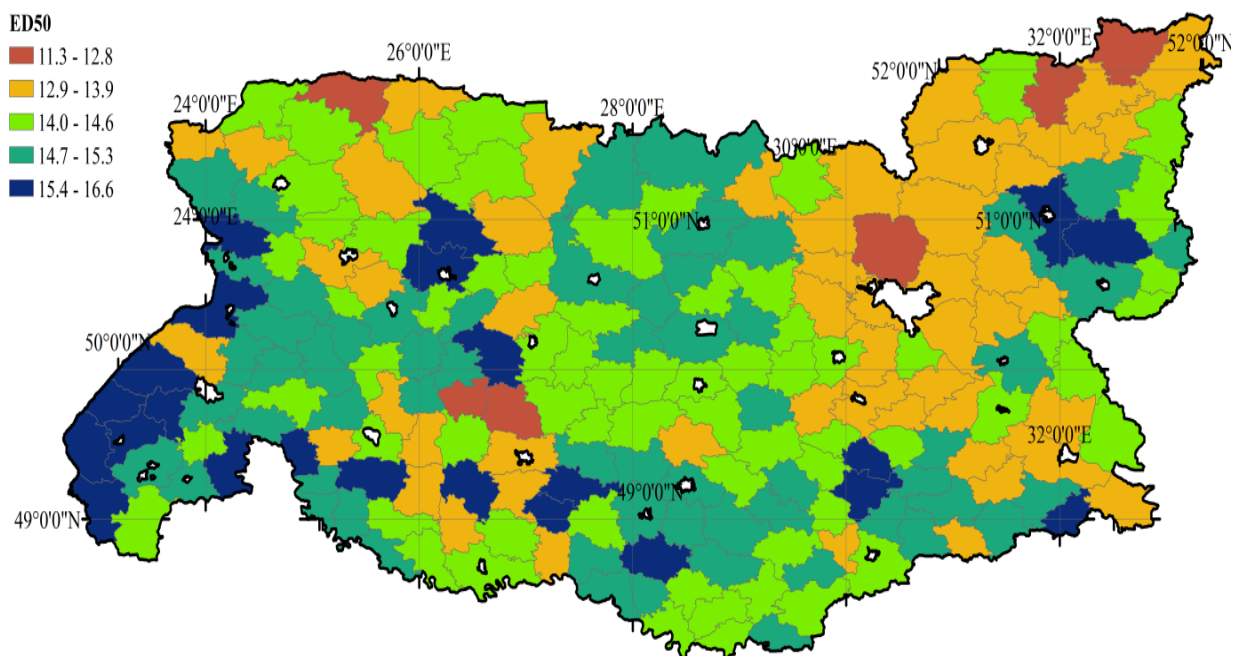

Figure 4: Spatial variation of the inflection time parameter (ED50) of the log-logistic model of potato yield dynamics

The study by Poveda *et al*. (2012) found a positive effect of landscape diversity on potato yields. Conservation of natural habitats in agricultural landscapes has been shown to be beneficial in providing "ecosystem services" such as reducing pest damage, increasing yields and increasing functional biodiversity (Cardinale *et al.*, 2003; Martin *et al.*, 2016). The simplification of agricultural landscapes through the increase in the cropped areas has caused the loss of habitats for many species that fulfill important ecosystem services such as crop pest regulation and potato yield (Poveda *et al*., 2012). Even though the yield variation

caused by the landscape diversity is insignificant, it may be a sufficient condition for the conservation of natural landscape elements within agricultural lands, due to their important ecological role.

The slope of the logarithmic curve, which determines the rate of yield growth is the parameter of the potato yield model that least dependent on agroecological factors (R_{adj}^2= 0.26). Nevertheless, the slope dependent on the soil principal components 3, 4, 5, and most correlates with the soil principal component 4 (R = –0.33 ± 0.12; p <0.05), which is responsible for the content of the silt fraction in the granulometric composition of the soil. That is, the lower the silt content in the soil. the faster the increase of potato yield. Potatoes are known to grow best on non-gleyed grey and sod-podzolic soils of different mechanical compositions (Fiers *et al.,* 2012). Heavy clay soils are unfavorable for potatoes (Johansen *et al.*, 2015). On such soils, especially in wet years, there is a risk of yield loss due to the rapid spread of plant diseases (Liao *et al.*, 2016; Shi *et al.*, 2019; Mugo *et al.*, 2020). Territorial units, where the rate of increase is higher, are in accordance with the predominance of light soils (Figure 1, Figure 5).
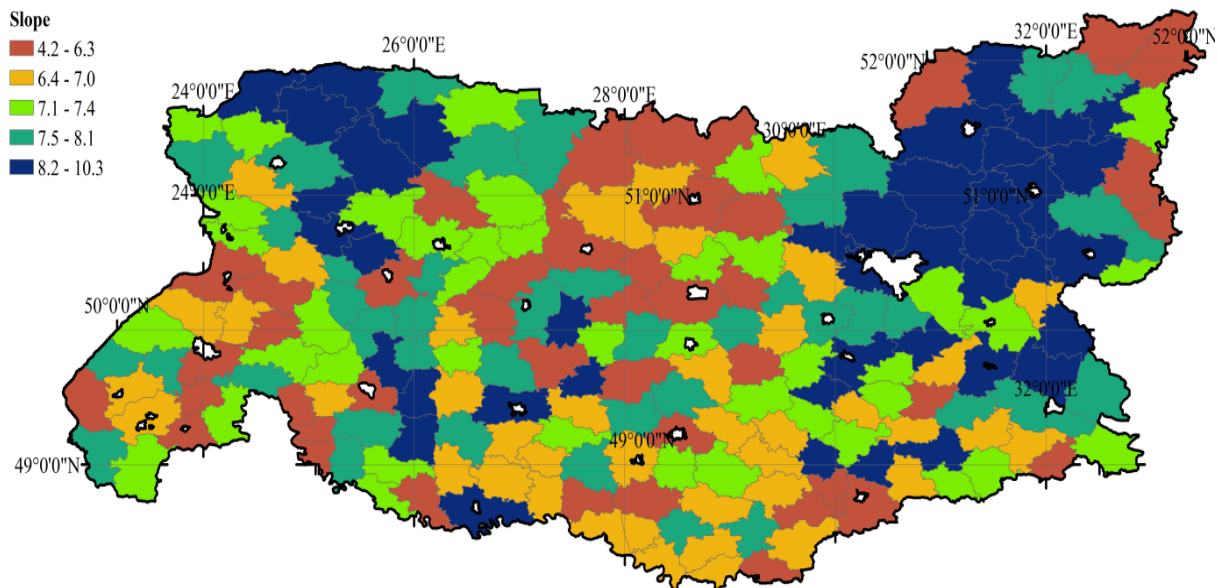

Figure 5: Spatial variation of the Slope parameter of the log-logistic model of potato yield dynamics

So, present study proves the fact that among the most influential factors driving potato yield variability between fields are soil texture components (sand, silt, clay), which in some cases have an even stronger impact on yield than the soil chemical properties (Redulla *et al.*, 2002). The lower and upper limits are the most sensitive potato yield parameters to ecological factors. The environmental factors determine 57% and 54% of the spatio-temporal variation of the lower and upper yield limit, respectively (Table 1). These potato yield parameters mostly depend on the climatic principal component 1 (R = – 0.85 ± 0.13 and R = –0.78 ± 0.14, respectively), which determines the climate continentality. Continentality reflects the most important climatic properties, such as the degree of variability of the annual temperature range. As continentality increases, summer temperatures rise, and winter temperatures fall (Driscoll and Fong, 1992). The soil principal component 4 is also a considerable determinant of lower and upper potato yield limits (R = – 0.65±0.09 and *R* = –0.60±0.10, respectively). The fact that these two parameters depend on the same ecological predictors, determines their similar spatial distribution (Figure 6).
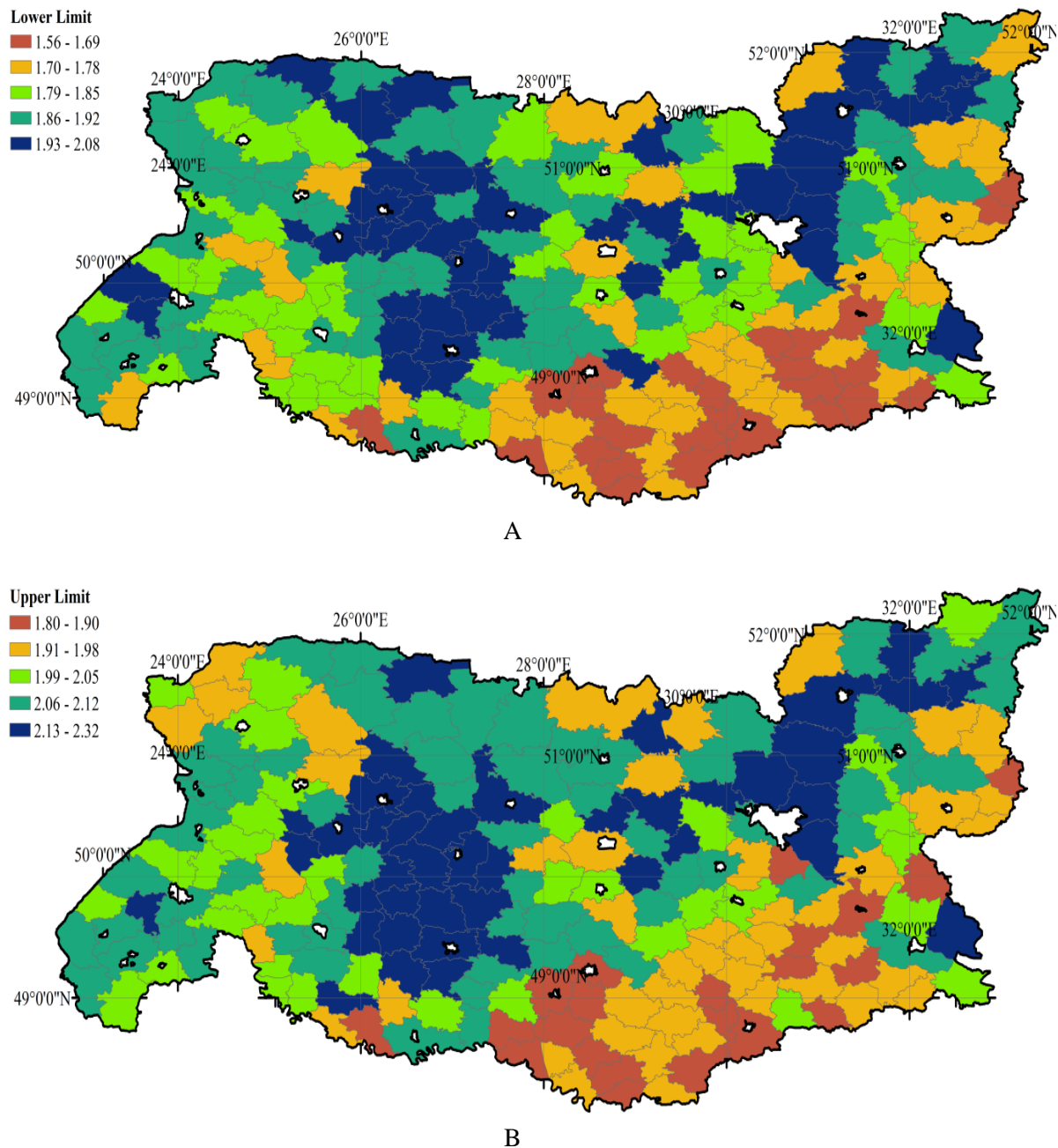
Figure 6: Spatial variation of the parameter of the lower limit (A) and upper limit (B) parameters of the log-logistic model of potato yield dynamics

Most of the potato farms in Ukraine are located on the black soils in the forest-steppe zone in central Ukraine, but the best yields are obtained in the Polissia wetlands of the north. The lowest potato yields both in the 1990s and at the current time are observed in the south-eastern regions of the country (Figure 6), which may be connected with the greater climate continentality of this area in particular. Analyses of historical climate data show an obvious trend towards increasing temperatures in Ukraine, and climate models predict further warming. especially regarding winter temperatures (IPCC, 2013). In other words, the climate became more continental in the Polissia zone of Ukraine (Zymaroieva *et al.,* 2021). The possible risks of such a climate change scenario will be the further research to be recommended.

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Conclusions

Potato yield is greatly determined by the diversity of landscape cover. The relationship between yield parameters and landscape-ecological diversity is non-linear, which determines the presence of optimal diversity of natural protected areas for the highest potato yields. Among climatic factors, the continental climate is of the greatest importance for potato yield, and among soil factors, the content of silt in the soil is the most influential factor, which obviously explains the higher potato yields in northern parts of Ukraine.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2	Author 3	Author 4	Author 5
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes	Yes
Collected the data	Yes	No	No	No	No
Contributed to data analysis & interpretation	Yes	Yes	Yes	Yes	Yes
Wrote the article/paper	Yes	No	No	No	No
Critical revision of the article/paper	Yes	Yes	Yes	Yes	Yes
Editing of the article/paper	Yes	No	Yes	No	Yes
Supervision	Yes	Yes	No	No	Yes
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