

Edaphoclimatic factors determining sunflower yields spatiotemporal dynamics in northern Ukraine[☆]

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Abstract – The climate and soil conditions have a significant impact on sunflower yields. Sunflower yield dynamics in the Central European mixed forests (Polissya) and Eastern European forest-steppe ecoregions in Ukraine from 1991 to 2017 was proved to fit a log-logistic model most adequately. The model has four characteristic parameters: the Lower Limit indicates the lowest level of yield over the study period; the Slope indicates the rate of yield increase over time; the ED50 is the time required to reach half of the maximum yield level and simultaneously the point with the highest rate of yield increase; the Upper Limit shows the highest yield level. The parameters of the yield model are used to meaningfully interpret the causes of yield dynamics. Edaphoclimatic factors account for 34 to 58% of the variation in the yield trend parameters. The soil texture and soil organic carbon (SOC) predominate among the edaphic factors that determine the variability of sunflower yield. Continentality of climate and degree of temperature variability during the growing season are the main climatic determinants of sunflower yield parameters.

Keywords: sunflower / yield / trend / climate / soil conditions

Résumé – Facteurs édaphoclimatiques déterminant la dynamique spatio-temporelle des rendements de tournesol dans le nord de l’Ukraine. Les conditions climatiques et pédologiques ont un impact significatif sur les rendements du tournesol. La dynamique du rendement du tournesol dans les écorégions de forêts mixtes d’Europe centrale (Polissya) et de forêts-steppes d’Europe orientale en Ukraine de 1991 à 2017 s’est avérée en adéquation avec un modèle log-logistique. Le modèle repose sur quatre paramètres caractéristiques : la limite inférieure indique le niveau de rendement le plus bas sur la période d’étude ; la pente indique le taux d’augmentation du rendement dans le temps ; l’ED50 est le temps nécessaire pour atteindre la moitié du niveau de rendement maximal et simultanément le point avec le taux d’augmentation du rendement le plus élevé ; la limite supérieure indique le niveau de rendement le plus élevé. Les paramètres du modèle de rendement sont utilisés pour interpréter de manière significative les causes de la dynamique du rendement. Les facteurs édaphoclimatiques représentent 34 à 58 % de la variation des paramètres de la tendance du rendement. La texture du sol et le carbone organique du sol (SOC) prédominent parmi les facteurs édaphiques qui déterminent la variabilité du rendement du tournesol. La continentalité du climat et le degré de variabilité de la température pendant la saison de croissance sont les principaux déterminants climatiques des paramètres de rendement du tournesol.

Mots clés : tournesol / rendement / tendance / climat / conditions pédologiques

[☆] Contribution to the Topical Issue “Sunflower / Tournesol”.

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1 Introduction

The world's food security is highly dependent on the rate of increase in yields of key crops (Grassini *et al.*, 2013). The global drivers of crop yields variability include technology, genetics, climate, soil, and field management practices (Kukal and Irmak, 2018; Kucharik and Ramankutty, 2005). The climate and soil conditions are the most important factors in agricultural productivity (Corwin *et al.*, 2003, Xiao *et al.*, 2015, Paixão *et al.*, 2020). It is widely believed that crop yields are highly sensitive to weather conditions. In particular, they depend on long-term trends and climate change (Nelson *et al.*, 2014). Thus, the recent trends in climate change were reported to have a major impact on crop yields, despite advances in cultivation technology (Iizumi and Ramankutty, 2016; Leng and Huang, 2017). Climate change is becoming an increasingly obvious threat to agriculture (Lesk *et al.*, 2016; Ureta *et al.*, 2019) as it causes temperature fluctuations, variations in the precipitation patterns, and more frequent extreme weather events (Schlenker and Roberts, 2009). Droughts and floods are predicted to become more frequent and intense in the near future (Lobell *et al.*, 2011; Fishman, 2016). There are many aspects of the global warming impact on agriculture. In particular, a minimal rise in temperature can increase yields in the temperate climates, while an extreme rise can lead to a decrease in yields (Lobell *et al.*, 2011). There is strong evidence that the frequency of extreme temperatures will increase in many regions of the world (Schlenker and Roberts, 2009). Therefore, it is important to understand how yields are affected by the changes in various climatic variables in order to develop more accurate yield predictions and appropriate adaptation and mitigation strategies (Lobell *et al.*, 2011; Ureta *et al.*, 2019).

The relationship between crop and soil is complex and depends on a variety of interactions between the physical and chemical properties of the soil and other external environmental factors (Sys *et al.*, 1991). A soil-plant interaction is considered to be the most significant factor contributing to the spatial variability of the crop yield (Corwin *et al.*, 2003). Despite the fact that many research publications have highlighted the influence of different soil properties on yield, a quantitative assessment of their contribution to the spatial variability of sunflower yield parameters has not yet been performed (Andrews and Carrol, 2001, Corwin *et al.*, 2003; Cox *et al.*, 2003, Rodrigues *et al.*, 2012; Fedoniuk *et al.*, 2020).

Sunflower (*Helianthus annuus* L.) is one of the top three oilseeds in the world (along with soybeans and rapeseed) and is one of the two most productive oilseeds in the European Union (along with rapeseed). According to a USDA report, Ukraine is now the world's number one producer of sunflowers, with a 29.3% share (40.57 million tons) of the world's total production of sunflowers (USDA, 2017). However, the environmental factors limit the average sunflower yield to between 1.5–3.0 t/ha. Although, according to a number of recent studies, the introduction of new high-yielding varieties and improvement of sunflower cultivation technologies for specific climatic zones will provide 2.9–3.5 t/ha of sunflower seeds (Melnyk *et al.*, 2018). It should be noted that further growth of global sunflower seed production is expected mainly from Ukraine without expansion of the cropland base. Therefore, understanding the

relationship between edaphic and climatic factors, on the one hand, and sunflower yields, on the other, might provide insights into yield forecasting and adaptation of this crop to predictable climatic changes.

In this study, we will focus on the three interrelated research questions: (1) what were the sunflower yield trends in Ukraine from 1991 to 2017; (2) whether the trend model parameters can be used to meaningfully interpret the causes of yield dynamics; and (3) what soil and climatic indicators are capable of predicting the spatial variation in sunflower yield parameters. The purpose of this study is to determine the contribution of edaphoclimatic factors to the spatial and temporal variation of sunflower yield parameters in the Central European mixed forests (Polissya) and Eastern European forest-steppe ecoregions in Ukraine.

2 Materials and methods

2.1 Yield data and study area

Sunflower yield data were retrieved from the State Statistics Service of Ukraine (<http://www.ukrstat.gov.ua/>). The time series data sets contain the average annual sunflower yields in 206 administrative districts of 10 regions of Ukraine (Cherkasy, Chernihiv, Khmel'nyts'kyi, Kiev, L'viv, Rivne, Ternopil', Vinnytsya, Volyn, Zhytomyr) for the period 1991–2017 (Fig. 1). The data represent the average yield values based on the spatial criterion without differentiation of soil water availability and fertility, irrigation management, cultivation and crop rotation. The study area is located in two natural vegetation and climate zones: the Forest zone (Polissya) and the Forest-steppe zone.

2.2 Selection of the yield dynamics model

Polynomials of different orders (Ray *et al.*, 2012) and a log-logistic model were considered to select the analytical form of the trend. The yield trends were analyzed using increasing order regression models for: an intercept-only model (constant) (Eq. (1)), a linear model (Eq. (2)), a quadratic model (Eq. (3)), a cubic model (Eq. (4)) and a quartic model (Eq. (5)):

$$Y_x = b, \quad (1)$$

$$Y_x = b + a_1x, \quad (2)$$

$$Y_x = b + a_1x + a_2x^2, \quad (3)$$

$$Y_x = b + a_1x + a_2x^2 + a_3x^3, \quad (4)$$

$$Y_x = b + a_1x + a_2x^2 + a_3x^3 + a_4x^4, \quad (5)$$

where: Y_x : crop yield at a certain period of time x ; b , a_1 , a_2 , a_3 , a_4 : coefficients.

We hypothesized that the sunflower yield trend can best be depicted by a sigmoid curve, namely a symmetric four-

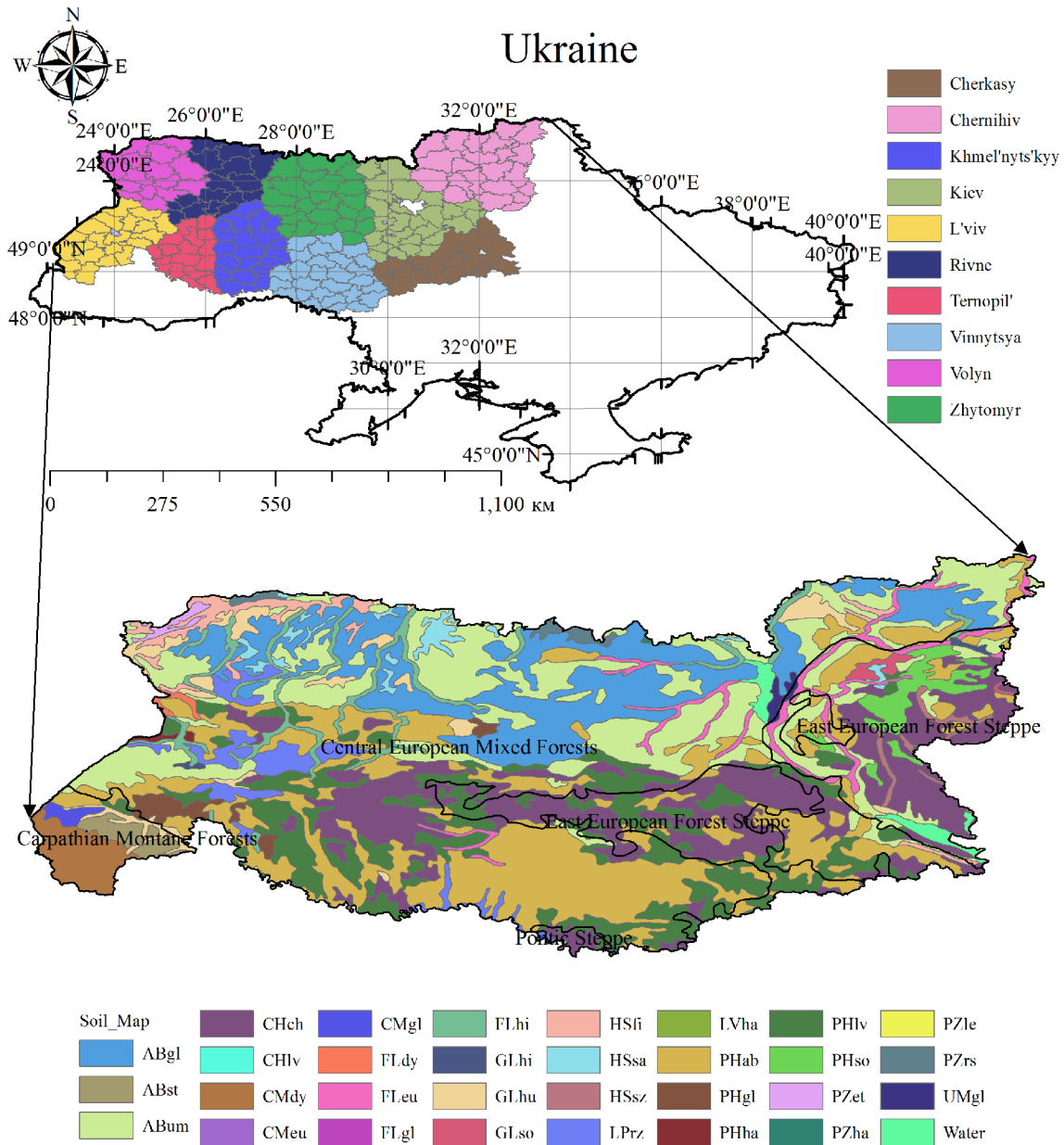


Fig. 1. Map of 10 administrative region in Ukraine, Ecoregions and soil map. Soil classification according World Reference Base for Soil Resources: ABgl–Albeluvisols Gleyic; ABst–Albeluvisols Stagnic; ABum–Albeluvisols Umbric; CHch–Chernozems Chernic; CHlv–Chernozems Luvic; CMdy–Cambisols Dystric; CMeu–Cambisols 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.

parameter log-logistic model (Eq. (6)):

$$Y = c + \frac{d - c}{1 + \exp(b(\log(x) + \log(ED50)))}, \quad (6)$$

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 half increase between the lower and upper limits). Lower Limit indicates the lowest level of yield over the study period; Slope – the slope of the trend curve, which shows the rate of change in yield over time; ED50–the time required to reach half of the maximum yield level, and the point with the highest rate of yield growth; Upper Limit – the highest level of yield, which at the present state of agricultural technology is determined by the biotic potential of the territory. The sigmoid

Table 1. Bioclimatic variables (according to <https://worldclim.org/data/worldclim21.html>).

Variable	Specification
bio_1	Annual Mean Temperature
bio_2	Mean Diurnal Range (Mean of monthly (temp _{max} –temp _{min}))
bio_3	Isothermality (bio_2/bio_7) (× 100)
bio_4	Temperature Seasonality (standard deviation × 100)
bio_5	Max Temperature of Warmest Month
bio_6	Min Temperature of Coldest Month
bio_7	Temperature Annual Range (bio_5–bio_6)
bio_8	Mean Temperature of Wettest Quarter
bio_9	Mean Temperature of Driest Quarter
bio_10	Mean Temperature of Warmest Quarter
bio_11	Mean Temperature of Coldest Quarter
bio_12	Annual Precipitation
bio_13	Precipitation of Wettest Month
bio_14	Precipitation of Driest Month
bio_15	Precipitation Seasonality (Coefficient of Variation)
bio_16	Precipitation of Wettest Quarter
bio_17	Precipitation of Driest Quarter
bio_18	Precipitation of Warmest Quarter
bio_19	Precipitation of Coldest Quarter

model is used to predict both the time effect of and the dose effect on the response being studied. Therefore, the parameter describing the inflection point of the sigmoid curve is traditionally designated as “ED50” (Ritz *et al.*, 2015).

The Akaike Information Criterion (AIC) developed by Akaike (1974) was used to estimate the compatibility of the statistical models (Eqs. (1)–(6)) with the observed data. AIC was computed for each of the six models (Eq. (7)):

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$$AIC = n \log \left(\frac{SS}{n} \right) + 2p, \quad (7)$$

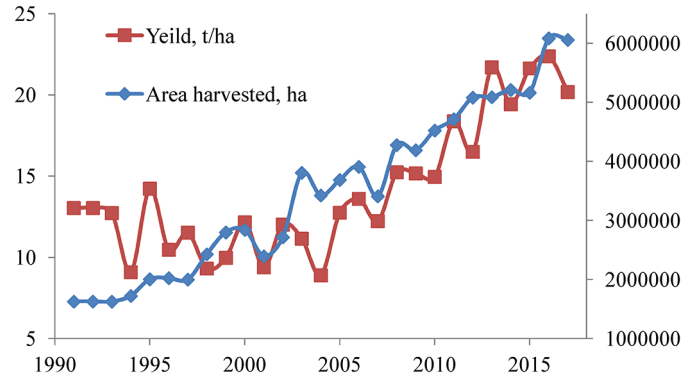
here, ss is the residual sum of squares, n is the sample size, and p is the number of parameters.

The best model to describe the yield dynamics per administrative district was the one with the lowest AIC. All calculations and data analyses were performed using R v 3.0.2 (R Development Core Team, 2018).

2.3 Edaphoclimatic characteristics

Bioclimatic data were retrieved from the WorldClim database version 2 (<http://worldclim.org/version2>) (Fick and Hijmans, 2017). The climatic information is presented in the form of raster maps with a resolution of 1 km, which is sufficient for the purposes of the study. The bioclimatic variables represent ecologically significant aspects of annual temperature and precipitation changes (Tab. 1).

Data on spatial variability of soil properties and information on soil classification were retrieved from the SoilGrids

**Fig. 2.** Dynamics of sunflower yields and area harvested in Ukraine in 1991–2017 (source – FAOSTAT, <http://www.fao.org>).

database (<https://soilgrids.org>) (Hengl *et al.*, 2017). The following indicators were used to analyze the influence of soil factors on yield: soil organic carbon (SOC), pH, soil bulk density, sand, clay or silt content in different soil layers.

3 Data analysis

The Box-Cox transformation was applied to transform non-normal dependent variables into a normal form, which was done using the AID library (Osman *et al.*, 2014) for a Language and Environment for Statistical Computing R (R Core Team, 2018). Principal component analysis was used for dimensionality reduction of climate and soil matrices. General linear models were employed to test the significance of the climate and soil influence on the yield parameters. Statistical analysis was performed using Statistica 10 software.

4 Results

4.1 Analysis of the spatial variation of yield trend parameters

Within Ukraine, the growth of sunflower cultivated areas during the study period was gradual, while the yield of this crop had a more complex dynamic (Fig. 2). The sunflower yield in the study region varied within a fairly narrow range until 2010, when there was a sharp increase with a peak in 2016 (Fig. 3). Along with the increase in yields, there was an expansion of cultivation areas, as sunflower became a strategically important crop for Ukraine (Zhygailo and Zhygailo, 2016; Melnyk *et al.*, 2018). The dynamics of sunflower yields in most administrative regions were best explained by the log-logistic model (Fig. 4). The parameters of the logistic model showed regular spatial patterns (Fig. 5), which were obviously caused in most cases by the spatial variability of edaphoclimatic factors. It is noteworthy that despite the higher average sunflower yields in the Forest-steppe ecoregion, Polissya exceeded it in the rate of yield growth (slope) (Fig. 5A). In accordance with the dependencies established in this work, both the minimum and the maximum sunflower yield levels were higher in the southern part of the study region (Forest-steppe) (Figs. 5C and 5D). Those areas,

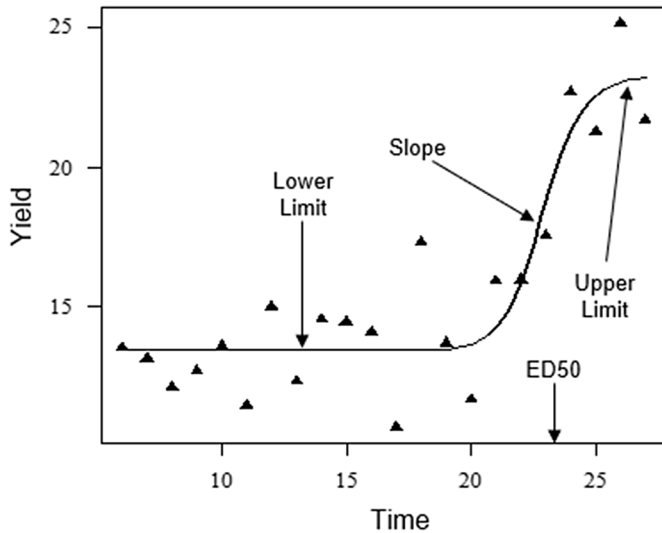


Fig. 3. Typical dynamics of the sunflower yield between 1991 and 2017 and its approximation by logistic model. The abscissa axis – years, the ordinate axis is the sunflower yield, $\text{dt} \cdot \text{ha}^{-1}$.

where the Upper Limit of sunflower yields was high (Fig. 5B), required longer periods of time to reach half of the maximum yield level (ED50), which is quite self-evident.

4.2 Principal component analysis of climatic variables

Principal component analysis allowed to identify four principal components, whose eigenvalues were greater than 1 and which together account for 92.5% of the total variance of climatic variables (Tab. 2). Principal component 1 (PC1) explains 54.45% of the total variance. PC1 was most strongly correlated with bioclimatic variable 8 (average temperature of the wettest quarter), bioclimatic variable 4 (temperature seasonality), bioclimatic variable 5 (maximum temperature of the warmest month), bioclimatic variable 10 (average temperature of the warmest quarter), bioclimatic variable 17 (precipitation of the driest quarter) and bioclimatic variable 18 (precipitation of the warmest quarter). The set of these variables indicates that PC1 can be interpreted as a characteristic feature of climatic continentality. The spatial variation of the values of PC1 in the latitudinal direction confirms our assumption (Fig. 6). Principal component 2 (PC2) accounts for 23.78% of the total variance. This component was most strongly correlated with bioclimatic variable 9 (mean temperature of the driest quarter), and 11 (mean temperature of the coldest quarter), which allowed PC2 to be interpreted as an indicator of temperature variability during extreme periods of the year. The northeastern and northern zones of the study area were clearly distinguished by the criterion of temperature extremity. Principal component 3 (PC3) accounts for 8.18% of the total variance. This component was most strongly influenced by bioclimatic variables 2 (mean diurnal range) and 3 (isothermality). These features reveal that PC3 indicates the degree of annual temperature variability. Principal component 4 (PC4) explains 6.03% of the total variance. PC4 was mostly determined by bioclimatic variable 2 (mean diurnal range), 6 (min temperature of the coldest month), and

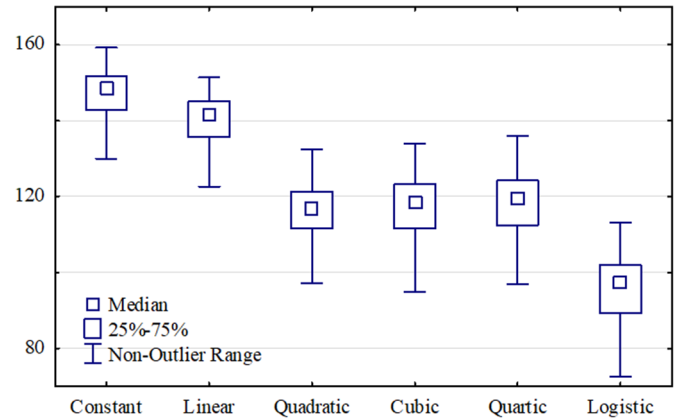


Fig. 4. The Akaike criterion for different models of the sunflower yield trend in administrative regions (N=206).

7 (temperature annual range). This component indicates annual temperature contrast.

4.3 Principal component analysis of soil properties

Principal component analysis (PCA) was performed to identify the soil indicators that have the greatest influence on the sunflower yield. The analysis revealed 6 principal components, which together explain 98.5% of the total variance of soil properties (Tab. 3). Principal component 1 (PC1) explains 65.63% of the total variance. PC1 correlated with most of the soil variables, but the highest correlation was observed with the sand, clay, and silt content. Consequently, PC1 is an indicator of granulometric composition and is most sensitive to the sand content. The spatial variation of this principal component is shown in Figure 7. The territories with the predominance of the sand fraction in the soil are located in the north of the studied region (Polissya). Principal component 2 accounts for 14.5% of the total variance. This component most closely correlates with the soil bulk density. The mapping of principal component 3 indicates a complexity of the spatial configuration of soils with different soil bulk densities (Fig. 6). PC3 explains 6.4% of the total variance of soil variables. PC3 was most strongly affected by SOC. Principal component 4 accounts for 5.69% of the total variance. PC4 was significantly correlated with the silt content in the soil. Soils with the highest silt content are located in the south and southwest of the study area, where there is also a very high content of SOC. Principal component 5 accounts for 3.88% of the total variance of soil variables, showing the strongest correlation with soil acidity (pH) and having higher values in the northeast of the study region. Principal component 6 accounts for 2.41% of the total variance and is most sensitive to the silt and clay fractions. The territories with higher PC6 indices are located in the south of the region.

4.4 Variation in parameters of yield models explained by edaphoclimatic factors

The results of the regression analysis showed that the climatic and edaphic principal components can explain from 34 to 58% of the variation in sunflower yield parameters

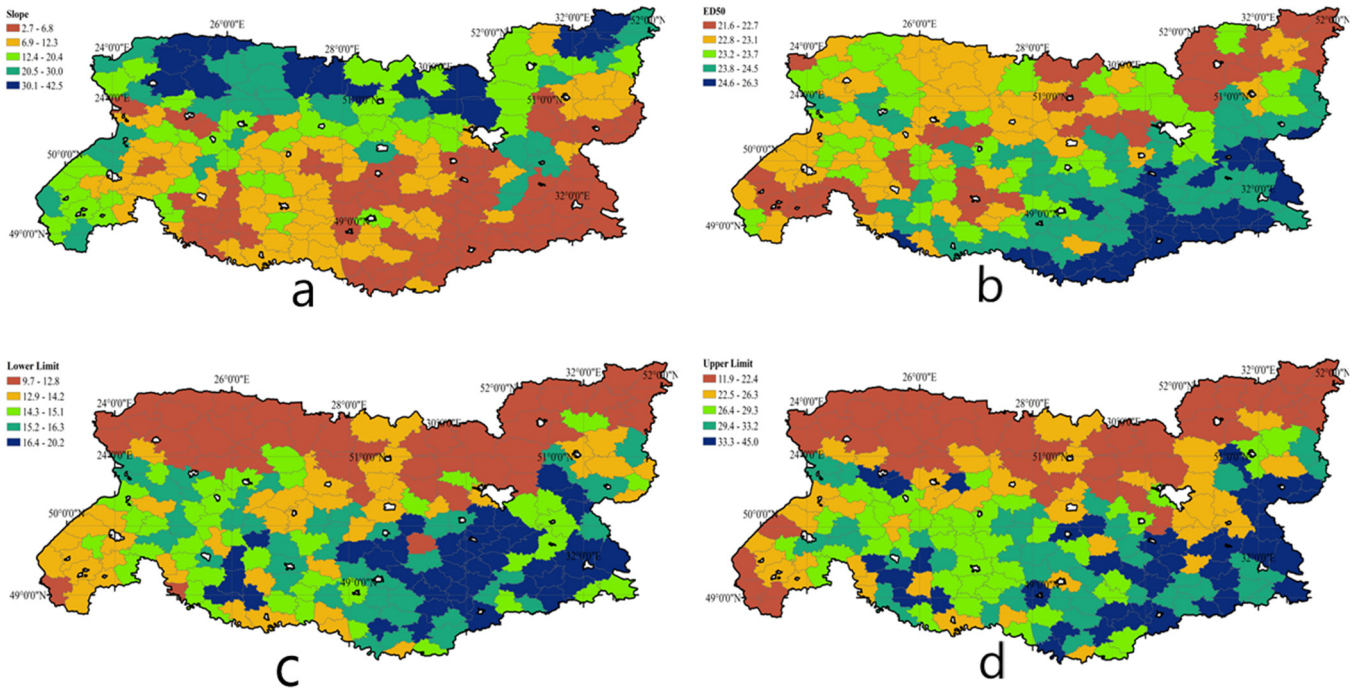


Fig. 5. Spatial variation of parameters of the sunflower yield dynamics log-logistic model: a: Slope; b: ED50; c: lower limit; d: upper limit.

Table 2. The principal component analysis of bioclimatic variables.

Variable	Principal components			
	PC 1	PC 2	PC 3	PC 4
bio_1	0.34	0.70	0.20	–
bio_2	–	0.29	0.80	0.62
bio_3	–0.70	0.64	0.48	–
bio_4	0.90	–0.59	–	0.22
bio_5	0.91	–0.17	0.16	0.26
bio_6	–0.55	0.85	–0.14	–0.49
bio_7	0.84	–0.59	0.17	0.43
bio_8	0.92	–0.31	–	–
bio_9	–0.42	0.86	0.15	–0.27
bio_10	0.91	–	–	–
bio_11	–0.53	0.94	–	–0.24
bio_12	–0.79	–	0.24	–
bio_13	–0.87	–	0.20	–
bio_14	–0.28	–0.62	0.42	–
bio_15	–0.70	0.50	–	0.44
bio_16	–0.90	–	0.20	–
bio_17	–0.90	–	0.20	–
bio_18	–0.89	–	0.19	–
bio_19	–	–0.54	0.35	–0.26
Eigenvalue	10.35	4.52	1.55	1.15
% total variance	54.45	23.78	8.18	6.03

The correlation coefficients statistically significant at $p < 0.05$ presented only.

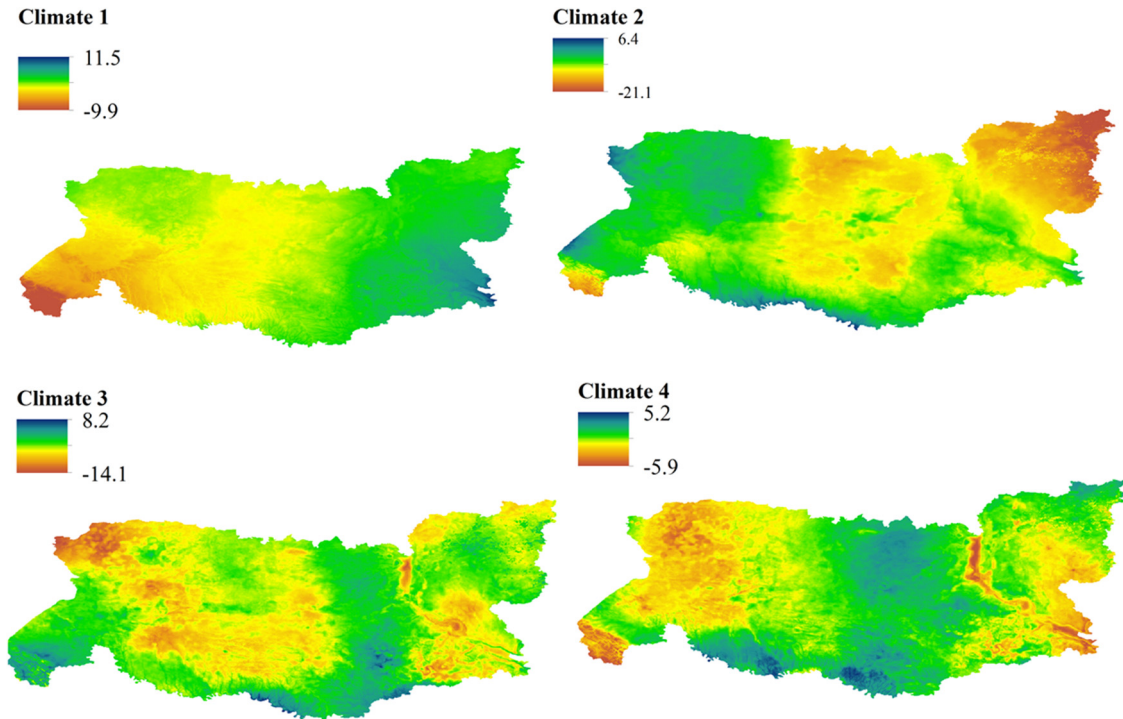


Fig. 6. Spatial variation of bioclimatic principal components.

(Tab. 4). Soil principal components 1 and 2 were the most important factors that determine the growth rate of sunflower yield (slope of the curve) (Tab. 4). Granulometric composition, which was explained by PC1, was the most important soil property determining a dynamic yield behavior. The relationship between the Slope parameter of the sunflower yield trend and edaphic PC1 may be described by the regression coefficient which was found to be equal $R=0.67\pm 0.09$, $P<0.01$. The climatic factors of temperature variability (climate principal components 2 and 3) have a much less impact on this parameter of the sunflower yield trend than the soil factors. The Lower Limit of sunflower yield was the most sensitive parameter of the sunflower yield trend to the effects of edaphic and climatic factors ($R_{adj2}=0.58$, $F=28.9$, $P<0.001$) (Tab. 4). This sunflower yield trend parameter was influenced by both climatic and edaphic factors. Among the climatic factors, PC1-climatic was the most important component (regression coefficient was 0.41 ± 0.09 , $P<0.01$), as well as with the edaphic factors PC1-edaphic was also the most significant one (regression coefficient was -0.59 ± 0.09 , $P<0.01$). A complex combination of climatic factors influenced the maximum sunflower yield parameter (Upper Limit) (Tab. 4). The abovementioned principal components are orthogonal variables, and thus statistically independent. Nevertheless, they all determined the Upper Limit of this crop yield. The predominant factors proved to be climatic continentality and degree of temperature variability. Among the soil properties, SOC was the most important factor that determined the upper limit of sunflower yield. The ED50 parameter showed sensitivity to almost the same factors as did the upper yield limit. ED50 was largely determined by climatic

PCs 1 and 3. The most important climatic factor for changes in this parameter, as well as for other sunflower yield parameters, was climatic continentality. In addition, the ED50 parameter was influenced by the SOC and the soil bulk density.

5 Discussion

5.1 The importance of a wide coverage of yield data for predicting the effects of global climate change in agriculture

The global climate change is causing significant transformations in agricultural practices (Bhadouria *et al.*, 2019). Prediction of such transformations can be based on retrospective studies of crop yields, which assumes a wide geographical coverage of territories (Challinor *et al.*, 2014; Iizumi *et al.*, 2017). This approach assumes that spatial climatic features can be a simulation model of future climate change over time (Schär *et al.*, 1996). Conditions that are observed in some period of time in the south will be observed over time in more and more northern areas (in the southern hemisphere – exactly the opposite). In addition to the trend of modal climatic characteristics (average temperature, total precipitation), which predominantly change in latitudinal direction, the variability of climatic conditions during a year or a growing season will be of particular importance. This variability is very close to such geographical phenomenon as continentality. The continentality in its turn changes gradually in the longitudinal direction. Thus, prediction of trends in agriculture under global climate change requires substantial data on crop yields over a significant temporal and spatial range.

Table 3. The principal component analysis of soil variables.

Variable	Layer, cm	Principal components					
		PC 1	PC 2	PC 3	PC 44	PC 5	PC 6
SOC	0–0.05	0.71	0.59	0.31	–	0.32	–
	0.05–0.15	0.41	0.86	0.21	–0.14	0.42	–
	0.15–0.3	0.19	0.90	0.41	–0.15	0.49	–
	0.3–0.6	0.24	0.84	0.52	–0.26	0.48	0.16
	0.6–1	0.38	0.78	0.49	–0.22	0.50	0.14
	1–2	0.38	0.79	0.43	–	0.53	0.14
pH	0	–0.86	–	–	–0.32	0.23	–
	0–0.05	–0.91	–	0.17	–0.14	0.18	–
	0.05–0.15	–0.91	–	0.18	–0.14	0.19	–
	0.15–0.3	–0.89	–	0.15	–0.15	0.19	–
	0.3–0.6	–0.88	–	0.25	–0.22	0.19	–
	0.6–1	–0.83	–	0.32	–0.29	0.21	–
Bulk density	1–2	–0.82	–	0.33	–0.29	0.21	–
	0	–0.82	–0.32	–	–	–0.17	0.14
	0–0.05	–0.57	–0.63	0.26	–	–	–
	0.05–0.15	–0.27	–0.75	0.34	–	–	–
	0.15–0.3	–	–0.78	0.28	0.31	–	–
	0.3–0.6	0.41	–0.63	–	0.39	–	0.22
Sand	0.6–1	0.81	–0.29	0.29	0.16	–	0.22
	1–2	0.81	–0.31	0.30	–	–	0.20
	0	0.98	–	0.34	–0.19	–0.14	–
	0–0.05	0.98	–	0.35	–0.19	–0.14	–
	0.05–0.15	0.98	–	0.34	–0.19	–0.14	–
	0.15–0.3	0.98	–	0.33	–0.18	–0.14	–
Clay	0.3–0.6	0.98	–	0.32	–0.17	–0.15	–
	0.6–1	0.98	–	0.32	–0.16	–0.15	–
	1–2	0.98	–	0.32	–0.16	–0.14	–
	0	–0.97	–	–0.19	0.20	–	0.16
	0–0.05	–0.97	–	–0.19	0.20	–	0.17
	0.05–0.15	–0.96	–	–0.18	0.21	–	0.18
Silt	0.15–0.3	–0.97	–	–0.16	0.21	–	0.18
	0.3–0.6	–0.96	–	–0.19	0.26	–	0.19
	0.6–1	–0.95	–	–0.20	0.28	–	0.18
	1–2	–0.95	–	–0.23	0.30	–	0.18
	0	–0.94	–	–0.34	0.37	0.18	–0.22
	0–0.05	–0.94	–	–0.34	0.37	0.18	–0.22
Silt	0.05–0.15	–0.94	–	–0.34	0.37	0.18	–0.23
	0.15–0.3	–0.94	–	–0.34	0.35	0.18	–0.23
	0.3–0.6	–0.95	–	–0.30	0.31	0.20	–0.24
	0.6–1	–0.95	–	–0.29	0.29	0.20	–0.24
	1–2	–0.96	–	–0.28	0.29	0.20	–0.23
	Eigenvalue	28.49	6.29	2.78	2.47	1.69	1.05
	% Total variance	65.63	14.50	6.40	5.69	3.88	2.41

The correlation coefficients statistically significant at $p < 0.05$ presented only.

5.2 Non-stationarity of agricultural production in Ukraine for the last 30 years

A possibility of prediction is based on the stationarity of the process to be predicted (Gyöfi and Lugosi, 2002; Ryabko and Hutter, 2008). Abrupt changes in the dynamics of the

process indicate its qualitative transformation, which makes it difficult or impossible to use retrospective data. Crop yield dynamics studies tend to refer to countries that have been developing systematically without catastrophic socio-economic crises. Recently, the long-term trends in crop yields on a global scale have been extensively studied around the world

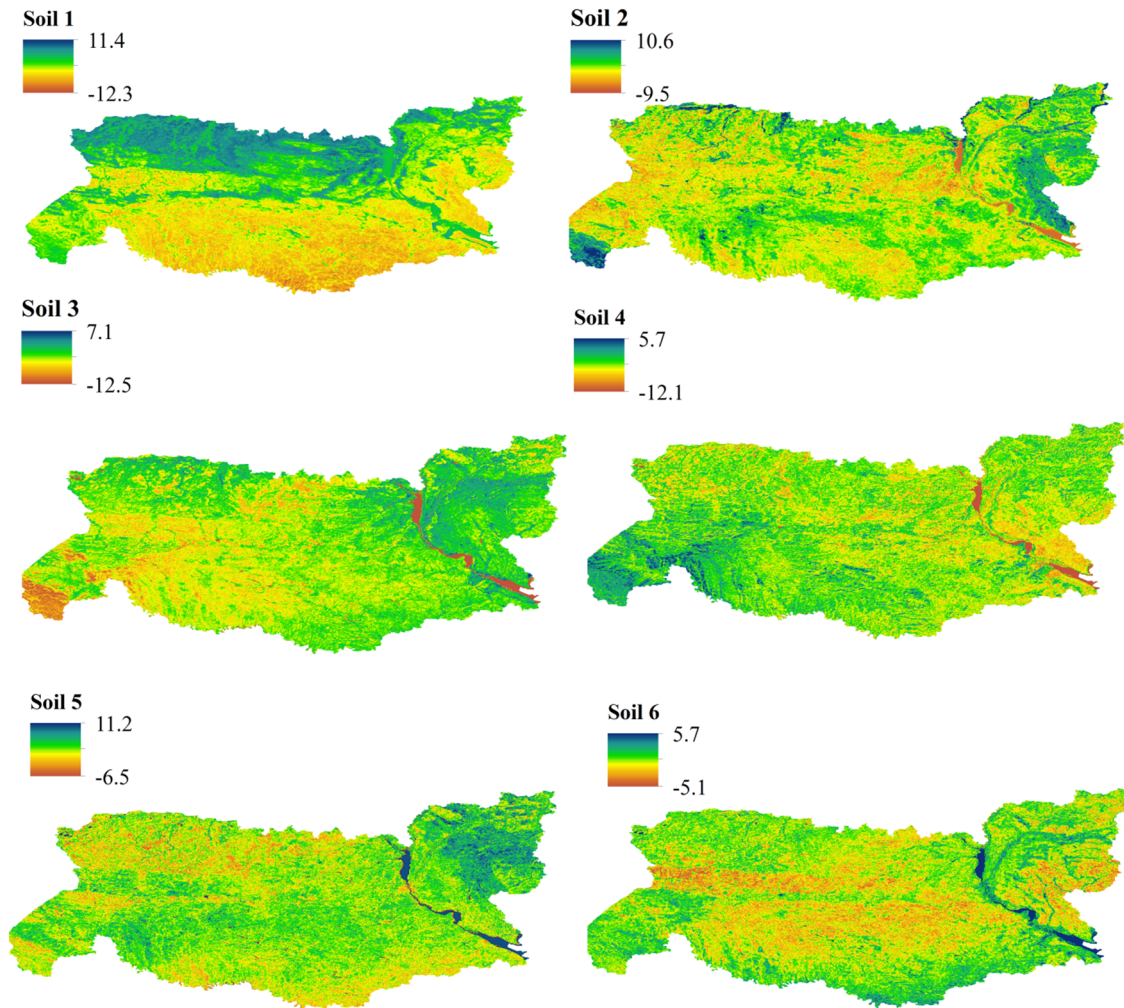


Fig. 7. Spatial variability of soil principal components 1–6.

Table 4. Regression dependence of the sunflower yield parameters on the climate and soil variables*.

Predictors	Parameters of the sunflower yield trend			
	Slope $R_{adj}^2 = 0.43$, $F = 16.7$, $p < 0.001$	Lower Limit $R_{adj}^2 = 0.58$, $F = 28.9$, $p < 0.001$	Upper Limit $R_{adj}^2 = 0.34$, $F = 11.7$, $p < 0.001$	ED50 $R_{adj}^2 = 0.37$, $F = 11.6$, $p < 0.001$
	Climate principal components			
Climate_1	–	0.41 ± 0.13	0.56 ± 0.13	0.54 ± 0.13
Climate_2	0.16 ± 0.08	–	0.19 ± 0.08	0.17 ± 0.08
Climate_3	-0.14 ± 0.06	–	0.30 ± 0.07	0.38 ± 0.07
Climate_4	–	–	-0.15 ± 0.07	-0.18 ± 0.07
	Edaphic principal components			
Soil_1	0.67 ± 0.09	-0.59 ± 0.10	-0.17 ± 0.08	–
Soil_2	0.12 ± 0.05	–	–	0.20 ± 0.07
Soil_3	–	–	0.24 ± 0.09	-0.33 ± 0.05
Soil_4	–	–	–	–
Soil_5	–	–	–	–
Soil_6	–	0.26 ± 0.07	-0.15 ± 0.07	–

*Note: Standardized regression coefficients, statistically significant at $P < 0.01$.

(Godfray *et al.*, 2010; Ray *et al.*, 2012; Lesk *et al.*, 2016). In particular, Chen (2018) demonstrated the application of a mathematical method in the analysis of spatial patterns in the long-term temporal yield trends of three major crops (rice, wheat, and soybeans) in Japan. Yield trends in the prefectures of Japan were divided into four types: Intercept-only model, Linear model, Quadratic model and Cubic model (Chen, 2018). In our previous study, it was found that the general trends in the yield of major crops in Ukraine for the period 1990–2017 best fitted the fourth order polynomial (Quartic model) (Kunah *et al.*, 2018, Zymarioieva *et al.*, 2019, Zymarioieva *et al.*, 2020a). During the study period, the sunflower yield tended to increase, except for the initial stage of research (1991–1997), when there was a rapid decrease in the crop (Zymarioieva *et al.*, 2019b). However, the used polynomials of increasing order cannot satisfactorily describe the observed dynamics of crop yields in Ukraine after the collapse of the USSR (Zhukov *et al.*, 2018). In addition, the parameters of such models, with the exception of the linear model, cannot be meaningfully interpreted, so there is no reason to use polynomial models to explain them with climatic or edaphic factors. Considering the dynamics of yield from the mid-90s to the current time, it can be depicted by a sigmoid curve, namely a log-logistic curve. Thus, in this study we showed that a symmetric log-logistic model most adequately reflects the dynamics of sunflower yield. This type of curve includes certain characteristic stages which meaningfully reflect the properties of the observed sunflower yield dynamics, namely: a) stagnation at the initial stage with a significant yield variability; b) a sharp growth in the middle part of the study period; c) stabilization of the growth in the last third of the study period, and in some cases reaching a plateau. These stages differ in their genesis, in which the ratio of economic and environmental factors changes over time. Of course, the initial stage was the result of the destruction of economic relations in agriculture caused by the collapse of the Soviet Union. Due to formation of market-based relations in agriculture, its efficiency was restored, which manifested itself in the growth of crop yields, including sunflowers. In the last third of the period under study, the maximum yields were achieved under the given level of agricultural technology and environmental conditions. The fourth-order nonlinear model made it possible to describe the above steps with the help of appropriate model parameters to which we attach a special significance. The model parameters correlate with climatic and edaphic predictors, which allowed us to find that the nature of the influence of environmental factors was different at each stage of the study period. The novelty of our approach is that to describe the dynamics of sunflower yield we applied a model, the parameters of which can be meaningfully interpreted and their spatial and temporal dynamics can be explained by the climatic and edaphic predictors.

5.3 Soil determinants of sunflower yields

Soil has a significant degree of resilience, so this component of the landscape is very stable under conditions of global climate change (Kunah *et al.*, 2019; Pakhomov *et al.*, 2019). Of course, climate is the most important factor of soil formation, so the soil will also be affected by global climate change. When predicting changes in sunflower yields, the role of soil conditions is considerable. The importance of soil

conditions for a particular crop can vary greatly depending on climatic conditions. Ion *et al.* (2015) concluded that soil and climatic conditions are among the environmental factors that have the greatest influence on sunflower yield. Among soil properties, soil granulometric structure and SOC are paramount. These findings are in accordance with our study results, indicating that under Ukrainian conditions, sunflower is quite sensitive to edaphic and climatic factors, which can explain from 34 to 58% of the variations in the parameters of the crop yield dynamics. It should be noted that sunflowers are adaptable to a wide variety of soils and are even successfully cultivated on sandy soils (Hamza and Safina, 2015), nevertheless, the crop gives the best results on good soils suitable for growing corn or wheat (Radanielson *et al.*, 2012). Our study confirmed that sunflower yields positively correlated with the SOC, which directly reflects soil fertility. However, the Upper Limit of sunflower yields was higher in the areas dominated by sandy soils. This may be due to the expansion of sunflower cultivation areas in Polissya, where soils with a high content of the sandy fraction are widespread. The possibility of such expansion is due to a significant warming of the climate, which provides the temperature conditions necessary for this crop in the more northern areas of Polissya. Undoubtedly, improvement of agricultural technology is a prerequisite for increasing the area of sunflower cultivation (Zymarioieva and Zhukov, 2020). It should be noted that a high proportion of the sand fraction should be combined with a high content of organic matter in the soil. Only under these conditions, a significant increase in the Upper Limit of sunflower yield can be expected. Such a combination of soil properties can be found in the floodplain soils of the region. The edaphoclimatic determinants of ED50 (the time that is required to achieve half of the maximum yield level) demonstrate a marked similarity with the Upper Limit determinants, which confirms these parameters close correlation.

5.4 Climate determinants of sunflower yields

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). Our study proved that continentality is the main climatic factor determining the spatial variability of sunflower yield. A higher level of continentality is associated with higher summer temperatures, which positively affects both the Lower and Upper Limits of the sunflower yield trend. This is quite consistent, given the increasing requirements of this crop to the temperature conditions during the reproductive growth period (Esmali *et al.*, 2012, Zhygailo and Zhygailo, 2016). All parameters of the yield trend, with the exception of the Slope, showed a dependence on the degree of temperature variability. The annual temperature variability is the result of temperature increase in the summer time period, which is critical for sunflower vegetation. The results obtained can be explained by physiological and environmental reasons. Physiology of yield expression in sunflower indicates that the germination rate of sunflower seeds increases exponentially between 3 and 30 °C, and the maximum percentage of germination is maintained

between 6 and 23 °C. The germination rate decreases rapidly at temperatures above 25 °C. Sunflower seeds are severely damaged and germination deteriorates at 37–40 °C (Connor and Sadras, 1992). The favorable temperatures for sunflower growth are in the range of 20–25 °C (Fernández-Luqueño *et al.*, 2014), so an increasing continentality of the climate contributes to the possibility of achieving optimal temperature conditions for sunflower growth. However, temperatures above 25 °C and frosts at any stage of growth, which are also signs of the climate's continentality, reduce the yield and oiliness of the seeds (Thomaz *et al.*, 2012). Most of the sunflowers are cultivated under rain-fed conditions in Ukraine. Although sunflowers are capable of adapting to dry conditions (Gürkan *et al.*, 2020), precipitation rate is considered one of the most effective climatic factors in sunflower cultivation under rain-fed conditions (Barros *et al.*, 2004). We found that the precipitation during the driest and warmest quarters also determines sunflower yield. This confirms that sunflower yield is subject to drought stress during the main growing and flowering periods.

Analyses of historical climate data, shows an obvious trend towards increasing temperatures in Ukraine, and climate models predict further warming, especially with regard to winter temperatures. Moreover, the amount of precipitation in the southern steppe zone of Ukraine decreased during 1961–2009 (Morgounov *et al.*, 2013). According to the forecasts of the Intergovernmental Panel on Climate Change (IPCC, 2013), temperatures in grain-producing regions of Ukraine will rise, with the greatest increases expected in the winter months. Summer precipitation is likely to decrease while winter precipitation is predicted to increase. Droughts may become more probable and long-lasting (Lioubimtseva and Henebry, 2012). Such climatic changes are expected to lead to a decrease in the sunflower yield in the steppe zone of Ukraine, which has already been confirmed for Turkey (Gürkan *et al.*, 2020), but at the same time, yields will increase in the Polissya (northern) region, where the climate is already more continental. Studying the possible effects of climate change on the future of sunflower crop cultivation in Ukraine will be the purpose of our further research.

5.5 Prospects for further research and practical recommendations

The global climate changes have a significant impact on the variability of climatic regimes. These circumstances require constant agro-ecological monitoring of crop yields, including sunflowers. Recording the sunflower yield per administrative district in Ukraine provides a significant amount of information, but this spatial level of accuracy of monitoring is not acceptable. Note that the boundaries of administrative districts do not coincide with the boundaries of natural landscape units, which greatly complicates the interpretation of the data obtained. The main argument in favor of yield accounting at the level of administrative districts is the possibility to compare the obtained information with the economic indicators, which correlate with administrative division of the territory. In this regard, assessment of economic factors in view of spatial and temporal variability of sunflower yield is of particular interest.

Long-term climate forecasts may become the basis for assessing the future prospects of sunflower cultivation in the north of Ukraine. The data we obtained also emphasize the importance of soil conditions. Therefore, we consider studies of the impact of climate change on soil cover and consequently on sunflower yields to be a very promising area of research. Sunflower itself is also a crop that substantially affects the soil, so the mutual influence of soil and sunflower in the context of global climate change is a perspective for further research.

The solution of these problems requires an effective system of agro-ecological monitoring, the creation of which can be considered as a practical recommendation. The procedures available in Ukraine for collecting agronomic, climatic and soil data are not linked into a comprehensive information system, whose setting up will provide adequate and balanced management decisions in the context of global climate change.

6 Conclusions

The present study reveals a statistically significant dependence between the edaphic and climatic factors and the parameters of the sunflower yield model in the north of Ukraine. It was found that the dynamics of sunflower yield in the studied area can be most adequately described by a log-logistic model. The parameters of the trend model (the Lower Limit, the Slope, the Upper Limit) are spatially dependent and can be used for a meaningful interpretation of the causes of sunflower yield dynamics. The study showed a significant influence of edaphoclimatic factors on sunflower yield parameters. The ratio of granulometric fractions and soil organic carbon (SOC) is the most important soil indicator, which closely correlates with the sunflower yield dynamics. The main climatic drivers of sunflower yields are changes in climate continentality.

Supplementary Material

The Supplementary Material is available at <http://www.ocl-journal.org/10.1051/oc/2021013/olm>.

Conflicts of interest. The authors declare that they have no conflicts of interest in relation to this paper.

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