THE RELATIONSHIP BETWEEN LANDSCAPE DIVERSITY AND CROPS PRODUCTIVITY: LANDSCAPE SCALE STUDY

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ABSTRACT

The present study evaluates the relationship between the crops productivity and ecosystem diversity. The spatial variability in ecosystem diversity was measured using the Shannon landscape diversity index and distance from biodiversity hotspots that are nature conservation areas. Three crops were selected for the study: soybeans, sunflowers and winter rye. The initial data included the average crops yields in administrative districts within 10 regions of Ukraine. It was found that the studied crops yield dynamics from the mid-90s of the previous century to the current period could be described by a sigmoid curve (log-logistic model). The parameters of the yield model are the following indicators: the minimum level of yield (Lower Limit); maximum level of productivity (Upper limit); the slope of the model, which shows the rate of change in yields over time; ED50 - the time required to achieve half, from the maximum yield level. Our studies have shown that there is a statistically significant regression relationship between the yield parameters of all the studied crops and biodiversity, even at the landscape level. Among the studied crops, soybean shows the strongest regression relationship between yields and indicators of landscape diversity. Sunflower yield is the least dependent on landscape diversity. Most of the established dependencies are nonlinear, which indicates the existence of an optimal level of landscape diversity to achieve the maximum possible crop yields. Therefore, the obtained patterns can be the basis for land-use planning and management, especially while creating new natural protected areas.

Keywords: sunflower, soybean, winter rye, yield, landscape diversity.

INTRODUCTION

In recent decades, agricultural management has transformed previously heterogeneous landscapes into monocultures, leading to degradation and local depletion of natural landscape elements (NLEs) (Tilman *et al*., 2001; Vitousek *et al*., 1997). However, natural landscape elements are valuable habitats and sources of food resources for many animals, such as invertebrates and birds (Amy *et al*., 2015; Fuller *et al*., 1995), which provide a range of "ecosystem services" such as biological pest control (Chaplin-Kramer *et al*., 2011; Woodcock *et al*., 2016) and plant pollination (Hipólito *et al*., 2018; Lindgren *et al*., 2018). Therefore, the diversity of landscapes on the local scale has a positive effect on the number of natural enemies and pollinating insects and, as a consequence, on yields (Chaplin-Kramer *et al.*, 2011; Bianchi *et al*., 2006). Besides, a more diverse landscape with different ecosystem elements is generally more resilient to the environmental changes, including climate change, than a homogeneous and uniform landscape (Schippers *et al*., 2015). Therefore, the study of the relationship between crop yields and landscape diversity is currently an extremely important issue.

Although there are a lot of researches on the value of natural landscape elements biodiversity (Billeter *et al*., 2008, Lyles *et al*., 1984, Ghosh *et al*., 2012), the impact of these natural sites on crop yields is less studied. There is strong evidence of a sustained impact of biodiversity on crop yields both in the natural landscapes (Hooper *et al*., 2005) and in agroecosystems (Picasso *et al*., 2008). Poveda *et al*. (2012) found a positive effect of landscape diversity on potato yields. Conservation of natural habitats in agro-landscapes has been shown to be beneficial in providing "ecosystem services" such as reducing pest damage, increasing yields and increasing functional biodiversity. It was declared that maize productivity also depends on ecosystem services and, consequently, on landscape diversity (CONABIO, 2017). Galpern *et al*. (2019) studied the impact of landscape diversity on crop yields over 250,000 km^2 by using a functional regression approach, and found evidence of a positive relationship between crop yield and landscape complexity in four of the seven studied crops. Although the variation in yields due to the landscape diversity is insignificant, it may be a sufficient condition for the preservation of natural centers near agro-landscapes, given their important ecological role.

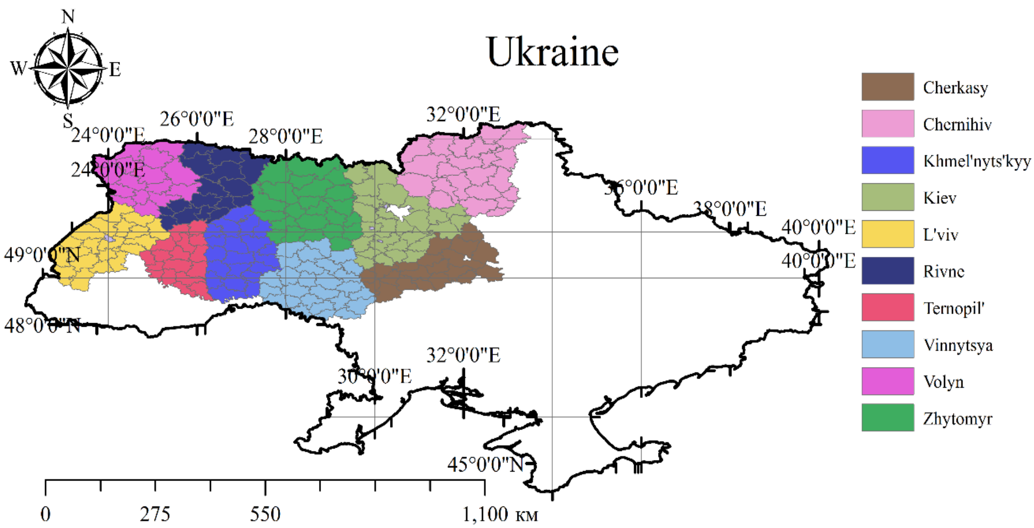
Assessing the role of diversity in the stability and functioning of ecosystems is the most important issue of modern ecology. The diversity-stability hypothesis postulates the key importance of biodiversity in forming ecosystem stability (Johnson *et al*., 1996; Loreau & de Mazancourt, 2013; Grzybowski, 2020). A hypothesis was formulated according to which an agricultural system based on the full potential of agrobiodiversity provides opportunities for a sustainable system in which both food production and nature can thrive (Willem Erisman *et al*., 2016). The agricultural diversification was proved to increase the crop production (Burchfield *et al*., 2019). It was suggested that more diverse agroecosystems are more productive and stable than less diverse landscapes (Kuchma *et al*., 2013). Biodiversity-based agriculture can increase its efficiency by expanding ecosystem services (Duru *et al*., 2015; Dudley & Alexander, 2017). Studies of different farming systems have shown that field vegetation diversification can improve yields and provide ecosystem services (Duarte *et al.*, 2018, Garbach *et al*., 2017). It was shown that in agricultural landscapes, the richness of bird species increased with the increase in heterogeneity of landscapes, which was estimated using the Shannon Index (Lee & Martin, 2017). Biodiversity conservation is discussed as an antipode to economic growth in agriculture (Moraes *et al*., 2017). However, it is important to find trade-offs between biodiversity conservation and the delivery of ecosystem services when making land-use decisions (Fastré *et al*., 2020). In our study we want to assess the role of biological diversity as a factor of sustainable agricultural practices. However, the impact of landscape complexity on crop yields in landscape units that are larger than the field size is more difficult to evaluate (Bommarco *et al*., 2013). Very few landscape-scale studies have estimated a relationship between landscape complexity and crop yields. In this study, we used mathematical modeling to identify the parameters of crop yield dynamics in order to investigate how they are influenced by the landscape diversity factors. Therefore, we focus on three closely related research issues: 1) what universal model would explain the yield dynamics of winter rye, sunflower and soybean in Ukraine during 1991 – 2017; 2) what trend model parameters can be used for meaningful interpretation of the causes of the yield dynamics; 3) whether there is a reliable relationship between crop yield parameters and indicators of landscape diversity. The aim of this study is to determine the role of landscape diversity in soybean, sunflower and winter rye yields variability.

MATERIALS AND METHODS

Yield data and study area

Three crops were chosen for the research: soybeans, winter rye and sunflower. Crops yield data were obtained from the State Statistics Service of Ukraine (http://www.ukrstat.gov.ua/). The time series datasets include averages of the crops annual yields in 206 administrative districts of 10 regions of Ukraine over the period of 1991–2017. The data represent the averages values of the yields on the basis of the spatial criterion within each administrative district without differentiating soil water availability and fertility, irrigation management, cultivar, and crop cycle. The research area is located in two natural vegetation and climatic zones: the Forest zone (Polissya) and the Forest-steppe zone. Twenty-seven years' data series of the sunflower yields were available for 10 administrative regions (Cherkasy, Chernihiv, Khmel'nyts'kyy, Kiev, L'viv, Rivne, Ternopil', Vinnytsya, Volyn, Zhytomyr) (Fig. 1).

Fig. 1: Map of research area (10 administrative regions in Ukraine)



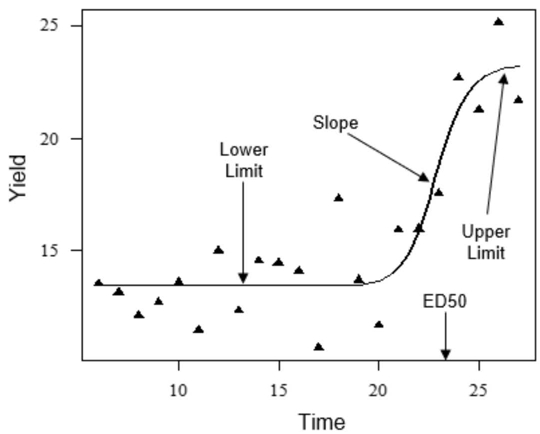
Yield dynamics model and its characteristic points

During the research period there were significant social and economic changes in agricultural production, which were associated with the crisis of the USSR collapse and the formation of new production models. Therefore, the dynamics of crop yields was significantly unsteady and was influenced not only by environmental, but also by socio-economic factors (Zymaroieva *et al.*, 2020a). The novelty of this work is that we studied not just the relationship between landscape diversity and yield, but considered crop yields 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. A symmetrical four-parameter log-logistic model was used to describe the yield dynamics of all the studied crops:

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

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 yields variation (shown on the example of sunflower yield dynamics) (Fig. 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.

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



The sigmoid model is used both for modeling the time effect and for modeling the dose effect on the response under study. Therefore, the parameter that characterizes the deflection point of the sigmoid curve is traditionally designated as "ED50" (Ritz *et al*., 2015). These characteristics of the soybean, winter rye and sunflower 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 (Zymaroieva, 2020b). A 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).

Assessment of landscape diversity of the studied area

The 300 m GlobCover Landscape Type Map, based on the two-month MEdium Resolution Imaging Spectrometer (MERIS) (Fritz *et al*., 2015; Ottlé *et al*., 2013; Pérez-Hoyos *et al*., 2017; Tsendbazar *et al*., 2015), was used as a basis for creating a landscape diversity map. The landscape diversity was evaluated using the Shannon diversity index (Dušek & Popelková, 2017). The landscape diversity may be calculated within each grid square using the Shannon (Shannon & Weaver, 1949) or Simpson (Simpson, 1949) diversity indices. The two landscape diversity indices were found to be highly significantly correlated with each other that's why only Shannon landscape diversity index was proposed to be used (Ewers *et al*., 2005). The Shannon index was recommended for landscape management within an ecological framework. Simpson's index can be used for specific situations where the dominant cover type is of interest (Nagendra, 2002). In our study, only the Shannon Index was used to assess landscape diversity. 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). The distance from nature conservation areas was suggested as a possible measure to assess their role in the surrounding landscape (Chape *et al*., 2005). The distance between natural protected areas (NPA)[1] 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 this territory. Data about natural protected areas was obtained at https://opengeo.intetics.com.ua/osm/pa/ in the form of a shape-file. The distance was calculated in ArcGIS 10.1.

RESULTS

Analysis of landscape diversity of the studied area

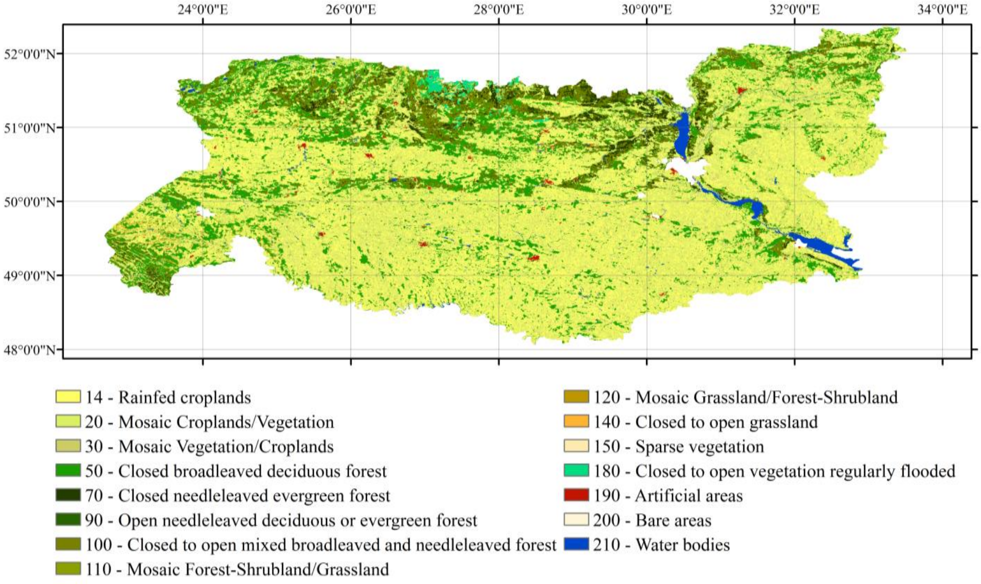
The total examined area covers 233739 km^2, which is 38.7 % of the total area of Ukraine. The largest area is occupied by agricultural land or its various combinations with natural types of the landscape cover (mosaic cropland, rainfed croplands) (Table 1). The closed broadleaved deciduous forests, mosaic vegetation, closed to open mixed broadleaved and needleleaved forests are predominate among the natural types. The agricultural lands prevail in the south and center of the territory under study, while the natural cover is most typical in the north of the territory (Fig. 1).

[1] NPA – Natural protected areas

Table 1: Landscape cover type structure

Code	Cover type	Square	
		km^2	%
14	Rainfed croplands	62384.9	26.69
20	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)	79835.5	34.16
30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	19731.1	8.44
50	Closed (>40%) broadleaved deciduous forest (>5m)	36311.6	15.54
70	Closed (>40%) needleleaved evergreen forest (>5m)	7525.2	3.22
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	1628.9	0.70
100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	17419.1	7.45
110	Mosaic forest or shrubland (50-70%) / grassland (20-50%)	53.8	0.02
120	Mosaic grassland (50-70%) / forest or shrubland (20-50%)	2469.0	1.06
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	212.5	0.09
150	Sparse (<15%) vegetation	542.7	0.23
180	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water	1345.0	0.58
190	Artificial surfaces and associated areas (Urban areas >50%)	1037.3	0.44
200	Bare areas	19.3	0.01
210	Water bodies	3223.2	1.38

Fig. 3: Spatial distribution of landscape cover types GlobCover

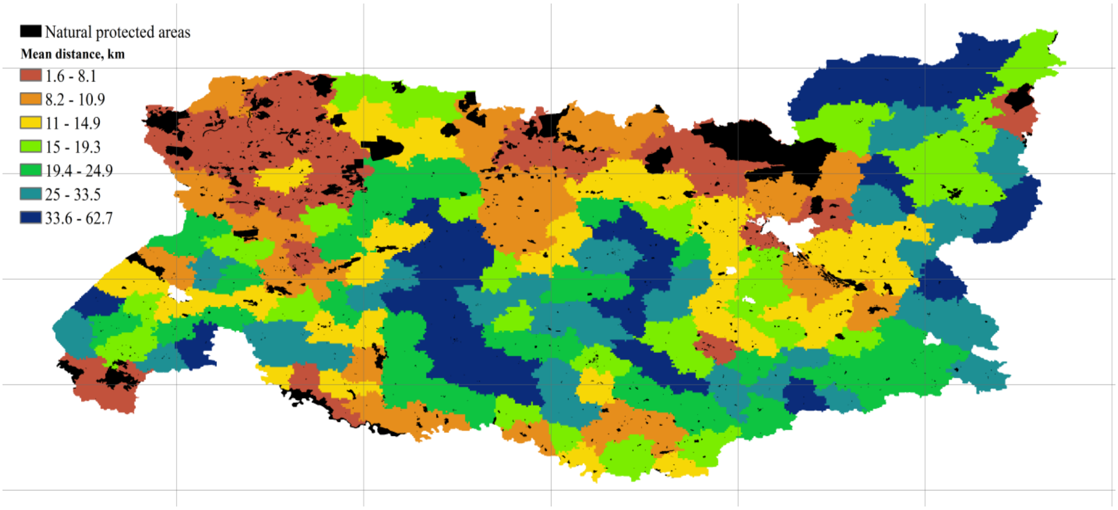


There are 782 natural protected areas (NPA) of various types within the territory under study with the total area of 10415 km^2, which is 4.5 % of the total area of the region (Table 2). NPAs have different area and protection regime. The largest objects in terms of coverage area are concentrated in the northern regions in Polissia and in the west – in the Carpathians (Fig. 1). The largest site in terms of area is Chernobyl Nuclear Power Plant Zone of Alienation (Chernobyl Exclusion Zone). Distribution of smaller sites is more even within the territory under study. The average distance to nature protected objects within the administrative district is 20.7±0.9 km and in 95 % of cases varies within the range from 4.9 to 52.8 km.

Table 2: Natural protected areas

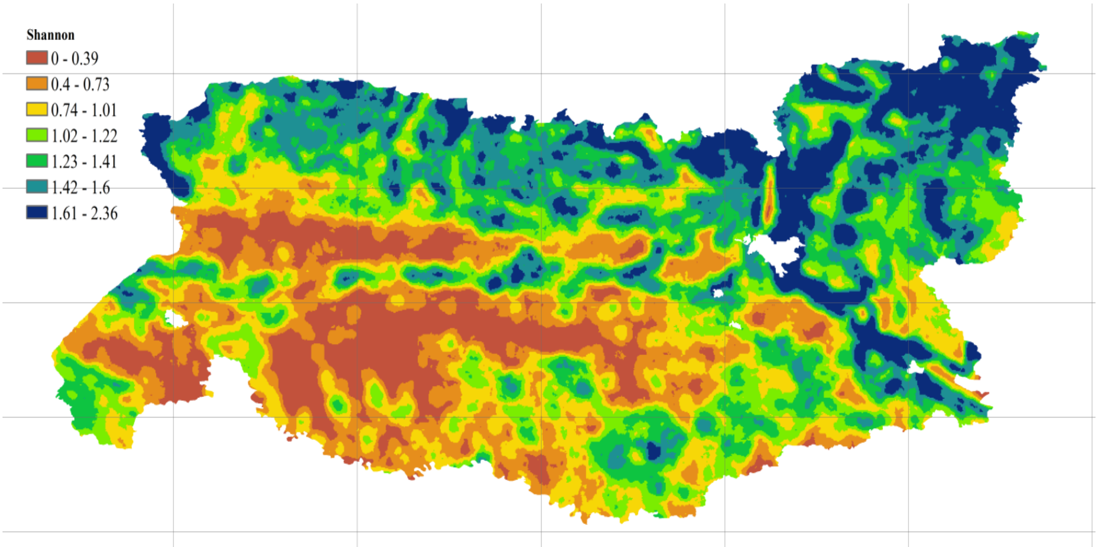
Type of the natural protected area	Number of the objects	Total square, km^2	Mean square per object, km^2
Regional landscape park	9	2613	290.36
National park	15	2479	165.28
Nature reserve	5	722	144.42
Zakaznyk	2	22	10.84
Protected site	409	4321	10.56
Conservation stow	68	189	2.78
Dendrological park	4	2.12	0.53
Botanic garden	7	2.26	0.32
Park monument of landscape art	87	24	0.27
Nature monument	174	41	0.23
Zoological park	2	0.14	0.07
Total	782	10415	13.32

Fig. 4: Location of natural protected areas of different levels and average distance to them within the administrative district, km



The diversity of types of landscape cover in accordance with the Shannon index is 0.96±0.03 and in 95 % of cases varies from 0.26 to 1.66. Naturally, the areas with the highest indices of landscape diversity by Shannon are located in the north and east of the study region (Fig. 5). As landscape diversity increases, the distance to the nearest NPA generally decreases, but this correlation is not statistically significant (r = –0.13, p = 0.07). It is worth noting that NPAs are characterized by a higher index of landscape diversity, which is a natural phenomenon. Also, on average, the Shannon index is higher in Polissya than in the Forest-Steppe (Struk, 1993; Fedonyuk *et al.*, 2020).

Fig. 5: Spatial variation of the Shannon landscape diversity index



Establishing the relationship between landscape diversity and crop yields

To determine the relationship between landscape diversity (Shannon index, distance to protected areas) and crop yield, we performed a regression analysis (Table 3).

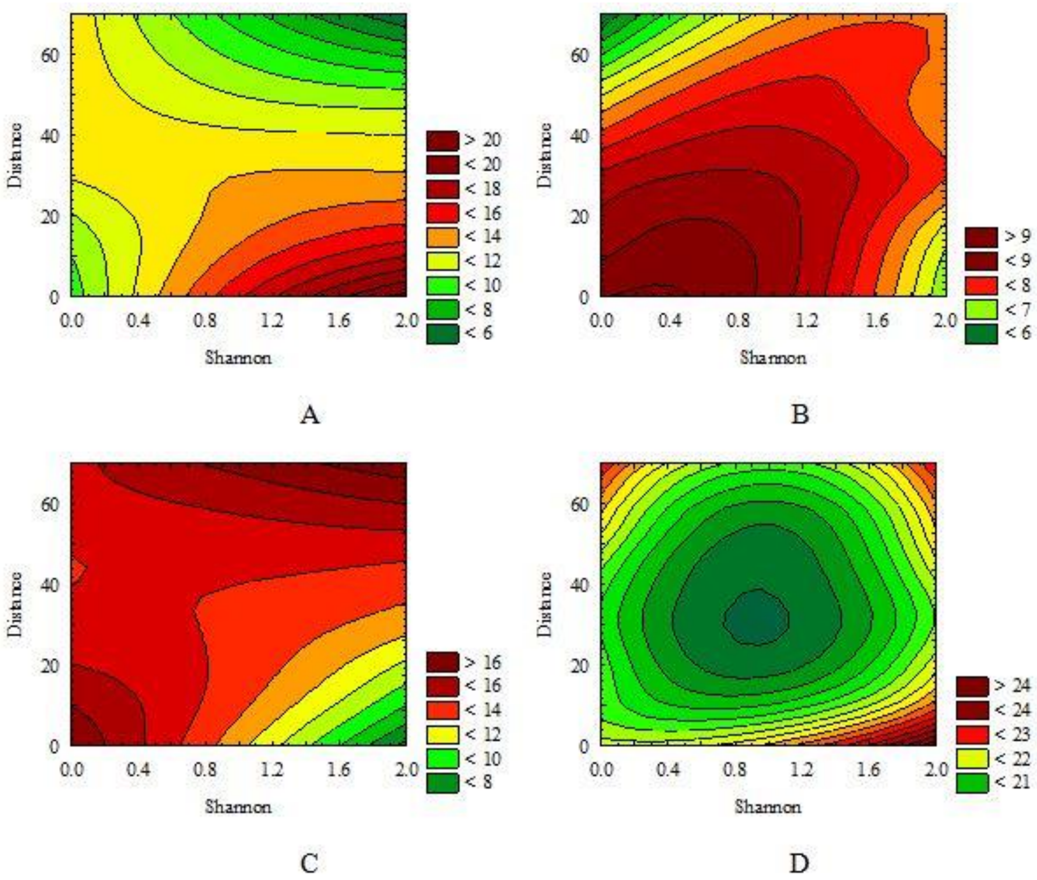
Table 3: Regression dependence of three crops yield parameters on indicators of landscape diversity*

Predictors	Characteristic points of the Yield dynamic			
	Slope	Lower Limit	Upper Limit	ED50
Soybean				
	$R_{adj}^2 = 0.20$	$R_{adj}^2 = 0.17$	$R_{adj}^2 = 0.41$	$R_{adj}^2 = 0.18$
Shannon (H)	0.64±0.32	–	–0.68±0.27	–0.64±0.32
Distance (D)	–	–	–0.54±0.23	–0.92±0.28
H*D	–0.66±0.18	0.53±0.18	0.92±0.15	–
H^2	–	–0.72±0.31	–	0.87±0.30
D^2	–	–	–	0.91±0.23
Sunflower				
	$R_{adj}^2 = 0.28$	$R_{adj}^2 = 0.18$	$R_{adj}^2 = 0.19$	$R_{adj}^2 = 0.11$
Shannon (H)	–	–	–	–
Distance (D)	–1.07±0.26	–	0.97±0.28	0.78±0.29
H*D	–	–	–	–
H^2	0.63±0.29	–0.90±0.30	–0.69±0.30	–
D^2	1.08±0.21	–0.54±0.23	–1.01±0.23	–0.97±0.24
Winter rye				
	$R_{adj}^2 = 0.10$	$R_{adj}^2 = 0.35$	$R_{adj}^2 = 0.37$	$R_{adj}^2 = 0.18$
Shannon (H)	0.86±0.34	–	–	–
Distance (D)	–	0.84±0.25	0.93±0.24	–0.69±0.28
H*D	–	0.64±0.16	0.61±0.15	–
H^2	–0.74±0.32	–0.92±0.27	–0.68±0.27	–
D^2	–	–1.25±0.20	–1.38±0.20	0.56±0.23

* Note - standardized regression coefficients are statistically significant for p <0,05

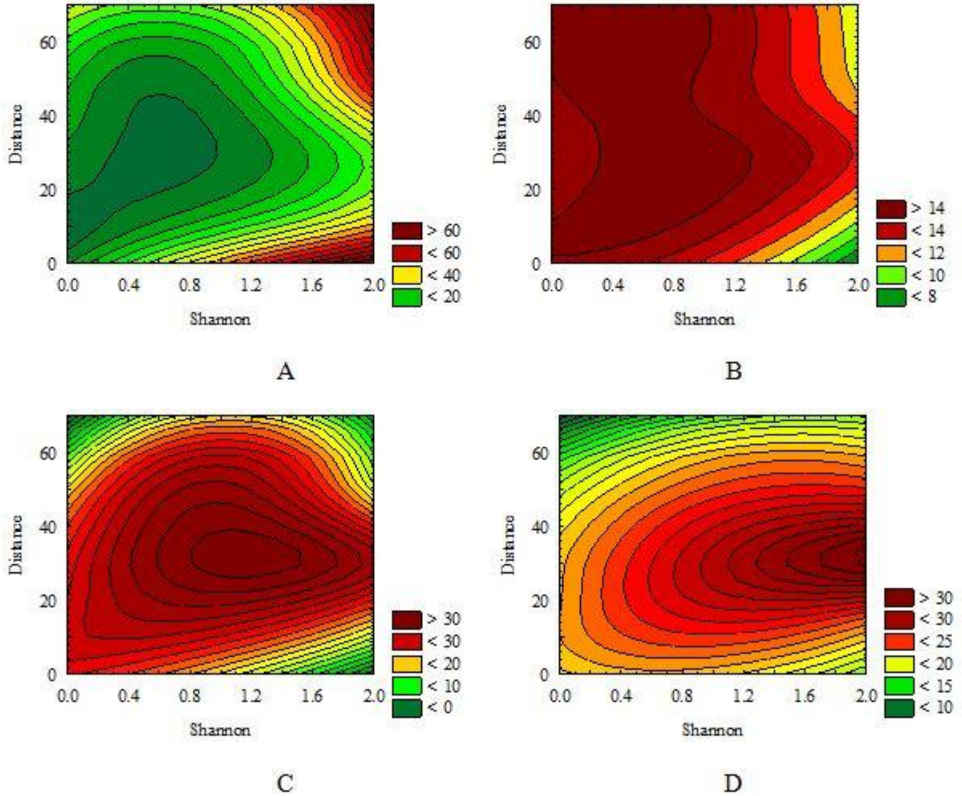
Soybean yield parameters are determined by landscape diversity by 17–41 % (Table 3). The rate of soybean yield increases between 2005 and 2015 (Slope) was characterized by a linear dependence on the Shannon index (R = 0.64±0.32; p <0.05). Thus, the more diverse the landscape, the faster the increase in soybean yields (Fig. 6 A). This index of landscape diversity determined the rate of soybean yield increase by 20 %. The Lower limit of soybean yield (Lower limit) was determined by the Shannon Index by 17 %, and this relationship was nonlinear (Fig. 6 B). The Upper limit of soybean yields is the most sensitive parameter to the factors of landscape diversity (R_{adj}^{2} = 0.41) and depends on both the Shannon index and the distance to natural protected areas. The interdependence between the yield parameter ED50 and both indicators of landscape diversity is described by a quadratic function. It should be noted that the impact of landscape diversity indicators (Shannon index and distance to protected areas) for all parameters of soybean yields, except ED50 is interdependent (Fig. 6 A-C). Moreover, the symmetrical configuration of Figure 6D shows certain independence of the influence of diversity and density of natural protected area at the time of reaching half of the maximum level of soybean yields.

Fig. 6: The dependence of characteristic points of the dynamic soybean yield model on landscape diversity (Shannon) and the average distance of the administrative district from the nearest natural protected area (Distance) (spline approximation). Model parameters: A – Slope; B – Lower Limit; C – Upper Limit; D – ED50



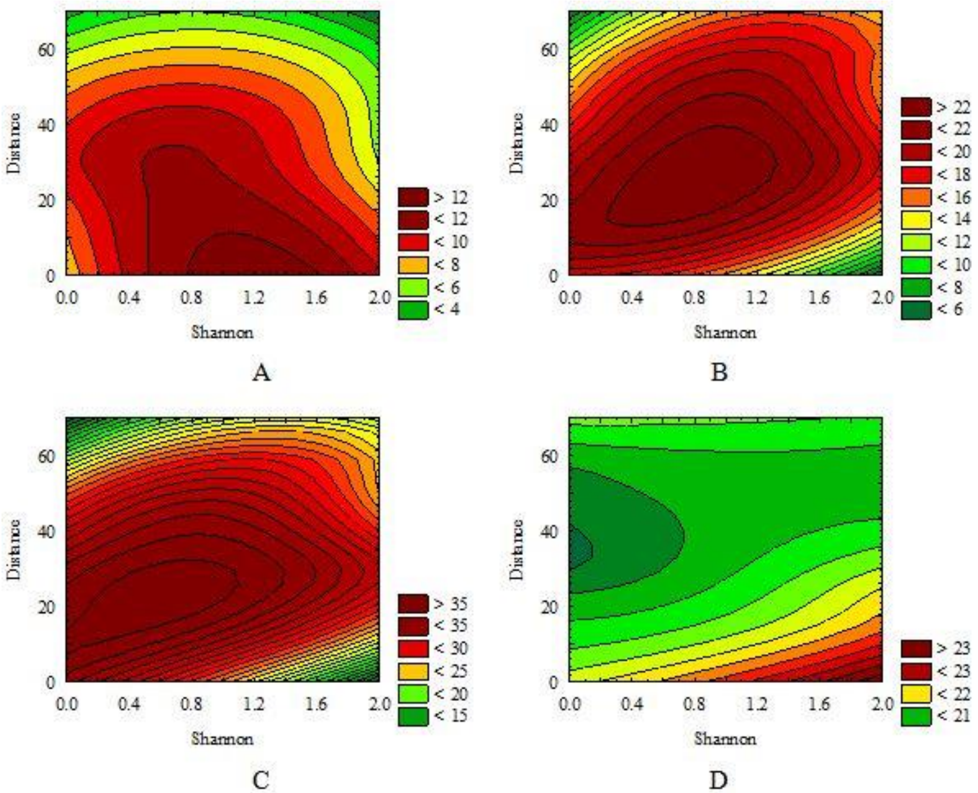
Landscape diversity determines the yields of sunflower by 11–28 % (Table 3). Moreover, the most sensitive sunflower yield parameter to the indicators of landscape diversity is the rate of yield growth (Slope), which is characterized by a nonlinear dependence on both the Shannon index and the distance to the protected areas (Fig. 7 A). The interaction between the Upper and Lower limits of sunflower yields and both indices of landscape diversity is described by a quadratic function (Fig. 7 B–C). ED50 is 11% dependent on the distance to the protected areas (Fig. 7D), and this regression dependence is non-linear. It is noteworthy that the influence of landscape diversity indicators on sunflower yields is independent.

Fig. 7: The dependence of characteristic points of the dynamic sunflower yield model on landscape diversity (Shannon) and the average distance of the administrative district from the nearest natural protected area (Distance) (spline approximation). Model parameters: A – Slope; B – Lower Limit; C – Upper Limit; D – ED50



It is significant that all the established parameters of winter rye yield dynamics depend on the diversity of the landscape cover (Table 3) by 10–37 %. All the established regression relationships between rye yield parameters and indices of landscape diversity are nonlinear. The Slope parameter is only 10% due to the influence of the Shannon index ($R = –0.74±0.32$; $p <0.05$), and the ED50 parameter is 18% determined by the distance to nature protected sites ($R = 0.56±0.23$; $p < 0.05$). Upper and Lower rye yield limits depend simultaneously on both indices of landscape diversity, and these indices are characterized by mutual influence (Fig. 8 B-C).

Fig. 8: The dependence of characteristic points of the dynamic rye yield model on landscape diversity (Shannon) and the average distance of the administrative district from the nearest nature protected area (Distance) (spline approximation). Model parameters: A – Slope; B – Lower Limit; C – Upper Limit; D – ED50



DISCUSSION

The compromise between meeting the growing world food needs and conserving biodiversity is one of the most pressing issues today, as the intensification of agriculture and the expansion of arable land have caused great loss of global biodiversity (Mattison & Norris, 2005; Dalu *et al*., 2017; Fanta & Petřík, 2018). On the other hand, strategies aimed at preserving the heterogeneity of the landscape reduce the intensity of agricultural land use (Cunningham *et al*., 2013). Therefore, to minimize the impact of intensification of agricultural production on natural systems and increase crop productivity it is advisable to stimulate the provision of ecosystem services in agricultural landscapes (Bommarco *et al*., 2013), by preserving, restoring or creating new natural landscape elements (NLEs) within the field or in neighboring areas (Tilman *et al.*, 2011; Landis, 2017).

The most common type of landscape in Ukraine is arable land. It is known that in the Forest-Steppe agricultural lands occupy 70% of the territory, of which 66 % are arable lands (Babich & Babich-Poberezhna, 2010). Which is quite natural considering the high agricultural potential of Ukraine. The highest density of nature protected areas is inherent in the northern regions of Ukraine (Fig. 4). This is due to the more diverse landscape, soils and vegetation (Struk, 1993), as well as the fact that large areas of the northern regions of Ukraine were contaminated with radionuclides as a result of the explosion at the Chernobyl nuclear power station. Currently, radioactively contaminated areas mostly have the status of natural protected areas. In particular, the largest reserve in Europe – the Chornobyl Radiation and Ecological Biosphere Reserve is located in the area of radioactive contamination, its area is almost 227,000 square kilometers (Bondarkov *et al*., 2011).

Our study demonstrates that there is a statistically significant relationship between crop yields and biodiversity, even at the landscape level. Most of the established dependences are nonlinear, as second-order predictors (H^2, D^2) are statistically significant (Table 3). It should be noted that the functional relationship between landscape diversity and yield is highly variable across crop types. Among the studied crops, the strongest regression relationship between yield and landscape diversity was found for soybean. The sunflower yield is the least dependent on landscape diversity (Table 3). The Upper crops yield limit, which proceeds in the present period of time (Fig. 2) is the most sensitive yield parameter to the landscape diversity (R_{adj}^2 = 0.19 - 0.41). This is due to the fact that with the modern development of agricultural technologies environmental drivers become more important. They include the level of landscape diversity, which determines the spatiotemporal dynamics of crops approaching the Upper yield limit (Zymaroieva *et al*., 2019).

Therefore, all parameters of soybean yield depend on the indices of landscape diversity. Only one soybean yield parameter – Slope is characterized by a linear dependence on the Shannon index, the other established dependences are nonlinear (Table 3). The presence of nonlinear regression relationships between factors of landscape diversity and yield parameters indicates that there is some optimal level of landscape diversity to achieve the maximum possible crop yield. Though testing the specific mechanisms and reasons for this phenomenon is beyond the scope of our analysis, the most common explanation is varied ecological services associated with landscape diversity such as pollination and biological control via complementarity (Tscharntke *et al*., 2005). In particular, studies of the impact of agricultural landscape structure on yields have shown that soybean productivity was related to distance-from-forest which, according to the authors, is related to pest regulation (Mitchell *et al*., 2014). The long-term analysis conducted by Ferrero *et al*. (2017) in Michigan (USA) showed that the combined effects of internal and external processes involving weed diversity were strongly associated with soybean yield fluctuations. There are other studies of evidence that increasing plant diversity in natural ecosystems, as well as in agroecosystems increases crop yield and yield stability (Abson *et al*., 2013; Forest *et al*., 2017; Duarte *et al*., 2018), which in general, confirm the patterns obtained in our research. Asymmetric and more complex configuration of yield parameters under the influence of a set of the landscape diversity indicators (Fig. 6 A-C) reflect the interaction of these indicators. In such a situation, the low landscape diversity can be compensated by the presence of natural protected areas.

Nonlinear relationships between all sunflower yield parameters and indicators of landscape diversity were revealed, indicating that there is an optimal value of landscape and ecological diversity, at which the rate of increase in sunflower yields (Slope), maximum yields in the 90s - early 2000s (Lower limit) and maximum yields at the present stage (Upper limit) reaches the highest level. Similarly, there is an optimal amount of NPAs within the area for the lowest value of ED50, which determines the time that has elapsed between the early 1990s and the moment of reaching half of the maximum sunflower yield. It is obvious that with a low level of nature protected areas density, the growth of the landscape diversity indexes has a positive effect on yield increasing. However, in the condition of a very high level of NPA diversity and density, further increasing indexes of the landscape diversity leads to the decreasing of maximum yields, due to the predominance of the landscape cover types that are unfavorable for agriculture because of low soil fertility. Our findings are consistent with studies conducted in Central Italy, which proved that sunflower seed yield was higher in fields surrounded by landscapes containing a greater abundance of beehives, early flowering crops, urban areas and woody linear elements; conversely, seed set was lower where herbaceous semi-natural habitats dominated the surrounding landscape (Bartual *et al.*, 2018). The positive effect of landscape heterogeneity on sunflower yields is primarily due to the diversity of pollinating insects. Thus, Nderitu *et al.* (2018) study demonstrates that areas to which insect pollinators had access, gave on average 53 % more seed yield compared to areas where insect pollinators were excluded. Thus, honeybee's pollination, which accounted for the vast majority of pollinators, increases the seed yield by 30 % and the oilcontent by more than 6 % in hybrid varieties (Furgala *et al.*, 1979; Jyoti & Brewer, 1999; Nderitu *et al.*, 2018). Moreover, sunflower has a potential for providing multiple ecosystem services in diverse cropping systems (Jones & Sieving, 2006; Franco *et al.*, 2016), that defines it as an environmentally-friendly crop (Debaeke *et al.*, 2017).

There are few studies that would generally describe the impact of biodiversity on winter rye yields, even at the field scale. Therefore, this research fills some gaps in the study of these interactions. In studies evaluating the yield of rye in pure and mixed crops, it was concluded that rye in the mixed cropping with wheat produced significantly higher spike weight and culm weight in comparison with sole cropping (Klimek-Kopyra *et al.*, 2017). Besides, it was stated that the winter rye yield did not correlate with the diversity of weeds. (Jastrzębska *et al.*, 2019). This study also demonstrates the ambiguous influence of landscape heterogeneity on rye yield, which is manifested by the presence of a nonlinear relationship between most parameters of rye yield and indicators of landscape diversity. The existence of a statistically significant relationship is evidence that the rye yield throughout the study period was influenced by the landscape structure of the territory. However, there is an optimal distance from natural protected areas, at which the parameters Lower yield limit, Slope (rate of yield increasing) and Upper yield limit take the highest values. There is also a nonlinear correlation between the ED50 parameter and the distance to the nearest natural protection area. Moreover, with increasing of landscape heterogeneity, the time to reaching half of the maximum yield of rye decreases. The reasons for the identified relationship need clarification and further research. Nevertheless, the results can be used to justify the creation of new nature reserves or natural landscape elements near agro-landscapes due to their important "ecosystem services". Moreover, based on the obtained statistical patterns, the above-mentioned "ecosystem services" can be statistically calculated.

CONCLUSIONS

Statistically significant regression relationships between all crop yield parameters (soybean, sunflower, winter rye) and indicators of landscape diversity (p <0.05) were revealed. Landscape diversity determines the yield of the studied crops by 11 – 41 %. Thus, it has been proved that there is an interaction between landscape diversity and crops yield variation, which is usually described by a nonlinear function. This gives reason to believe that there are areas with an optimal structure of the landscape, as well as areas where it is necessary to increase the percentage of natural diversity, in order to increase the crop productive potential. The reasons for the existence of these relationships need to be further clarified and will be studied in our future research.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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