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The spatio-temporal trend of rapeseed yields in Ukraine as a marker of agro-economic factors influence

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Abstract. The paper demonstrates the applicability of several statistical methods to the analysis and interpretation of the average rapeseed yield data. It proves our hypothesis that the general trend of rapeseed yield variations in Ukraine during 1991–2017 occurred due to agro-economic and agro-technological factors, which are the determinants of the revealed general trend. The temporal trend of rapeseed yield in most administrative districts can be described by a fourth-degree polynomial, namely, its characteristic points enabled us to describe and interpret the dynamics of rapeseed yields. The absolute term of the polynomial shows the initial conditions of the process, and its mapping allows us to identify the areas with the most favorable soil-climatic conditions for the rapeseed cultivation. Indicators of the maximum rate of growth and decrease of yields are the markers of stability of agro-ecosystems to the external influences. Therefore, the mapping of the maximum rate of decline and increase of yields reveal areas in which yields respond rapidly (increasing / falling) to the changes in agro-economic and agro-technological conditions, as well as areas where yields are more stable and change gradually. Thus, the form of the yield trend is determined by the influence of agro-technological and agro-economic factors, whose contribution to the fluctuation in rapeseed yields varies from 53% to 90%.

Key words: yield, rapeseed, trend, dynamics, variability, agro-economic factors, agro-technological factors.

INTRODUCTION

Rapeseed (*Brassica napus L.*) is an important crop due to its use as a source of vegetable oil for food purposes, as a fuel for biodiesel production and a high-protein animal feed (Takashima et al., 2013). It ranks third by production among oilseeds in the world (Rondanini et al., 2012). Currently, rapeseed is grown in 30 countries on an area of 30 million hectares, with total production up to 6 million tones (Cherevko, 2016).

Improved agronomic practices and advances in breeding led to increasing of rapeseed yields in European countries (Gardner, 1994; Habekotte, 1997). Thus, through the optimization of agronomic measures such as sowing rate, sowing date, irrigation, nutrition, pest and disease control, as well as the congruous cultivar, it was possible to achieve the rape seed yield potential (Diepenbrock, 2000).

Ukraine has favorable soil and climatic conditions for growing winter and spring rapeseeds. In particular, appropriate soil fertility, relevant water and air permeability of soil, optimal rainfall and temperature make it possible to produce yields of up to 4 t ha^{-1} due to the adequate cultivation technology (Babiy, 2015; Harbar et al., 2016). Nevertheless, at present, the average rapeseed yields in Ukraine are below the European ones and little is known about the limiting factors of the productive potential of this crop in the country.

Although global rapeseed yields increase, it is accompanied by a significant spatio-temporal variation (Rondanini et al., 2012). For example, in Europe, more stable yields are characteristic for regions with low average yields (Brown et al., 2019). Low temporal variability of crop yields is advantageous for many reasons including reduced income risk and stability of supplies potentially leading to less instability in food prices (Osborne & Wheeler, 2013). Nevertheless, the crop yields variations in space and time are the reality of agriculture. Annual fluctuation in yields may be caused by differences in factors such as seasonal weather conditions, weed, pest and disease pressures, and relevance of management decisions (Lauzon et al., 2005; Nowosad et al., 2016; Brown et al., 2019). Hence, understanding the mechanisms that determine not only the yield potential but also the yield dynamics is critical to global food security.

Therefore, the crop yields spatio-temporal variability is caused by a large number of factors, which are divided into two groups (Rauner, 1981). The first group includes agro-economic and agro-technological factors: the achievement of genetics and breeding, technology of soil cultivation, provision of fertilizers, plant protection, land reclamation etc. The second group combines environmental factors, which determine significant fluctuations of the average yield in some years (Polevoy et al., 2011). Among the environmental factors, weather and climate are the most influential factors of crop productivity. Thus, it has been shown that the latest trends in climate change can significantly affect crop yields, despite the advancement of agronomic practices (Iizumi & Ramankutty, 2016; Lesk et al., 2016; Leng & Huang, 2017). In particular, extreme changes in temperature and precipitation have a profound effect on oilseed rape yield (Brown et al 2019).

However, in practice, there is often a need to separately assess the degree of impact on the yield of both agro-economic (agro-technological) and ecological factors (Polevoy et al., 2011). This assessment based on the idea of decomposing the yields time series into two components: regular (stationary) and irregular (random) (Rauner, 1981; Chen, 2018). The stationary component determines the general trend of yield change in the analyzed period. The trend quite precisely characterizes the average level of yield, due to the level of technology, economic and natural conditions of the area.

In the paper we advance two hypotheses. Hypothesis 1 is that the time series trend of the rapeseed production in Ukraine during 1991–2017 may be an effect of agro-economic and agro-technological factors. Hypothesis 2 is that the residuals of the time series regression model may be an outcome of agro-ecological factors.

In this study we focus on three interconnected research questions: 1) what was the trend of rapeseed yield in Ukraine during 1991–2017; 2) whether the trend can be considered as a marker of the impact of agro-economic factors; 3) whether the agro-economic component is spatially dependent.

MATERIALS AND METHODS

Data of rapeseed yield

Crop data were obtained from State statistics service of Ukraine (http://www.ukrstat.gov.ua/) and its territorial offices. The time series datasets include average crop yields in 267 administrative districts of the annual yield of rapeseed of 10 regions of Ukraine over 27 years, i.e. 1991–2017. The research area is located in two natural vegetation and climatic zones: the Forest (Polissya) and Forest-steppe zone. The research territory includes 10 administrative regions (Cherkasy, Chernihiv, Khmel'nyts'kyy, Kyiv, L'viv, Rivne, Ternopil', Vinnytsya, Volyn, Zhytomyr) (Fig. 1). Information about the annual yields of rapeseed in Ukraine was obtained from FAO (FAOSTAT, 2018).

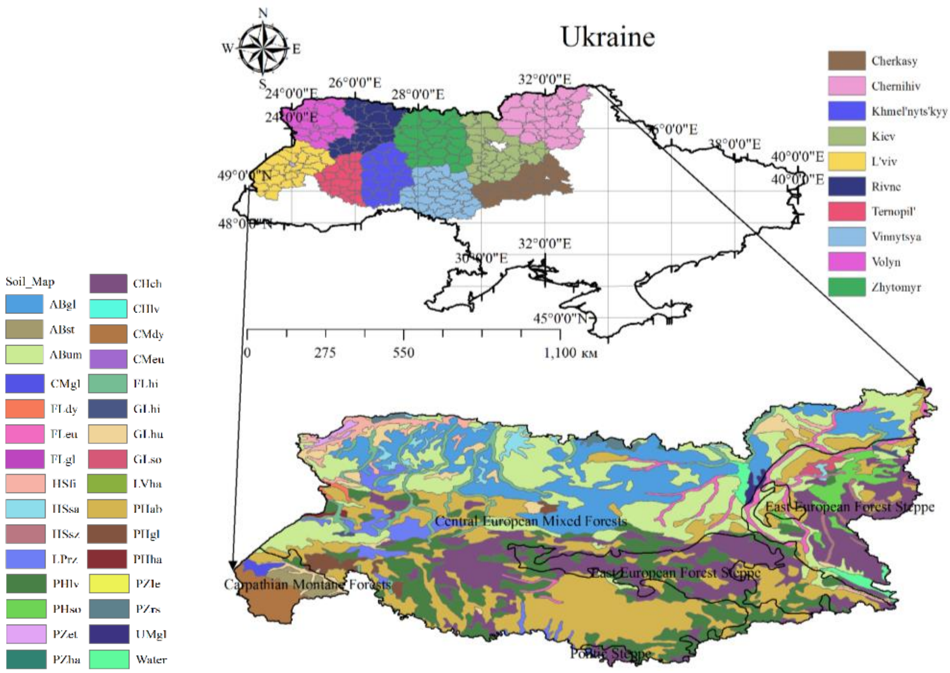

Figure 1. Map of 10 administrative regions in Ukraine, Ecoregions and soil map.

Legend: Soil classification according to 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.

Choosing the statistical model that best represents yield trends

As an analytic form of the trend we chose between polynomials of different degree (Ray et al., 2012, Zymaroieva et al., 2019b). Based on the chosen model parameters, crop yield trends may be classified into four main categories (Chen, 2018): increasing, stagnating, collapsed, and never improved. These categories may be considered as a qualitative property of the yield trends.

The Akaike Information Criterion (AIC) developed by Akaike (1974) was used to estimate the likelihood of a statistical model to the observed crop yield data. A good model is the one that has minimum AIC in comparison with all the other models and was chosen as the best representation of the yield trend for a given administrative district. All calculations and data analyses were performed using R v 3.0.2 (R Development Core Team, 2013).

The yield trend within the investigated area can best be described by a fourth-degree polynomial:

$$Y_x = b + a_1x + a_2x^2 + a_3x^3 + a_4x^4 \quad (1)$$

where Y_x – crop yield at the time moment x; b, a_1, a_2, a_3, a_4 – coefficients.

Therefore, in the following analysis phase for the quantitative comparison, the productivity trends in all administrative districts were described by the fourth- degree polynomials. Consequently, we selected the characteristic points of the fourth- degree polynomials: constant, the maximum rate of yields decreases in the range between the first maximum and minimum, the maximum rate of yields increases in the range between minimum and the second maximum (Fig. 2). To quantitatively estimate the special points values, the following calculations are performed.

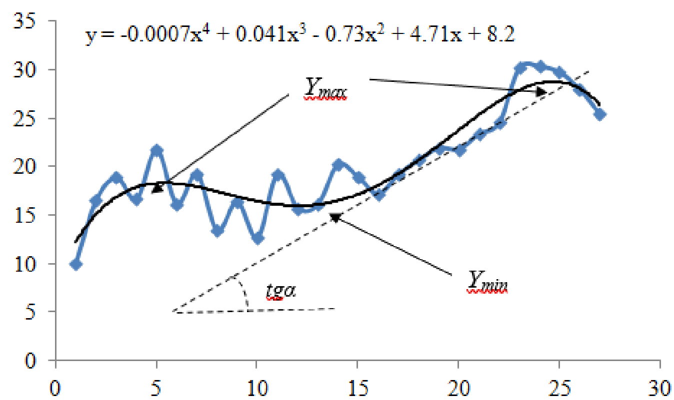

Figure 2. The typical rapeseed yields dynamics during 1991–2017 and approximation of the trend by the fourth-degree polynomial.

Legend: axis of abscissas – time (1–1991, 27–2017); ordinate axis – yields, dt ha^{-1}; b is an absolute term of polynomial equation; YMin – the value of the polynomial at the point of the local minimum; YMax – the value of the polynomial at the points of local maxima; tgα – the maximum rate of increasing crop yields at the time between minimum and maximum, the tangent of the angle of inclination of the tangent to the curve of the polynomial at the inflection point (similar to the maximum rate of yields decline in the downstream branch).

Differentiating the fourth-degree polynomial enables to establish the rate of yields change over time:

$$Y_x' = a_1 + 2a_2x + 3a_3^2 + 4a_4^3 \quad (2)$$

Points of inflection of the function are where the second derivative is zero:

$$Y_x'' = 2a_2 + 6a_3 + 12a_4^2 = 0 \quad (3)$$

The corresponding quadratic equation has two roots:

$$x_{1,2} = \frac{-6a_3 \pm \sqrt{36a_3^2 - 96a_4a_2}}{24a_4} \quad (4)$$

Substituting the solutions of Eq. (2) into Eq. (3) we obtain the maximum rates of the decrease and increase of the yields within the study period. These indicators are characteristic of a fourth-degree polynomial. Moreover, the slope of linear regression shows the convergence rate of the approximate trend in the respective statistical model (Marchev et al., 2015). This permits also exploring efficiency and comparison of different statistical models.

A spatial regularity of the crop yields and trend parameters variation were investigated by *I*-Moran statistics (Moran, 1950). The global Moran's statistics were calculated using Geoda095i (http://www.geoda.uiuc.edu/) (Anselin et al., 2005). Spatial database was created in ArcGIS 10.2. The statistical analysis was performed by Statistica 10 software.

RESULTS AND DISCUSSION

Average rapeseed yields in the studied region ranged from 6.9 to 21.9 dt ha^{-1} (Fig. 3, A). The northeastern and southeastern regions are characterized by the lowest yields, and the southeastern regions of the study area have the highest values of yields. The highest values of the rapeseed yield coefficient of variation (45.4–74.3%) are in the northern regions, and the lowest (27.2–39.8%) are in the eastern and southern regions of the study area (Fig. 3, B). The mean of rape yields and its coefficient of variation are spatially structured (Moran *I* statistic 0.51; $p < 0.001$ and 0.28; $p < 0.001$, respectively). There is a negative dependence between the mean of rapeseed yields and the coefficient of variation ($R = –0.77$; $p < 0.001$). In general, the following pattern is observed – areas with a higher rapeseed yield usually have a lower coefficient of variation.

According to FAO data, the average annual rapeseed yield varied from 6.6 (in 1999) to 27.9 dt ha^{-1} (in 2017), with a mean of 15.0 dt ha^{-1} and standard deviation 6.1 during the 27-year period between 1991 and 2017. According to our data, rapeseed yield in 10 regions of the Polissya and Forest-Steppe zones ranged from 9.1 (1996) to 26.48 dt ha^{-1} (2014) during the period of 1991–2017, with the mean 15.6 dt ha^{-1} and standard deviation 5.8. A statistically significant correlation ($r = 0.95$; $p < 0.001$) is observed between the average rapeseed yield in Ukraine and the yield in the research region. It indicates that the temporal dynamics of rapeseed yield variation has the universal pattern for Ukraine.

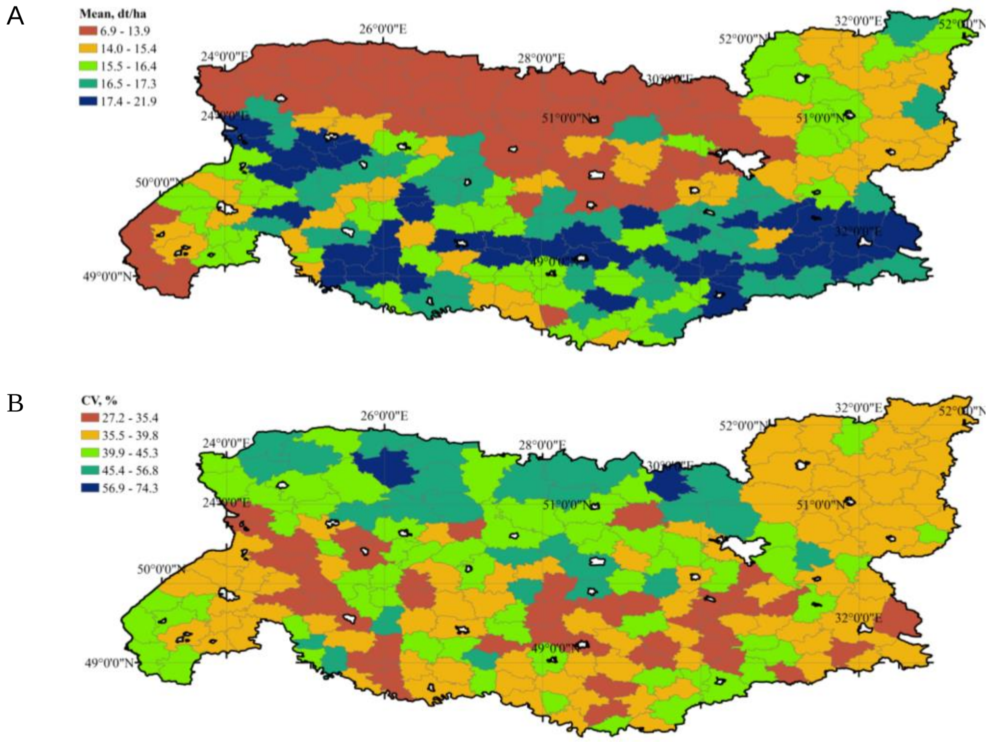

Figure 3. Spatial variation of the mean of rapeseed yield in the studied region of Ukraine (A) and rapeseed yield coefficient of variation (B).

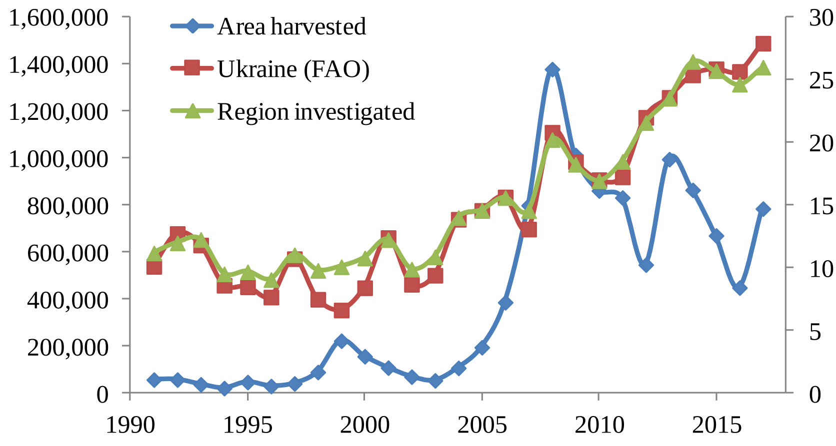

Figure 4. The rapeseed area harvested (ha, left *y*-axis) and yields dynamics during the period from 1991 to 2017 in Ukraine and in region investigated (dt·ha^{-1}, right *y*-axis).

The rapeseed harvested area remained almost unchanged from the early 90s to the middle of 2000s (Fig. 4). It is known that the revival of rapeseed cultivation in Ukraine began only in 1980 and the largest areas under rapeseed were in 1986–1990 (Haidash, 2002; Overchenko & Mishenko, 2007). From our data it is evident that in 2,000 there was a slight increase in the rapeseed harvested area up to 0.22 million hectares (Fig. 4). This tendency is also characteristic for the entire Ukrainian territory, since in 2000 it was planned to plant rapeseed on an area of 0.5 million hectares with the prospect of further expansion to 1.2–1.5 million hectares. However, the growth of acreage in Ukraine in 1990–2000 was much lower than the planned one due mainly to the lack of processing plants and the decrease in the demand for seeds (Haidash, 2002). However, since 2005, there has been a rapid expansion of areas under rapeseed, up to a maximum of 1.4 billion hectares in 2008 (Fig. 4). After 2008, the rapeseed cultivation area has declined slightly, but yields continue to increase, indicating Ukraine's transition to intensive agricultural technologies.

We used the Akaike information criterion to evaluate the suitability of different mathematical models for the explanation of rapeseed yield dynamics in 206 administrative regions of Ukraine. It was found that the overall trend of rapeseed yield in most areas is best described by the cubic function (Fig. 5). Thus, the rapeseed yield has been increasing since the early 2000s, but at present, it has reached its maximum point and started to decline.

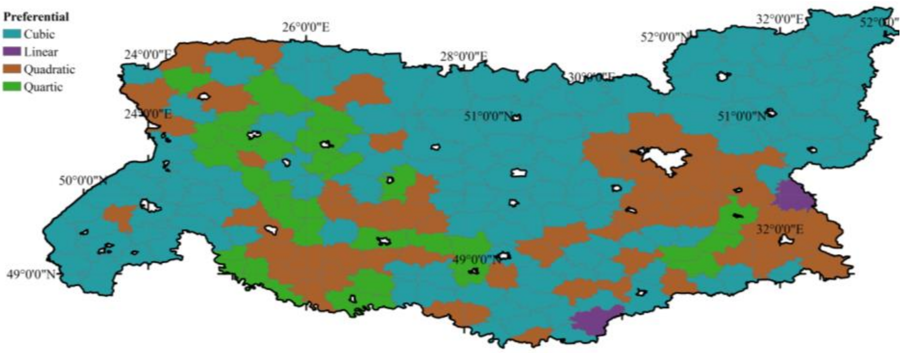

Figure 5. Spatial variations of the yield trend types.

Nevertheless, in this study, we are trying to identify the economic determinants of rapeseed yields. And for this purpose, the fourth-degree polynomial is best suited, since its form is completely in line with the economic cycle that Ukraine has undergone since its independence (Zymaroieva et al., 2019a). Thus, we assume that the rapeseed yield trend is determined by agro-economic factors. Moreover, the fourth-degree polynomial has greater explanatory power and has characteristic points that can be used for meaningful interpretation of rapeseed yield dynamics (Fig. 2).

The trend of rapeseed yields is characterized by two local maximums (Y_{max}) and one local minimum (Y_{min}) (Fig. 2). The local minimum reflects the lowest yields of rapeseed for the entire study period and, in our case, occurred in 2003 and is the result of a protracted socio-economic crisis caused by the collapse of the Soviet Union. The collapse of the Soviet Union caused massive socio-economic and institutional changes, which led to a significant decline in agriculture in Ukraine (Swinnen et al., 2017). The agricultural sectors of the former USSR countries were suddenly faced with increasing international competition, while the spending on agriculture was sharply reduced (Lerman et al., 2004). The rural population left the countryside en masse, the use of fertilizers declined significantly, and agricultural productivity decreased. These events led to a significant decrease in land use and average yield of major crops in the first years of Ukraine's independence (Schaffartzik et al., 2014; Swinnen et al., 2017). Nevertheless, agrosystems have some ‘inertia’ in the face of changing economic conditions, so even after the collapse of the Soviet Union in 1991, for a few more years the yields of main crops will remain almost unchanged, which is related to a previously well-planned agricultural system. Since the mid-1990s the economic crisis has reached Ukraine's agriculture and led to a rapid decline in yields to a minimum in Early 00s (Zymaroieva et al., 2019b).

The local maximums took place in 1993 and 2015 and correspond to the highest rapeseed productivity over the study period. The existence of a local maximum in 1993 was due to a sharp decline in the coming years, and the local maximum in 2015 is explained only by the fact that it is unclear how the rapeseed yield will behave in the coming years, whether there will be a plateau or whether there will be further growth. Since the local maximums are located in points, which close to the edges of the study period range, their exact determination seems doubtful. In many cases, the real maximums are beyond the study period. Therefore, we do not use the value of the function in local maxima as characteristic indicators of rapeseed yield dynamics.

The constant term of polynomial equation (constant *b*) indicates the productivity of rapeseed in the starting period. The constant *b* reflects the yield potential at the initial period of research and it is an independent parameter of the temporary dynamics of rapeseed yields variability in time (Zymaroieva et al., 2019b). The starting level of rapeseed yield in the research region ranged from 5.2 to 20.1 dt ha^{-1} (Fig. 6).

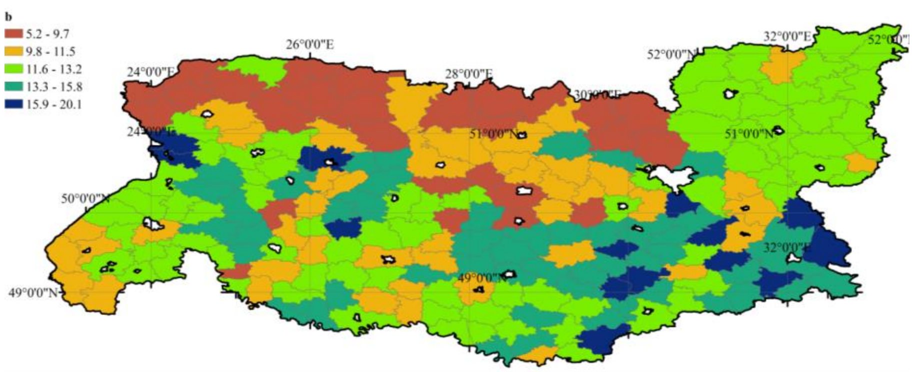

Figure 6. Spatial variations in the level of rapeseed yield in the initial period of research (constant *b* of the regression equation).

Areas with low values of the starting levels are situated in the north and with high values are in the southeast of the study area. The mean yield for the study period and the initial yield (coefficient b of the polynomial equation) are significantly positively correlated ($r = 0.98$; $p < 0.001$). This explains the fact that the variation of the coefficient b values (Fig. 6) is spatially dependent, that was confirmed by Moran test (Moran's *I*-statistic 0.34; $p < 0.001$). The values of this indicator identify the areas with the most favorable conditions for rapeseed cultivation.

From the agro-ecological point of view, Ukrainian Polissya and the Forest-Steppe zone have the most favorable soil and climatic conditions for growing winter and spring rapeseed (Barankova, 2007). According to our research, the highest potential for rapeseed cultivation have Chernihiv, Cherkasy and Vinnytsia regions, which is confirmed by indicators of the starting and average yields.

Indicators of the maximum rate of yield decline and the maximum rate of yield increase can be used as markers of the agro-ecosystem stability to external factors. The rate of rapeseed yield decline (Fig. 7) was not spatially dependent (*I*-Moran statistic 0.02; $p = 0.27$). The initial yield level correlates with the maximum rate of rapeseed yields decline in the first phase of research ($r = -0.14$; $p = 0.03$). Consequently, a higher rate of the starting yield corresponds to a more stable crop yield under adverse conditions.

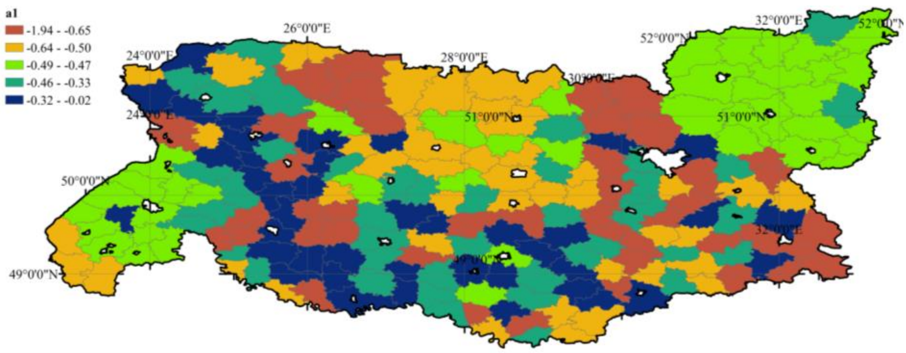

Figure 7. Spatial variation of the maximum rate of yields decline.

The rate of yield recovery was proportional to the intensity of the previous yield decline ($r = 0.25$; $p < 0.001$), indicating that these parameters are interrelated. The intensity of yield growth (Fig. 8) is spatially dependent (Moran *I*-statistic 0.21; $p < 0.001$).

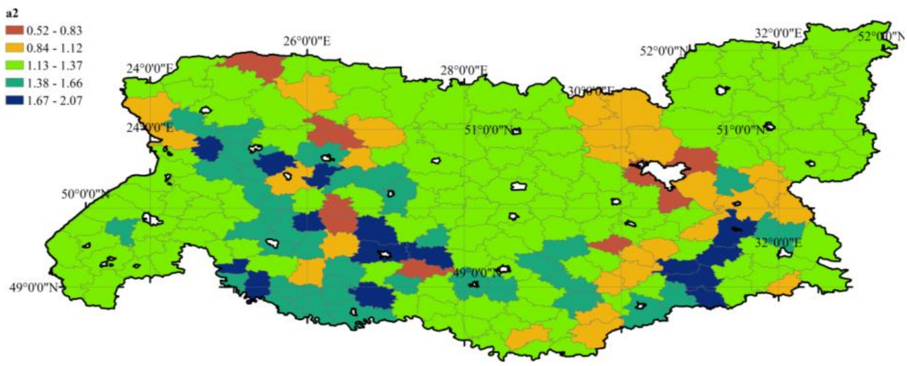

Figure 8. Spatial variations of the maximum rate of yields increase.

The presence of a trend in rapeseed yields, the mathematical form of which is unchanged within different regions of Ukraine, indicates the presence of constant external factors that affected the yield dynamics. The only factor that simultaneously influences the yields of rapeseed on the entire territory of Ukraine is of economic nature, which determines the development of agro-technology (breeding) and, as a result, affects the yields. Moreover, the fourth-degree polynomial describes the yield dynamics of other crops (soybean, rye, grain) in Ukraine at the same period (Kunah et al., 2018, Zymaroieva et al., 2019a), which confirms our theory of the universality of the trend determinant and its economic origin.

The coefficient of determination indicates the level of compliance of the chosen trend with the actual data. Since the yield trend mostly has an agro-economic origin, the determination coefficient can be interpreted as an indicator of the contribution of the agro-technological and agro-economic factors to the rapeseed yield dynamics. The values of the determination coefficient indicate that these factors explain 59–97% of the temporal variation in rapeseed yields (Fig. 9). Thus, the impact of these factors on the productivity of rapeseed in some areas is crucial.

The coefficient of variation is spatially determined (Moran *I*-statistic 0.36; $p < 0.001$), which indicates that the impact of agro-economic (agro-technological) factors has regional differences.

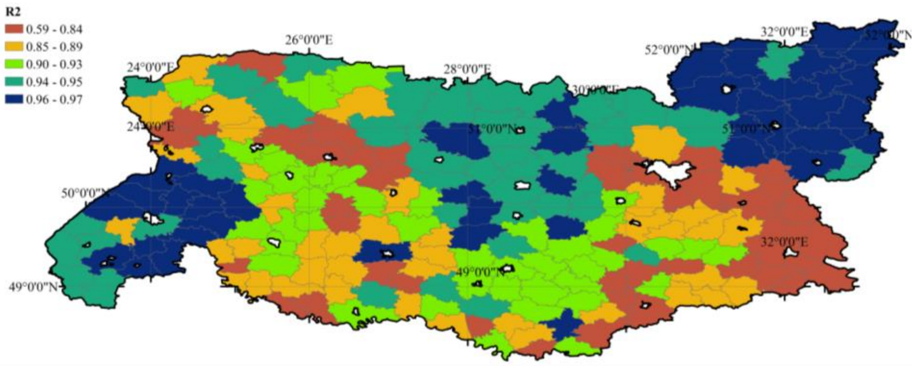

Figure 9. Spatial variation of the determination coefficient of the forth-degree regression model.

Agro-economic factors of the yield trend formation are complex. Differences in both technological investment and agro-technology, such as plant protection, sowing and fertilizer application, can lead to differences in yield as well (Annicchiarico & Iannucci, 2008). A large number of studies have analyzed the extent of crop yield spatial variation according to the types of cultivation, nitrogen fertilization, and soil type and fertility (Aydinalp & Cresser, 2008; Chen et al., 2014; Chen, 2018). However, no such studies have been conducted in Ukraine. Unfortunately, it is not possible to determine what specific agro-economic and agro-technological factors caused the rapeseed yield(s) fluctuation, since accurate accounting of economic conditions was not carried out because Ukraine was in deep crisis during 1990–2000. We have tested and proved the hypothesis that due to the yield trend, we can separate the economic component of yield variation from environmental ones.

Ukraine is considered to belong to countries with relatively large untapped yield potential of many crops (Schierhorn et al., 2013; Ryabchenko & Nonhebel, 2016), including rapeseed (Schaffartzik et al., 2014). In particular, Deppermann et al., 2017 found that oilseeds (rapeseed, soybean, and sunflower) total production could increase by 84% to 50 million tons in Ukraine. However, the reasons for the rapeseed yield gap in Ukraine are uncertain.

Studies focused on the spatial and temporal variability of crop yields are quite important both in terms of forecasting (simulation) models and in terms of farmland management. Therefore, the implications of the research should be reflected in the national agricultural policy, as well as in regional crop management. We consider that agro-economic factors were the major determinants of spatial variability of rapeseed yield in 1991–2017. At the current stage of development of agricultural production in Ukraine, environmental factors, such as climate change, may have a greater impact on rapeseed yield. Investigation of the environmental factors influence on the rapeseed yield variations will be the aim of our further research.

CONCLUSIONS

Our study shows that the trend of rapeseed yield within the study area is best described by a fourth-degree polynomial. The existence of this type of trend is due to the influence of agro-economic factors, whose contribution to the overall variation in yield ranges from 59 to 97%. The impact of agro-economic (agro-technological) factors has regional differences. We also indicated the areas with favorable soil and climate conditions for rapeseed cultivation, which spatially coincide with the regions with the highest rapeseed yields. Indicators of the maximum rate of yield decline and maximum rate of yield increase are the markers of agro-ecosystems resilience to the external factors, in particular, agro-technological and agro-economic ones. Regions with higher levels of yields in the initial period are more stable in the transitional economic period. Besides, the yields in areas with favorable soil and climatic conditions for rape cultivation are less dependent on the influence of agro-economic and agro-technological factors. Therefore, Ukraine has all the prerequisites for increasing yield potential of rapeseed, especially in the areas where the impact of agro-technology and breeding is crucial.

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