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The spatial patterns of long-term temporal trends in yields of soybean (*Glycine max* (L.) Merril) in the Central European Mixed Forests (Polissya) and East European Forest Steppe ecoregions within Ukraine

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ABSTRACT

This research aimed to characterize the spatial and temporal yields trend of soybeans in 267 administrative districts in Polissya and Forest-steppe ecoregions within Ukraine over 27 years (1991 – 2017). The common feature of temporal changes for all administrative districts is the existence of the trend that can be described by the fourth-degree polynomial. The trend type indicates its agro-economic (agro-technological) origin. Soybean yield dynamics can be described and interpreted by characteristic points of the fourth-degree polynomial. The absolute term of polynomial equation indicates the productivity of the soybean in the starting period. This indicator enables identifying areas with the most favorable soil conditions for soybeans cultivation. It is more appropriate to grow soybeans in the forest-steppe zone of Ukraine, and less appropriate in Polissya. The indicators of the maximum rate of reduction and the maximum rate of increase of yields can be used as markers of agroecosystem stability to agro-economic agro-technological factors. The value of the coefficient of determination indicates the contribution of agro-technological and agro-economic factors in soybean yields variation. These factors determine 7 – 89% of soybean yield depending on the area. The soybean yields in southern and eastern areas of the research region are the most sensitive to agro-technological and agro-economic factors and yields in the northern and western areas are the least sensitive.

Keywords: dynamics, pattern, productivity, soybean, trend, variability, yield

INTRODUCTION

Long-term trends in crop yields were investigated by using the data on global scales (Aizen et al., 2008; Aizen et al., 2009; Godfray et al., 2010; Lesk et al., 2016; Ray et al., 2012; Ray et al., 2013). Spatio-temporal variation of ecological processes can be decomposed into its spatial and temporal components (Hammond and Kolasa, 2014). Synchrony and persistence are important components of spatial and temporal variability. When the yield of certain crops increases or decreases in the same year in each of the two places, the culture of these places is in synchrony. On the other hand, the persistence manifests itself in the fact that the average yield is different in two locations or other spatial units (Li, 2015). Spatial patterns are diagnostic when they are used to uncover the hidden mechanisms in the landscape and are predictive as they indicate the most probable future behaviour of processes (Hammond and Kolasa, 2014).

The crop yield trends by using parsimonious regression models of increasing order may be classified into four categories including (1) increasing, (2) stagnating, (3) collapsed, and (4) never improved (Chen, 2018). “Yields never improved” – areas that have witnessed no significant yield improvements to date. “Yields stagnated” – areas where yields previously improved, but now are stagnating or declining. “Yields collapsed” – areas where yields decreased or initially increased and then collapsed to the initial level. "Yields still increasing" – areas where yields are still increasing (Ray et al., 2012).

The percentage of number of yield-not-improving prefecture was higher in low latitude regions than high latitude regions for the three crops (rice, wheat, and soybean) in Japan (Chen, 2018). The southern and southeastern areas of Rwanda registered a trend decline in food crop yields perhaps due to an increase in aridity (Muhire et al., 2014). The drivers of agricultural production and their variability include technology, genetics, climate, soil, field management practices and associated management decisions such as fertilizer applications, tillage and crop hybrid selection, irrigation (Kukal and Irmak, 2018). Ecological regimes can explain large parts of overall yield variability, especially in regions with stable management conditions (Müller et al., 2017; Ray et al., 2015). More intensive soybean management practices increased biomass and seed yield (Enrico et al., 2018). In some cases, soybean cultivar decisions should be based on selecting the highest yielding cultivars adapted to a particular geographic region and location regardless of the management system (Pedersen and Lauer, 2003).

The steady trend of increasing the global human population (Godfray et al., 2010) causes the urgent need to increase the production of quality agricultural products (Godfray et al., 2010; Tscharntke et al., 2012). Soybean (*Glycine max* (L.) Merril) is one of the main sources of protein and vegetable oil of the world being grown commercially and used as animal and human food for hundreds of years (Hilton et al., 2013, Dalposso et al., 2016). Considerable interest in this culture is due to fact that it contains the highest percentage of protein (40%) among the crops and second only to peanuts in terms of oil content (20%) of food crops. Soybean provides approximately one-fourth of the world's edible oil and two-thirds of world production of protein meal (Golbitz, 2001). Soy proteins represent an excellent source of high-quality protein due to its excellent amino acid composition and a high level of digestibility (Rackis et al., 1971).

Across the 10 years from 2006 to 2016, world soybean production increased from 222 to 335 million metric tons (51% increase) (FAOSTAT, 2018). It is suggested that the high rates of increase in soybean worldwide production (more than five million tons/year in the period from 1970 to 2007) should continue due to the global population growth (70 million/year) and to the change in eating habits of the population (Tyagi et al, 2010; Hilton et al., 2013). On the other hand, the intense search for alternative sources of energy also stimulates consumption of soybean oil as a fuel. Thus, in the future soybean may also become the major energy crop. Although use rates of soybean do not increase as oil, demand for soybean as animal feed also increases (Hilton et al., 2013; Fernández-Tirado et al., 2017).

In current market conditions in the agriculture of Ukraine noticeable change priorities for growing economically beneficial crops, leading to increased soybean acreage (Zuza et al., 2015; Shcherbachuk, 2016). Ukraine is the largest producer of soybeans in Europe, and the 8th largest in the world (Chekhov, 2015). Now soybean is the 4th among the largest crops in the country, after cereals, sunflowers, and maize (Bezruchko and Kolisnychenko, 2011). The soybean market is one of the most rapidly growing markets in Ukraine (Babich and Babich-Poberezhna, 2011; Chekhov, 2015). Even though extensive experimental and productive soybean crops in Ukraine started only in 1926 (Enkin, 1959), the accounting of yield and gross harvest was fixed only since 1965. In 1990, this culture had a share of only 0.3% of the total acreage of agricultural enterprises and gross harvest amounted to 99 thousand tones. Since 2003, the active expansion of the soybean area in Ukraine began. In 2015, soybeans have a share of 11% of the total acreage of agricultural enterprises and there is the prospect of further growth (Babich and Babich-Poberezhna, 2010; Shcherbachuk, 2016).

The country fully satisfies domestic demand and exports more than half of the soybean (2.8 million UNPO in 2016/17). Such growth has occurred due to the high profitability of crops, high prices, the requirements of external markets and geographical location (Bakhmat, 2012; Kozhukhar, 2017). However, due to economic reasons and lack of government support, farmers can not comply with optimal technology for growing crops. The deficit financing leads to destabilization of agriculture in general, and particularly soybean. The average soybean yield in Ukraine is about 2 tones/ha, and it is almost 30% less than the average yield in the other top-producing countries (Shcherbachuk, 2016). So now there is a significant potential for increased production, which can be realized by increasing productivity without any changes in the area of crops (Kozhukhar, 2017).

Therefore, the study of the spatiotemporal dynamics of soybean productivity is extremely important to assess the potential of increasing productivity and factors that constrain it. This study aims to characterize the spatial and temporal trend in soybean yield in 267 administrative districts that are in Central European Mixed Forests (Polissya) and East European Forest Steppe ecoregions within Ukraine over 27 years from 1991 to 2017.

MATERIALS AND METHODS

Data of crop 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 averages by administrative districts of the annual yield of soybeans for 10 regions of Ukraine, which include 267 administrative districts over 27 years from 1991– 2017. The research area is located in two natural vegetation and climatic zones: Forest zone (Polissya) and Forest steppe zone. Twenty-seven years' data of soybeans from 1991 to 2017 were available for 10 administrative regions (Cherkasy, Chernihiv, Khmel'nyts'kyy, Kyiv, L'viv, Rivne, Ternopil', Vinnytsya, Volyn, Zhytomyr) (Figure 1). Information about the annual yield of soybeans for Ukraine was obtained from FAO (FAOSTAT, 2018).

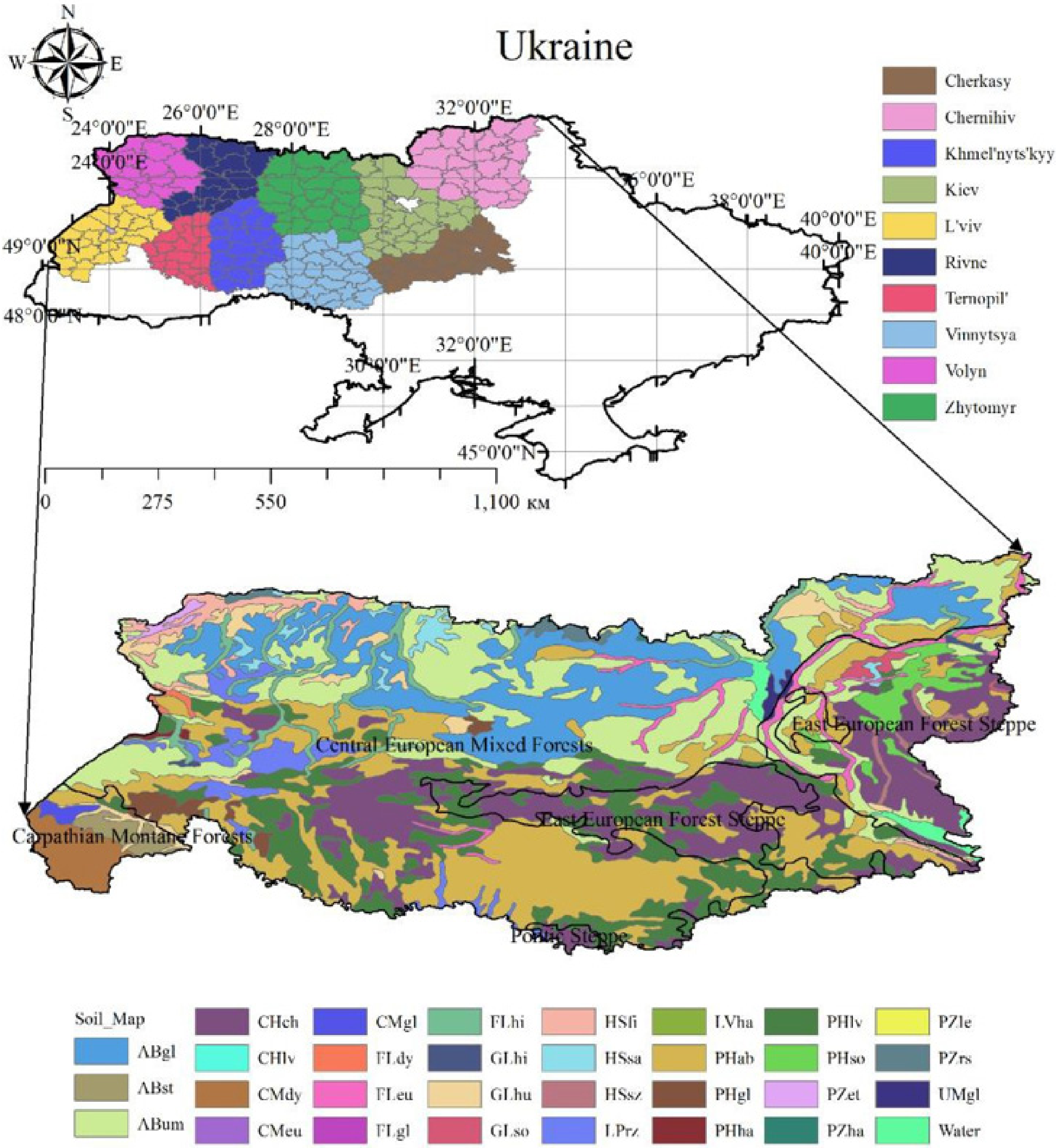
Climate and soil condition

Central European Mixed Forests ecoregion or Forest zone of Ukraine (Polissya) has a continental climate. The average temperature in July is +17 – +19 °C, in January it declines to -4.5 – -7.8 °C. The vegetation season lasts from the second decade of April to the third decade of October. The period with the average daily temperatures above +15 °C lasts approximately 95-125 days. The annual amount of temperatures exceeding +10 °C is around 2,600. This geographical zone has a flat terrain. The average annual precipitation is 550-650 mm. The highest precipitation, at the level of 400-450 mm, falls within the area of Albeluvisols Gleyic, which occupies about 75% of the territory of Polissya. The average forest cover of the zone is 30%. The regional cropland occupies 33% of the whole territory of the zone, which is over 4 million hectares (Struk, 1993).

The climate of East European Forest Steppe ecoregion is moderately continental. The average annual precipitation varies from 450-500 mm in the south-eastern part to 550 mm in the central and 600-700 mm in the west of the zone. The thermal regime of this soil-climatic zone has the following characteristics: the sum of the average daily temperatures above 10°C in May-September is 2500-2750 °C, the duration of the period with a temperature above 15 °C - 100-120 days. In Forest-steppe the fertile soils are located: Phaeozems Haplic, Chernozems Chernic, Phaeozems Luvic, Phaeozems Albic and others (Figure 1). Forests cover is insignificant - about 12%. Agricultural lands occupy 70% of the territory; including 66% of arable land (Babich and Babich- Poberezhna, 2010; Struk, 1993).

Yield trend analysis

As an analytic form of the trend we chose between polynomials of different order (Ray et al., 2012). Yield trends were analyzed using parsimonious regression models of increasing order for: an intercept-only model (Equation 1), a linear model (Equation 2), a quadratic model (Equation 3), a cubic model (Equation 4) and a quartic model (Equation 5):



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

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

$Y_x = b$ (1)
$Y_x = b + a_1x$ (2)
$Y_x = b + a_1x + a_2x_2$ (3)
$Y_x = b + a_1x + a_2x_2 + a_3x_3$ (4)
$Y_x = b + a_1x + a_2x_2 + a_3x_3 + a_4x_4$ (5)

where:

Y_x – crop yield in the time moment *x*, b, a_1, a_2, a_3, a_4 – coefficients.

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. But important is quantitative characteristic of the trend in comparable terms. When the Akaike Information Criterion (AIC) criterion suggested a constant model, this implied that the yield-year relationship was a constant or that "yields never improved". When the model chosen was linear, the yield trend may be classified based on the sign of the slope. If the slope was negative it meant that yields were decreasing always and thus they may be classified as "yields collapsed". There wasn't any case with a trend that may be classified as "yields collapsed" in our dataset. If the slope of the linear equation was positive, it meant that yields were increasing and thus were classified such areas as "yields increasing". When the chosen model was quadratic and if the quadratic term was positive the trend was classified as "yields increasing". When the quadratic term was negative the trend was classified as "yields stagnating". When the chosen model was quartic the trend was classified as "yields stagnating".

Choosing the statistical model that best represents yield trends

The Akaike Information Criterion (AIC) developed by Akaike (1974) was used to estimate the likelihood of a statistical model to the observed data, and computed AIC (Equation 6) for each of the five models (Equations 1–5):

$$AIC = n\log(ss/n) + 2p, \quad (6)$$

here, *ss* is the residual sum of squares, *n* is the sample size, and *p* is the number of parameters. A good model is the one that has minimum AIC among 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).

Each parameter of the linear model may be independently interpreted in such a way that it can be given a clear physical meaning. The magnitude derived from the slopes of the regression lines may be presented spatially in the form of maps (Muhire et al., 2014). This allows the appropriate coefficients treated as independent variables and explore their behavior depending on the other environmental variables, or explore the features of their spatial variability. The coefficients of polynomials of the higher-order, unless constant term, cannot be interpreted meaningfully. Lower order polynomials can be viewed as a simplified version polynomial of a higher order.

The total yield trend within the investigated area can best be described by a fourth- degree polynomial. Therefore, in the next 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 fist maximum and minimum, the maximum rate of yields increases in the range between minimum and second maximum (Figure 2). To quantitatively estimate the special points values following calculations are performed.

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

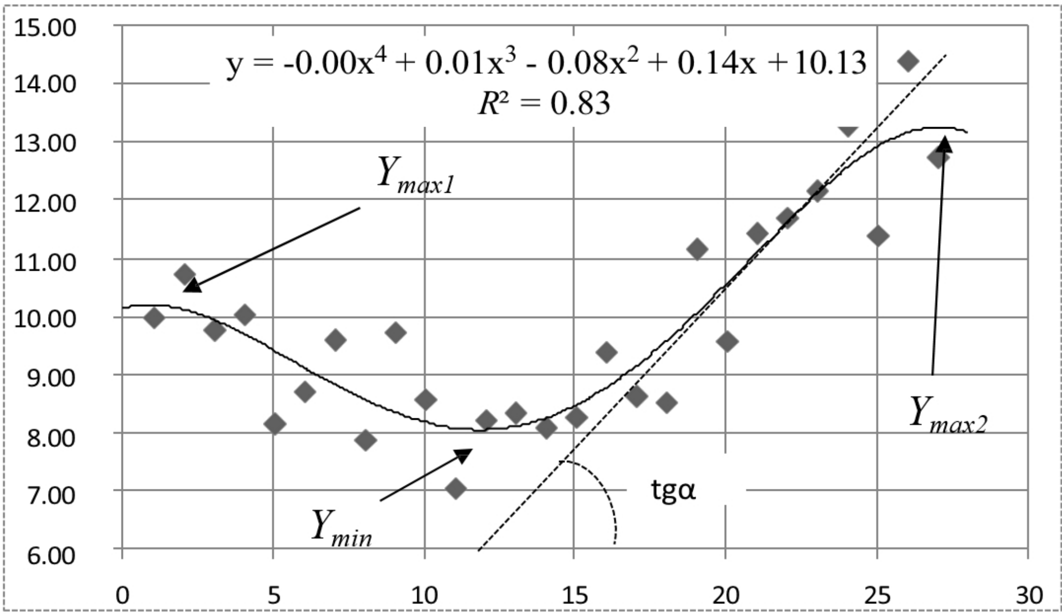
$$y_x' = a_1 + 2a_2x + 3a_3^2 + 4a_4^3 \quad (7)$$

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

$$y''_x = 2a_2 + 6a_3 + 12a_4^2 = 0 \quad (8)$$

The corresponding quadratic equation has two roots:

$$x_{1,2} = \frac{-6a_3 \pm \sqrt{36a_3^2 - 96a_4a_2}}{24a_4} \quad (9)$$



Axis of abscissas – time (1 – 1991, 27 – 2017); ordinate axis – yields, dt/ha; b is an absolute term of polynomial equation; Y_{Min} – the value of the polynomial at the point of the local minimum; Y_{Max} – the value of a polynomial at the points of local maxima; tgα – the maximum rate of increasing crop yields in 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)

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

Substituting the solutions of equation (8) into equation (7) we obtain the maximum rates of the decrease and increase the yield 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

The annual temporal variation in average soybean yield in Ukrainian ranged between 7.2 (in 1994) and 23.0 (in 2016) dt/ha, with a mean of 13.9 dt/ha and standard deviation 4.7, during the 25-year period between 1992 and 2016. The annual temporal variation in average soybean yield in the region investigated ranged between 7.1 (in 2001) and 14.4 (in 2016) dt/ha, with a mean of 9.9 dt/ha and standard deviation 1.8, during the 27 years between 1991 and 2017. Between the average yield of soybean in Ukraine and yield in the investigated area, there is a statistically significant correlation ($r=0.71$, $P<0.001$) (Figure 3 B). But the nature of the trend in both cases is fundamentally different. For Ukraine, the general trend may be best described by a second-degree polynomial (AIC=104.6, F=112.2, $P<0.001$) with a constant increase in productivity within the studied period. For the research area, the overall trend could be best described by a fourth-degree polynomial (AIC=73.4, F=26.2, $P<0.001$).

Figure 3. The soybean yields dynamics during 1992-2016 total in Ukraine (dt/ha, left y-coordinate) and in region investigated (dt/ha, right y-coordinate) (A) and scatter plot of soybean yields total in Ukraine against soybean yields in region investigated (B).

It is established that the large majority of trend dynamics types in the soybean yield of the administrative regions can be described by the second or fourth-degree polynomials (Figure 4).

Fourth-degree polynomial best describes the trend dynamics in 106 administrative districts (51.5% of the total), and a second-degree polynomial best describes the trend dynamics in 87 administrative districts (42.2% of the total). The northern part of the investigated area is represented by administrative districts, the dynamics of productivity which is best described by the second-degree polynomial. This trend can be classified as "yields increasing". The southern part of the investigated area is represented by administrative districts, the dynamics of productivity which is best described by a fourth-degree polynomial. This trend can be classified as "yields stagnating".

The total dynamics of averaged data of soybean yields in the studied region may be characterized by fourth-order polynomial. Such an approach allows us to characterize each administrative district using a common mathematical model. These models have three critical points: two local maxima and one local minimum. Soybean yield dynamics can be described and interpreted using characteristics of the inflection points of the fourth-degree polynomial (Figure 2). The trend of soybean yield is described by the constant term of polynomial equation, the maximum rate of reduction and the maximum rate of increase in yield which are occurred in inflection points, and the coefficient of determination of the regression models.

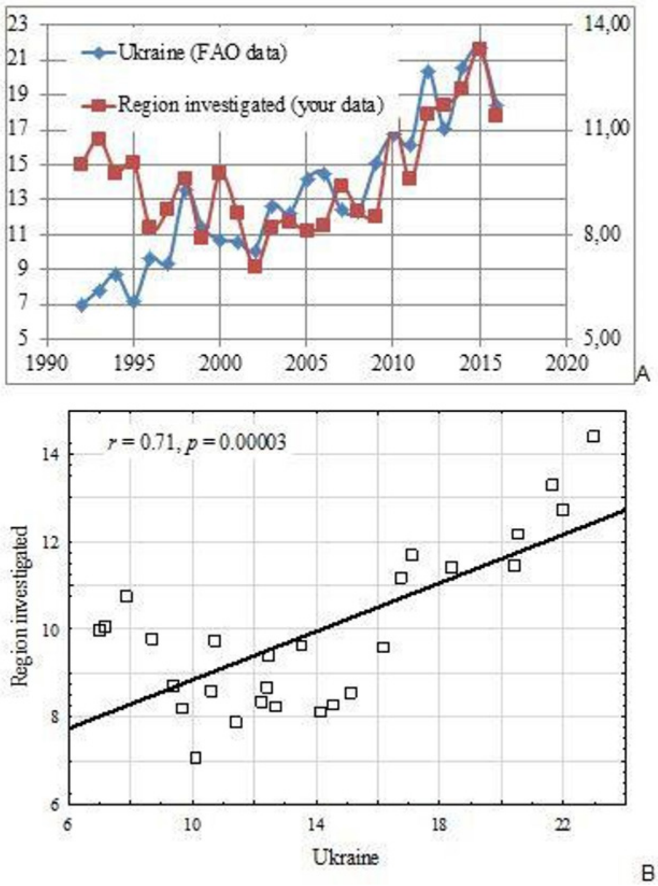


Figure 3. The soybean yields dynamics during 1992-2016 total in Ukraine (dt/ha, left y-coordinate) and in region investigated (dt/ha, right y-coordinate) (A) and scatter plot of soybean yields total in Ukraine against soybean yields in region investigated (B)

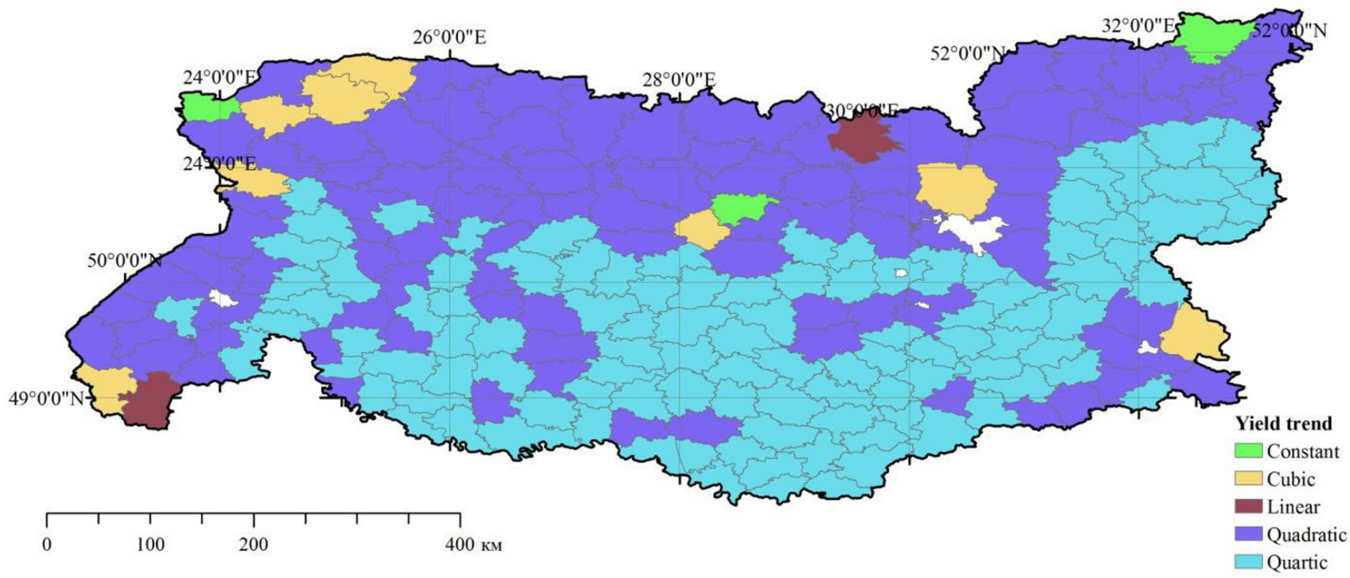


Figure 4. Spatial variations of the yield trend types

The constant term of polynomial equation (constant *b*) indicates the productivity of the soybean in the starting period. The constant b reflects the potential of yield at the initial period of research and it is an independent parameter of the temporary dynamics of soybean yields variability in time. The starting level of soybean yields is spatially dependent (Moran *I*-statistics is 0.61, P=0.001) and varies from 5.6 dt/ha (northern and north-eastern regions) to 14.7 dt/ha (southern and south-eastern regions) (Figure 5). This indicator enables identifying areas with the most favorable conditions for soybeans cultivation. It is more appropriate to grow soybeans in the forest-steppe zone of Ukraine, and less appropriate in Polissya.

The function value at the point of local minimum Y_{Min} indicates the "bottom" of the crop productivity dynamics and the value of Y_{Max} shows the highest yield of soy for the entire period of research. The state of maximum productivity Y_{Max} of the culture reflects a certain balance between factors of agro-economic and agro-technological origin on the one hand and biological potential on the other hand. In such a situation, one should expect the yield on the plateau, in which the yields variation will be determined by natural fluctuations only, which will be common in both natural ecosystems and agroecosystems by their origin. Instead of a plateau, there can be a decrease in yield, which itself generates a local maximum. Still, most researchers believe that shortly soybean productivity in Ukraine will increase (Bezruchko and Kolisnychenko, 2011; Bakhmat, 2012). Since local maxima are in the zones close to the edge of the range of the studied period, their exact definition is useless. In many cases, the maxima are outside the scope of the research period. Therefore, we do not use the value of the function in local maxima as the characteristic indicators of yields dynamics.

Between the local maximum and minimum on the one hand and the minimum and maximum of yields - on the other hand, there is an inflection of the polynomial curve, where the second derivative equals zero. At these points, the rate of decrease or increase of the crop yields becomes the largest, and the corresponding dynamics can be approximated by the linear dependence. The angle of the tangent to the regression line at the inflection point indicates the maximum rate of yields reduction or increase, respectively, this can be a characteristic indicator of the yields dynamics (Zymaroieva et al. 2019b).

By substituting the corresponding values of the arguments x_1 and x_2 into the derivatives of the regression equation, we can set a value that acquires the rate of

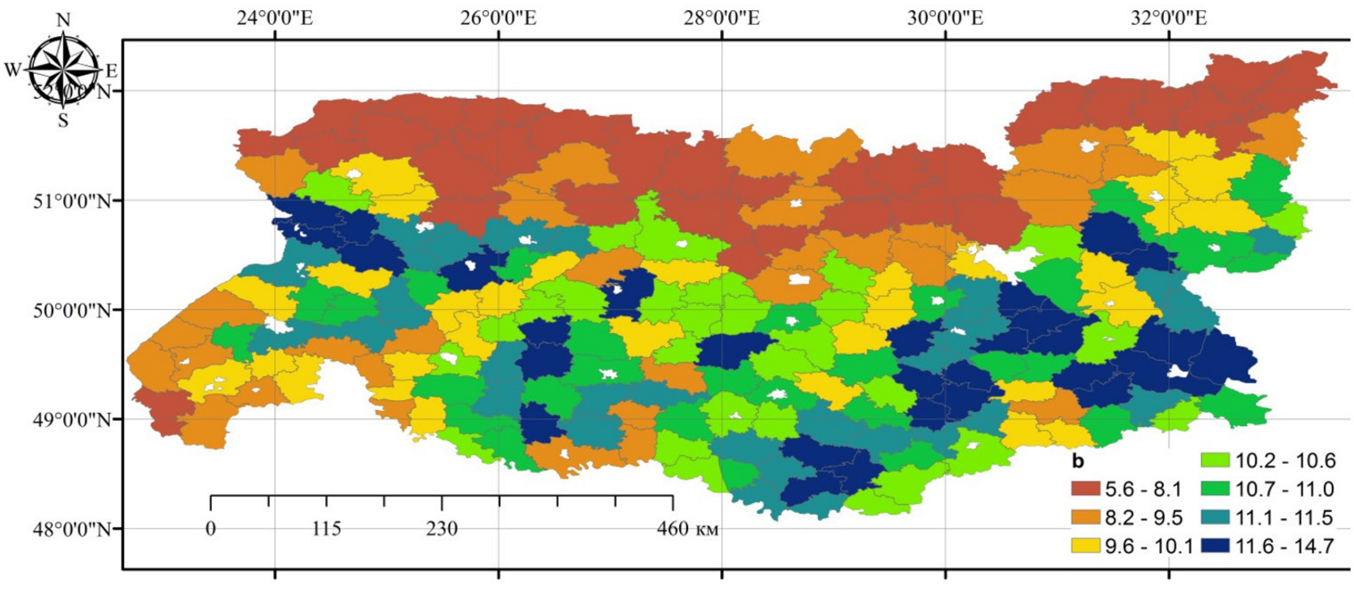


Figure 5. Spatial variations in the level of soybean yields in the initial period of research (constant *b* of the regression equation)

yields change at these points, which are maximal by the modulo. The indicators of the maximum rate of reduction and the maximum rate of increase of yields can be used as markers of agroecosystem stability to external factors (Figure 6 and 7).

Variation of the rate of crop yield reduction is spatially dependent (*I*-Moran statistics is 0.66, P=0.001). Variation of the rate of productivity growth is also spatially dependent (*I*-Moran statistics is 0.57, P=0.001).

Areas where soybean yield slowly reacts to changes in economic and technological conditions are in the west and south of the research region. The soybean yields in southern, central and eastern areas are less stable and more responsive to changes in technology, increasing productivity under favorable conditions.

The quality of the fourth-degree polynomial model is characterized by the coefficient of determination. The coefficient of determination indicates the level of compliance of the model with the real data and varies from 0.07 to 0.89 (Figure 8). Polynomial has the character of global regression.

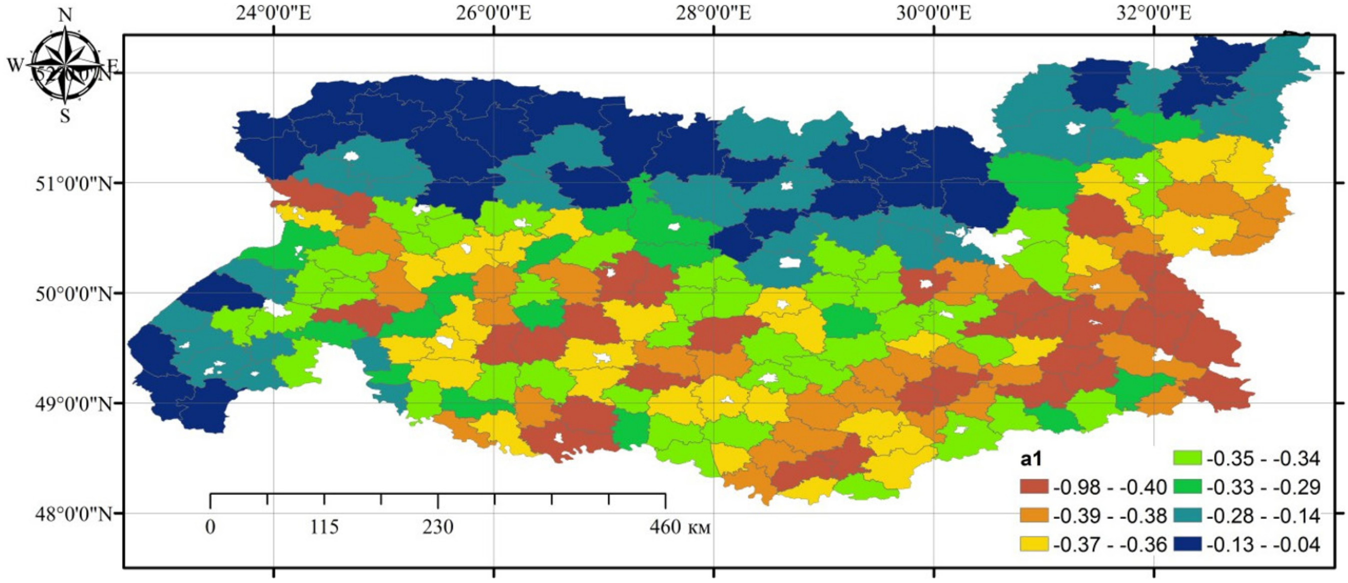


Figure 6. Spatial variation of the maximum rate of yields decline

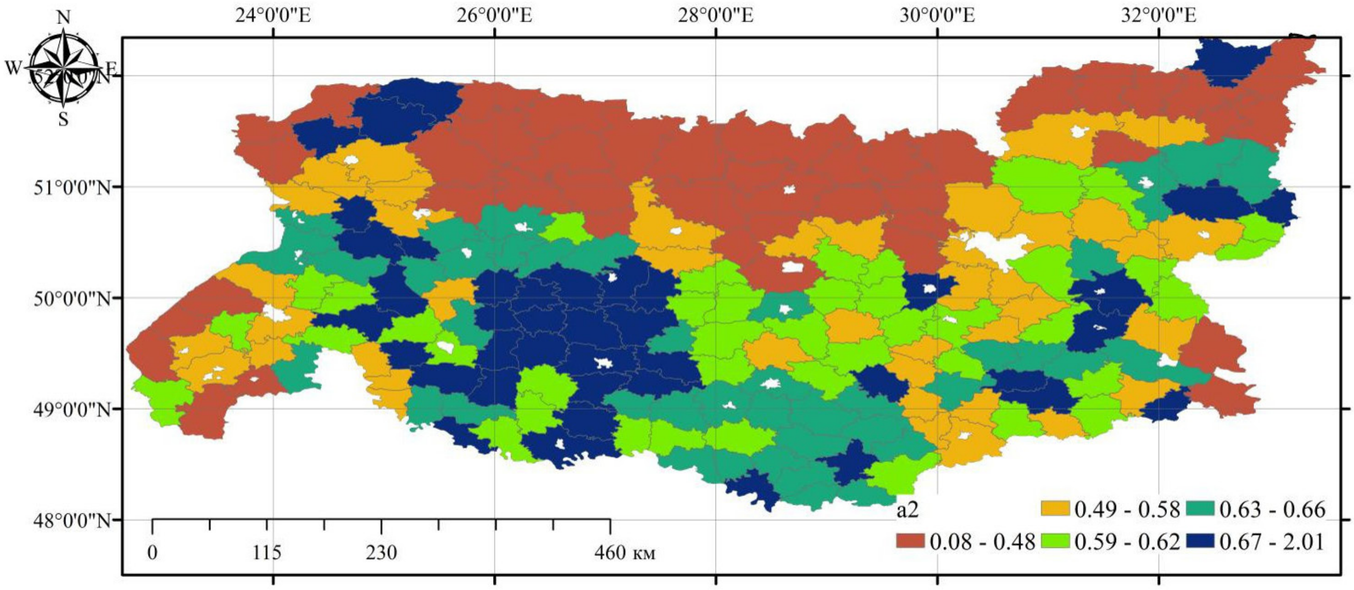


Figure 7. Spatial variations of the maximum rate of yields increase

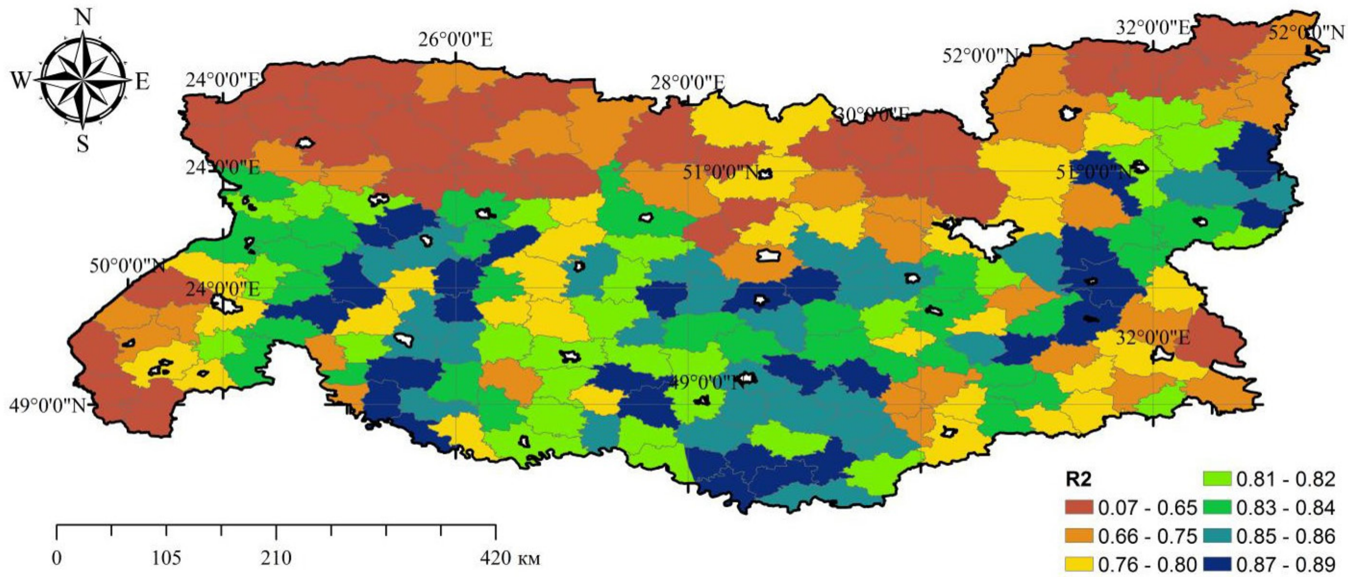


Figure 8. Spatial variation of the coefficient of determination of the regression model

The existence of such a relationship occurs as a result of the impact of the constant external factor that affects the yields. The character of the general dynamics of yields, explained by regression, indicates that such factors are agro-technological and agro-ecological conditions of agricultural production. Consequently, the coefficient of determination can be interpreted as an indicator of the role of agro-technological and agro-economic factors in yields dynamics. The obtained data indicated that these aspects of productivity are the most important. The variation of the coefficient of determination is spatially dependent (*I*-Moran's statistics is 0.50, p=0.001).

The southern and eastern areas of the research region are the most sensitive to agro- technological and agro-economic factors and the northern and western areas are the least sensitive (Figure 8). The cluster with the highest sensitivity to non-ecological regular factors of yield dynamics is formed in the central areas of the region.

Comparative analysis (Minkova et al., 2019) and grouping (Milev et al., 2017) are other statistical methods that could be used for the classification of different geographical areas according to factors, e.g. agro-technological and agro-economic factors.

DISCUSSION

The need for soybeans in the world continues to grow based on strong demand for animal feed worldwide and significant growth in demand for biodiesel feedstock (Wolf and Cowan, 1975, Masuda and Goldsmith, 2009, Hilton et al., 2013). The current production of soybean in Ukraine however, is still far from reaching its potential. Soon, it should be selected intensive or extensive types of growth for this crop cultivation (Babich and Babich-Poberezhna, 2011; Bakhmat, 2012,). The dynamic of soybean yield during the period of independence of Ukraine (1991 - 2017) has the character of the fourth- degree polynomial, which respectively has two local maxima and one local minimum. The first local maximum of the soybeans yields was achieved in the pre-reform period (1990–1993) when intensive technologies of cultivation of this crop were widely used (Lukomets et al., 2013). The minimum soybean yield was at the end of the 90s and it was caused by the socio-economic crisis, which arose as a continuation of the collapse of the USSR (Lukomets et al., 2013). The most severe decline in yields occurred in 1995. Since the early 2000s, soybean production has increased, soy crops have started to expand throughout Ukraine. The highest rate of yield growth occurred in 2015. The second local maximum was in 2017. Although, most scientists predict a further increase of soybean yield in Ukraine, and not only due to the expansion of sown areas, but also due to the intensification of growing technology (Babich et al., 2013; Kozhukhar, 2017).

The characteristic points of the regression model may be the basis of zoning the territory of Ukraine and identifying the regions with the most favorable conditions for the cultivation of soybeans. Thus, the map of spatial variations in the level of soybean yields in the initial period of research (constant *b* of the regression equation) indicates the more favorable conditions for soybean cultivation in the central and southern regions of the research area. Consequently, in general, soybean cultivation is more appropriate in the Forest-steppe zone of Ukraine and less appropriate in the Polissya.

Babych and Babich-Poberezhna (2010) argue that the production of soy eventually involves the formation of a soybean belt in Forest-steppe of Ukraine. Here, the soil-climatic conditions are best suited to the biological needs of this culture, as a result, soybean achieves full maturity and forms a high yield. However, this research is more precise and allows to determine areas that may also be included in the soybean belt. With the help of the maximum rates of increase and reduction of yields, the areas where yields are more stable and less dependent on fluctuations in external factors, in particular, agro-economic and agro-ecological factors can be identified. Obviously, regions with the lower potential of productivity (southern and western regions) are more stable.

The coefficient of determination can be interpreted as an indicator of the role of agro- technological and agro-economic factors in yield dynamics. The obtained data indicate that these factors are critical in some areas (R^2=0.89), and in some areas, their influence is negligible (R^2=0.07). Soybean yield in southern, eastern and western areas of the research region are the most sensitive to agro-technological and agro- economic factors and in the northern areas are the least sensitive. The cluster with the highest yield sensitivity to non-ecological regular factors of yield dynamics is formed in the central areas of the region.

Application of the new generation of soybean varieties, qualitative implementation of modern technologies of its cultivation, taking into consideration the features of soil and climatic conditions of the regions - are the opportunities for increasing the yield of soybeans in the future. Moreover, there is acreage growth potential, as the sowing area could increase up to 3 million ha (in comparison with the 2 million ha now) (Kozhukhar, 2017).

The environmental factors, such as climate, clearly also affect crop yields (Lobell et al., 2011; Tigchelaar et al., 2018; Li, 2015; Urban et al., 2015).It was found that the contribution of the ecological factors to the overall variation in soybean yields ranged from 11 to 93% (Zymaroieva et al., 2019a). A detailed study of the climate change impact on soybean yield will be the objective of our subsequent studies.

CONCLUSIONS

The general trend of soybean yield for 1990-2017 is a fourth-degree polynomial. The trend type indicates its agro-economic (agro-technological) origin. Soybean yield dynamic can be described and interpreted by characteristic points of the fourth-degree polynomial: the absolute term of polynomial equation, the maximum rate of yield reduction, the maximum rate of yield increases and the coefficient of determination. The map of spatial variations in the level of soybean yields in the initial period of research (constant *b* of the regression equation) indicates the more favorable conditions for soybean cultivation in the central and southern regions of the research area. Consequently, in general, soybean cultivation is more rational in the Forest- steppe zone of Ukraine (East European Forest ecoregion) and less appropriate in the Polissya (Central European Mixed Forests ecoregion). Areas where soybean yield slowly reacts to changes in economic and technological conditions are in the west and south of the research region, in the southern, central and eastern areas the soybeans productivity is less stable. The coefficient of determination can be interpreted as an indicator of the role of agro-technological and agro-economic factors in yield dynamics. Areas, where these factors are the major determinant of soybean yield, are in the south and east of the research region. Soybean yields in the northern and western areas are less dependent on agro-technological and agro-economic factors.

REFERENCES

Aizen, M. A., Garibaldi, L. A., Cunningham, S. A., Klein, A. M. (2008) Long-term global trends in crop yield and production reveal no current pollination shortage but increasing pollinator dependency. Current Biology, 18, 1572–1575. DOI: https://doi.org/10.1016/j.cub.2008.08.066.

Aizen, M.A., Garibaldi, L.A., Cunningham, S.A., Klein, A.M. (2009) How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. Annals of Botany, 103, 1579–1588. DOI: https://doi.org/10.1093/aob/mcp076.

Akaike, H. (1974) A new look at the statistical model identification. IEEE Transactions on Automatic Control, 19, 716–723. DOI: https://doi.org/10.1109/TAC.1974.1100705.

Anselin, L, Ibnu, S, Youngihn, Kh. (2005) GeoDa: An Introduction to Spatial Data Analysis. Geographical Analysis, 38 (1), 5–22. DOI: https://doi.org/10.1111/j.0016-7363.2005.00671.x.

Babich, A.O, Babich-Poberezhna, A.A. (2011) Selection, production, trade and use of soybeans in the world, Kyiv, Agricultural Sciences. (in Ukrainian)

Babich, A.O, Babich-Poberezhna, A.A. (2010) The soybean belt and placement of soybean production in Ukraine. Propozyitciia 4, 52-56. (in Ukrainian)

Babych A. A, Ivanyuk, S. V, Vilgota, N. V. (2013) Influence of chemical mutagens on the productivity elements of soybean plants. Feeds and Feed Production 77, 3-8. (in Ukrainian)

Bakhmat, O.M. (2012) Simulation of Adaptive Technology soybean: monograph. Kam'yanets-Podilsky, PP Zvolenko D.G.

Bezruchko, O, Kolisnychenko, O. (2011) Ukraine's Market of Plant Varieties: Soybean (*Glycine max* (L.) Merr.). Plant varieties studying and protection, 2 (14), 46-56. (in Ukrainian)

Chekhov, S. (2015) Functioning of the market of soybean in Ukraine. Academic Bulletin Poltava National Technical Yuri Kondratyuk University Economics and region, 4 (15), 61-66. (in Ukrainian)

Chen, H. (2018) The spatial patterns in long-term temporal trends of three major crops' yields in Japan. Plant Production Science, 21 (3), 177-185. DOI: https://doi.org/10.1080/1343943X.2018.1459752.

Dalposso, G. H, Uribe-Opazo, M. A, Johann, J. A. (2016) Soybean yield modeling using bootstrap methods for small samples. Spanish Journal of Agricultural Research, 14 (3), e0207. DOI: http://dx.doi.org/10.5424/sjar/2016143-8635

Enkin, V. B. (1959). The soybean. Moscow: State publishing house of agricultural literature. (in Russian)

Enrico, J. M., García, F., Stewart, M., Francisco, E., Balboa, G., Ciampitti, I., Salvagiotti, F. (2018) Integrating Crop and Fertilization Management Strategies for Soybean in the Central Pampas. Better Crops, 102 (2), 6–10. DOI: https://doi.org/10.24047/BC10226.

FAOSTAT (2018) Food and Agriculture Organization of the United Nations.

FAOSTAT. [Online] Available at: www.fao.org [Accessed 5 December 2018]

Fernández-Tirado, F, Parra-López, C, Romero-Gámez, M. (2017) Evaluating the environmental sustainability of energy crops: A life cycle assessment of Spanish rapeseed and Argentinean soybean cultivation. Spanish Journal of Agricultural Research, 15 (1), e0107. DOI: https://doi.org/10.5424/sjar/2017151-9287

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., Toulmin, C. (2010) Food security: the challenge of feeding 9 billion people. Science, 327 (5967), 812–818.

Golbitz, P. (2001) Soya and Oilseed Blue Book. Soyatech Inc. Bar Habor, ME.

Hammond, M. P., Kolasa, J. (2014) Spatial variation as a tool for inferring temporal variation and diagnosing types of mechanisms in ecosystems. PloS one, 9 (2), e89245. DOI: https://doi.org/10.1371/journal.pone.0089245

Hilton, S. P, Avila, A. M. H., Cardoso, A. O. (2013) Challenges to Increased Soybean Production in Brazil. In: Board, J. E., ed. A Comprehensive Survey of International Soybean Research. Rijeka: IntechOpen, pp. 199-207.

Kozhukhar, T. (2017) Soy in Ukraine: Market Research - Kleffmann Group. [Online] Available at: https://www.kleffmann.com/en/information-center/information-center/soy- in-ukraine/ [Accessed 10 January 2018].

Kukal, M. S., Irmak, S. (2018) Climate-Driven Crop Yield and Yield Variability and Climate Change Impacts on the U.S. Great Plains Agricultural Production. Scientific reports, 8 (1), 3450. DOI: https://doi.org/10.1038/s41598-018-21848-2.

Lesk, C., Rowhani, P., Ramankutty, N. (2016) Influence of extreme weather disasters on global crop production. Nature, 529, 84–87. DOI: https://doi.org/10.1038/nature16467

Li, L.H.C. (2015) Assessing the spatiotemporal dynamics of crop yields and exploring the factors affecting yield synchrony. A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the degree Master of Science. Hamilton, Ontario: McMaster University.

Lobell, D.B., Schlenker, W., Costa-Roberts, J. (2011) Climate trends and global crop production since 1980. Science, 333, 616–620. DOI: https://doi.org/10.1126/science.1204531

Lukomets, V.M, Kochegura, A.V, Baranov, V.F, Makhonin, V.L. (2013) Soybean in Russia - reality and possibility. Krasnodar: State Scientific Institution All-Russia Research Institute of Oil Crops by the name of Pustovoit V.S. of Russian Academy of Agricultural Sciences. (in Russian)

Marchev, A., Malechkova, A., Milev, M., Kabaivanov, S., Markovska, V., Nikolova, Kr. (2015) A Step Beyond the Monte Carlo Method in Economics. In: Application of Multivariate Normal Distribution, AIP Conference Proceedings, 8-13 June 2015, vol. 1690, 65-73.

Masuda, T, Goldsmith, P. G. (2009) World Soybean Production: Area Harvested Yield, and Long-Term Projections. International Food and Agribusiness Management Review, 12 (4), 143 -162.

Milev, M., Nikolova, Kr., Ivanova, Ir., Minkova, St., Evtimov, T., Krustev, St. (2017) Grouping of Bulgarian wines according to grape variety by using statistical methods. In: Proceedings of the AIP Conference Proceedings, 1910, 020003. DOI: https://doi.org/10.1063/1.5013940

Minkova, S., Milev, M., Nikolova, K., Ivanova, I., Hristova-Avakumuva, N., Hadjimitova, V., Kakalova, M., Vladev, V. (2019) Comparative analysis of red wines on the base of optical and chemical characteristics by statistical methods. Journal of Physics: Conference Series, 1186 (1),012019.

Moran, P. A. P. (1950) Notes on continuous stochastic phenomena. Biometrika, 37 (1/2), 17–23.

Muhire, I., Ahmed, F., Abutaleb, K. (2014) Spatio-Temporal Trends in Major Food Crop Yields in Rwanda. Global Journal of Human-social science: B Geography, Geo-Sciences, Environmental Disaster Management, 14 (4), 25–42.

Müller, C., Elliott, J., Chryssanthacopoulos, J., Arneth, A., Balkovič, J., Ciais, P., Deryng, D., Folberth, C., Glotter, M., Hoek, S., Iizumi, T., Izaurralde, R.C., Jones, C., Khabarov, N., Lawrence, P., Liu, W., Olin, S., Pugh, T.A.M., Ray, D., Reddy, A., Rosenzweig, C., Ruane, A.C., Sakurai, G., Schmid, E., Skalsky, R., Song, C.X., Wang, X., de Wit, A., Yang, H. (2017) Global gridded crop model evaluation: Benchmarking, skills, deficiencies and implications. Geoscience Model Development, 10 (4), 1403–1422. DOI: https://doi.org/10.5194/gmd-10-1403-2017

Pedersen, P., Lauer, J. G. (2003) Soybean Agronomic Response to Management Systems in the Upper Midwest. Agronomy Journal, 95, 1146-1151.

Rackis, J. J., Honig, D. H., Sessa, D. J., Cavins, J. F. (1971) Soybean whey proteins- Recovery and amino acid analysis. Journal of Food Science. 36(1), 10–13. DOI: https://doi.org/10.1111/j.1365-2621.1971.tb02020.x

Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C., Foley, J. A. (2012) Recent patterns of crop yield growth and stagnation. Nature Communications, 3, 1293. DOI: https://doi.org/10.1038/ncomms2296

Ray, D. K., Mueller, N. D., West, P. C., Foley, J. A. (2013) Yield trends are insufficient to double global crop production by 2050. PLoS ONE, 8, e66428. DOI: https://doi.org/10.1371/journal.pone.0066428

Ray, D. K., Gerber, J. S., MacDonald, G. K., West, P. C. (2015) Climate variation explains a third of global crop yield variability. Nature communications, 6. Article number: 5989. DOI: https://doi.org/10.1038/ncomms6989

Shcherbachuk, V. M. (2016) Optimization of soybean growing technology elements under Western Forest-Steppe of Ukraine condition. PhD thesis. Lviv: Institute of Feed Research and Agriculture of Podillya of NAAS. (in Ukrainian)

Struk, D. H. (1993). Encyclopedia of Ukraine. Vol. 4, Ph-Sr. Toronto: University of Toronto press.

Tigchelaar, M., Battisti, D.S., Naylor, R. L., Ray, D. K. (2018) Future warming increases probability of globally synchronized maize production shocks. PNAS, 115 (26), 6644-6649. DOI: https://doi.org/10.1073/pnas.1718031115

Tscharntke, T., Tylianakis, J., Rand, T., Didham, R., Fahrig, L., Batary, P., Bengtsson, J., Clough, Y., Crist, T., Dormann, C., Ewers, R., Holt, R., Holzschuh, A., Klein, A., Kremen, C., Landis, D., Laurance, W., Lindenmayer, D., Scherber, C., Sodhi, N., Steffan–Dewenter, I., Thies, C., vanderPutten, W., Westphal, C. (2012) Landscape moderation of biodiversity patterns and processes – eight hypotheses. Biological Reviews, 87, 661–685. DOI: https://doi.org/10.1111/j.1469-185X.2011.00216.x

Tyagi, S. D, Khan, M. H, Silva, J. A. T. (2010) Yield Stability of some Soybean Genotypes across Diverse Environments. International Journal of Plant Breeding, 5 (1), 37-41.

Urban, D.W, Sheffield, J., Lobell, D.B. (2015) The impacts of future climate and carbon dioxide changes on the average and variability of US maize yields under two emission scenarios. Environmental Research Letters, 10, 045003

Zuza, V. S, Rozhkov, A. O, Hutianskyi, R. A. (2015) Dependence of soybean yields on predecessor, meteorological conditions and herbicide efficiency. Bulletin of Poltava State Agrarian Academy, 1, 22–24. (in Ukrainian)

Zymaroieva, A., Zhukov, O., Fedonyuk, T., Pinkin, A. (2019a) Application of geographically weighted principal components analysis based on soybean yield spatial variation for agro-ecological zoning of the territory. Agronomy Research, 17 (6), 2460-2473. DOI: https://doi.org/10.15159/AR.19.208

Zymaroieva, A., Zhukov, O., Romanchuck, L., Pinkin, A. (2019b) Spatiotemporal dynamics of cereals grains and grain legumes yield in Ukraine. Bulgarian Journal of Agricultural Science, 25 (6), 1107–1113.