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Spatiotemporal dynamics of cereals grains and grain legumes yield in Ukraine

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Abstract

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Currently, little is known about the spatial and temporal variability of grain and grain legumes yield in Ukraine. The aim of this research was to characterize the spatial and temporal yield variability of cereals grain and grain legumes grown in 155 administrative districts in Polissya and Forest-steppezone of Ukraine in 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. We provide agroeconomic and agrotechnological origin to the nature of the trend. The yields dynamics of grain and grain legumes is described by the absolute term, which reflects the starting conditions of soil fertility in the initial period of research and the indicators of maximum rate of yields decline in the 90s and the maximum rate of yields increase in the 2000s. The indicators of the maximum rate of reduction and the maximum rate of increase of yield can be used as markers of agroecosystem stability to external factors. It can be noted that the southern regions of Ukraine are less stable and more exposed to the destructive influence, while the central and western regions are more stable and rapidly increase productivity under favorable conditions. This research has found that the agroecological systems of the regions of Ukraine are far from the maximum ecological capacity, and agroeconomic and agrotechnological factors are the limiting now.

Keywords: spatiotemporal variability; crop yield; cereals grains; grain legumes; spatial pattern; productivity; Ukraine

Introduction

Food security and land required for food production largely depend on rate of yield gain of major cereal crops (Grassini et al., 2013). The global drivers of crop yield and their variability include technology, genetics, climate, soil, field management practices and associated decisions such as fertilizer applications, tillage and crop hybrid selection, irrigation management, row spacing, panting date and depth, population density, etc. (Kukal & Irmak, 2018; Kucharik & Ramankutty, 2005). Amongst the ecological factors, weather and climate are prominent drivers or influencers of agricultural production systems and it has been shown that recent trends in change of climate indicators may be responsible for substantially affecting crop yield trends despite advances in technology and other fronts (Leng & Huang, 2017; Iizumi & Ramankutty, 2016; Li et al., 2016; Xiao et al., 2015). Differences in agronomic challenges such as pest/pathogen infestation and level of irrigation can result in differences in yield between countries. Differences in technological investments, as well as differing agricultural management such as crop protection, sowing and fertilizer use can also contribute to the variation in yield (Annicchiarico & Iannucci, 2008; Ruzdik et al., 2015).

Low variability of crop production from year to year is desirable for many reasons including reduced income risk and stability of supplies potentially leading to less volatile food prices (Osborne & Wheeler, 2013). Variations in crop yield from one year to the next are caused by numerous factors, including fluctuations in weather, pest and diseases incidence, use of inputs, and the uptake of technology (Osborne & Wheeler, 2013; Anderson et al., 2013).

Achieving maximum crop yield at minimum cost is one of the goals of agricultural production. Early detection and management of problems associated with crop yield indicators can help increase yield and subsequent profit. Agricultural monitoring, especially in developing countries, can improve food production and support humanitarian efforts in light of climate change and droughts (Anderson et al., 2013; Delibaltova et al., 2014). These approaches are very successful in the United States and European countries, where data are plentiful and of relatively high quality. Comprehensive surveys of weather parameters such as the Daymet (Thornton et al., 2014) and land cover types such as the Cropland Data Layer are publicly available and greatly facilitate the crop yield prediction task (You et al., 2017). However, information about weather, soil properties, and precise land cover data are typically not available in developing countries, such as Ukraine, where reliable yield predictions are also needed.

In future decades, the global demand for cereals will increase due to growing demand for food and feed and use of cereal crops as a source for biofuels. Some studies on cereal production within Europe have identified the Ukraine as a country with a large potential to increase production. However, the Ukraine is widely known for its high-quality soils, but its yield is relatively low 2.6 t/ha of wheat in Ukraine (compared to 5.5 t/ha in the EU, 4.7 t/ha in China, and 2.9 t/ha in the United States) (Lioubimtseva & Geoffrey, 2012; Ryabchenko & Nonhebel, 2016). The rate of recovery of food production in Ukraine and the ability to realize its full agricultural potential is likely to have an impact on the global food security in the near future. It will depend on several internal and external factors, such as success of agriculture reforms, subsequent land-use changes, climate variability and changes, and global economic trends.

Currently, little is known about the spatial and temporal variability of grain and grain legumes yields patterns in Ukraine. This information is needed before implementing any site-specific management strategy. The objective of this research was to characterize the spatial and temporal yields variability of grain and grain legumes grown in 155 administrative districts in Polissya and Forest-steppe zone of Ukraine.

Materials and Methods

Crop data were obtained from State statistics service of Ukraine (http://www.ukrstat.gov.ua/) and its territorial offices. Specifically, the organized data set included the average per year yields of the grain and grain legumes (pulses) for 7 regions of Ukraine, which include 155 administrative districts over 27 years from 1991– 2017. The research area is located in the two natural vegetation and climatic zones: Polissya (woodland and marsh) and Forest-steppe of Ukraine.

Time series of crop yields for each administrative district were divided into two components: total trend and trend residual. Total trend was explained by the dependence of the yield from time. As an analytic form of the trend we chose between polynomials of different degree. Lower degree polynomials (simpler in their analytic form) are preferred, because of their easier interpretation. Parameters of the linear model can be interpreted independently in such a way that it can be given the obvious ecological content. It allows to consider certain coefficients as independent variables and to investigate their effect depending on other agroecological factors, or to study the features of their spatial variability, therefore, the search for their analytical dependencies on external variables, or the study of the peculiarities of their spatial variability, is not environmentally meaningful. The coefficients of polynomials of the higher order, unless absolute term cannot be interpreted meaningfully. Consequently, we studied the characteristic points of the fourth degree polynomials: the minimum and maximum of the corresponding functions, the maximum rate of yields increase in the range between minimum and maximum, inflection points.

Spatial regularity of the crop yields variation and trend parameters variation were investigated by *I*-Moran statistics (Zhukov & Ponomarenko, 2017). 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 great yield range was caused by spatial variation component (Zhukov & Ponomarenko, 2018). The typical dynamics of averaged data of grain and grain legumes yields in the studied region is characterized by the presence of three points of extremums: two local maxima and one local minimum. The dependence of the available three extremes points can be described by the fourth degree polynomial:

$$Y_x = b + a_1x + a_2x^2 + a_3x^3 + a_4x^4,$$

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

Characteristic points of the fourth degree polynomial can be meaningfully interpreted and applied to describe the dynamics of grain and grain legumes yields (Figure 1).

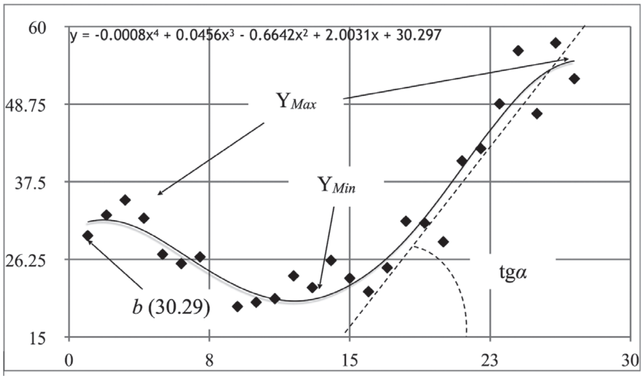

Fig. 1. The typical grain and grain legumes yields dynamics during 1991-2017 and the approximation of the trend by fourth degree polynomial

Legend: axis of abscissas – time (1 – 1991, 27 – 2017); ordinate axis – yields, c/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).

The absolute term of polynomial equation – constant b – indicates the productivity of the culture in the starting period. Assuming that $x = 0$ at the beginning of the research period, the absolute term will indicate the level of productivity at this time. It should be noted that the description of real dynamics by the chosen analytic function is the generalization and simplification in a certain way. The form of the function and its parameters can be chosen based on interpolation and there is no reason to use such a function for extrapolation or for retrospective forecast. Moreover, the validity of such forecasts will be significantly reduced with the increasing of the time period within which the forecast is taking place. In addition, there is no reason to assume that even with a lag equal to time measurement unit, the system does not change its properties significantly. Hence, constant b indicates the starting conditions of the considered process and it is an independent parameter of the temporary dynamics of grain and grain legumes yields variability in time.

The function value at the point of local minimum Y_{Min} indicates the "bottom" of the crop productivity dynamics. We provide agroeconomic and agrotechnological origin to the nature of the trend.

The state of maximum productivity Y_{Max} of the culture reflects a certain balance between factors of agroeconomic and agrotechnological origin on the one hand and biological potential on the other hand. In this case, productivity output on a plateau or decline in the future.

Between the local maximum and minimum on the one hand and the minimum and maximum of yields – on the other hand, there is a bend of the polynomial curve, where the second derivative equals to 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 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.

The coordinates of extreme points of the function that describes the dynamics of grain and grain legumes yields, can be found after solving the equation obtained as a result of the differentiation the fourth degree polynomial:

$$Y'_x = a_1 + 2a_2x + 3a_3^2 + 4a_4^3.$$

The bend point of function x_i is located in place where the second derivative of the function is zero:

$$Y''_x = 2a_2 + 6a_3 + 12a_4^2 = 0.$$

The corresponding quadratic equation has two roots:

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

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 yields change at these points, which are maximal by the modulo.

Since local maxima are in the zones close to the edge of the range of the studied period, so their exact definition is questionable. In many cases, the maxima are outside the scope of research period. Therefore, we do not use the value of the function in local maxima as the characteristic indicators of yields dynamics.

Also, the quality of selection the fourth degree polynomial as spatial pattern is characterized by coefficient of determination.

The coefficient of determination indicates the level of compliance of the model with the real data and varies from 0.55 to 0.96. Polynomial has the character of global regression. 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 yields dynamics, explained by regression, indicates that such factors are agrotechnological and agroecological conditions of agricultural production. Consequently, the coefficient of determination can be interpreted as an indicator of the role of agrotechno-

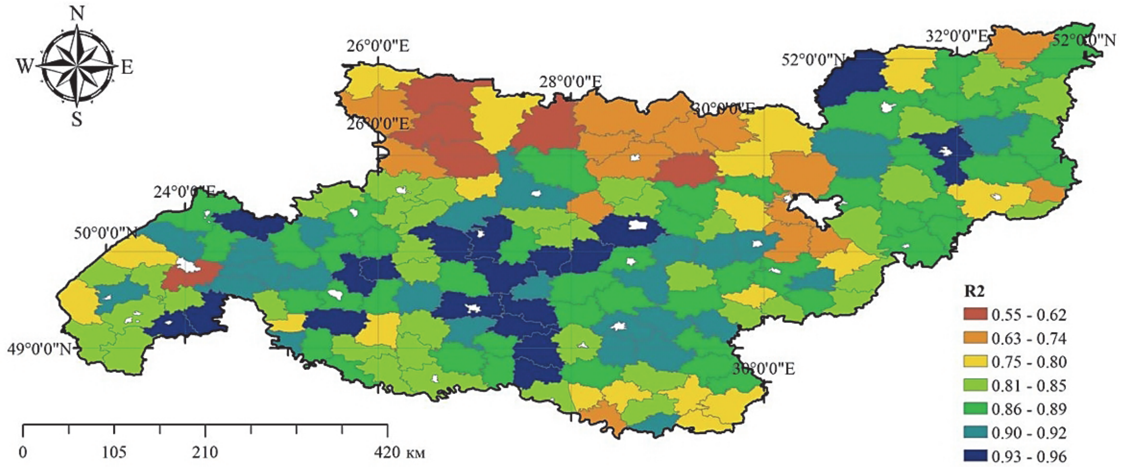

Fig. 2. Spatial variation of the coefficient of determination of the regression model

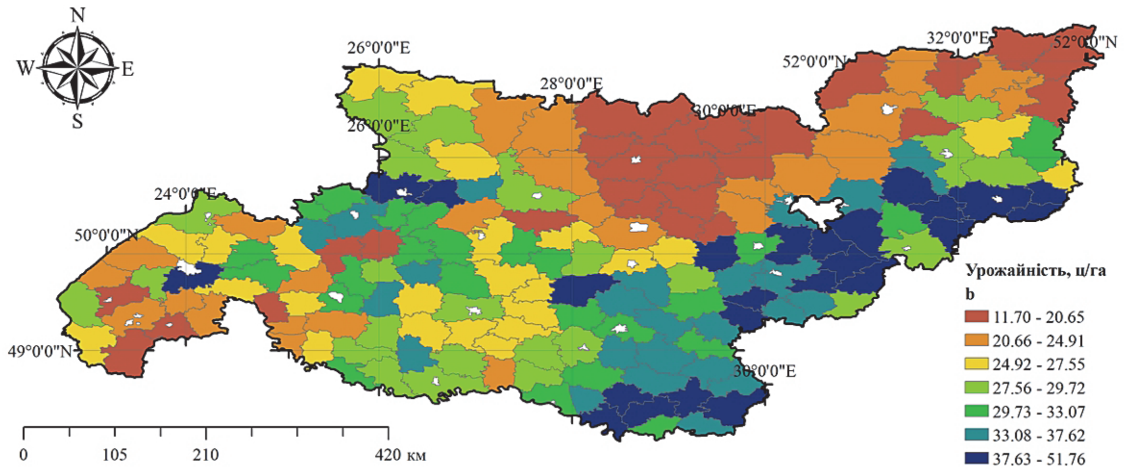

Fig. 3. Spatial variations in the level of crop yields in the initial period of research (constant *b* of the regression equation)

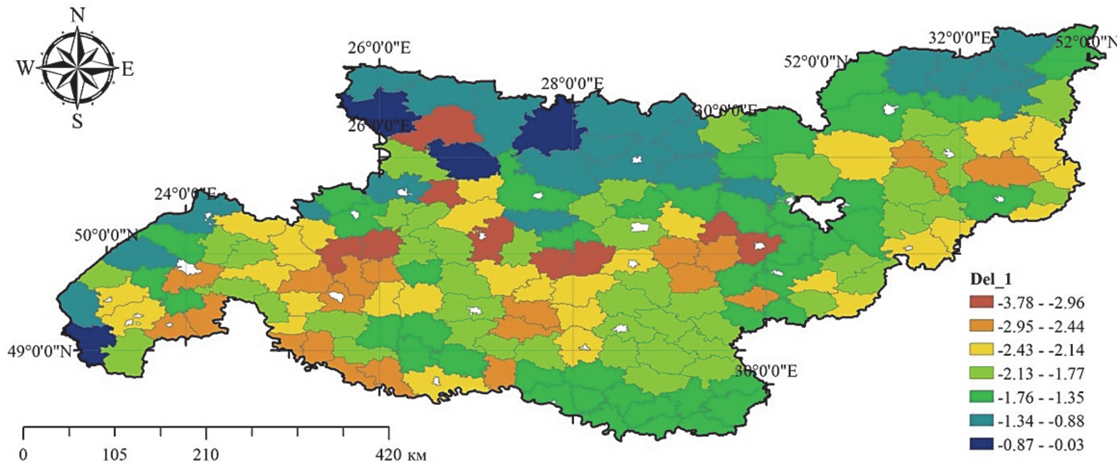

Fig. 4. Spatial variation of the maximum rate of yields decline

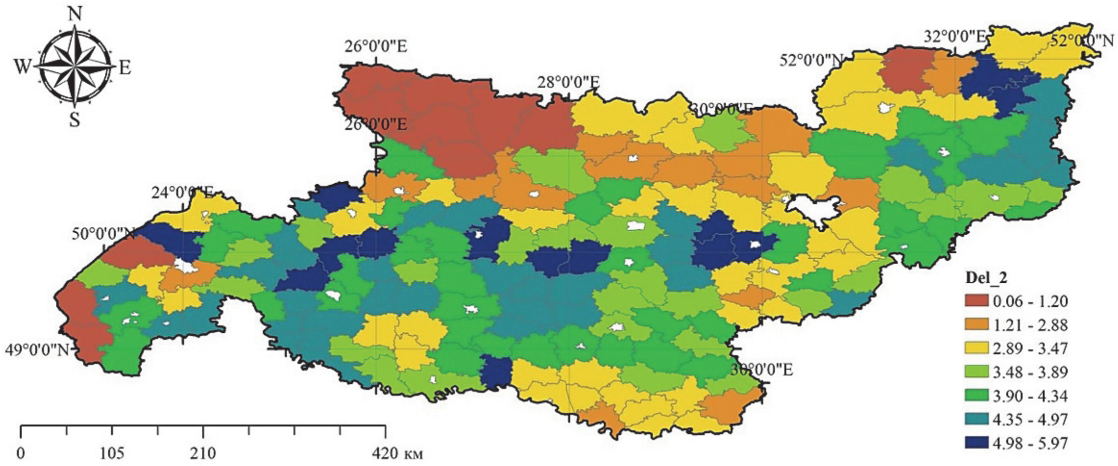

Fig. 5. Spatial variations of the maximum rate of yields increase

logical and agroeconomic factors in yields dynamics. The obtained data testify that these aspects of productivity are the most important. The variation of the coefficient of determination is spatially dependent (Moran's-I statistics 0.39, $p = 0.001$). The southern, eastern and western areas of the research region are the most sensitive to agrotechnological and agroeconomic factors and the northern areas – least sensitive (Figure 2). The cluster with the highest sensitivity to non-ecological regular factors of yields dynamics is formed in the central areas of the region.

The starting level of crop yields varies from 11.70 dt/ha (northern and northeastern regions) to 51.76 dt/ha (southern and south-eastern regions) (Figure 3).

Variation of the starting productivity is spatially dependent (I-statistics of Moran 0.59, $p = 0.001$).

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 (Figures 4 and 5).

It can be noted that the southern regions of Ukraine are less stable and more exposed to the destructive influence. And the central and western regions are more stable and rapidly increase productivity under favorable conditions.

Discussion

The analysis of the spatial and temporal dynamics of grain and legumes yields showed the complex nature of the processes that determine it. 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.

We provide agroeconomic and agrotechnological origin to the nature of the trend. Therefore, the trend dynamics has the characteristics of the economic cycle with its phases: rise, peak, decline, and bottom. The observed bottom of the crops productivity coincided with the socio-economic crisis of the 1990s, which arose as a continuation of the collapse of the USSR.

The breakdown of socialism caused massive socio-economic and institutional changes that led to substantial agricultural land abandonment (Prishchepov et al., 2013). The agricultural sectors of former Soviet countries suddenly faced increasing international competition, while at the same time input- and output-subsides were drastically reduced (Lerman et al., 2004). The rural population increasingly left the countryside (Prishchepov et al., 2013, Lieskovský et al., 2014), fertilizer consumption dropped significantly (Schaffartzik et al., 2014; Swinnen et al., 2017) and agricultural productivity and output declined. The livestock sector was particularly affected and an enormous decline in livestock production resulted in diminishing demand for animal feed. These developments led to strong declines in land use and average yields in the first years of transition (Deppermann et al., 2018).

At the end of the 90s, the crisis in agriculture ended and the preconditions for sustainable development are emerging, which manifests itself almost in the linear growth of grain and grain legumes yields until the peak of this indicator in the late 2010s.

The state of maximum productivity Y_{Max} of culture reflects a certain balance between factors of agroeconomic and agrotechnological origin on the one hand and biological potential on the other hand. It is obvious that at a given level of economic provision and agro-technology system, agricultural lands are capable to produce the best possible yield. Consequently, productivity should output on a plateau. In this case, the variations of yields will be conditioned only by natural fluctuations, which are common in both natural ecosystems and agroecosystems. Yield plateau is mainly due to almost complete adoption of existent technology and no new technology coming up for the near future (Grassini et al., 2013). Sometimes resource constraints lack of fertilizers, pesticides available at the proper time, limitations by natural factors such as water, fertility exhaustion, market limitations also restrict the yields levels (Wart et al., 2013).

Instead of a plateau there can occur decrease in yields, in consequence of which generated a local maximum. Reasons for reducing grain and grain legumes yields after reaching the maximum require their research in the economic plan as well, but in our opinion, the most reasons are of agrotechnological origin.

The yields dynamics of cereals grains and grain legumes is described by the absolute term, which reflects the starting conditions of soil fertility in the initial period of research and the indicators of maximum rate of yields decline in the 90s and the maximum rate of yields increase in the 2000s.

The southern, eastern and western areas of the research region are the most sensitive to agrotechnological and agroeconomic factors and the northern areas are the least sensitive. The cluster with the highest sensitivity to non-ecological regular factors of yields dynamics is formed in the central areas of the region.

Conclusion

This research has found that the agroecological systems of the regions of Ukraine are far from the maximum ecological capacity, and agroeconomic and agrotechnological factors are the limiting now. Under the condition of qualitative restructuring of agricultural production, which requires economic costs and the introduction of the latest agrotechnological approaches, Ukraine has the potential to become a reliable breadbasket of the world.

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