Analysis of the spatio-temporal trend of sugar beet yield in Polissya and forest steppe ecoregions within Ukraine

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Abstract. Ukraine has all the preconditions to increase the sugar beet yield, but, at present, comprehensive studies of spatio-temporal variation in the yield of sugar beet in the country have not been conducted. Though, such research is essential for the formation of crop management and yield forecasting in the future. The study aim is to analyze the general spatio-temporal dynamics of sugar beet yield within 10 regions of Ukraine, to identify the determinants of this trend and to characterize the areas of Ukraine regarding the sugar beet yield. Several statistical methods have been applied to the average sugar beet yields data which were provided by the State Statistics Service of Ukraine. The Akaike Information Criterion (AIC) was used to estimate the likelihood of a statistical model to the observed data. To calculate the global spatial autocorrelation coefficient, I-Moran statistics were computed using the Geoda095i program. A spatial database was created in ArcGIS 10.2. The average sugar beet yields within the study area ranged from 154.5 dt/ha to 495.7 dt/ha. The spatio-temporal trend of sugar beet yield has been described by a fourth-degree polynomial. It was determined that the overall trend of sugar beet yields is determined by agroeconomic and agro-technological factors, whose contribution to the yield variation is 72-96%. The areas where high sugar beet yields are ensured by favorable natural conditions, such as soil fertility, were identified, as well as areas with high crop yield potential provided that agricultural and breeding techniques are adequately used.

1. Introduction

A high crop yield potential is decisive for the efficient use of available arable land [1–4]. An yield potential is defined as the yield of a variety grown under the conditions to which it is adapted, without any restrictions in water or nutrients, and under the effective control of pests, diseases, weeds, and other stresses [5–7]. In recent decades, the annual increase in the yield of sugar beet varieties in European countries has been about 1.5% [1, 8, 9]. This increase in yield is due to an increase in the average temperature at the beginning of the growing season [10–12] and the improvement of agricultural technology, in particular, the optimization of fertilizer use [13–15] and crop protection [16, 17]. Also, the increase in crop yield potential in European countries is achieved by the improving crop management systems and is not due to the increased production intensity, but rather to the better usage of available natural resources and growth
factors [9, 18, 19]. However, the key driver for increasing sugar beet yield potential is breeding progress [1, 20], which allows the increase of sugar content from 4% at the beginning of crop cultivation to over 18% today [21, 22]. Thus, about 50% of the increase in yield and quality of sugar beet was achieved by the progress of selection [23], which, in turn, led to an increase in its yield potential [24]. Currently, some studies claim that the yield potential of sugar beets in developed countries is approaching its limit. Hoffmann and Kenter [1] estimated the yield potential of sugar beet at 24 t sugar ha$^{-1}$.

Nevertheless, the actual yield is always lower than the potential one, since many factors limit sugar beet yields, such as non-optimal weather conditions (water supply, length, and temperature of the growing period) and management practices [4, 25, 26]. The climate change is one of the most pressing issues confronting agronomy today [19, 27, 28]. Most likely climate change will result in significant increases in sugar beet yield potential (due to accelerated growth during warmer springs) as well as losses due to drought stress [29].

Even though the production of sugar beet in Ukraine has been growing rapidly over the past 10 years, the yield of sugar beet in our country is low compared to EU countries. Thus, in 2019, the average yield of sugar beet in Ukraine was 461.1 ha$^{-1}$, and in European Union countries was 738.1 ha$^{-1}$ [30, 31]. The average yield potential of sugar beet hybrids in Ukraine is realized only by 50–60% [32]. Due to the increasing crop yields Ukraine can double its sugar production and become a significant exporter.

The sugar beet cultivation is focused in Ukraine’s central area, where the soil conditions, water supply, and temperature are all suited for the optimal crop yields and sugar content in beets. This is also due to the proximity of sugar beet processing plants in the same region. Vinnytsia, Poltava, Kyiv, Khmelnytskyi, and Ternopil are the five leading sugar beet cultivation regions in Ukraine, accounting for 61% of total sugar beet production [33]. However, the productive potential of other regions of the country for sugar beet cultivation has not yet been assessed. It should be noted that Ukraine has all the prerequisites to increase the yield of sugar beet, but, at present, comprehensive studies of variations in the yield of sugar beet in the regions of Ukraine in spatial and temporal aspects have not been conducted. And such research is essential for the formation of crop management and yield forecasting in the future.

2. Research aim and objectives

Thus, Ukraine has all of the prerequisites for increasing sugar beet yield, but comprehensive studies of sugar beet yield variations in Ukraine’s regions in spatial and temporal aspects have yet to be conducted. And such research is essential for the future development of crop management systems and yield forecasting.

The aim of our work was therefore to solve three tasks:

(i) to analyze the spatiotemporal variation of sugar beet yield in 10 regions of Ukraine (206 districts);

(ii) to determine the nature of the general trend of sugar beet yield;

(iii) to identify areas with the most favorable growing conditions for this crop.

3. Material and methods

3.1. Data of crop yield

Crop data were obtained from the Ukrainian State Statistics Service and its territorial offices (http://www.ukrstat.gov.ua/). The time-series datasets include annual yield averages by the administrative district for 10 regions of Ukraine, which include 267 administrative districts, over 27 years from 1991 to 2017. The research area is divided into two natural vegetation and climatic zones: the Polissya Forest Zone and the Forest Steppe Zone (Zymaroieva et al., 2020). From 1991 to 2017, data on soybeans were available for ten administrative regions (Cherkasy,
Chernihiv, Khmelnytskyi, Kyiv, Lviv, Rivne, Ternopil, Vinnytsia, Volyn, Zhytomyr). FAO provided information on the annual yield of soybeans in Ukraine [31].

3.2. Yield trend analysis
As an analytic form of the trend, we chose between polynomials of a different order [34]. Yield trends were analyzed using parsimonious regression models of increasing order for: an intercept-only model, a linear model, a quadratic model, a cubic model, and a quartic model [35,36].

The Akaike Information Criterion (AIC) [37] was calculated for each of the five regression models to estimate the likelihood of a statistical model to the observed data. A good model has the lowest AIC of all the models and was chosen as the best representation of the yield trend for a specific administrative district. R 3.0.2 was used for all calculations and data analysis.

A fourth-degree polynomial best describes the total yield trend within the investigated area. As a result, the yields trends in all administrative districts were described by fourth-degree polynomials in the next analysis phase for quantitative comparison. As a result, we chose the following characteristics of fourth-degree polynomials: constant, the maximum rate of yields decreases in the range between the first maximum and the minimum, and the maximum rate of yields increases in the range between the minimum and the second maximum [38] (Figure 1).

![Figure 1. The typical sugar beet yields dynamics during 1991-2017 and approximation of the trend by fourth-degree polynomial: axis of abscissas – time (1 – 1991, 27 – 2017); ordinate axis – yields, dt/ha; b is an absolute term of the 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; \( tg\alpha \) – the maximum rate of increasing crop yields in time between the 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).](image-url here)

A spatial regularity of the crop yields and trend parameters variation were investigated by I-Moran statistics [39]. The global Moran’s statistics were calculated using Geoda095i (http://www.geoda.uiuc.edu/) [40]. A spatial database was created in ArcGIS 10.2. The statistical analysis was performed by Statistica 10 software.
4. Results
To assess the representativeness of the obtained data, we compared them with the average sugar beet yields throughout Ukraine, which were presented by the Food and Agriculture Organization of the United Nations (FAO) (figure 2, a). It was found that between the average yield of sugar beet in general in Ukraine and the yield in the study region there is a statistically significant correlation ($r = 0.97, p < 0.001$) (figure 2, b), which indicates the high accuracy of our data and the synchronicity of yield fluctuations throughout Ukraine. Such synchronicity is the result of a constant external factor, which in our opinion has an agro-economic origin.

![Figure 2](image)

**Figure 2.** The sugar beet yields dynamics during 1991–2017 total in Ukraine (dt/ha, left $y$-coordinate) and in the region investigated (dt/ha, right $y$-coordinate) (a) and a scatter plot of sugar beet yields total in Ukraine against sugar beet yields in the region investigated (b).

The average yield of sugar beet in the study region ranged from 154.5 dt/ha to 495.7 dt/ha (figure 3). The highest average yields are in the central and southern regions of the region, and the lowest in the north. The coefficient of variation is the highest in the southwest (29.4–32.7%), for the rest of the territory, the coefficient of variation at the level of 20.14–29.3% is predominant.
There is a weak negative correlation between the average sugar beet yield and the coefficient of variation at the probable level ($r = -0.19$, $p < 0.007$) (figure 4). This suggests that areas with higher yields tend to have a lower coefficient of variation, i.e., are more stable to external factors.

![Figure 3. Average yield (A) and coefficient of variation of sugar beet yield (B).](image)

The average yield and its coefficient of variation are spatially dependent (Moran’s $I$-statistics 0.36, $p < 0.001$ and 0.17, $p < 0.001$, respectively). The dynamics of sugar beet yield in 144 administrative districts (70% of the total) is best described by a fourth-degree polynomial (figure 5). Therefore, according to the Aikake information criterion (AIC), we have identified this type of trend as the main one. Since the chosen model is a fourth-degree equation, the sugar beet yield trend can be classified as "yield stagnation" [41].

Since the final dynamics of the averaged data of sugar beet yield in the study region can be characterized by a fourth-degree polynomial, the yield dynamics can be described and interpreted using the following characteristic points and indicators: maximum and minimum points, inflection points (figure 1). The trend of sugar beet yield is also described by the constant term of the polynomial equation, the maximum rate of yield decrease, the maximum rate of yield increase occurring at inflection points, and the coefficient of determination of the regression model.

The general trend of sugar beet yield is characterized by two local maxima ($Y_{Max}$) and one local minimum ($Y_{Min}$) (figure 1). In our case, the local minimum reflects the lowest yield over the entire research period and occurs in 2010. Local maxima fall in 1993 and 2016 correspond to the highest crop productivity during the study period.
Since local maxima occur at the edges of the studied range, their further study is questionable. Another indicator used in the study of the general yield trend is the absolute term of the polynomial – the constant b, which indicates the yield of the crop in the initial period (figure 1). Thus, the constant b indicates the initial conditions for describing the course of the process and is an independent parameter of the temporal dynamics of crop yields over time. The initial level of sugar beet yield varies from 175 dt/ha to 421 dt/ha (figure 6). This indicator allows identifying areas with the most favourable soil conditions for sugar beets cultivation.

The average yield level for the study period and the initial yield level (coefficient b of the polynomial equation) were significantly positively correlated ($r = 0.98$, $p < 0.001$). This explains the fact that the spatial variation of the values of coefficient b (figure 1) is spatially dependent, which is confirmed by the Moran test (Moran’s I-statistics 0.42, $p < 0.001$). Between the local maximum and minimum on the one hand and the minimum and maximum yield on the other, there is an inflection of the polynomial curve, where the second derivative is zero (figure 1). At these points, the rate of decline or increase in yield becomes greatest, and the corresponding

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**Figure 4.** The relationship between the average sugar beet yield and its coefficient of variation.

**Figure 5.** Spatial variations of the sugar beet yield trend types.
The indicators of the maximum rate of decrease and the maximum rate of yield increase can be used as indicators of the resilience of the agroecosystem to external factors (figure 7, 8). Areas, where sugar beet yields decline rapidly during the transition period, are in the north of the study region (figure 7), and areas, where yields tend to increase rapidly, are in the south (figure 8).

The initial yield level is negatively correlated with the rate of decline in crop yield in the first stage of research ($r = -0.72$, $p < 0.001$). The rate of yield decrease (figure 7) is spatially dependent (Moran’s $I$-statistics 0.33, $p < 0.001$). The rate of yield increase is proportional to the intensity of the previous decrease ($r = -0.57$, $p < 0.001$). The rate of yield increase (figure 8) is also spatially dependent (Moran’s $I$-statistics 0.28, $p < 0.001$).

The coefficient of determination indicates how accurately the model described the overall yield trend. The fourth-degree polynomial explains 72–96% of the sugar beet yield temporal variation (figure 9). This indicator is spatially dependent (Moran’s $I$-statistics 0.29, $p < 0.001$).
5. Discussion

The high level of correlation between the average yield of sugar beet in Ukraine (FAO data) and the sugar beet yield in the study region (our data) indicates the high accuracy of our data and the synchronicity of yield fluctuations throughout Ukraine. Such synchronicity is the result of a constant external factor, which, in our opinion, has an agro-economic origin. This assumption is confirmed by the general form of the trend, which has the form of an economic cycle with ups and downs [43, 44]. Thus, according to the Food and Agriculture Organization of the United Nations, in Ukraine, there was a sharp decline in sugar beet yields in the period after the collapse of the Soviet Union. The "bottom" of yields dates back to the early 2000s [33]. After 2010, the increase in yield is almost linear and reaches a local maximum in 2016. It is known that agroecological factors are closely related to agro-technology and selection [45], so these factors can be combined into one group. Despite the general increase in sugar beet yield in the last decade of the study period, the general trend can be described as "stagnation of yield", which indicates that the increase in productivity is still quite slow.

With the help of the "initial yield" indicator, we can identify areas that have the most fertile soils and are characterized by high sugar beet yield potential. The high correlation of this indicator with the sugar beet average yield indicates that these conditions (soil fertility) are a decisive factor in achieving high yields [46]. Thus, the highest average yield and initial level of yield geographically correspond to Ternopil, Vinnytsia, Khmelnytskyi, and Cherkasy regions (figure 3), which are the main producers of sugar beets in Ukraine [32]. The research is also valuable because it allows for district differentiation of crop yields.
By mapping the indicators of the maximum rate of decline and maximum rate of yield increase, we can identify areas that respond to rapid decline or increase in yield to changes in management conditions, as well as areas with more stable yields (figure 7, 8). It was also found that the higher the initial yield, the slower it decreases, even in adverse conditions for sugar beets cultivation. Since we determined that the general trend is of agro-economic and agrotechnological origin, the coefficient of determination can be interpreted as an indicator of these factors’ role in the dynamics of sugar beet yield. The obtained data indicate that these aspects of yield are of paramount importance (72–96% of the contribution to the overall variation in crop yields). The central and northern regions are the most sensitive to agro-technological and agro-economic factors, and the southern regions are the least sensitive.

6. Conclusion
According to the findings of the study, the general trend of sugar beet yield within the study area is best described by a fourth-degree polynomial. The existence of a trend of this form is due to the influence of agro-economic factors, whose contribution to the overall variation in yield is from 72 to 96%. We have also identified areas that have the best soil and climatic conditions for growing sugar beets. Spatially, they coincide with the regions with the highest crop yields. Indicators of the maximum rate of decline and maximum rate of increase in yield can be used as markers of resistance of the agroecosystem to external factors, including agrotechnological and agroeconomic. Regions with initial high yields are more stable in transition periods. The yield in areas with favorable soil and climatic conditions for sugar beet cultivation is less dependent on the impact of agro-economic and agrotechnological factors. Thus, Ukraine has all the prerequisites for increasing the yield of sugar beet, especially in areas where the impact of agricultural technology and breeding is crucial.

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