CROP PRODUCTION EFFICIENCY IN UKRAINE UNDER CLIMATE CHANGE CONDITIONS

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Abstract. *Crop production in Ukraine is a significant component of agriculture and the national economy. It holds a prominent position in world markets and impacts global food security. Plant products contribute substantially to the country's export potential, influencing the balance of payments. The impact of climate change on global agriculture is a proven fact, and despite increasing countermeasures, its effects continue to intensify. Crop production is particularly vulnerable to changes in climatic conditions. While the severity of climate change in Ukraine is less than in some other regions the country's role in ensuring global food security places it under significant scrutiny regarding potential changes in crop production. The aim of the article is to assess potential changes in the efficiency of crop production, specifically the dynamics of yield for major agricultural crops, in response to long-term changes in agro-climatic conditions, and their impact on the production potential. Research methods include general scientific and specialized approaches, both qualitative and quantitative, theoretical (descriptive analysis) and empirical (review of official documentation and legislative acts), comparative analysis, analytical alignment of time series by the least squares method and others statistical methods. In Ukraine's agro-climatic zones, the impact of climatic factors on productivity varies significantly. In the Steppe zone, which is increasingly becoming a zone of risky agriculture, climatic factors have had the greatest impact. In contrast, the Polissia zone has seen significant productivity increases primarily due to agrotechnical factors. Therefore, to maintain the efficiency of crop production under changing climatic conditions, it is essential to adapt the components of crop-growing agrotechnologies. This underscores the need to implement national programs of observing and studying climate change, and to leverage the best domestic practices in land use and agricultural technologies aimed at adapting to climate change and mitigating its negative consequences.*
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Introduction. Historically, agriculture in Ukraine has been a strategically important sector for the country's economy. The successful operation of this sector is crucial for the functioning of many economic activities, such as the food industry, non-food processing of agricultural products, logistics, trade, and industries that supply resources for agriculture. Before the war, agriculture employed 7,1% of all wage-employed workers were engaged in agriculture, and when considering informal employment, this sector accounted for nearly 20% of all those employed in Ukraine's economic activities. In 2021, the share of agriculture in the gross value added was 12,7%, and together with the production of food, beverages, and tobacco products, it reached 16,5%. The influence of agriculture on the national balance of payments is also significant. Despite challenging wartime conditions, the sector exports more than 22 billion USD worth of products annually, which in 2023 accounted for 60,8% of all state export revenues from goods trade. The country's agricultural sector shows a higher level of resilience compared to other sectors. For instance, during the wartime year of 2022, agricultural output decreased by only 25% despite a 20% reduction in sown areas due to hostilities and occupation, and the loss of more than 10% of livestock and poultry. Meanwhile, the overall economy experienced a 30,4% decline in output. Moreover, agricultural producers maintained profitability, with a profit margin of 11,6% in 2023, compared to 8,1% for the economy as a whole. Domestic agri-food production ensures 80% of the saturation of the internal food market.

In 2023, crop production accounted for 81,1% of the gross agricultural output. Furthermore, crop products dominate agricultural exports (53% of agri-food exports) and contribute significantly to the sector's profitability. Ukraine is one of the world's leading producers of wheat, barley, corn, sunflower, and sugar beet. This dominance leads to an imbalance in the specialization structure of the sector and poses risks to the overall functioning of the industry and Ukraine's food security.

Such a narrow specialization and the use of intensive technologies focused on achieving short- and medium-term economic gains have led to excessive land plowing, disruption of the natural soil formation process, and an environmentally unbalanced ratio between agricultural lands. This has already resulted in soil degradation processes spreading over an area of 1,1 million hectares. The problems of land degradation and desertification are exacerbated by the rapid pace of climate change, which is accompanied by rising average annual temperatures, increased frequency and intensity of extreme weather events, including droughts that affect 10 to 30% of the country's territory every two to three years and 50 to 70% of its total area every 10 to 12 years.

The impacts of global climate change in different regions of Ukraine vary in their vulnerability level to climate change due to unique geographical location and functioning of those regions. Certain climate threats, such as an increase in the number of hot days or more frequent heavy downpours, will create different risks for northern, southern, western, and eastern regions of Ukraine, given the significant differences in the landscape and climatic conditions of these regions. This necessitates an understanding of the regional consequences of climate change and an assessment of the vulnerability of different production sectors to effectively prepare for future risks.

Climate change is profoundly transforming the conditions under which agricultural activities are conducted. For crop production, the primary directions of this transformation include the impact of climate change on the yields of major agricultural crops and the geographical shifts in production conditions for all types of agricultural activities (FAO, 2015).

The aim of the article is to assess potential changes in the efficiency of crop production, specifically the dynamics of yield for major agricultural crops, in response to long-term changes in agroclimatic conditions, and their impact on the production potential.

Literature review. Scientists emphasize that a major challenge to global food security is the continuous increase in agricultural yield variability (Lesk et al., 2016). Significant yield variability leads to unstable incomes for farmers (Hurley et al., 2018). It has already been demonstrated that climate change has contributed to the increase in agricultural yield variability (Döring and Reckling, 2018). Agricultural yields are influenced by various factors, including economic and political disruptions (Wright, 2011), pest outbreaks (Oerke, 2006), fungal diseases such as rust (Singh et al., 2008), and choices in technology, specifically soil management methods, crop varieties, and the application of fertilizers or pesticides (Gregory et al., 2009). However, the most significant contributors to global yield variability are the annual fluctuations in climatic and weather conditions (Frieler et al., 2017).

The effectiveness of measures aimed at reducing agricultural yield volatility through plant breeding and agronomic management (Hatfield et al., 2018) critically depends on a better understanding of the impacts of long-term climate trends and the rapid onset of extreme weather events on yield volatility (Webber et al., 2018).

Schierhorn et al. (2021) have estimated that average climatic conditions and extreme weather events in Ukraine account for approximately 53-62% and 36-40% of wheat yield volatility, respectively.

Main results. The northward shift of homogeneous agroclimatic zones in Europe under the influence of changing climate conditions is a well-established fact. It has been determined that the gradual warming in Europe has contributed to the extension of the growing season and an increase in accumulated heat, which is accompanied by more frequent occurrences of warm extreme climatic events. Over the past 40 years, the migration rate of agroclimatic zones in Eastern Europe has been 100 km per decade, and in the coming decades, it may reach twice the speed compared to that observed during the period 1975–2016 (Ceglar et al., 2021).

Ukraine is a global leader in the production of industrial crops, particularly sunflower, rapeseed, and sugar beet, with soybean cultivation areas also steadily expanding. Over the past 30 years, Ukraine has significantly increased its production of sunflower, soybean, and rapeseed. The primary factor driving these changes has been the globalization of agricultural production and the entry of domestic producers into global markets. Therefore, this article examines the zonal shifts in the production of industrial crops, particularly sunflower, under the influence of climate change and the impact of military actions.

Compared to 1990, *sunflower seed production* increased by 6,4 times, rapeseed by 22,5 times, and soybean by 35,2 times, transforming the production of the latter two crops from niche to mainstream (Table 1).

Table 1. **Changes in the structure of production of industrial crops in the agroclimatic zones of Ukraine, %**

Agroclimatic zone	Harvested area			Production		
	1990	2021	2023	1990	2021	2023
Sunflower seeds						
Steppe	79,4	57,5	47,1	75,9	51,7	42,0
Forest-Steppe	20,4	34,8	43,4	23,9	39,9	47,9
Polyssia	0,1	7,2	9,1	0,1	7,8	9,6
Precarpathia	0,1	0,5	0,4	0,1	0,6	0,5
Rapeseed						
Steppe	4,0	46,2	43,3	3,6	39,6	33,8
Forest-Steppe	61,1	36,3	43,0	64,6	42,3	51,5
Polyssia	29,2	15,3	12,2	24,6	15,7	12,7
Precarpathia	5,7	2,2	1,6	7,2	2,4	1,9
Soybeans						
Steppe	59,7	13,2	6,4	61,4	14,2	4,7
Forest-Steppe	38,9	63,9	69,0	37,4	62,7	70,9
Polyssia	0,4	18,9	20,4	0,2	18,9	19,1
Precarpathia	1,0	4,0	4,2	1,0	4,2	5,3

Source: calculated for data of the State Statistics Service of Ukraine

This has radically altered the overall structure of agricultural production. At the same time, changes in crop distribution have been influenced by climate changes. Warming has allowed sunflower cultivation to shift from the Steppe zone to the Forest-Steppe and Polissia zones. In 1990, more than three-quarters of all sunflower production occurred in the Steppe zone, whereas by 2021, this share had decreased to 51,7%. Military actions have further impacted the distribution of agricultural crops, reducing sunflower production in the Steppe zone to 42%. Meanwhile, production continues to shift to the Forest-Steppe and Polissia zones, where yields are significantly higher.

Compared to 1990, *soybean production*, which was concentrated in the Steppe zone (61,4%), has shifted to the Forest-Steppe and Polissia zones (where soybeans were not previously grown due to climatic conditions). Currently, 89,4% of soybean plantings are located in these zones, accounting for 90,0% of total production. This suggests a near-complete abandonment of soybean cultivation in the Steppe zone by producers.

Changes in the distribution of *rapeseed production* were also observed during the study period, with an increase in cultivation in the Steppe zone and a decrease in the Polissia region. In 2023 the zonal distribution of industrial crop production was affected by the destruction of the Kakhovka Hydroelectric Power Plant. The overall environmental impact has not been critical due to the rapid recovery of biota; however, the disaster's negative effect on irrigation capabilities in the arid Steppe zone remains significant.

Data presented in Table 2 indicate that in the Forest-Steppe and Polissia regions, improved moisture conditions and reduced risks of heat stress have led to a higher increase in sunflower yields compared to those in the Steppe zone. Yields in the Pre-Carpathian zone have also significantly increased, although the limited availability of arable land in this region means it does not substantially impact overall production. The most significant increase in rapeseed yield occurred in the Polissia zone, with a 2,5-fold rise.

High soybean yields in the Steppe zone are primarily ensured through irrigation. However, under conditions of water resource scarcity, the trend of shifting this crop northward will persist, while production in southern regions is expected to decrease, as evidenced by data from 2023. Thus, both innovative factors (such as technologies, seeds, etc.) and climate change impact crop yields. Agricultural crop yields result from the combination of the genetic characteristics of biological entities and environmental conditions, with climatic conditions playing a critical role. Climate dictates which crops are grown in a given region, while actual weather during the growing season determines the yields of these crops.

Table 2. **Dynamics of technical crops yield in the agroclimatic zones of Ukraine, centners/ha**

Agroclimatic zone	**Yield**			
	1990	**2000**	**2021**	**2023**
Sunflower seeds				
Steppe	15,3	12,1	22,1	21,9
Forest-Steppe	18,8	13,2	28,2	27,1
Polyssia	17,1	6,9	26,9	25,8
Precarpathia	15,2	11,3	27,5	30,7
Rapeseed				
Steppe	12,9	6,8	25,1	22,8
Forest-Steppe	15,3	9,1	34,1	35,0
Polyssia	12,2	7,1	30,2	30,6
Precarpathia	18,3	12,4	34,6	36,6
Soybeans				
Steppe	10,9	10,3	28,5	18,8
Forest-Steppe	10,2	11,3	25,9	26,6
Polyssia	6,7	10,8	26,4	24,2
Precarpathia	10,0	0,0	27,7	32,9

Source: calculated for data of the State Statistics Service of Ukraine.

In the early 1990s, sunflowers were mostly grown for feed in the Polissia region because, due to the weather, they did not have time to mature, and the primary production of sunflowers was concentrated in the Steppe zone. Currently, due to climate change and agrotechnical innovations, the situation has drastically changed, making it essential to investigate how individual factors have influenced sunflower yields in the major agroclimatic zones.

Sunflower cultivation areas in the Steppe zone doubled between 1990 and 2023, increasing from 1254 thousand hectares to 2448 thousand hectares, with yield rising from 15,3 c/ha in 1990 to 21,9 c/ha in 2023 (in the pre-war year of 2021, it was 3834 thousand hectares). In Polissia and the Forest-Steppe zones, the area under this crop increased from 1,4 thousand to 475 thousand hectares and from 321,8 thousand to 2257 thousand hectares, respectively. This indicates significant long-term shifts in the geographical distribution of sunflower cultivation.

The dynamics of sunflower yield in the main agroclimatic zones show a general long-term upward trend, though it remains highly volatile (Figure 1).

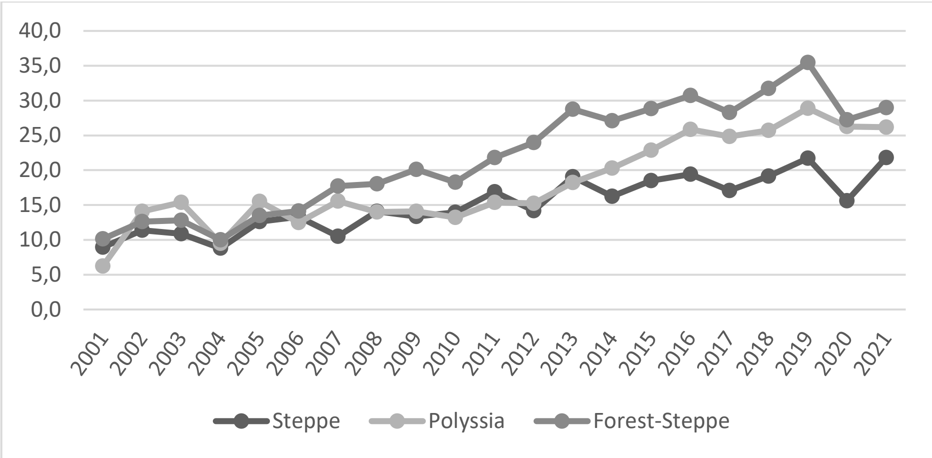

Figure 1. **The dynamics of sunflower yield in the main agroclimatic zones of Ukraine, centners/ha**

Source: developed according to the data of the State Statistics Service of Ukraine

To determine the impact of the cumulative effect of a set of agrotechnical factors on crop yield, one of the optimal methods is analytical smoothing of time series using the least squares method.

For smoothing this time series, we will use the equation of a straight line:

$$y_t = a_0 + a_1 t$$

Calculations were conducted for equalization of the dynamic series of sunflower productivity by the least squares method for the Steppe, Polissia and Forest-Steppe zones.

We will first conduct a study on sunflower yield in the Steppe zone.

The regression coefficient a_1=0,564 c/ha indicates that, on average, during the study period, sunflower yield increased annually by 0,564 c/ha. The increase in yield is primarily attributed to improvements in agricultural practices. The average sunflower yield for the period 2001-2021 was 15,69 c/ha. Thus, the linear trend model has the following form:

$$y_t = 15{,}69 + 0{,}564t$$

Let us decompose the variability in yield into contributions from agrotechnical factors and climatic conditions. To do this, we will use the results obtained earlier, as well as determine the deviation of the actual yield from the yields smoothed by the regression equation and from the average yield over the entire period. In this context, the deviation of the actual yield from the smoothed values characterizes yield variability under the influence of climatic factors, while the deviation of the actual yield from the average yield over the entire period reflects the variability due to all conditions and causes (both economic and meteorological).

The variation in yield due to all factors is determined using the overall variance:

$$\sigma^2_{total} = \frac{\sum(y-\bar{y})^2}{n} = 14{,}911$$

The random variance characterizing the yield variation under the influence of climatic conditions should be determined:

$$\sigma^2_r = \frac{\sum(y-\tilde{y})^2}{n} = 3{,}265$$

It is necessary to find the factor dispersion that characterizes the variation in productivity under the influence of agrotechnical factors:

$$\sigma^2_f = \sigma^2_{total} - \sigma^2_r = 14{,}911 - 3{,}265 = 11{,}646$$

From this it can be determined that 78% of the total yield fluctuation is due to agrotechnical factors, and 22% is due to the effect of climatic factors. Now we will conduct a study of sunflower productivity in the Polissia zone, making calculations similar to those for the Steppe zone (only the results of these calculations are given in the article). The regression coefficient a_1 =0,925 c/ha indicates that, on average, during the studied period, the yield of sunflowers increased annually by 0,925 c/ha. The increase in yield is mainly related to the improvement of the level of agricultural technology. The average level of sunflower productivity for the period 2001-2021 is 18,08 c/ha.

The linear trend model is as follows:

$$y_t = 18{,}08 + 0{,}925t$$

Yield fluctuations are decomposed into those obtained under the influence of agrotechnical factors and climatic conditions for the data in the Polissia zone. The yield variation under the influence of all factors is determined using the general variance:

$$\sigma^2_{total} = \frac{\sum(y-\bar{y})^2}{n} = 37{,}867$$

Random dispersion characterizing the yield variation under the influence of climatic conditions:

$$\sigma^2_r = \frac{\sum(y-\tilde{y})^2}{n} = 6{,}516$$

Factor dispersion, which characterizes the yield variation under the influence of agrotechnical factors:

$$\sigma^2_f = \sigma^2_{total} - \sigma^2_r = 37{,}867 - 6{,}516 = 31{,}351$$

For the Polissia zone, the data indicate that 83% of the total variation in yield is attributable to agrotechnical factors, and 17% to the effect of climatic factors. That is, in the Steppe zone, the influence of climatic factors is more significant, and in the Polissia zone, a significant increase in productivity was achieved primarily due to agrotechnical factors, namely, the introduction of technologies, the use of new types of seeds, etc., namely, the innovative component that made it possible to make the climatic conditions of Polissia favorable for growing corn for grain. Although the impact of climate change and the increase in the sum of active temperatures in this zone certainly had their impact.

To fully assess the situation, we examine the sunflower yield in the Forest-Steppe zone. The regression coefficient a_1 = 1,195 c/ha indicates that, on average, during the studied period, the sunflower yield in the Forest-Steppe zone increased at the fastest rate—by 1,195 c/ha annually. The average sunflower yield for the period of 2001-2021 is also the highest—21,92 c/ha.

Thus, the linear trend model is as follows:

$$y_t = 21{,}92 + 1{,}195$$

The next step will involve the decomposition of yield fluctuations due to agrotechnical factors and climatic conditions for data from the Forest-Steppe zone. The variation in yield under the influence of all factors is determined using the total variance:

$$\sigma^2_{total} = \frac{\sum(y-\bar{y})^2}{n} = 58{,}735$$

Random dispersion characterizing the yield variation under the influence of climatic conditions:

$$\sigma^2_r = \frac{\sum(y-\tilde{y})^2}{n} = 6{,}381$$

Factor dispersion, which characterizes the yield variation under the influence of agrotechnical factors:

$$\sigma^2_f = \sigma^2_{total} - \sigma^2_r = 58{,}735 - 6{,}381 = 52{,}354$$

The data for the Forest-Steppe zone indicates that 89% of the total variability in yield is attributed to agronomic factors, while 11% is influenced by climatic factors. In other words, in the Steppe zone, climatic factors have a more pronounced impact, whereas in the Forest-Steppe and Polissia zones, significant yield increases have been primarily achieved through agronomic factors, particularly the implementation of technologies, the use of new seed varieties, and other innovations. These innovations have made the climatic conditions in the Forest-Steppe and Polissia zones favorable for sunflower cultivation. However, the influence of climate change and the increase in accumulated active temperatures in this zone have also played a role.

Discussion and conclusions. In addition to a significant territorial redistribution of the crop structure of agricultural plants, there is a noted unevenness in the dynamics and growth rates of their productivity. Overall, the increase in the yield of technical crops across Ukraine has been primarily driven by the more humid regions of the Forest-Steppe and especially Polissia. Long-term statistical data indicate changes in the yields of technical crops. While in the 1990s the main production region was the Steppe, in the past decade the leading region has shifted to the central part of Ukraine, and it is now gradually moving towards the Polissia zone. Regions within the Forest-Steppe and Polissia zones have the highest yields of technical crops, as well as the most dynamic growth in productivity. These changes must be considered when planning and organizing the appropriate infrastructure for processing, storage, and sale of these crops.

This dynamic has been influenced by climate change, which in different regions of Ukraine shows a tendency toward significant warming, accompanied by a decrease in precipitation. A substantial part of the impact of extreme weather conditions is shaped by climatic factors. Heatwaves, frosts, and droughts during various phases of crop growth have been key factors that worsen agricultural productivity. The significant impact of extreme weather events in Ukraine necessitates the intensification of adaptation measures to enhance the resilience of agriculture to extreme climate conditions, as such events are likely to occur more frequently in the future.

To ensure the continued success of agricultural activities amidst the inevitable climate changes occurring in Ukraine, the implementation of climate-adapted agricultural practices is essential. These practices enable agriculture to adjust to climate change, reduce its vulnerability to extreme climate conditions (such as droughts, floods, and temperature fluctuations), and ensure stable food production in a changing climate.

Farmers must adopt measures such as selecting crop varieties resistant to drought, salinity, high temperatures, or other extreme climatic conditions; employing water management techniques that help conserve moisture (e.g., drip irrigation, rainwater harvesting systems); using soil moisture conservation technologies (e.g., mulching); adjusting planting calendars to avoid extreme weather during critical growth phases; introducing agricultural technologies that reduce greenhouse gas emissions (e.g., reduced tillage, cover cropping); and utilizing disease- and pest-resistant crops to minimize pesticide use under changing climate conditions (Shubravska et al, 2019).

Support programs for farmers should focus on promoting climate-adapted practices that simultaneously interact with and complement environmentally sustainable agricultural practices. These practices aim to preserve the environment, maintain ecosystem health, and collectively contribute to achieving sustainable agriculture.

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