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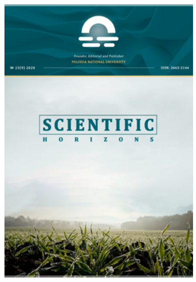


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# Forecasting the adaptability of heat-loving crops to climate change in Ukraine

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**Abstract**. Ukraine has a developed agricultural sector of the economy, where agriculture accounts for 10.4% of the gross domestic product. The relevance of the subject is due to the fact that agricultural production, which is of strategic importance for the country, is very sensitive to ongoing climate changes. Therewith, the crop industry is already undergoing a process of adaptation to the consequences of climate change and agrometeorological factors, which is manifested in the expansion of the range of cultivated crops. The purpose of this study was to predict the adaptability of heat-loving agricultural crops by their yield in various natural and climatic zones of Ukraine. In the course of the research, such methods as analysis, synthesis, factor analysis, correlation-regression, and mathematical-statistical were used. Based on the results of the conducted studies, the expediency of considering climate change



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to obtain high yields of both conventional agricultural crops and heat-loving ones, which were not typical for Polissia and Forest-Steppe, is proved. Based on the analysis of the dynamics of crop yields, it is identified that it is advisable to reorient agricultural production to the cultivation of heat-loving crops – corn, sunflower, soy, and rapeseed in the Forest-Steppe, which in recent years give the same or slightly higher yields than in the south of Ukraine. Growing these crops in the Polissia zone is unprofitable – the yield is quite low, so in these regions, it is worth continuing to grow conventional crops (cereals, legumes, vegetables, potatoes). The established dependences of crop yields on climatic and agrometeorological factors allowed identifying a complex of factors that play a major role in the formation of the yield of specific crops. The developed crop yield models based on multiple correlation allow for predicting it. The results of the study can be useful in planning and optimising the activities of agricultural enterprises, and agriculture in general, in various natural and climatic zones of Ukraine, as a strategic branch of the economy

**Keywords**: climate change; agricultural adaptability; heat-loving crops; abiotic factors; agroecosystems

## INTRODUCTION

Timely adaptation of the agro-industrial complex of Ukraine to climate change is an urgent environmental, scientific, and industrial problem. The development of a strategy for the sustainable development of agricultural production in Ukraine should provide for adaptation measures considering climatic conditions. There are about 20 predictive models of climate change at the global level developed by researchers from different countries of the world (Adamenko, 2019).

According to the results of such studies, by the end of the 21st century, there may be an increase in temperature by 2-4°C throughout Ukraine (Yatsyuk *et al.*, 2021; Christidis & Stott, 2021). Climate change trends are characterised by an upward vector of growth in the average annual atmospheric temperature, and therefore, in the next 20 years, there is a high potential risk of factual loss of arable land for intensive farming not only in the Steppe zone of Ukraine but also over half of the area of agricultural land throughout the country (FAO, 2022).

Therewith, Ukraine has all the prerequisites for effective management and further development of agriculture, including: fertile soils, favourable agroclimatic conditions, established historical traditions of agricultural activities, sufficient availability of labour resources, etc. Thus, in 2021, the total share of exports of corn, barley, rapeseed, and sunflower oil on the world export market from Ukraine amounted to almost 63% (Chumak *et al.*, 2012; Mirzoeva, 2022).

Changing climatic conditions in Ukraine cause the shift of the boundaries of agroclimatic zones from south to north and northwest, causing the development of unfavourable agrometeorological phenomena, which are manifested in a lack of moisture and increased temperatures of atmospheric air and soil. Based on the current situation, Howden *et al.* (2007), Romaschenko *et al.* (2003) proposed areas of scientific research aimed at adapting agricultural production to climate change in Ukraine and at the planetary level in general. According to O.G. Tarariko *et al.* (2016), the most important task of the agro-industrial complex of Ukraine, given the inertial nature of agricultural production, is its timely adaptation to climate change. Therewith, the scientific justification of approaches to more efficient use of heat as additional agricultural resource potential, and minimising possible risks manifested by all sorts of extreme phenomena that can substantially worsen both the ecological state of agricultural landscapes and substantially reduce the productivity of agroecosystems themselves is necessary. Muller (2009) considers the transition to organic farming to be the most effective way to adapt agriculture to changing climatic conditions.

In addition to the problematic consequences, climate change also has positive aspects. Thus, Stefanovska and Pidlisniuk (2010) consider the lengthening of the growing season, the shift to the north of the area of cultivation of heat-loving agricultural crops, the improvement of the physiological state of fruit crops in winter, and the increase in grain yields under the influence of an increase in the concentration of $CO_2$ in the atmosphere as positive. Pisarenko and Khlebnikova (2015) believe that high crop yields can be caused, among other things, by an increase in solar activity. As a result of climate change, it became possible to grow heat-loving industrial crops – corn, rapeseed, sunflower, and soybeans in the Polissia and Forest-Steppe zones. This was also facilitated by the pricing policy, agricultural market conditions and the orientation of agricultural producers to high yields and substantial profits at low costs. Every year, the volume of production of these crops is growing, and that of the agricultural crops typical for growing in these agroclimatic conditions is decreasing (Klymenko *et al.*, 2021). In recent years, there has been a tendency to increase the area under heat-loving crops, violate their cultivation technologies, and, as a result, an increase in the area of depleted and degraded soils. Thus, agricultural production in the Steppe zone is already substantially affected by the effects of climate change, intensive and extensive farming, and existing imbalances in the structure of crops. For example, climate changes that manifest themselves in the form of abnormal droughts, frosts, and dust storms in recent years have caused substantial yield losses in all southern regions of Ukraine (Mirzoeva, 2022; Pichura *et al.*, 2022).

The purpose of the study is to examine the features of adaptation and expediency of growing agricultural crops in new agroecological conditions in various natural and climatic zones of Ukraine.

## MATERIALS AND METHODS

The research period was from 2010 to 2021. The analysis of climate changes was conducted according to meteorological (annual average air temperature, maximum and minimum soil surface temperatures, average temperature of the arable soil layer and precipitation during the growing season) and agrometeorological (sum of effective and positive temperatures, reserves of productive moisture in the arable soil layer, and hydrothermal coefficient for the growing season) indicators. Technical agricultural crops were selected to examine the issue of adaptation to new agroecological conditions – corn, sunflower, soy, rapeseed (they are more resistant to climate change) – their yield in different natural zones of Ukraine (in Polissia, in the Forest-Steppe, and Steppe).

The information database for the research was the materials of the State Statistics Service of Ukraine; the Main Department of Statistics in Rivne, Volyn, Zhytomyr, Vinnytsia, Poltava, Kirovohrad, Kherson, Mykolaiv, Odesa, and Zaporizhia regions; the Departments of Agro-Industrial Development and Departments of Ecology and Natural Resources of the above-mentioned regions; materials of meteorological observations of regional centres of Ukraine on hydrometeorology and weather stations; papers of Ukrainian and foreign researchers, periodicals.

The study was conducted using the following general scientific, specific scientific, and special methods of scientific knowledge:

– analysis and synthesis – for collecting and analysing statistical information on meteorological, agrometeorological data and indicators of agricultural production; for assessing the factual state, dynamics, and trends in the development of crop production in the Polissia, Forest-Steppe, and Steppe zones of Ukraine;

– factor analysis – for detailed analysis of natural and anthropogenic factors influencing the productivity indicators of agricultural production of crop products;

– correlation-regression analysis – establishing the dependence of the yield of corn, sunflower, soy, and rapeseed on climatic and agrometeorological indicators separately performed based on the values of correlation coefficients and determination, complex action – using the multiple correlation function (R), which characterises the degree of tightness of the relationship between the dependent variable (yield) and several independent variables (climatic and agrometeorological indicators). These coefficients were determined using mathematical-statistical methods, namely regression analysis, using Microsoft Excel software tools, which allowed forming mathematical models for predicting the adaptability of agricultural crops (by yield indicator) from climatic and agrometeorological factors. The statistical reliability of regression models with a small sample of data was checked using the *F*- criterion (Fischer's criterion).

## RESULTS AND DISCUSSION

The natural-climatic conditions in the territory of Ukraine are quite favourable for the development of agricultural production. Therewith, its further intensification has certain negative consequences. Thus, due to the increase in the level of anthropogenic load in Ukraine in 2018, for the first time since 1990, the issue of carbon dioxide in the atmospheric air from agricultural activities exceeded the volume, which can be accumulated by forests. Therewith, there is a decrease in the absorption of greenhouse gases by forests by about 20%. Depending on management practices and weather conditions, the flow of greenhouse gases into the atmosphere from arable land and pastures varies substantially. Thus, in the early 90s, the introduction of substantial amounts of organic and mineral fertilisers provided sufficient absorption of greenhouse gases. Modern organic application rates have substantially decreased compared to 1990 and amount to only 5%, while mineral fertilisers – approximately 88%. In addition, due to changes in the ratio between industrial and oil crops, the overall structure of agricultural land has also been transformed. Thus, the share of industrial crops (hemp, sugar beet, flax) decreased from 35% to 10%, and the share of oilseeds (soybeans, sunflower, rapeseed) increased from 7 to 30%. This radically changed the trend of carbon dioxide absorption in the range of 5 million tonnes-eq of $CO_2$ to the emission at the level of 48 million tonnes-eq of $CO_2$FAO. STAT., 2022). All this makes it necessary to control the structure of agricultural land and crop rotations.

Notably, withan increase in the anthropogenic load on agroecosystems intensifies the consequences of uncontrolled manifestations of climate change. It is established that in the Polissia and Forest-Steppe zones of Ukraine, the average annual air temperature increased by 0.8-1.0°C over the centuries and by about 0.5°C – in the Steppe, while the number of natural phenomena increased by 7-15% (Adamenko, 2019; Klymenko *et al.*, 2021). Therewith, according to the Ukrainian hydrometeorological centre, over the past 30 years, the average annual air temperature in the whole country has already increased by 1.2°C. The same trend is established based on the results of statistical studies, the data of which are presented on the official FAO website (Fig. 1) (Ministry of EEP of Ukraine, 2020).

The increase in air temperature from November to March averages 1.3°C, and from April to October – 1.1°C. Notably, in the entire history of instrumental meteorological observations on the territory of Ukraine, the deviation from the normal air temperature for the period of 1989-2019 was the largest. In each subsequent decade, since 1991, the air temperature has increased by: 0.5°C in 1991-2000, 1.2°C in 2001-2010, and 1.7°C in 2011-2019. Analysis of regional warming rates for 1975-2019 indicates a substantial rate of increase in atmospheric air temperature in the region – by 0.61-0.82°C/10 years, while in neighbouring countries – 0.47-0.59°C/10 years (Adamenko, 2019).

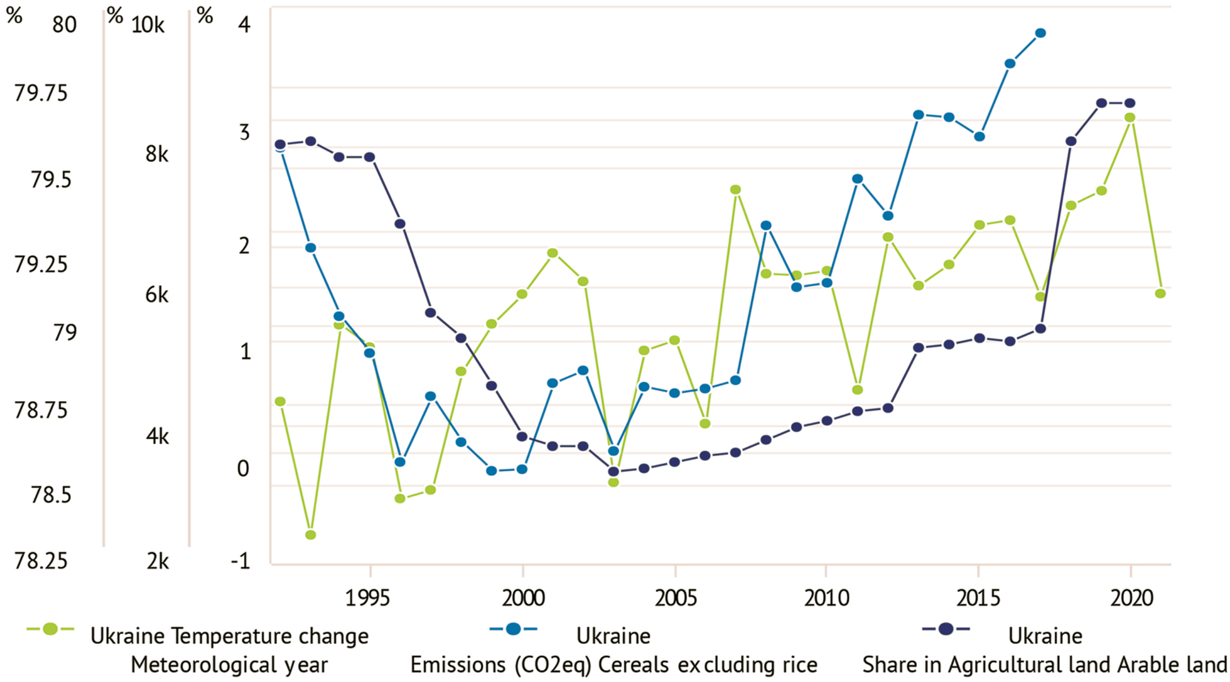



***Figure 1**. Dynamics of average annual atmospheric air temperature, $CO_2$ emissions into the atmospheric air, and the share of arable land in the structure of agricultural landscapes for 1990-2021*
***Source:** FAO. STAT., 2022*

According to the results of joint study by researchers of the Chinese Academy of Agricultural Sciences (CAAS) Meng Fanhua and Zhou Chian and researchers of Sumy National Agrarian University, due to the manifestation of adverse weather conditions caused by climate change, the cultivation of winter wheat is accompanied by substantial yield instability (Bakumenko *et al.*, 2019). There is a negative trend in the correlation between the yield of the main crops and the values of the average maximum and minimum temperatures during the growing season. The development of such a situation may lead to the need for irrigation and those crops that have not previously required it (Tao *et al.*, 2006). In accordance with potential changes in climatic factors, farmers are forced to change the range of crops grown to those that are more economically feasible. However, the adaptation of the crop industry to climate change and shifting climate zones may have substantial promising trends (Kussul *et al.*, 2020).

Considering the actual climate changes on the territory of Ukraine, the dynamics of meteorological (average air temperature, maximum and minimum soil surface temperature, average temperature of the arable soil layer, the amount of precipitation) and agrometeorological (sums of positive and effective temperatures, reserves of productive moisture of the arable soil layer, hydrothermal coefficient) factors were analysed (Klymenko *et al.*, 2021) for the period 2010-2021 in the Polissia, Forest-Steppe, and Steppe zones.

In Polissia and the Forest-Steppe, the average air temperature during the growing season is almost the same and ranges from 13-14°C during the study period. In the Steppe zone, this indicator is 1.4 times higher and is in the range of 18-20°C. Changes in the temperature regime during the warm period of the year affected the thermal resources of Ukraine. The indicator of the sum of active air temperatures above +10°C accumulated during the warm period was used to evaluate them. Analysis of the dynamics of these amounts for different periods allowed recording their increase by an average of 200-400°C. In the far south, a thermal zone has formed, where the sum of temperatures exceeds 3400-3700°C – these are the southern districts of Kherson, Mykolaiv, Odesa, and Zaporizhia regions, where there is quite enough heat for very heat-loving crops. In addition, in the previous decade, the heat supply of the Vinnytsia, Poltava, Kharkiv, and Kirovohrad regions in the period 2010-2019 was the same as that of the Kherson region. Thus, the regions of the Northern Steppe and Southern Forest-Steppe of Ukraine are already close to the conditions of the Southern Steppe. However, it is noted that the increase in the amount of heat is more rapid in the northern regions (indicated in parentheses in Table 1), for example, the increase in active temperatures over the past decade for the Steppe zone was +150°C, Forest-Steppe – +200°C, Polissia – +220°C (Adamenko, 2019).

***Table 1**. Sums of active air temperatures above +10°C in agroclimatic zones of Ukraine for different periods*

| Agroclimatic zone | Periods | | |
|---|---|---|---|
| | 1961–1990 | 1991–2009 | 2010–2019 |
| Steppe | 3145 | 3400 *(+255)* | 3550 *(+150)* |
| Forest-Steppe | 2705 | 2950 *(+245)* | 3150 (+200) |
| Polissia | 2500 | 2770 *(+200)* | 2950 *(+220)* |

***Source:** Adamenko, 2019*

The sums of positive and effective temperatures of 10°C and above for the Steppe zone range from 4030-4353°C and 2805-3198°C, respectively (Fig. 2). For the Polissia and Forest-Steppe zones, the values of these indicators are the same, changes occurred in the range of 2805-3245°C and 1190-1350°C, respectively, which is 1.4 and 2.1 times less than the indicators of the Steppe zone.

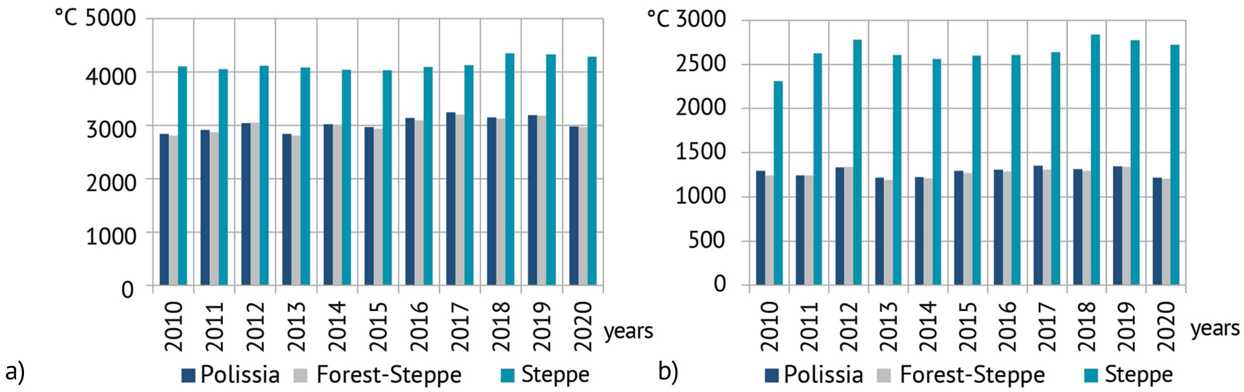



***Figure 2**. Dynamics of the sum of positive (a) and effective (b) temperatures of 10°Cand above during the growing season*
***Source:** compiled by the authors*

The maximum soil surface temperature is slightly higher in the Steppe than in Polissia and Forest-Steppe (Fig. 3), but in percentage terms, it does not exceed an average of 8 and 14%. The values of this indicator for the study period range from 56-64°C in Polissia, 55-61°C in the Forest-Steppe, and 62-66°C in the Steppe. It should also be noted that the Forest-Steppe and Polissia zones are more characterised by extreme temperatures of the minimum soil surface.

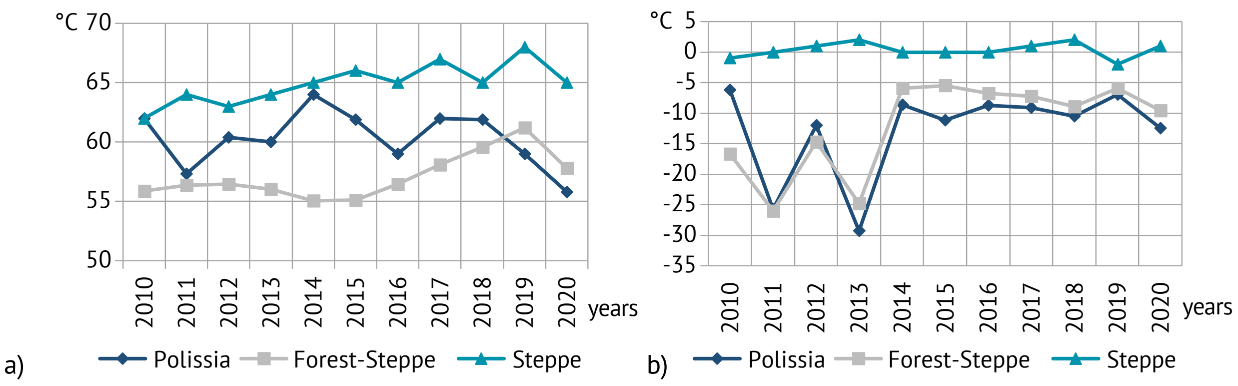



***Figure 3**. Dynamics of maximum (a) and minimum (b) soil surface temperatures during the growing season*
***Source:** compiled by the authors*

As shown in Figure 3 (b), the minimum soil surface temperature is substantially higher in the Steppe area and varies within -2...+2°C. Therewith, in Polissia and in the Forest-Steppe zone, this indicator is almost the same and ranges from -6...-29°C and -6...-25°C, respectively. Notably, since 2014, the minimum soil surface temperature in the examined zones of Polissia and Forest-Steppe has not lowered below -13°C and -10°C, respectively.

The average temperature of the arable layer (0-20 cm) of soil during the growing season (Fig. 4) in the Steppe zone is 28% and 19% higher relative to the same indicator in the Polissia and Forest-Steppe zones, respectively. In general, the value of the average temperature of the arable soil layer for the study period varied in the range of 11-17°C in Polissia, 14-17°C in the Forest-Steppe, and 17-20°C in the Steppe.

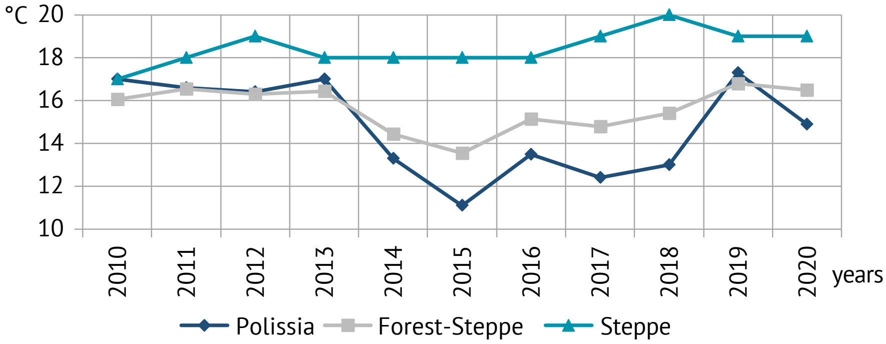



***Figure 4**. Dynamics of the average temperature of the arable soil layer (0-20 cm) during the growing season of 2010-2021*
***Source:** compiled by the authors*

Almost all areas of agricultural crops in Ukraine are in the zone of risky farming, that is, in areas with a natural lack of precipitation, where in an excessively dry year there is a constant risk of loss of harvest volumes or in a too rainy year – loss of harvest quality, while global climate change factors only increase such risks.

Depending on the level of natural moisture, the territory of Ukraine is divided into six typical zones: excessively humid (4.5% of the territory), humid (30%), insufficiently humid (16%), arid (20%), dry (22%), and extremely dry (7.5%). During the period of 1991-2015, compared to 1961-1990, the area of territories with a substantial water supply deficit increased by 7% and already covers almost a third (29.5%) of the area of Ukraine or 11.6 million ha (37%) of arable land. The area of the territory with excessive and sufficient atmospheric moisture decreased by 10% and amounts to 22.5%, including 7.6 million ha of arable land. According to the medium-term forecast until 2050, the temperature regime is expected to continue to increase by 1.24°C-1.48°C compared to the current period. Given this, it can be assumed that the area with insufficient moisture will increase by 56% and only 28% of the territory will have humid and excessively humid conditions (Yatsyuk *et al.*, 2021).

In the agroclimatic zones of Polissia and Forest-Steppe, the amount of precipitation is 2.1-2.2 times higher compared to the Steppe zone. The total amount of precipitation for the study period of 2010-2021 varied in the range of 326-627 mm/year in Polissia, 326-598 mm/year in the Forest-Steppe, and 134-297 mm/year in the Steppe (Fig. 5). Considering the fact that the norm of this indicator for sustainable agriculture is 700 mm/year or more (Adamenko, 2019), today a moisture deficit of 100-150 mm/year is already determined for the Polissia and Forest-Steppe zones.

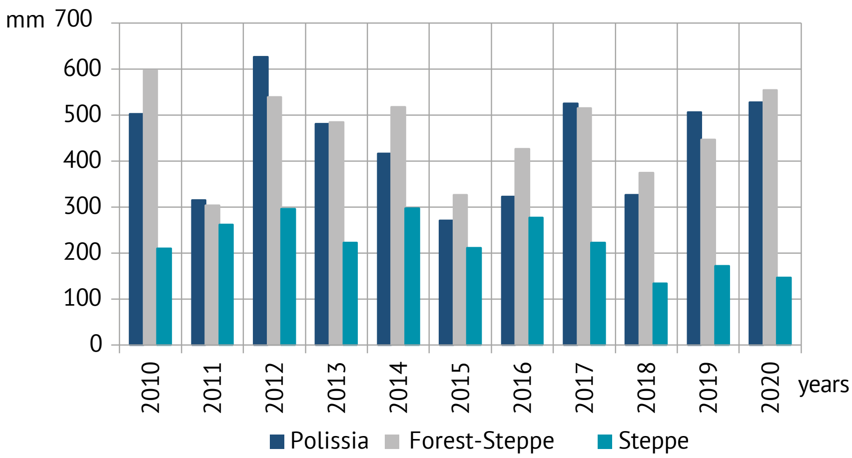
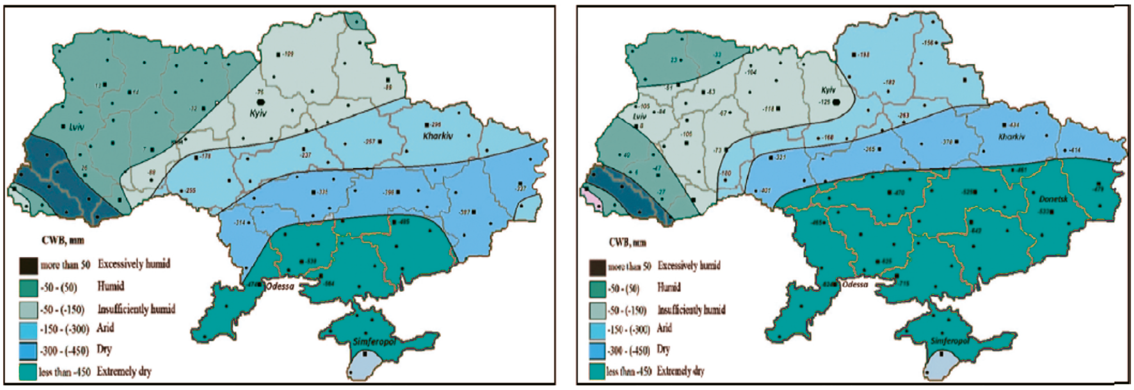



***Figure 5**. Dynamics of precipitation during the growing season for 2010-2021, mm*
***Source:** compiled by the authors*

In accordance with one of the climate scenarios, which considers the increase in atmospheric air temperature by 1.5°C, the total climatic balance of the territory of Ukraine by 2050 will decrease by 45-115 mm, and its deficit in the Steppe zone is projected to be ⩾560 mm, the percentage of territories with insufficient moisture will increase to 56%. The forecast model for 2100 indicates a lack of water supply in the southern, central, and eastern regions – 400-470 mm, and this corresponds to the current conditions of the Steppe zone of Ukraine. The percentage of territories with insufficient moisture can reach 71%, and those with sufficient moisture will not exceed 12% (Fig. 6) (Yatsyuk *et al.*, 2021).




2050 2100

***Figure 6****. Forecast models of the natural water supply of the territory of Ukraine, considering potential climate changes*
***Source:*** *Yatsyuk et al. (2021)*

Another substantial factor that negatively affects the yield is the lack of soil moisture during the growing season, the main source of which is precipitation or irrigation systems of irrigation agriculture. It is the amount of precipitation that determines the level of soil moisture supply. As shown in Figure 7, the reserves of productive moisture of the arable soil layer on the territory of the Forest-Steppe are higher and during the period under study varied in the range of 25-36 mm, which is 1.6 times more than in Polissia (15-26 mm), and 1.7 times more than in the Steppe zone (15-21 mm).

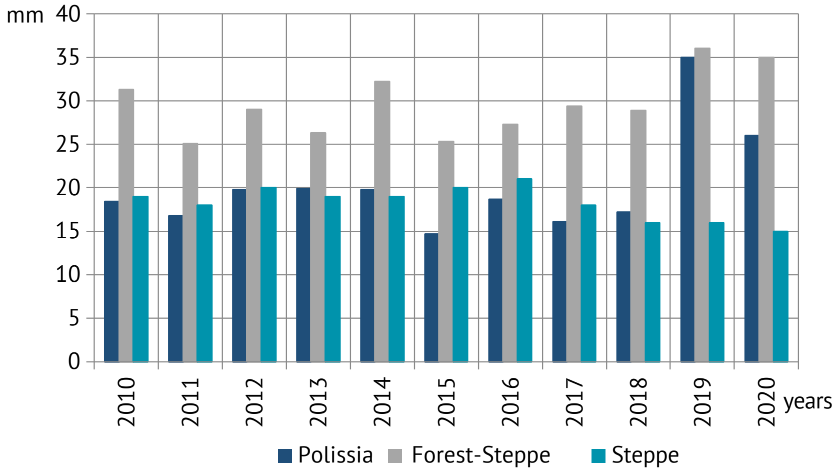



***Figure 7****. Dynamics of the productive moisture reserve of the arable soil layer (0-20 cm) during the growing season in 2010-2021, mm*
***Source:*** *compiled by the authors*

The hydrothermal coefficient (HTC), which is an indicator of the moisture content of the territory during the growing season, is determined. The amount of precipitation for the period in which the average daily air temperature is above 10°C and the sum of active temperatures for the same period during 2010-2021 were considered (Fig. 8).

On the territory of Polissia and Forest-Steppe, the HTC was almost the same, its value ranged from 0.8, which is typical for dry conditions, to 1.8 – conditions of excessive moisture. In the Steppe zone, it ranged from 0.2-1 (extremely dry conditions – satisfactory moisture). The average value of the HTC for the period under review was 1.3 for Polissia and Forest-Steppe and 0.5 – for Steppe.

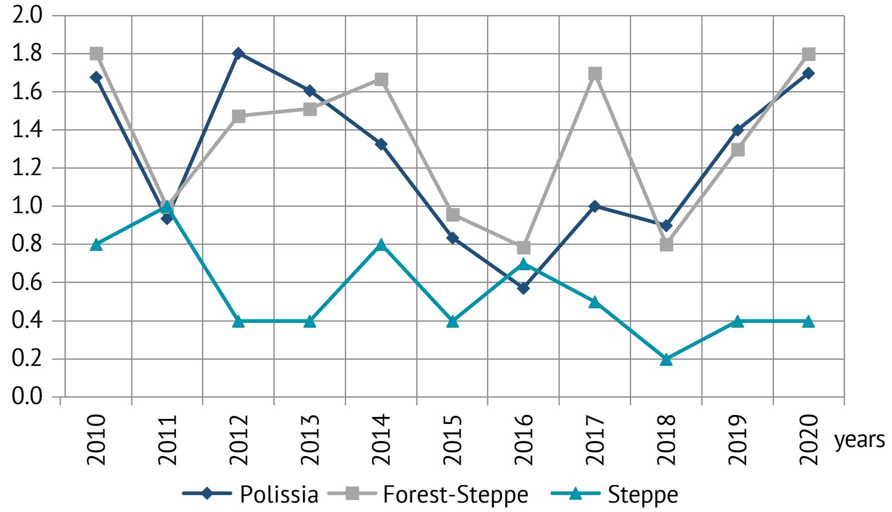



***Figure 8**. Dynamics of the hydrothermal coefficient for the growing season in 2010-2021*
***Source:** compiled by the authors*

The yield of agricultural crops is determined by natural-climatic conditions and organisational-economic capabilities, depends on many factors, and therefore can act as a qualitative complex indicator. During the study, the yield of heat-loving agricultural crops in the Polissia, Forest-Steppe, and Steppe zones was analysed. Figure 9 shows the dynamics of corn yield for 2010-2021.

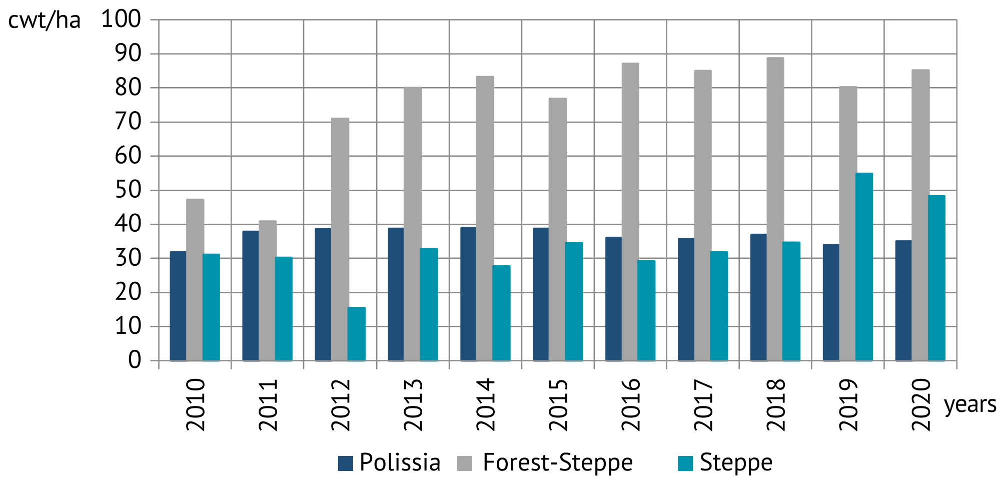



***Figure 9**. Dynamics of corn yield for 2010-2021., cwt/ha*
***Source:** compiled by the authors*

Analysis of the dynamics of corn yield in different natural and climatic zones allows concluding that the most favourable conditions for growing corn were formed in the Forest-Steppe zone, with an average yield of 2.1 and 2.4 times higher than in Polissia and Steppe, respectively (with the exception of 2021). In general, for the period 2010-2021, the yield of corn varied in the range of 32-39 cwt/ha in Polissia, 41-89 cwt/ha in the Forest-Steppe, and 16-75 cwt/ha in the Steppe.

For both corn and sunflower, the Forest-Steppe zone was identified to be more suitable for cultivation (Fig. 10). Sunflower yields are on average 3.5 and 1.4 times higher than in Polissia and Steppe, respectively. In general, for the period 2010-2021, the yield of sunflower varied from 1.7 to 13.2 cwt/ha in Polissia, 11.3-28.3 cwt/ha in the Forest-Steppe, and 12.6-20 cwt/ha in the Steppe. Consequently, it is unprofitable to cultivate sunflower in the Polissia zone, but there is a tendency to increase its yield in the Forest-Steppe zone and instability in obtaining high yields in the Steppe.

For agricultural enterprises located in the Steppe zone, for many years in a row, the practice of managing with substantial violations of sunflower cultivation technology has been inherent, which consists in insufficient consideration of its biological characteristics and possible impact on the yield of subsequent crops. As a result, an unreasonably high share of this crop in the structure of acreage, which exceeds 15%, causes drying of the upper and lower layers of the soil, which, in turn, will negatively affect the yield of 2-3 harvest following it (Mirzoeva, 2022).

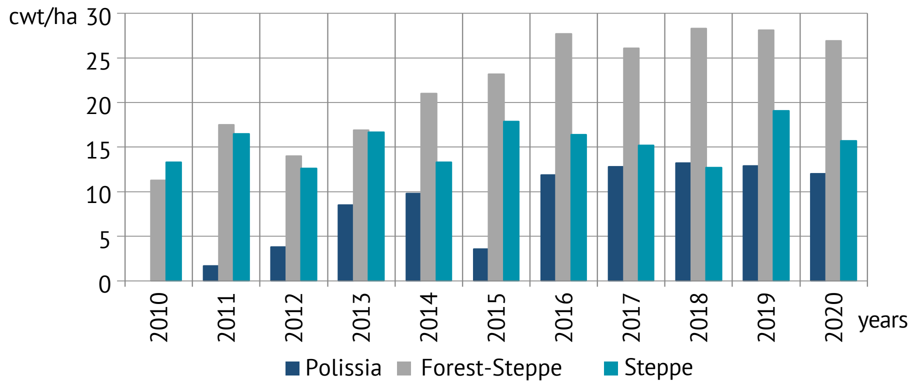



***Figure 10**. Dynamics of sunflower yield for 2010-2021, cwt/ha*

***Source:** compiled by the authors*

The Steppe zone is more suitable for growing soybean (Fig. 11) since its yield is 2.3 and 1.3 times higher than in the Polissia and Forest-Steppe zones, respectively. During the period under study, there was an increase in soybean yield from North to South in all the examined zones, indicators fluctuated in the Polissia zone in the range of 7-21 cwt/ha, in the Forest-Steppe zone – 11-29 cwt/ha, and 18-36 cwt/ha in the Steppe.

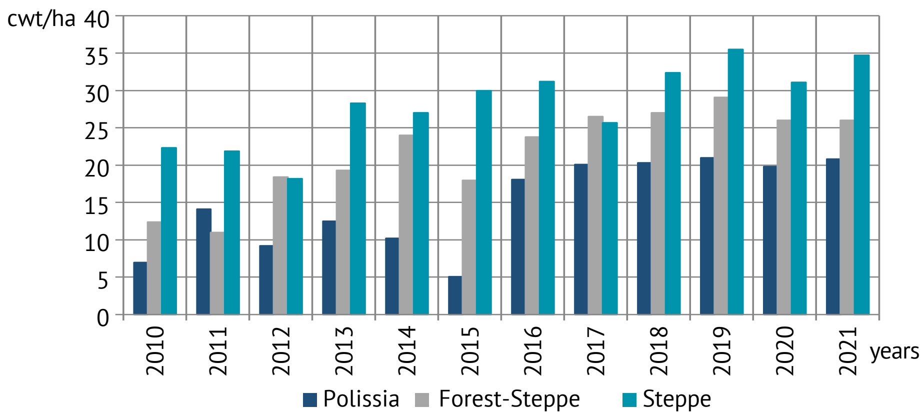



***Figure 11**. Dynamics of soybean yield for 2010-2021, cwt/ha*

***Source:** compiled by the authors*

The yield of rapeseed is substantially higher in the Forest-Steppe compared to Polissia, and slightly higher or close to the yield in the Steppe zone. However, as Figure 12 shows, from 2014 to 2015, there was a decrease in rapeseed yield by 1.7 times in the Forest-Steppe zone and by 15 times in the Polissia zone. In the Steppe, on the contrary, there is some stability in the yield of this agricultural crop. In general, rapeseed yield during the study period was in the range of 0.5-15.1 cwt/ha in Polissia, 20.1-34 cwt/ha in the Forest-Steppe, and 12.7-24.6 cwt/ha in the Steppe.

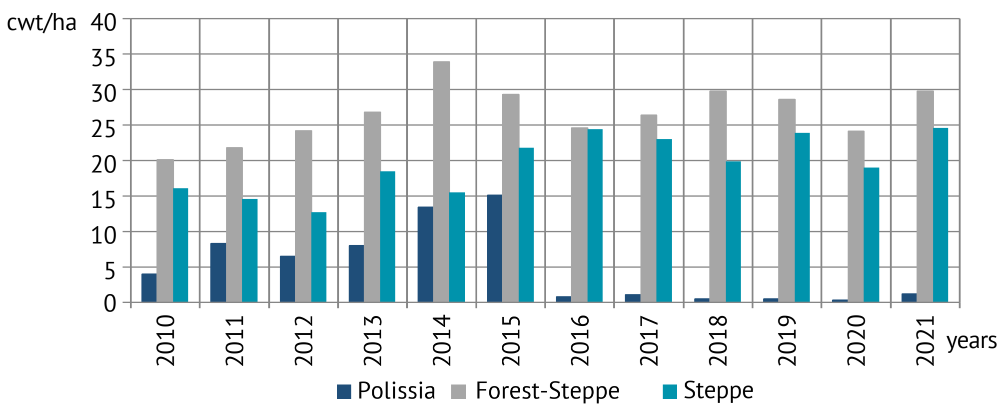



***Figure 12**. Dynamics of rapeseed yield in 2010-2021, cwt/ha*

***Source:** compiled by the authors*

Based on the above information, the influence of meteorological and agrometeorological factors on the yield of heat-loving agricultural crops in Polissia, Forest-Steppe, and Steppe of Ukraine for the period 2010-2021 is analysed. Results of calculation of correlation coefficient values are presented in Table 2.

***Table 2**. Results of the correlation coefficient calculation*

| Name of the culture | Indicators | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | meteorological | | | | | agrometeorological | | | |
| | average air temperature | maximum soil surface temperature | minimum soil surface temperature | average temperature of the arable layer | amount of precipitation | sum of effective temperatures | sum of positive temperatures | productive moisture reserves | HTC |
| **Polissia** | | | | | | | | | |
| corn | -0.20 | 0.18 | -0.50 | -0.32 | -0.29 | -0.33 | -0.11 | -0.40 | -0.19 |
| sunflower | 0.36 | 0.07 | 0.50 | -0.16 | 0.18 | 0.22 | 0.65 | 0.42 | -0.06 |
| soybean | 0.23 | -0.43 | 0.09 | -0.01 | 0.07 | 0.23 | 0.68 | 0.45 | -0.23 |
| rapeseed | -0.29 | 0.42 | -0.28 | -0.22 | -0.33 | -0.42 | -0.51 | -0.42 | -0.02 |
| **Forest-Steppe** | | | | | | | | | |
| corn | 0.42 | 0.32 | 0.68 | -0.34 | 0.09 | 0.14 | 0.62 | 0.26 | -0.08 |
| sunflower | 0.46 | 0.60 | 0.69 | -0.24 | -0.32 | 0.27 | 0.73 | 0.28 | -0.38 |
| soybean | 0.57 | 0.66 | 0.72 | -0.11 | 0.13 | 0.30 | 0.80 | 0.56 | 0.00 |
| rapeseed | 0.38 | 0.10 | 0.56 | -0.54 | -0.20 | 0.01 | 0.41 | 0.14 | -0.14 |
| **Steppe** | | | | | | | | | |
| corn | 0.00 | 0.65 | 0.29 | 0.27 | -0.07 | -0.06 | 0.19 | 0.61 | 0.06 |
| sunflower | -0.18 | 0.22 | 0.05 | 0.07 | -0.45 | 0.02 | 0.02 | -0.03 | -0.27 |
| soybean | 0.29 | 0.54 | 0.06 | 0.60 | -0.25 | 0.18 | 0.02 | 0.49 | -0.35 |
| rapeseed | 0.28 | 0.47 | 0.59 | -0.29 | -0.24 | 0.31 | 0.54 | 0.11 | -0.33 |

***Source:** compiled by the authors*

Analysis of the results of calculating the correlation coefficient shown in Table 2 allows concluding that each individual factor taken from the examined factors does not have a substantial importance in the formation of crop yields. This is confirmed by the results of correlation analysis – in most cases, an insubstantial relationship was established (r<0.7). Therewith, the results obtained allowed for establishing limiting factors of influence on the yield of heat-loving industrial crops. These include the average temperature value, the sum of positive temperatures, and the soil surface temperature (r=0.57-0.80).

A mathematical analysis of the data was performed using the multiple correlation coefficient to confirm the overall effect of the limiting factors established as a result of the study on crop yields. The results of calculation are presented in Table 3.

***Table 3**. Results of the multiple correlation coefficient calculation*

| Name of the culture | Factors | | |
|---|---|---|---|
| | meteorological | agrometeorological | meteorological and agrometeorological |
| **Polissia** | | | |
| corn | 0.819 | 0.573 | 0.997 |
| sunflower | 0.568 | 0.862 | 1 |
| soybean | 0.634 | 0.817 | 0.997 |
| rapeseed | 0.699 | 0.617 | 0.968 |
| **Forest-Steppe** | | | |
| corn | 0.739 | 0.782 | 0.927 |

*Table 3, Continued*

| Name of the culture | Factors | | |
|---|---|---|---|
| | meteorological | agrometeorological | meteorological and agrometeorological |
| Forest-Steppe | | | |
| sunflower | 0.933 | 0.925 | 0.998 |
| soybean | 0.891 | 0.934 | 0.975 |
| rapeseed | 0.658 | 0.637 | 0.813 |
| Steppe | | | |
| corn | 0.942 | 0.766 | 0.999 |
| sunflower | 0.823 | 0.153 | 0.967 |
| soybean | 1 | 0.979 | 1 |
| rapeseed | 0.84 | 0.452 | 0.992 |

***Source:*** *developed by the authors (Klymenko et al., 2021; Sobko et al., 2021)*

The results of calculating the multiple correlation coefficient (Table 3) give grounds to assert that it is the combined effect of meteorological and agrometeorological factors that has a substantial impact on the yield of the considered agricultural crops in the territories of the examined agroclimatic zones. The greatest dependence of yield on the group of meteorological factors was identified for corn in Polissia (R=0.819), sunflower in the Forest-Steppe (R=0.933), soybeans in the Steppe (R=1); on agrometeorological factors – in Polissia for sunflower (R=0.862), soybeans in the Forest-Steppe (R=0.934) and Steppe (R=0.979); on meteorological and agrometeorological factors together – for sunflower in Polissia (R=1) and Forest-Steppe (R=0.998), soybeans in the Steppe (R=1).

Regression models are proposed (Table 4), which consider meteorological and agrometeorological factors characteristic of the Polissia, Forest-Steppe, and Steppe zones of Ukraine to predict the yield of the considered agricultural crops.

***Table 4****. Regression models of crop yields*

| Name of the cultural tour | Group of factors | Regression models | F-criterion | |
|---|---|---|---|---|
| | | | P≤0.05 | $F_{calc}$ |
| 1 | 2 | 3 | 4 | 5 |
| *POLISSIA* | | | | |
| corn | climatic | $y=2.86*x_1+0.23*x_2-0.36*x_3-0.53*x_4+0.002*x_5-14.02$ | 3.2 | 3.05 |
| | agrometeorological | $y=-0.03*x_6+0.01*x_7-0.2*x_8+0.25*x_9+52.27$ | 3.36 | 1.15 |
| | climatic and agrometeorological | $y=18.53*x_1-0.07*x_2-0.66*x_3-0.61*x_4+0.01*x_5-0.05*x_6-0.02*x_7+0.13*x_8-2.32*x_9-97.87$ | 2.9 | 24.75 |
| sunflower | climatic | $y=-5.79*x_1+0.04*x_2+0.58*x_3+0.17*x_4+00.04*x_5+89.86$ | 3.33 | 0.59 |
| | agrometeorological | $y=-0.07*x_6+0.05*x_7+0.14*x_8+0.44*x_9-41.58$ | 3.48 | 5.69 |
| | climatic and agrometeorological | $y=-182.73*x_1+3.19*x_2+7.33*x_3+9.45*x_4-0.11*x_5+0.5*x_6+0.12*x_7-2.91*x_8+27.92*x_9+1357.24$ | 3.02 | 12.38 |
| soybean | climatic | $y=9.36*x_1-1.57*x_2-0.19*x_3-0.4*x_4+0.004*x_5-17.97$ | 3.2 | 1 |
| | agrometeorological | $y=-0.05*x_6+0.04*x_7+0.34*x_8-1.55*x_9-38.51$ | 3.36 | 4.74 |
| | climatic and agrometeorological | $y=-32.17*x_1-0.59*x_2+0.61*x_3+1.1*x_4-0.05*x_5+0.04*x_6+0.11*x_7-0.46*x_8+16.18*x_9+111.01$ | 2.9 | 24.75 |
| rapeseed | climatic | $y=-5.37*x_1+1.3*x_2-0.15*x_3-0.31*x_4-0.01*x_5+6.55$ | 3.2 | 1.44 |
| | agrometeorological | $y=-0.02*x_6-0.02*x_7-0.25*x_8-1.59*x_9+79.79$ | 3.36 | 1.43 |
| | climatic and agrometeorological | $y=37.75*x_1+0.95*x_2-1.01*x_3-1.68*x_4+0.05*x_5-0.09*x_6-0.1*x_7+0.82*x_8-18.28*x_9-161.39$ | 2.9 | 3.92 |

*Table 4, Continued*

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| | | *FOREST-STEPPE* | | |
| corn | climatic | $y=-15.77*x_1+3.61*x_2+1.51*x_3-4.05*x_4+0.02*x_5+154.94$ | 3.2 | 1.83 |
| | agrometeorological | $y=-0.23*x_6+0.14*x_7-0.33*x_8-1.91*x_9-30.61$ | 3.36 | 3.65 |
| | climatic and agrometeorological | $y=32.48*x_1+6.07*x_2+4.97*x_3+24.01*x_4+0.05*x_5-0.48*x_6+0.02*x_7-10.6*x_8+23.27*x_9-224.35$ | 2.9 | 1.54 |
| sunflower | climatic | $y=-8.4*x_1+1.66*x_2+0.85*x_3+0.43*x_4-0.02*x_5+56.25$ | 3.2 | 10.04 |
| | agrometeorological | $y=-0.09*x_6+0.05*x_7+0.45*x_8-8.6*x_9-10.66$ | 3.36 | 14.33 |
| | climatic and agrometeorological | $y=-3.76*x_1+1.32*x_2+1.28*x_3+4.94*x_4-0.02*x_5-0.08*x_6+0.02*x_7-1.49*x_8+3.35*x_9+15.11$ | 2.9 | 24.75 |
| soybean | climatic | $y=-4.68*x_1+2.07*x_2+0.57*x_3-0.57*x_4+0.01*x_5-21.16$ | 3.2 | 5.64 |
| | agrometeorological | $y=-0.07*x_6+0.05*x_7+0.47*x_8-1.92*x_9-47.46$ | 3.36 | 15.62 |
| | climatic and agrometeorological | $y=4.11*x_1+1.84*x_2+0.91*x_3+4.02*x_4+0.01*x_5-0.11*x_6+0.02*x_7-1.54*x_8+3.65*x_9-91.25$ | 2.9 | 4.75 |
| rapeseed | climatic | $y=-1.15*x_1+0.62*x_2+0.14*x_3-1.99*x_4+40.72$ | 3.2 | 1.13 |
| | agrometeorological | $y=-0.06*x_6+0.03*x_7-0.03*x_8-1.91*x_9+22.63$ | 3.36 | 1.62 |
| | climatic and agrometeorological | $y=8.64*x_1+0.58*x_2-0.34*x_3-2.8*x_4-0.01*x_5-0.08*x_6+0.01*x_7+0.3*x_8-0.24*x_9-26.82$ | 2.9 | 0.49 |
| | | *STEPPE* | | |
| corn | climatic | $y=-4.34*x_1+1.28*x_2-4.26*x_3+3.3*x_4-0.13*x_5+2.03$ | 3.2 | 12.14 |
| | agrometeorological | $y=-0.02*x_6+0.02*x_7-3.41*x_8-4.17*x_9+60.55$ | 3.36 | 3.5 |
| | climatic and agrometeorological | $y=-10.1*x_1+0.59*x_2-5.3*x_3+0.12*x_4+0.06*x_5-0.02*x_6+0.06*x_7-3.08*x_8-33.06*x_9+50.38$ | 2.9 | 24.75 |
| sunflower | climatic | $y=-1.24*x_1+0.73*x_2-0.53*x_3-0.07*x_4-0.01*x_5-5.64$ | 3.2 | 3.19 |
| | agrometeorological | $y=-0.01*x_7-0.29*x_8-0.49*x_9+38.39$ | 3.36 | 0.05 |
| | climatic and agrometeorological | $y=2.46*x_1+1.73*x_2+1.65*x_3-9.85*x_4-0.05*x_5+0.04*x_6+0.32*x_8+8.3*x_9-53.59$ | 2.9 | 3.92 |
| soybean | climatic | $y=5.32*x_1-2.49*x_2-2.17*x_3-3.15*x_4-0.02*x_5+157.69$ | 4.39 | 24.75 |
| | agrometeorological | $y=-0.26*x_6+0.23*x_7+5.29*x_8-57.3*x_9-317.82$ | 4.53 | 16 |
| | climatic and agrometeorological | $y=-1.87*x_2-2.85*x_3+0.04*x_6-0.01*x_7+95.35$ | 4.1 | -37.13 |
| rapeseed | climatic | $y=1.17*x_1+2.42*x_2+1.08*x_3-3.49*x_4-0.02*x_5-91.13$ | 3.2 | 3.67 |
| | agrometeorological | $y=-0.01*x_6+0.02*x_7+0.77*x_8-4.22*x_9-60.37$ | 3.36 | 0.58 |
| | climatic and agrometeorological | $y=-4.34*x_1+1.45*x_2-0.88*x_3+4.95*x_4-0.02*x_6+0.04*x_7+2.44*x_8-4.53*x_9-238.62$ | 2.9 | 12.25 |
| Note | $x_1$ – average air temperature for the growing season, °C; $x_2$ – maximum soil surface temperature during the growing season, °C; $x_3$ – minimum soil surface temperature during the growing season, °C; $x_4$ – average temperature of the arable soil layer (20 cm) during the growing season, °C; $x_5$ – the amount of precipitation during the growing season, mm; $x_6$ – the sum of effective temperatures of 10°C and above for the growing season, °C; $x_7$ – the sum of positive temperatures of 10°C and above for the growing season, °C; $x_8$ – reserves of productive moisture in the arable soil layer (0-20 cm) during the growing season, mm; $x_9$ – hydrothermal coefficient (HTC) for the growing season.<br>– the regression model is statistically substantial $P \leqslant 0.05$ (condition $F_{calc} > F_{table}$ is observed**)** **(**Klymenko *et al.*, 2021**)** | | | |

***Source:*** *compiled by the authors*

The trends established as a result of the study are confirmed by a number of researchers. Thus, researchers of the Scientific Centre for Aerospace Research of the Earth of the National Academy of Sciences of Ukraine (Lyalko *et al.*, 2020) established that according to the average annual indicators of gross primary productivity of vegetation cover, the most highly productive territories include the western regions (with the exception of Khmelnitska and Ternopil) and Zhytomyr region using MOD17 A3 satellite images. Most of Podillia (Vinnytsia, Ternopil, Khmelnytska regions), the remaining northern regions and the Cherkasy region form a normally productive part of the territory of Ukraine. Other administrative regions belong to a moderately productive part of the territory of the state.

The examination of the trend in the dynamics of yield of heat-loving crops is confirmed by the results of the study by O.S. Budziak, (2022). Due to the increase in the sum of effective temperatures, favourable conditions have emerged In the Western Forest-Steppe zone for growing heat-loving crops such as sunflower, corn for grain, soybeans, etc. The area under them is constantly growing, which causes changes in the structure of both acreage and agricultural landscapes. In 2000-2021, the area of crops increased rapidly – under soybeans (20 times), rapeseed (5 times), corn for grain (4 times), and sunflower (2 times). The change in land use management practices from grain-feed to grain-technical was also caused by an economic factor (Budziak *et al.*, 2022).

Poliovyi (2019) notes that the total amount of precipitation for the year and for the growing season cannot be a reliable initial criterion for assessing the real moisture supply of agricultural crops during the growing season. The data obtained by the researcher indicate that the processes caused by global warming have substantially worsened the supply of moisture to plants. It was identified that the reserves of productive moisture under winter wheat in the soil layer of 0-100 cm, with almost the same amount of precipitation in June-July of 2013-2018, were half as much as in 1985-1990. There is a gradual aridisation of the territory. Although due to an increase in the amount of winter precipitation and its better assimilation by the soil if it freezes slightly early spring moisture reserves somewhat increase, in summer there are clearly pronounced downward trends.

An increase in air and soil temperature during the growing season of agricultural crops, combined with increased winds and a decrease in relative humidity, substantially increases the evaporation of moisture, which leads to a worse moisture supply for plants, even if the amount of precipitation does not decrease (Poliovyi *et al.*, 2019). The hydrothermal coefficient established in the course of the study, which is an indicator of the moisture content of the territory during the growing season, confirms this trend.

In the modern agricultural production of Ukraine, a special place is occupied by corn, which is characterised by high potential productivity compared to other grain crops. Since 1998, the area under corn and sunflower crops in Polissia has substantially increased. Previously, agroclimatic conditions were not favourable for growing these heat-loving crops in the Polissia zone, since they did not have time to ripen at insufficient temperatures. However, due to climate change, this has become attainable, and in some areas, it is now possible to get even two harvests from one field per season (Liu *et al.*, 2021; Johnston & Chiotti, 2000). Over the past 20 years, the acreage under corn in the Polissia zone has increased by 98,843 hectares, and sunflower – by 126,963 hectares, while in the Steppe zone these areas are 361,551 hectares for corn and 473,044 hectares for sunflower. Over the past decade, the area of corn crops in Ukraine has increased more than 2 times and amounts to about 5 million tonnes despite the fact that according to scientific recommendations, the optimal area of corn sowing for grain and silage in Ukraine should be within 3 million hectares (FAO, 2022).

Corn yields in Ukraine almost doubled from 2000 to 2021 – from 27 cwt/ha (2000) to 50 cwt/ha (2021). The maximum yield of corn in individual agricultural enterprises located in the Forest-Steppe zone, under the conditions of production intensification, reached 170-180 cwt/ha (Tkachuk & Bondarenko, 2022).

Notably, the cultivation of not only conventional agricultural crops but also heat-loving ones forms a tendency to intensify the development of degradation processes of the soil cover, which in turn causes an increase in the area of degraded and depleted soils. This is due to a violation of the technology of agricultural production when growing heat-loving crops on unreasonably large areas. A study by V.S. Chumak *et al.* (2012) allowed establishing that "with one ton of the main product of rapeseed, 65 kg of nitrogen, 24 kg of phosphorus, and 42 kg of potassium are removed from the soil, sunflower – 43 kg, 17 kg, and 10 kg, respectively, corn 24 kg, 9 kg, and 22 kg, respectively". Thus, a negative balance of nutrients in the soil is formed, which can only be partially compensated by the introduction of mineral and organic fertilisers. Due to this, in the conditions of intensive farming, there is a decrease in soil fertility, which leads to a decrease in yield (Stepanenko *et al.*, 2011; Klymenko *et al.*, 2021).

It is necessary that climatic and agrometeorological indicators are within certain optimal limits to obtain the planned yield of agricultural crops (Hanson *et al.*, 2007; Khudaverdiyeva, 2022), which is confirmed by the environmental laws of J. Liebig (the law of the minimum) and V. Shelford (the law of tolerance). The processes taking place in the agricultural sector due to climate change are ambiguous. Fast and excessive heat accumulation caused by them can lead to a reduction in the growing season, premature ripening of crops, and a decrease in yield (Petersen, 2008; Nelson *et al.*, 2014).

T.I. Adamenko (2019) states that there is a high probability of the transition of Polissia and Western Forest-Steppe from a zone of sufficient moisture to a zone of unstable and insufficient moisture. This is due to the fact that in the coming years not only an increase in air temperature is to be expected, but also a decrease in precipitation. This trend requires attention and further research.

## CONCLUSIONS

This study confirmed that climate changes take an active part in the complex process of forming the productivity of agroecosystems of Polissia, the Forest-Steppe, and the Steppe of Ukraine, considering which will allow agricultural enterprises to obtain high yields of both conventional agricultural crops and heat-loving ones. Crop yields are largely determined, along with other factors, by climatic and agrometeorological factors. The obtained results of correlation analysis allowed establishing limiting factors of influence on the yield of corn, sunflower, soy, and rapeseed, namely: the average value of air temperature, the sum of positive temperatures and soil surface temperature (r=0.57-0.80). The complex effect of meteorological and agrometeorological factors has a more substantial impact on the yield of the considered agricultural crops in the territories of the examined agroclimatic zones (R>0.7). The greatest dependence of yield on the group of meteorological factors was identified for corn in Polissia (R=0.819), sunflower in the Forest-Steppe (R=0.933), soybeans in the Steppe (R=1); on agrometeorological factors – in Polissia for sunflower (R=0.862), soybeans in the Forest-Steppe (R=0.934) and Steppe (R=0.979); on meteorological and agrometeorological factors together – for sunflower in Polissia (R=1) and Forest-Steppe (R=0.998), soybeans in the Steppe (R=1).

Considering the forecasts of further increase in air temperature, which leads to substantial changes in climatic and agrometeorological factors, there is an urgent need to quickly adapt to the variability of natural conditions and search for optimal methods of agricultural activity. Following the strategy of sustainable development, in the post-war period, it will be necessary for Ukraine, as an independent state with strong agricultural potential, to restore agricultural production with high crop yields, considering the potential risks of natural and anthropogenic origin. It is suggested to forecast the adaptability of agricultural crops in different natural and climatic zones of Ukraine by yield indicator using the developed regression models, most of which are statistically reliable with an error level of no over 5% (P⩽0.05) to solve this problem. Further research will be aimed at investigating the possibility of introducing other agricultural crops into crop rotations, their adaptation to new agroecological conditions, and the possible consequences of such actions for agroecosystems.

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## CONFLICT OF INTEREST

None.

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## Прогнозування адаптивності теплолюбних культур до змін клімату в умовах України

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**Анотація**. Україна має розвинутий аграрний сектор економіки, де 10,4 % валового внутрішнього продукту припадає на сільське господарство. Актуальність теми обумовлена тим, що сільськогосподарське виробництво, яке має стратегічне значення для країни, дуже чутливе до кліматичних змін, що відбуваються. При цьому вже проходить процес адаптації рослинницької галузі до наслідків зміни клімату та агрометеорологічних факторів, що проявляється у розширенні спектру вирощуваних сільськогосподарських культур. Метою даного дослідження було прогнозування адаптивності теплолюбних сільськогосподарських культур за їх врожайністю в різних природно-кліматичних зонах України. У процесі досліджень було використано такі методи, як: аналіз, синтез, факторний аналіз, кореляційно-регресійний, математико-статистичний. За результатами проведених досліджень доведено доцільність врахування кліматичних змін для отримання високих врожаїв як традиційних сільськогосподарських культур, так і теплолюбних, які не були типовими для Полісся та Лісостепу. На підставі аналізу динаміки врожайності сільськогосподарських культур було встановлено, що на території Лісостепу доцільно здійснювати переорієнтацію сільськогосподарського виробництва на вирощування теплолюбних культур – кукурудзи, соняшника, сої, ріпаку, які в останні роки дають такі ж або й дещо вищі врожаї ніж на півдні України. Вирощування ж цих культур у Поліській зоні є збитковим – врожайність досить низька, тому в цих регіонах варто продовжувати вирощувати традиційні культури (зернові, зернобобові, овочеві культури, картоплю). Встановлені залежності врожайності сільськогосподарських культур від кліматичних і агрометеорологічних чинників дозволили виявити комплекс факторів, що відіграють головну роль у формуванні врожаю конкретних культур. Розроблені моделі врожайності сільськогосподарських культур на основі множинної кореляції дозволяють здійснювати її прогнозування. Результати дослідження можуть бути корисними при плануванні та оптимізації діяльності сільськогосподарських підприємств, і в цілому сільського господарства, в різних природно-кліматичних зонах України, як стратегічної галузі економіки

**Ключові слова**: зміна клімату; адаптивність сільського господарства; теплолюбні культури; абіотичні фактори; агроекосистеми