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Effects of Climate Change on the Dynamics of Crops Yield - Case of Ukraine

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Abstract The purpose of the publication is to determine the influence of meteorological factors on the yield of grain crops in different regions of Ukraine, as well as to study the correlation dependence of grain yield on meteorological factors. The research methodology is represented by general scientific and special methods (use of satellite information, climate models, data from long-term agrotechnical experiments, and statistical information). Empirical-theoretical (heuristic analysis and generalization), system methods, modeling, and formalization methods should be distinguished among the methods; economic and mathematical methods and methods of statistical analysis. The results of the research can be used as a basis for the formation of new strategies for adaptation to climate change in the fields of agriculture, namely crop production. And also, to take into account changes in the planning of grain crops and the organization of the appropriate infrastructure for their cultivation, storage, and sale. This research indicates noticeable climate changes in different regions of Ukraine over the past 24 years in the direction of significant warming, which is accompanied by a decrease in precipitation. These changes directly affect changes in grain crop yields. Originality / scientific novelty. The scientific novelty of this research is in linking meteorological factors, such as average monthly temperature and monthly precipitations with values of grain yield in the regions of Ukraine. Furthermore, this research studies the dependence of grain yields on meteorological factors. Practical value/implications. The results of the research can be used as a base for formulating new strategies regarding adaptation to climate change in the fields of agriculture, namely crop production. As well as for considering changes when planning grain crops and organizing appropriate infrastructure for their cultivation, storage, and sale.

Keywords Grain Production, Meteorological Factors, Precipitation, Correlation Dependence, Cluster Analysis, Forecast

1. Introduction

The question of the dependence of crop yields on climatic factors was studied by various Ukrainian scientists. *Demydenko* studied the adaptation of farms to changing weather conditions and changing climate [1]. *Popytchenko* conducted research on the weather-climatic conditions of the vegetation of winter wheat in Ukraine [2]. Barabash *et. al*. studied changes and variations of precipitations on the boundary of the XX and XXI centuries under conditions of global climate warming [3].

Researcher *Bumbescu* states that in Ukraine - agriculture is one of the most important branches of the national economy, having a significant growth potential due to the existing natural and human resources [4]. According to authors *Cop and Njavro*, the new paradigm of climate change has begun in the late seventies in the last century [5]. Before that time climate was considered as a stable system and the year-by-year variability of climate elements was taken by chance. Agriculture is exposed to climate change and extreme weather events [6]. Among other sectors, agriculture and forestry are evidently most dependent on climate and climate change has a direct and indirect impact on biotic and abiotic disturbances with strong implications [7]. Crops and livestock are directly impacted by adverse local weather and climate [8].

At present, agricultural land in Ukraine occupies almost 71% of the territory [9]. Thanks to the development of agricultural production in recent years, Ukraine has entered the world grain market as one of the most powerful exporters [10]. To maintain the achieved positions, stable growth of grain production is necessary. Researcher *Hunkar Zemankovics* states that the formation of grain crops is associated with a complex of abiotic factors, among which an important place is occupied by natural and climatic conditions [6]. Despite the large number of studies aimed at establishing the relationship between meteorological factors and the biological productivity of different crops, the optimal indicators of meteorological factors for similar agroclimatic conditions vary widely. This problem remains relevant today, as the need to periodically update the optimum amounts of moisture and heat will always exist due to changing weather conditions. Effective development of grain production requires a scientific justification for the rational placement of acreage for grain crops, taking into account potential yields and climatic conditions that have changed significantly over the past decades. This led to a change in the range of cereals grown and the geography of their location.

According to author *Lotze-Campen*, the agricultural sector is directly affected by changes in temperature, and precipitation [11]. Agricultural crops are increasingly subject to drought due to the effects of global climate change [12], and the same is true for Ukraine due to the constant rise in mean annual temperatures and uneven rainfall distribution. According to researchers, *Chowdappa* crops play an important and irreplaceable role in ensuring the livelihoods of millions of people [13]. For better information support of agricultural production, and forecasting the productivity of individual crops, it is advisable to conduct research at the local, regional, and state levels [14]. One of the problems of plant adaptation to local agroclimatic conditions is the establishment of an optimal level of heat and moisture [2].

The issue of the effects of climate change on crop production is widely represented in various Ukrainian and foreign scientific publications, but the outlined topic requires current research on the effects of climate change on the dynamics of crop yields. However, the analyzed studies do not reveal the correlation between climatic factors and crop yields. Our research is aimed at solving this problem.

The purpose of the article. The goal of the research is to analyze the change of meteorological factors such as average temperature and precipitation for the time period 2007-2020 in order to determine negative or positive increases/decrease in mentioned above values. The analysis of such factors is needed for a better understanding how it affects the yields of grain crops.

2. Materials and Methods

One of the easiest ways to show possible changes in climate conditions for any meteorological quantity is to compare it with past data, especially long-term averages over a base period. Thus, the starting materials for the research were the data of average multi-year agroclimatic indicators for the period 1995-2019. The twenty-four-year scenario period was divided into two segments in order to assess the dynamics of changes in climatic conditions: 1995-2007 and 2007-2019. Further calculations were performed with using the model of formation of crop yields developed by Polevym. This model has been modified and adapted in relation to agricultural crops [13].

In the research we use the regression analysis to forecast the average annual temperature and total rainfall in Ukraine. Since from the very nature of atmospheric precipitations are affected by seasonality, it is necessary to estimate their value also with this factor. In the case of using the multiplicative approach we quantify seasonality using seasonality indexes St, which we calculate as a proportion of the actual (empirical) and expected (theoretical) value of the total precipitation in each period studied. To get a quantitative assessment of the seasonal component, we use the average seasonality index for individual quarters, which we calculate as an average of individual seasonality indexes for given seasons.

The influence of meteorological factors on the yield of grain crops was established using correlation and regression analysis. We investigated the dependence of grain yield indicators on weather data such as average monthly air temperature in Celsius Degree and precipitation in mm, for the most important months of the growing season – April, May, June, July, September, October. Data on the yield of grain crops were taken from the materials from the website of the State Statistics Service of Ukraine [15]. Hydrometeorological data was obtained from the Central Geophysical Observatory named after Boris Sreznevsky for the period 1995-2019 [16]. Mean-temperature data was obtained from the Climate Change Knowledge Portal for the period 2007-2020 [17].

To determine the impact of climate change on grain crops yields, the correlation analysis method was applied. We divided the entire period into two equal segments with a length of 12 years (1995-2007 and 2007-2019) to identify changes and trends. This observation period is sufficient to ensure the statistical significance of the correlation coefficient (r) and its stability with respect to time window shifts [18].

In order to determine the clusters of countries, the Ward Cluster Analysis [19] has been applied. This multivariate clustering method has the advantage that it divides the sample into clusters with similar number of elements [20]. Using the Statistical software package (the STATISTICA system, designed for data analysis, visualization, forecasting and many other statistical analyses), we identified groups of areas where the dynamics of yield changes are the same.

3. Results and Discussion

3.1. Development and Forecast of Precipitation in Ukraine

Firstly, it is necessary to take into consideration the dynamics of changes in the average temperature. These data are presented in Table 1.

Based on the obtained data, it can be stated that the highest average temperature was in 2020. During the considered period, the lowest average temperature occurred in 2011. Atmospheric precipitation, along with air temperature, is considered the most important meteorological element. Precipitation is the most variable meteorological element in both spatial and temporal terms [21]. Atmospheric precipitation is mainly affected by altitude, geographical location of the territory, and windiness of the territory.

In Figure 1 we can observe an average level of precipitation with an excess or deficit of precipitation in Ukraine for the period 2007-2020. The website of the Ukrainian Hydro-Meteorological center states that the annual average level of precipitation is 753 mm. The most significant year according to the total rainfall is the year 2010 with an annual level of precipitation – 906 mm, which amounted to an excess of 153 mm. The driest year (according to Figure 1) is 2019 with a number of rainfalls – of 625 mm, which led to a deficit in the amount of 128 mm. In the years 2017-2018 the level of precipitation was almost on the same level with a slight deficit. We can see that from year to year the values decrease, and dry years occur more often, and this is on average every 4 years.

Table 1. Observed annual mean-temperature, 2007-2020 Ukraine

Period	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
T C°	10.22	9.72	9.67	9.46	9.08	9.53	9.76	9.75	10.36	9.71	9.84	9.88	10.67	10.86

Source: Climate Change Knowledge Portal [17], author's processing

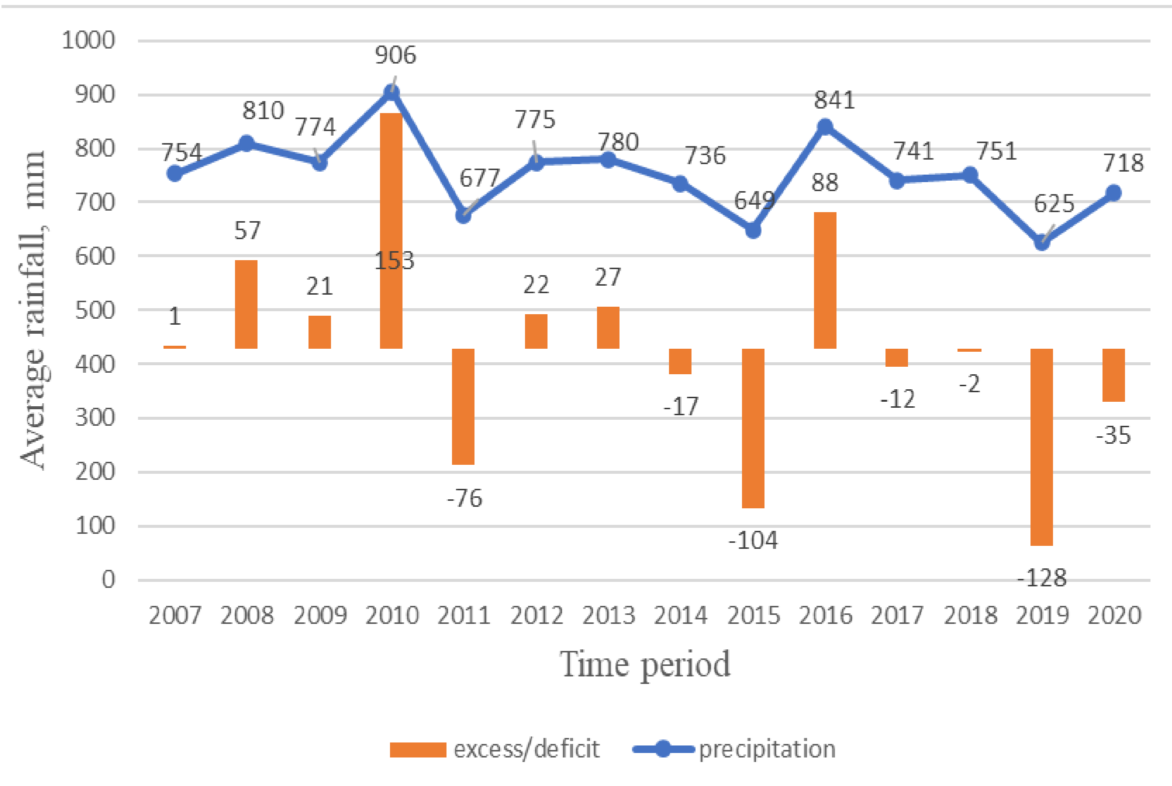


Figure 1. Average precipitation in mm in Ukraine from 2007 to 2020. Source: Central Geophysical Observatory named after Boris Sreznevsky [16], author's processing

The main amount of precipitation (80%) in Ukraine falls in the form of rain, and the rest – is in the form of snow. Throughout the territory, the maximum precipitation falls in the summer, and only on the southern coast Crimea – in the winter. Based on this data, we can say that precipitation is mainly affected by seasonality, which we decided to use when monitoring the development of precipitation in the period 2007-2020 and forecasting for the years 2022-2024.

However, the winter period consists of the months of December, January, and February, which means, the month of the previous year is also included there. In this case, we could not break down the years by seasons, but we divided the years into 4 quarters, where the 1st quarter includes the three first months of the year (January, February, March), the 2nd quarter includes the following months (April, May, June) and so on as shown in Table 2.

Based on the data from Table 2, which is processed in quarters, we will make a forecast of the quarterly total of precipitation for the following years 2022 to 2024. Our task is to estimate the parameters of the trend in the time series and make a prediction of the development of the studied indicator for the next three whole periods of time (three years broken down into quarters).

To process the data, we had to adjust individual data over time, resulting in a total of 56 observations (Table 3).

Table 2. Total atmospheric precipitation in mm in Ukraine for the period 2007-2020

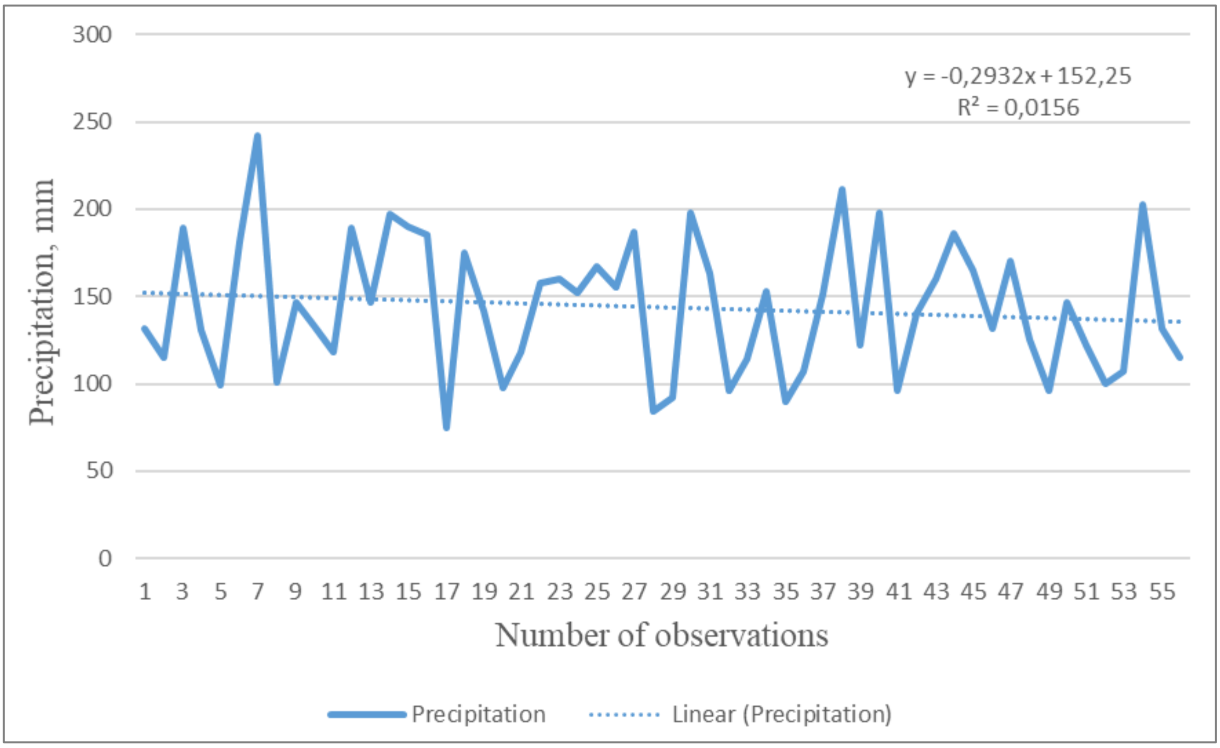
quarter/year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
1	132	99	147	147	75	118	167	92	114	151	96	165	96	107
2	115	181	133	197	175	158	155	198	153	211	140	132	147	203
3	189	242	118	190	142	160	187	163	90	122	160	170	122	132
4	131	101	189	185	98	152	84	96	107	198	186	125	100	115

Source: Central Geophysical Observatory named after Boris Sreznevsky [16], author's calculation

Table 3. Adjusted table of total atmospheric precipitation over time, mm

t	1	2	3	4	5	6	7	8	9	10	11	12
precipitations	132	115	189	131	99	181	242	101	147	133	118	189
t	13	14	15	16	17	18	19	20	21	22	23	24
precipitations	147	197	190	185	75	175	142	98	118	158	160	152
t	25	26	27	28	29	30	31	32	33	34	35	36
precipitations	167	155	187	84	92	198	163	96	114	153	90	107
t	37	38	39	40	41	42	43	44	45	46	47	48
precipitations	151	211	122	198	96	140	160	186	165	132	170	125
t	49	50	51	52	53	54	55	56				
precipitations	96	147	122	100	107	203	132	115				

Source: Central Geophysical Observatory named after Boris Sreznevsky [16], author's calculation



Source: Central Geophysical Observatory named after Boris Sreznevsky [16], author's calculation

Figure 2. Average precipitation in mm

Table 4. Output for estimating linear trend function parameters

	Coefficients	Standard Error	t Stat	P-value
Intercept	36,1565946	8,55886973	4,224459	9,27E-05
X Variable 1	-0,0532104	0,057514848	-0,92516	0,358999

Source: author's calculation

Afterward, we estimate the parameters of the trend component using regression analysis. The observations together with the trend function are shown on Figure 2. For the needs of our research, we will consider a linear function for which R2, that is the coefficient of determination, came out to 0,0156.

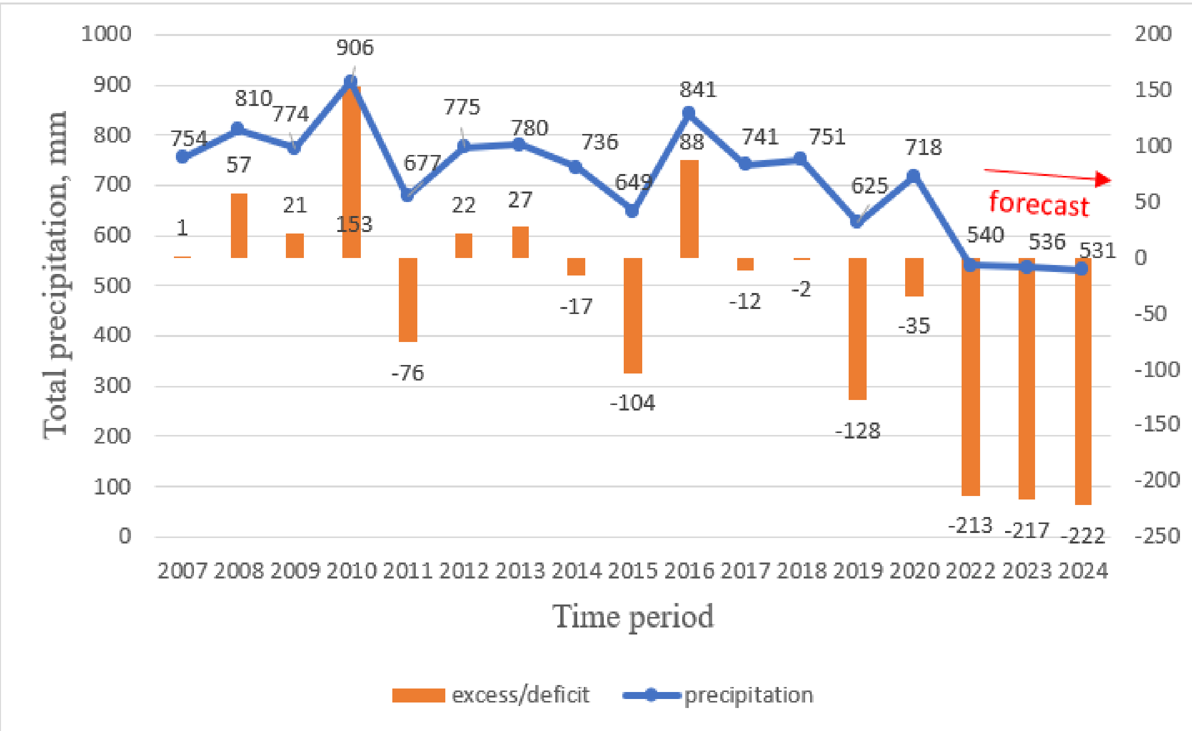
The estimated trend function will have the following form: $y_t \hat{=} 36,156 - 0,053*t$ (Table 4).

From the estimated trend function (Table 4), we then calculate the balanced theoretical values of the total atmospheric precipitation. That is, we estimate the values of precipitation under the conditions of the absence of a cyclic and random component, so the output data will be distorted and will not correspond to the actual values. Since the very nature of atmospheric precipitations is affected by seasonality, it is necessary to estimate their value also with this factor. In the case of using the multiplicative approach, we quantify seasonality using seasonality indexes St (Table 5) which we calculate as a proportion of the actual (empirical) and expected (theoretical) value of the total precipitation in each period studied. To get a quantitative assessment of the seasonal component, we use the average seasonality index for individual quarters, which we calculate as an average of individual seasonality indexes for given seasons. The sum of these average seasonality indexes should be equal to 4 since we observed time series within which there were quarters. If the sum is not equal to 4, we need to estimate the corrected average seasonality indices, with which we can already calculate the prediction of the total atmospheric precipitation in mm for the years 2022, 2023, and 2024.

Table 5. Seasonality indexes and forecast of total precipitation in mm for 2022-2024

Quarter	Average seasonality index	Corrected seasonality index	Estimated precipitation for 2022	Estimated precipitation for 2023	Estimated precipitation for 2024
1	0,844643	0,844665	114	113	113
2	1,141904	1,141919	154	153	152
3	1,083615	1,083629	146	145	144
4	0,929772	0,929787	125	124	123
	3,999934	4	540	536	531

Source: author's calculation



Source: Central Geophysical Observatory named after Boris Sreznevsky [16], author's calculation

Figure 3. Total atmospheric precipitation in mm and amount of excess or deficit of precipitation in Ukraine for the years 2007-2020 with forecast for the years 2022-2024

According to the forecast from Table 5, for the year 2022, we assume a total average precipitation the amount of 540 mm, which is a deficit of 213 mm compared to the average annual precipitation of 753 mm. For 2023, the forecast is 536 mm of precipitation, and for 2024 the precipitation again decreases by 8 mm to 531 mm per year. The greatest amount of precipitation, in each forecasted year, is expected inquarterrters, i.e., in the months of April, May, June July with a value, of 154, 153, and 152 mm.

Figure 3 shows a more clearly complex analysis of total atmospheric precipitation and the amount of excess and deficit of precipitation in Ukraine with forecasts for the years 2022-2024.

Overall, we assess the results of the forecast negatively, since the deficit of precipitation is expected in 2022-2024, however, with this level of precipitation we can expect no floods. If this situation does not improve in the future and the amount of precipitation will continue to decrease, we will face undesirable droughts, lack of groundwater, and water for irrigation, thus the entire agrarian sector, which is unconditionally dependent on water, will be threatened.

3.2. Development and Forecast of Air Temperature in Ukraine

Nowadays, we can see that winters are becoming milder and later, and summers are often wet [10]. The off-season is getting longer: spring comes very slowly and lasts until mid-June, and autumn can last until December-January. Average January temperatures drop from -1 ℃ in the flat

Crimea to -8 ℃ in the far north of Ukraine and from -4 ℃ in the west to -8 ℃ in the far east of the country. The warmest winter temperatures are along the southwestern and southern coasts of Crimea, where average January temperatures are positive and reach +4 ℃. The coldest January is, except for the northern and eastern regions, in the Carpathians (-8 ℃).

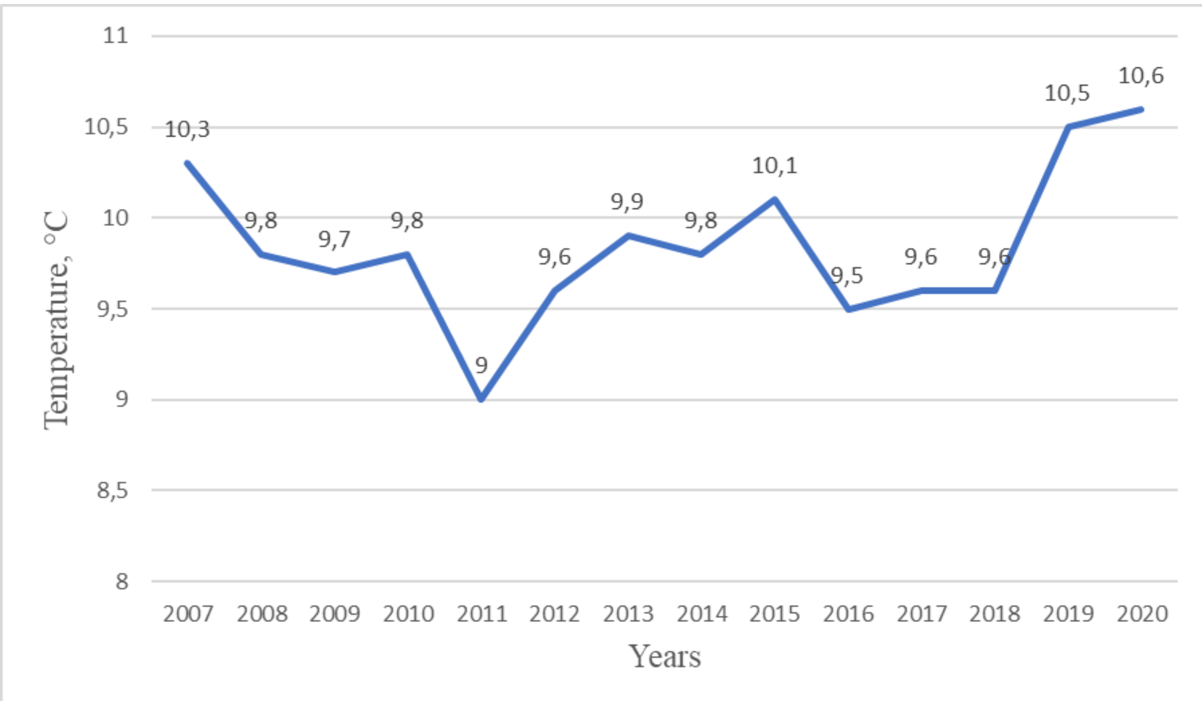
Average July temperatures rise from +18 ℃ in the north of Ukraine to +23 ℃ in the south and from +17 ℃ in the west to +21 °C in the East. In the Crimean Mountains, the average July temperature drops to +16 ℃, and in the Ukrainian Carpathians (at an altitude of more than 1000 m) - to +14 ℃.

In Figure 4, we can observe an average annual temperature in Ukraine for the period 2007-2020.

Analyzing Figure 4, it becomes obvious that over the past 14 years, the average annual temperature has increased with slight fluctuations and amounted to a minimum value of 9 ℃ in the year 2011 and a maximum value of 10.6 ℃ in the year 2020.

To predict the development of temperature in the coming years, we used the same method as when forecasting atmospheric precipitation. We split the years into quarters, with 1st quarter corresponding to the months of January, February, and March. Quarter number 2 corresponded to the months of April, May, and June; in this style, we divided each year into 4 parts. Thus, we reused the seasonal component when processing the data, since the air temperature is also closely linked to the season in which it is measured (see Table 6).

From Table 6 we can see that the warming refers to all months and to the whole year, not just one period of the year.



Source: Central Geophysical Observatory named after Boris Sreznevsky [16], author’s calculation

Figure 4. Average annual temperature in Ukraine for the period 2007-2020, ℃

Table 6. The average temperature in ℃ in Ukraine for the period 2007-2020 by quarter

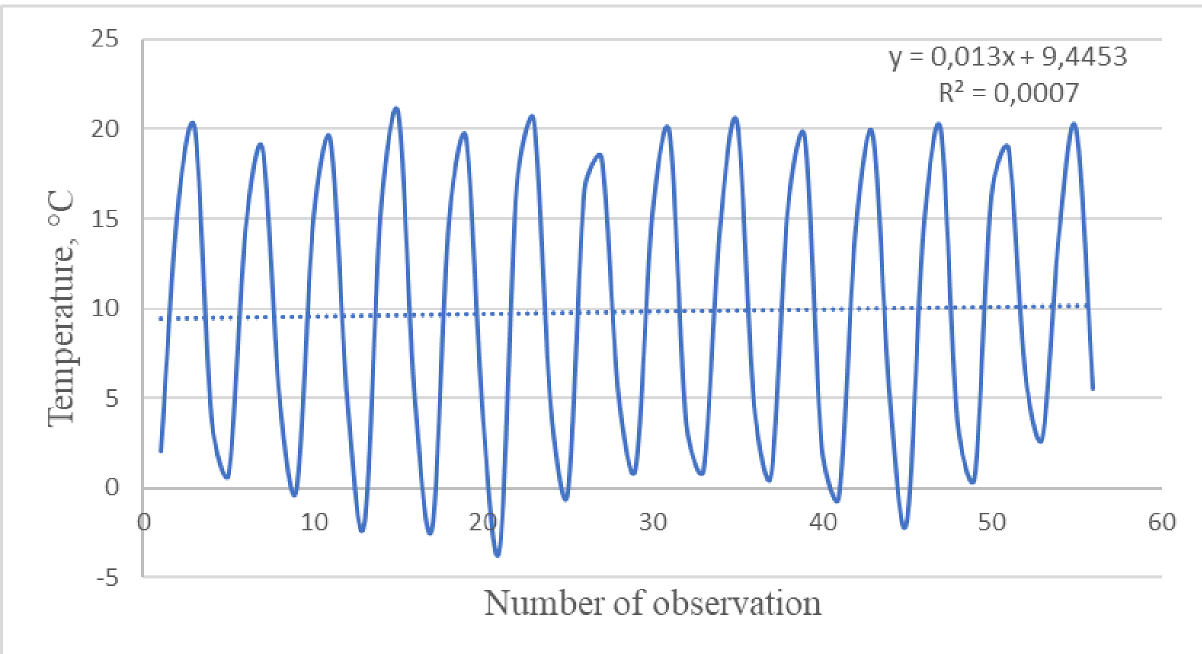
quarter/year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
1	2,0	0,7	-0,2	-2,1	-2,3	-3,4	-0,4	1,0	0,9	0,6	-0,6	-2,0	0,5	2,7
2	15,6	14,4	14,9	15,7	14,9	16,8	16,6	15,2	14,6	15,6	14,4	14,4	16,3	14,2
3	20,0	18,9	19,4	20,9	19,5	20,5	18,4	19,8	20,3	19,5	19,7	20,0	18,9	20,0
4	3,7	5,0	4,9	4,7	4,0	4,6	5,2	3,5	4,6	2,2	5,1	3,6	6,3	5,5

Source: Central Geophysical Observatory named after Boris Sreznevsky [16], author’s calculation

Table 7. Adjusted table of annual average temperature in Ukraine, ℃

t	1	2	3	4	5	6	7	8	9	10	11	12
temperature	2	15,6	20	3,7	0,7	14,4	18,9	5	-0,2	14,9	19,4	4,9
t	13	14	15	16	17	18	19	20	21	22	23	24
temperature	-2,1	15,7	20,9	4,7	-2,3	14,9	19,5	4	-3,4	16,8	20,5	4,6
t	25	26	27	28	29	30	31	32	33	34	35	36
temperature	-0,4	16,6	18,4	5,2	1	15,2	19,8	3,5	0,9	14,6	20,3	4,6
t	37	38	39	40	41	42	43	44	45	46	47	48
temperature	0,6	15,6	19,5	2,2	-0,6	14,4	19,7	5,1	-2	14,4	20	3,6
t	49	50	51	52	53	54	55	56				
temperature	0,5	16,3	18,9	6,3	2,7	14,2	20	5,5				

Source: Central Geophysical Observatory named after Boris Sreznevsky [16], author's calculation



Source: Central Geophysical Observatory named after Boris Sreznevsky [16], author's calculation

Figure 5. Average annual temperature, ℃

Table 8. Output for estimating linear trend function parameters

	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	27,9878095	3,462046251	8,084181	7,22E-11
X Variable 1	0,05217877	0,27242583	0,191534	0,848826

Source: author's calculation

In order to make the forecast, we had to re-edit the data over time, which again gave us 56 observations, which we can see in more detail in Table 7.

In the next step, we estimate the parameters of the trend component using regression analysis. The observations together with the trend function are shown in Figure 5. There are several kinds of functions, however, for the needs of our research, we will consider only a linear function for which the coefficient of determination came out to 0,0007. Table 8 has shown outputs for estimating linear trend function parameters.

The estimated trend function will have the following form: y_t ´=27.988+0,052 *t.

From the estimated trend function, we then calculate the balanced theoretical values of the average annual air temperatures. That is, we will estimate the values of air temperatures under conditions of the absence of a cyclic and random component, so the output data will be distorted and will not correspond to the actual values, thus, similarly to precipitation, the air temperature is affected by seasonality, so it is necessary to make a forecast with this component. In the case of using the multiplicative approach, we quantify seasonality using the seasonality indexes St (Table 5), which we calculate as a proportion of the actual (empirical) and expected (theoretical) value of the total temperature in each period studied. To quantify the seasonal component, we will use the same procedure that we described in more detail in the previous sub-chapter on atmospheric precipitation. The forecast values for the years 2022 to 2024 are shown in Table 9.

The forecast of the average annual temperature for 2022 came out on average 8.7 ℃, for 2023 – 8.6 ℃, and for the year 2024 it came out – 8.6 ℃. For a more informative analysis, the forecast, together with the actual values, is shown in Figure 6.

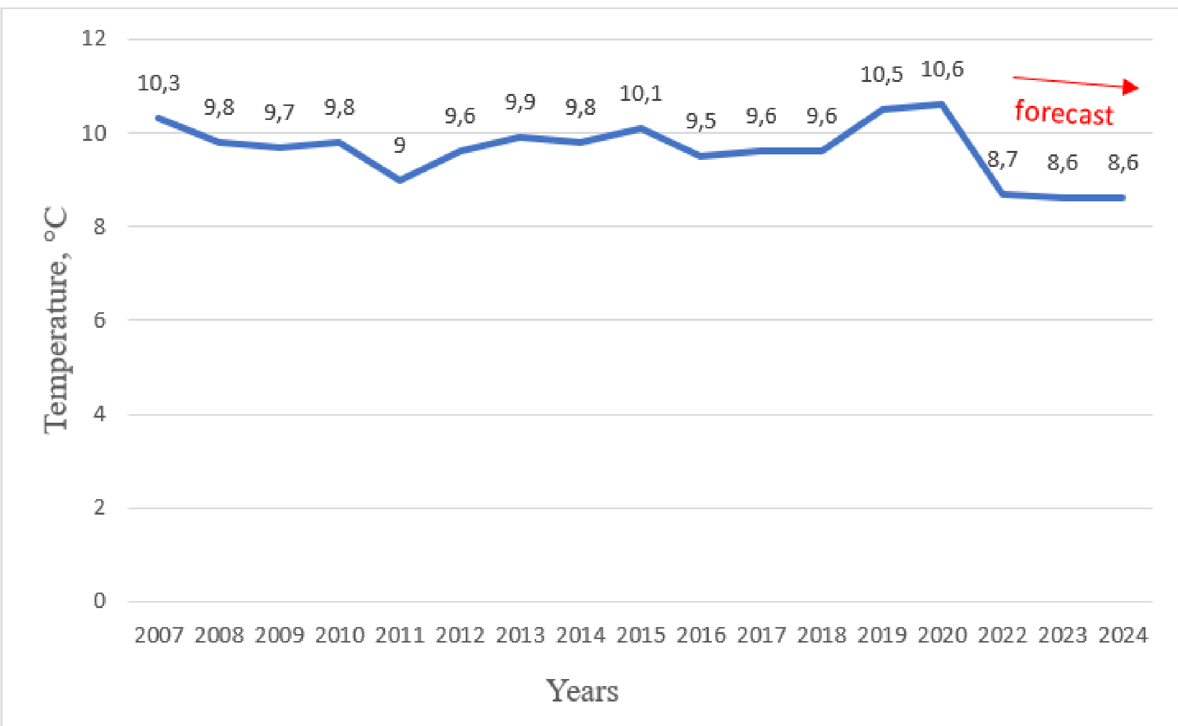
Therefore, we can conclude that the annual average temperature in Ukraine in the years 2022-2024 won't fluctuate much from previous periods with an average temperature 8-10 ℃. It should be mentioned that there is still an increase in air temperature compared to the values of the previous century. According to the Ukrainian Hydrometeorological Center, the most significant increase in the global surface temperature of the globe by 2009 was 1.8 ° - 4.0 ° (with possible ranges of changes from 1.1 ° to 6.4 °).

The analysis and forecast of climatic factors give us a better understanding of its influence on the yield of grain crops, which will be studied in the following section.

Table 9. Seasonality indexes and forecast of air temperature variations in ℃ for the years 2022 to 2024

Quarter	Average seasonality index	Corrected seasonality index	Estimated temperature value for 2022	Estimated temperature value for 2023	Estimated temperature value for 2024
1	-0,0197108	-0,0197273	7,35	7,31	7,26
2	1,6805971	1,5605859	9,92	9,87	9,81
3	2,1735129	1,9727799	9,40	9,35	9,29
4	0,4968509	0,4863616	8,06	8,01	7,96
	4,33125	4	8,7	8,6	8,6

Source: author's calculation



Source: author's calculation

Figure 6. Average annual temperature in Ukraine for the period 2007-2020 with forecast for 2022-2024

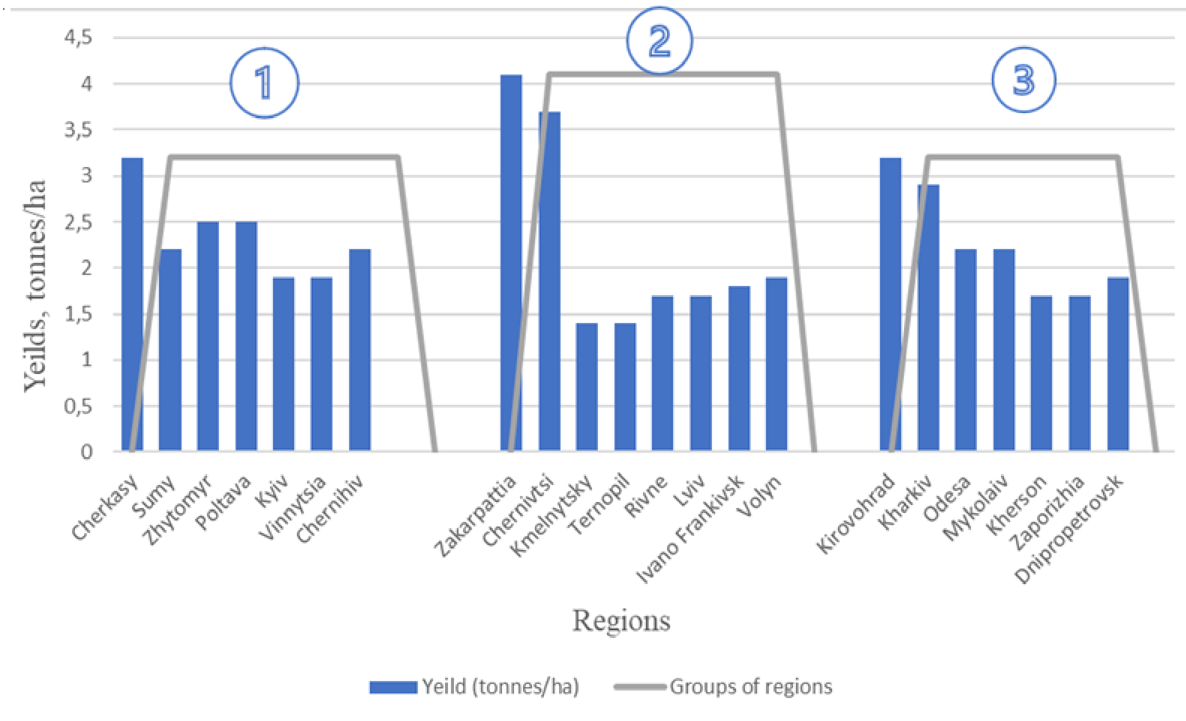
3.3. The Influence of Meteorological Factors on the Yield of Grain Crops

For research, we used the method of cluster analysis [15], using the Statistical software, resulting in three groups of regions (Figure 7).

The first group (Central Region) includes Poltava, Kyiv, Zhytomyr, Cherkasy, Vinnytsia, Chernihiv, and Sumy regions. They are characterized by high yields and high growth rates. The second group (Western Region) includes Volyn, Rivne, Khmelnytsky, Ternopil, Chernivtsi, Ivano-Frankivsk, Zakarpattia, and Lviv regions. They are characterized by average yields and growth rates. The third group (South-Eastern, or steppe, cluster) includes Kharkiv, Dnipropetrovsk, Zaporizhia, Kirovohrad, Kherson, Mykolaiv, and Odesa regions. This group is characterized by low yields and growth rates. Data exclude the temporarily occupied territory of the Autonomous Republic of Crimea, the city of Sevastopol, and a part of temporarily occupied territories in the Donetsk and Luhansk regions.

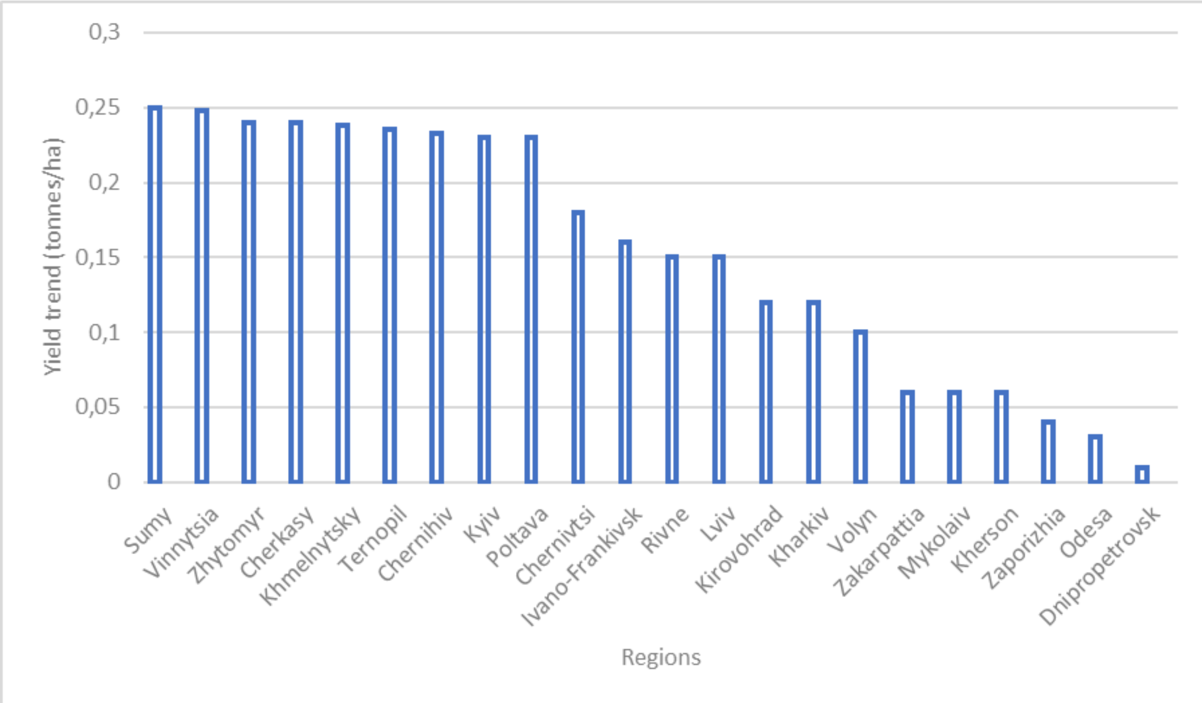
The grain production clusters we have identified reflect the peculiarities of the climate and soil cover of the respective regions. Graphic illustration of the classification is presented on Figure 7. Considering the geographical location, we decided to include the Chernivtsi region in the Western cluster, although this is not consistent with the results of the cluster analysis.

According to statistical data for the past 15 years, the highest grain crops yields were observed in Cherkasy, Kyiv, Chernivtsi, Vinnytsia, Zakarpattia and Poltava regions. The highest rates of yield increased during this period in Sumy, Vinnytsia, Zhytomyr, Cherkasy, Khmelnytsky, Ternopil, Chernivtsi, Kyiv, and Poltava regions (Figure 8). These regions form the main region of grain crops production in Ukraine. In the steppe zone, the increase in yield was hardly noticeable. It is only possible to raise it in this region by applying irrigation. Thus, over the past decade, the role of the central regions of Ukraine in the formation of the gross grain crops harvest has significantly increased, while the contribution of the steppe zone regions has decreased.



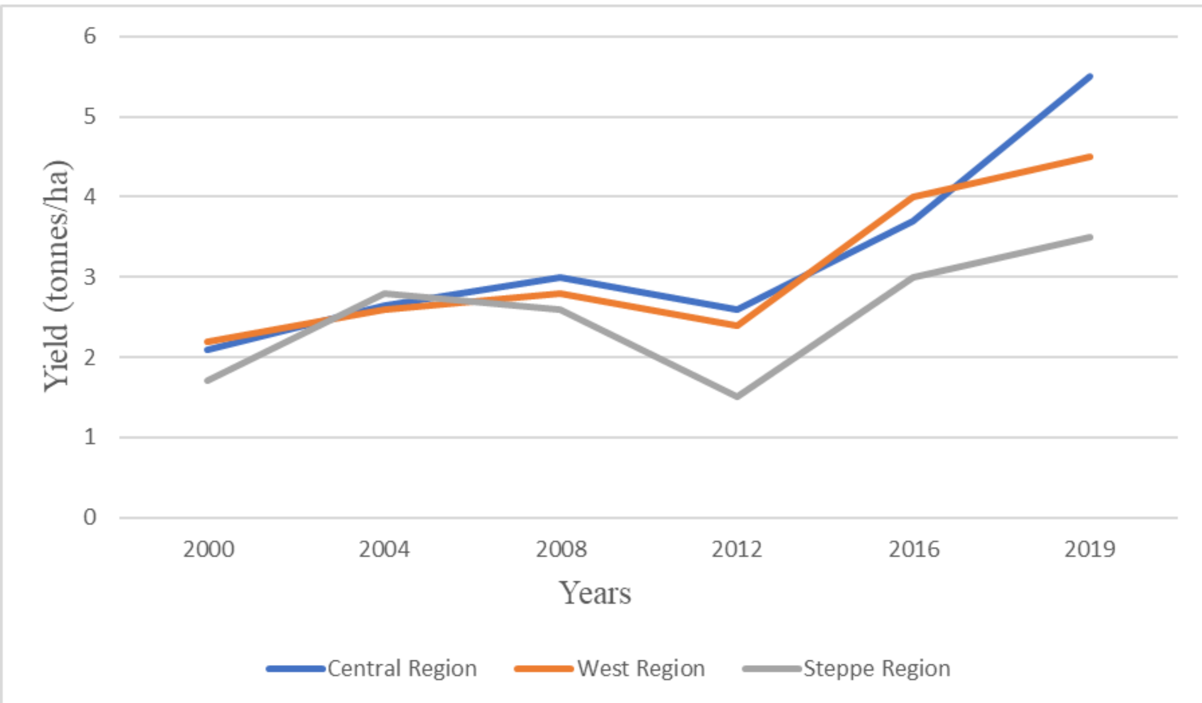
Source: authors' calculation.

Figure 7. Cluster analysis of grain crops yield dynamics in the regions of Ukraine, kilogram/hectare (tonnes/ha)



Source: formed by the author based on data from statistical bulletins of the State Statistics Service of Ukraine for the years 1995-2019 [15].

Figure 8. Annual growth rates of grain crop yield in the regions of Ukraine in 1995-2019, (tonnes/ha)



Source: processed by the author based on data from statistical bulletins of the State Statistics Service of Ukraine for the years 1995-2019 [15].

Figure 9. Dynamics of grain crops yield in the regions of Ukraine, (tonnes/ha)

If we analyze the dynamics of grain crops yield by region, it should be noted that the average yield of the central region increased the most – from 2.7 tonnes/ha to 5 tonnes/ha, and the average grain crops yield of the western region is from 2.9 tonnes/ha to 4.3 tonnes/ha. In the steppe region, the increase in grain crop yield is insignificant - from 2.6 tonnes/ha to 2.9 tonnes/ha (Figure 9). Thus, in recent years there has been a steady increase in grain crop yields in Ukraine. This turned out to be possible thanks to the use of the latest agricultural technologies by the largest grain crop producers. At the same time, there are dynamic changes in yield, which reflect changes in the climate in recent years.

The growing season of winter cereals begins in autumn and ends in the summer of the following year. Since the growing season stops in winter, the most important months can be considered September, October, April, May, and June. For the vegetation of spring crops, only the last three months are important, each of which playscertain role in the growth and development of plants. The importance of the influence of weather conditions can be identified by evaluating the correlation of yields with climatic factors of each month. The main factors are the average monthly temperature and monthly precipitation which were analyzed in the previous section.

Analysis of climate changes in different regions of Ukraine over the past 24 years has allowed us to determine the characteristic features. For the first group, this is a decrease in precipitation in April (by 10-30%). In some regions (Poltava, Sumy) the decrease in precipitation in April reaches 50%. This is accompanied by an increase in the average monthly temperature in April by 0.5-1.0 ℃. Similar climate changes apply to September. In some regions (Zhytomyr, Poltava, Sumy, Chernihiv), there is an increase in the average monthly temperature in October by 1.0 ℃. The most noticeable change for the regions of the western region is an increase in precipitation in May, on average – by 30%.

The steppe region is characterized by a decrease in precipitation in April by 30-50%. The average temperature increase in May is 1.5 ℃. For some regions (Dnipropetrovsk, Zaporizhia, Odessa), this is compensated by an increase in precipitation in May by 20-30%. There is a negative correlation between changes in precipitation and average temperature in the steppe region. It is especially noticeable for the autumn months (September, October), when an increase in average temperature is accompanied by a decrease in precipitation.

The significance of the correlation coefficient r is determined when comparing the actual value of the student's t-test $t\text{-}test\ t_r = \frac{r}{\sqrt{1-r^2}} * \sqrt{n-1}$with its tabular value of $d(f) = n-2$ degrees of freedom (n-number of observations) [22].

The stability of the correlation coefficient means that when the time window moves 1 year ahead, it will change insignificantly. For the observation period *n=12* years the limit of statistical significance of the correlation coefficient at a confidence level of 95% is $|r|=0.56$ and with confidence level of 75% $|r|=0.35$.

It should be noted that due to the stochastic nature of climatic processes, climatic factors of one month, even for neighboring areas, can differ significantly [23]. First of all, this concerns the amount of precipitation. Therefore, in order to more clearly determine the dynamics of changes in climatic factors and their impact on grain yields, it is advisable to analyze not by region, but in the context of the regions we have identified.

Analysis of climatic factors showed that over the past 24 years, the central region has been characterized by a decrease in precipitation in April and in autumn (in September, October). This is accompanied by an increase in temperature in the spring and summer months.

In the western region, during this period, the amount of precipitation in autumn (in September, October) decreased, and in May – increased. For the steppe region, there is a sharp decrease in precipitation in April and less noticeable in June. The average temperature in May – June increased by 3-4 ℃.

Indicators of the correlation coefficient between yield and average values of climatic factors for the selected regions of Ukraine are shown in Table 10.

In the Table 10 the following designations were used: R_4-precipitation in April; T_4-average monthly temperature in April; R_5-precipitation in May; T_5-average monthly temperature in May; R_6-precipitation in June; T_6-average monthly temperature in June; R_9 -precipitation in September; T_9-average monthly temperature in September; R_{10} -precipitation in October; T_{10} -average monthly temperature in October.

Table 10. Correlation coefficient between yield and precipitation/average monthly temperature for the regions of Ukraine[1] [2]

Region	Period	R_4	R_5	R_6	R_9	R_{10}	T_4	T_5	T_6	T_9	T_{10}
Center	1995-2007	0.08	0.24	0.28	-0.12	-0.30	-0.29	-0.09	-0.59	0.00	0.05
	2007-2019	0.13	0.37	0.24	0.28	-0.35	0.56	0.23	0.37	0.00	0.20
West	1995-2007	-0.51	0.29	-0.05	0.37	0.45	-0.42	-0.12	-0.47	0.18	-0.11
	2007-2019	0.13	0.26	0.06	0.29	-0.42	0.57	0.16	0.18	0.07	0.10
Steppe	1995-2007	0.12	0.47	0.59	0.20	-0.28	-0.12	-0.47	-0.42	-0.34	0.12
	2007-2019	0.52	0.34	0.34	0.23	0.36	0.37	0.38	-0.13	-0.27	0.08

Source: authors' calculations.

1 Calculated according to the data of the state statistics service of Ukraine and weather stations located in the territories of the regions of Ukraine for the period 1995-2019 [15].

2 Data exclude the temporarily occupied territory of the Autonomous Republic of Crimea, the city of Sevastopol and a part of temporarily occupied territories in the Donetsk and Luhansk regions.

Analysis of the Table 10 allows us to draw certain conclusions. For the central region of Ukraine in 1995-2007, the most important climatic factor was the average temperature in June – for high yields, this month should have been cool. In 2007-2019, the most important factors were a fairly warm April, sufficient precipitation in May and a small amount of it in October.

For the regions of the western region, grain crop yields in the 1990s were determined by a sufficient amount of precipitation in autumn, and April, on the contrary, should have been low-rain and cool. And in 2007-2019, the most important factors were warm April and low-rain October. Grain crops yields in the steppe region in 1995-2007 were determined by rainy and cool May and June. In 2007-2019, the main factors contributing to high yields were rainy and warm April and rainy and cool May.

In our research, the focus was on 2019, as the need for an immediate response to climate change arose after the publication in October 2018 of the report of the Intergovernmental Panel on Climate Change, a leading international scientific organization for the study of climate change. The IPCC warns that to avoid catastrophic global warming, we must not reach, or at least must not cross, the level of global temperature increase of 1.5 ℃ above pre-industrial levels. The report describes a significant difference between warming of 1.5 ℃ and 2 ℃.

Also, the public importance and social significance of the investigated problem is confirmed by the fact that the "word of the year 2019" (according to the Oxford Dictionary's editors) became the expression "climate emergency" ("climate emergency"), which is defined as "a situation in which urgent action is required to reduce or halt climate change and avoid potentially irreversible environmental damage as a result."

Yes, there is a steady rise in air temperature in all seasons. The weather conditions of 2019 confirm this because many temperature records have been set in Ukraine as well. The average monthly air temperature in February, March, June, October, and November 2019 was the highest or one of the highest for these months during the entire period of instrumental weather observations. Climatologists call such abnormally warm years "windows into the future." Unfortunately, along with warming, the frequency of extreme temperatures and precipitation increases which negatively affects the yield of agricultural crops.

4. Conclusions

Today, the effects of climate change are already being felt and will continue to increase in the future. Dangerous weather events caused by climate change lead to significant economic losses around the world. According to our forecast, the average precipitation values in the following years 2022-2024 will be – 540 mm, 536 mm, and 531mm respectively with an annual average level for previous periods of 753 mm. We assess the results of the forecast negatively since the deficit of precipitation is expected in 2022-2024, however, with this level of precipitation we can expect no floods. If this situation does not improve in the future and the amount of precipitation will continue to decrease, we will face undesirable droughts, lack of groundwater, and water for irrigation, thus the entire agrarian sector, which is unconditionally dependent on water, will be threatened.

At the same time, it should be emphasized that only the development and implementation of complex adaptation systems and their requirements make it possible to effectively use additional thermal resources and reduce various risks of temperature increase. In this regard, the ecosystem approach to the preservation and reproduction of natural capital, which is now widely implemented in EU countries, deserves special attention. All this requires scientific research, the concentration of intellectual potential and financial resources on the priority areas of adaptation, close integration of scientific and practical activities in the context of reproduction of the resource potential of agriculture and balanced development of rural areas in conditions of climate change.

Therefore, decisive measures to adapt crop production to climate change should include improvements in agronomy and genotyping. However, in order to develop and implement such adaptive changes, it is necessary to actively attract public and private investments in R&D. For example, investing in long-term climate-friendly farming technologies will help maintain or even increase crop yields despite high temperatures and total evaporation. Policymakers and investors should promote the expansion and intensification of food production in those parts of Ukraine where suitable agricultural land can be expanded in response to projected climate change. Since Ukraine is of particular interest in this regard, as the country has a large area of agricultural land and is an important player in the world food market. However, under high-impact scenarios (currently more likely due to the use of conventional farming patterns), cereal yields could be significantly reduced, especially in southern areas. Conversely, high temperatures and increased precipitation may slightly lengthen the growing season and lead to a slight increase in yield on the less fertile soils of northern Ukraine.

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