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Impact of Global and Regional Climate Changes upon the Crop Yields

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ABSTRACT

The negative impact of global and regional climate changes upon the crop yields leads to the violation of the crop production stability. The development of reliable methods for assessment of the climatic factors by the reaction of the crops to them in order to minimize the impact of climatic stresses upon the sustainability of food systems is an urgent scientific task. This problem was studied on the example of growing corn. A mathematical analysis of the main meteorological indicators for 16 years of research has been performed on the basis of which the frequency and direction of the occurrence of atypical and extreme weather conditions in various periods of the corn vegetation season were established by the coefficient of significance of deviations of the weather elements from the average long-term norm. It has been proved that the probability of occurrence of such weather conditions in the period from April to September is 38–81% in terms of the average temperature of the month, and 31–69% in terms of precipitation. By using the information base of the corn yields in a stationary field experiment with the gradations of factors: A (the fertilizer option) – A1-A12, B (the crop care method) – B1-B3, C (the hybrid) – C1-C7, the most critical month of the corn ontogeny was established when the weather has a decisive influence upon the formation of the crop. With the help of the correlation-regression analysis it was proved that the corn yield most significantly depends on the average monthly temperature in June, and for the hybrids with FAO 200–299 – on the amount of precipitation in the month of May. The obtained mathematical models make it possible to predict the yield of corn at a high level of reliability depending on the indicators of the main climate-forming factors in June, that is, even before the flowering of the plants (before the stage of BBCH 61).

Keywords: climate, vegetation, models, weather, forecast, productivity.

INTRODUCTION

The increasing world's population predetermines the need for its stable food supply. Therefore, the production of a sufficient amount of crop production in appropriate volumes is the most important task of the agricultural sector of the economy of every country in the world.

Among the agricultural crops corn (maize) (*Zea mays* L.) is one of the leading grain crops the yield growth rate of which, due to genetic improvement and the efficiency of technological factors, significantly exceeds other sorts.

The level of crop yields of agricultural crops, including corn, is influenced by a number of abiotic and biotic factors, among which the role of climate in the recent decades has increased significantly. Accordingly attention of the scientific community has also increased to the development of methods and ways for the assessment of the impact of variable weather conditions upon the formation of the productivity of agrocenoses, both in the regional and global aspects (Parkers et al., 2018; Fatima et al., 2020; Guntukula and Goyari, 2020). In particular, in the major corn (maize) producing countries, the probability of a yield decline in the future has increased significantly due to the increased frequency of combinations of dry and hot conditions (Feng et al., 2019).

In the USA, near-and long-term corn yield forecasting studies have been conducted in the 'Corn Belt' states (Bhattarai et al., 2017; Chen et al., 2019; Kucharik 2020; Lobell et al., 2020). Dependences of the crop productivity on the amount of precipitations, temperature and air humidity have been established, and various scenarios of productivity variability have been modeled taking into account the greenhouse gas emissions. Scientists use various methods and approaches – from the classical statistical methods to the methods of neural systems (Crane-Droesch, 2018).

The assessment of an ability of corn (maize) to adapt to the future warming in the EU countries has shown a generally high adaptive potential (Moore and Lobell, 2014) and a significant effect of temperature and precipitations upon the formation of the corn (maize) productivity (Bachmair et al., 2018). The investigations, conducted in the EU-15 countries, show that, in order to model productivity in the future, it is necessary to include not only the weather indicators but also organizational and economic characteristics of the farms, which significantly increases the reliability of the forecast (Reidsma et al., 2009). Based on the climate change forecasts, there has been identified the possibility of a significant expansion of the area, suitable for growing corn in Central Europe (Pavlik et al., 2019). At the same time in Eastern Europe the corn (maize) yields will decrease due to the climate warming (Pinke and Lövei, 2017).

For China, which today is experiencing an ever-increasing significant need for the corn grain due to the increase in the population of the country in the coming years to 1.45 billion people, ways to adapt to the climate change are also being worked out (Zhang and Yang, 2019).

Ukraine is today one of the leading suppliers of the corn grain to the world market, so the adaptation of the grain production industry to the changing climatic conditions is also the most important task of agricultural science and practice (Nechyporenko, 2020). It has been established that in the long term, compared to the present time, there is expected, a decrease in the yield of the corn grain by 2–8% (Polevoy et al., 2021). This trend is caused by an increase in air temperature against the background of a decrease in the average annual precipitations.

There are various scenarios being developed for the impact of the climate change upon the crop production systems for the corn (maize) grain, the realization of productivity potential, and plant phenology (Fatima et al., 2020; Barwicki et al., 2012). In connection with the results obtained, the sowing dates, hybrid composition and other elements of the corn (maize) cultivation technology are adjusted (Hatfield et al., 2011; Gaile, 2012; Bonea, 2016; Baum et al., 2020; Su et al., 2021).

Therefore the assessment of the influence of the main climate-forming meteorological factors upon the crop yields in order to predict their productivity in a short and a long term is important in the context of developing a strategy and managing the corn grain production in a changing climate.

MATERIALS AND METHODS

The study of the influence of the main weather indicators upon the formation of the corn productivity was performed using mathematical analysis. The study of the influence of the main weather indicators on the formation of corn yields was carried out using statistical, correlation and regression methods of mathematical analysis using software "Statistics 6.1". The information base included the corn yield data, indicators of the average monthly air temperature and the monthly precipitations during the vegetation season of the crop 2004–2019.

In order to analyze the influence of the weather factors upon the yield of corn, there were determined the coefficients of significance of deviations in the amount of precipitations and average daily temperatures from the long-term data (Formula 1):

$$K_c = (X_i - \bar{X}) \cdot S^{-1} \quad (1)$$

where: K_c – the deviation significance (importance) coefficient;
X_i – weather element (average monthly air temperature or rainfall for a particular month);
$\bar{X}$ – indicator of the average long-term value (norm);
S – the root mean square deviation;
i – serial number of the year.

The level of the significance (importance) coefficient of deviations corresponded to the gradation: K_c = 0÷1 – conditions close to normal;

K_c = 1÷2 – conditions are significantly different from the long-term averages; K_c > 2 – conditions are close to extreme.

Determining the significance coefficients of deviation makes it possible to classify months and years according to the level of favorable conditions for the growth and development of plants.

The field investigations were conducted in the Forest-Steppe zone of Ukraine, on dark gray podzolized coarse silt-light loamy soil with a very low level of nitrogen supply, with an increased and high level of potassium and phosphorus content. Corn was grown after winter wheat in the crop rotation of a long-term stationary experiment, established in 1987, using the split-plot method.

The information base of the corn yields consisted of experimental variants with gradations of factors: A (the fertilizer option) – A1-A12, B (the crop care method) – B1-B3, C (the hybrid) – C1-C7. Factor A included 12 combinations of mineral fertilizers and by-products of the predecessor – from absolute control (without fertilizers) to the application of the maximum dose of $N_{240}P_{120}K_{240}$ (for a planned yield of 10 t ha^{-1}) against the background of ploughing 6.5 t ha^{-1} of chopped winter wheat straw. Factor B included three options for controlling segetal vegetation by agrotechnical and chemical methods in combination with foliar application of micronutrient fertilizers and plant growth stimulants in various regulations. Early ripe and mid-early corn hybrids with FAO up to 299 recommended for cultivation in the Forest-Steppe zone of Ukraine were sown.

The field investigations were carried out according to generally accepted methods of conducting agrotechnical experiments (Skrypchuk et al., 2020; Wojciechowski et al., 2020). The research results were processed by methods of the correlation-regression analysis to identify the closest relationships between the corn yield, the average monthly air temperature and the monthly precipitations, followed by the construction of mathematical models of the relationship between these indicators (Welham, 2015; Bulgakov et al., 2022).

RESULTS AND DISCUSSION

It was established that over the years of research, the weather conditions in the vegetation season of corn differed significantly from the average long-term norm in terms of temperature in the direction of its excess, and in terms of precipitations - in the direction of decreasing their amount (Table 1).

By the frequency of repeatability of the air temperature indicators, which differ significantly from the average long-term norm, April differed – 7 years from 16, July – 6 years, May and June – 5 years each, while August and September – 3 years each. At the same time extreme temperature conditions most often developed in August – in 10 out of 16 years, in June and July half as much – in 5 years, in April – in 4 years, and most seldom the air temperature was extremely different from the norm in May and September – 3 years.

Consequently, among 16 years of research, only 5 or 31% of typical weather conditions in April and July were characterized by typical weather conditions, 8 or 50% in May, 7 or 44% in June, and 2 or 13% in August. September conditions were the most typical – in 10 or 63% of years.

In all cases when K_c exceeded 1, deviation from the long-term average norm occurred in the direction of increased average monthly temperature, which convincingly indicates a steady trend towards the climate warming.

In terms of monthly precipitation, extreme conditions with K_c > 2 most often developed during the vegetation season in August – in 5 out of 16 years, in April and September - in 3 years, while in May, June and July - only once in 16 years. The frequency of occurrence of the weather conditions significantly different from the typical ones, in terms of precipitations, was the highest in July – 8 out of 16 years, in August – 6, June – 5, May – 4, April – 3 and September – 2. As by its temperature, September was most often characterized by typical conditions, as well as May – in 11 years or 69% of cases. During 10 years, or in 63% of cases, the moisture content of April and June was typical. The lowest frequency of typical according to the monthly precipitations was in August and July – 5 and 7 years, respectively, or 31 and 44%.

No doubt that such a type of climate, characterized by both weather fluctuations and already confirmed stable trends towards its change, affects the course of physiological processes in the corn plants, which are considered a drought-resistant heat-loving crop. Its transpiration rate is significantly lower than for the other crops, and the C_4 type of photosynthesis provides twice greater photosynthetic capacity. Due to the physiological characteristics of plants, these advantages can be realized with strong solar insolation and elevated temperatures. Therefore, corn

Table 1. Significance coefficients of deviations of the weather conditions of the vegetation period of corn from the average long-term norm

Year	Month					
	IV	V	VI	VII	VIII	IX
Average monthly air temperature						
2004	0.70	-1.09	-0.16	1.52	1.66	0.33
2005	1.85	0.82	0.05	2.01	1.65	1.48
2006	1.46	-0.33	0.52	1.93	2.06	1.83
2007	-0.01	2.10	2.15	1.83	2.69	0.57
2008	2.14	-0.35	1.08	1.87	3.02	0.52
2009	1.66	0.20	2.00	2.20	0.78	2.29
2010	0.93	1.01	2.09	3.29	3.92	-0.04
2011	0.29	0.34	1.24	1.74	0.72	0.69
2012	2.05	1.39	0.85	2.79	1.15	0.94
2013	1.46	2.23	2.09	0.62	0.92	-0.97
2014	1.44	1.02	0.02	1.37	2.09	0.38
2015	0.49	0.52	1.64	-0.21	2.99	1.11
2016	3.24	0.14	0.54	0.17	2.73	0.22
2017	1.25	-0.02	0.45	3.12	3.27	2.90
2018	3.79	2.50	1.55	0.92	3.09	2.30
2019	1.75	1.11	3.52	0.67	3.06	0.50
Precipitations						
2004	-0.74	-0.27	-2.00	0.07	1.41	0.08
2005	0.34	0.33	0.42	-1.31	-0.21	-0.66
2006	-0.72	1.56	0.70	-1.14	-0.03	-0.09
2007	-1.15	-0.22	0.69	0.21	-0.49	-0.15
2008	2.21	-0.30	-0.18	0.26	-1.49	1.30
2009	-1.39	-0.72	-0.52	-1.53	-1.99	-0.56
2010	-0.40	0.18	-0.66	0.13	-0.73	-0.18
2011	-0.77	-0.32	1.30	0.97	-1.13	-0.53
2012	0.33	0.13	1.25	-1.54	0.10	-0.61
2013	-0.88	-0.57	-0.67	-2.09	-1.48	2.62
2014	-0.58	2.60	-0.66	-1.26	-1.76	-0.24
2015	-2.04	-0.28	-1.51	-1.75	-4.91	-2.05
2016	0.31	1.16	-1.34	-1.95	-3.72	-3.07
2017	-1.22	-1.33	-1.51	-1.04	-2.74	-0.54
2018	-2.04	-1.22	0.85	0.13	-5.22	-0.91
2019	-0.61	-0.28	-0.86	-2.45	-3.80	-1.86

is already now one of the agricultural crops that has undergone significant changes in the areas of guaranteed and risky cultivation in the recent decades due to the climate warming.

At the same time the biological optimum air temperature for the development of the corn plants during the period of intensive growth is within the range from 18 to 25 °C, and its extreme increase above 35–40 °C leads to a stop of physiological processes. Thus in China the limiting high air temperature threshold for corn is 36.06 °C, exceeding which leads to a significant decrease in the crop yields (Zhang and Yang, 2019). At the stage of BBCH 63–65 of the plant development, when flowering and fertilization take place, exposure to abnormally high temperatures, especially in combination with low air humidity, causes sterility of the pollen and unseeded cobs.

By the correlation-regression analysis of the corn yield and the main elements of the weather – the average monthly air temperature and the amount of precipitations per month there were determined the closeness and direction of the dependence of the crop productivity upon the

Table 2. Dependence of the corn yield upon the weather conditions

Indicator	Elemet of weather											
	Average monthly temperature, °C						Monthly precipitations, mm pp.					
	IV	V	VI	VII	VIII	IX	IV	V	VI	VII	VIII	IX
Hybrids with FAO 100–299												
R	0.414	0.268	0.748	0.310	0.588	0.205	0.119	0.481	0.131	0.224	0.278	0.198
%	16.3	10.6	29.5	12.2	23.2	8.1	8.3	33.6	9.2	15.7	19.4	13.8
D, %	17.1	7.2	56.0	9.6	34.6	4.2	1.4	23.1	1.7	5.0	7.7	3.9
Early maturing hybrids with FAO 100–199												
R	0.097	0.448	0.905	0.605	0.351	0.223	0.359	0.160	0.433	0.291	0.519	0.178
%	3.7	17.0	34.4	23.0	13.4	8.5	18.5	8.2	22.3	15.0	26.8	9.2
D, %	0.9	20.1	81.9	36.6	12.3	5.0	12.9	2.6	18.7	8.5	26.9	3.2
Mid-early hybrids with FAO 200–299												
R	0.558	0.283	0.718	0.338	0.649	0.324	0.576	0.811	0.426	0.314	0.304	0.317
%	19.4	9.9	25.0	11.8	22.6	11.3	21.0	29.5	15.5	11.4	11.1	11.5
D, %	31.1	8.0	51.6	11.4	42.1	10.5	33.2	65.8	18.1	9.9	9.2	10.0

Note: *R* – multiple correlation coefficient; *D* – coefficient of determination ($R^2 \cdot 100$).

meteorological factors; there were identified periods when the weather exerts a determining influence upon the grain yield (Table 2).

It was found that the corn yield mostly depended on the average monthly temperature in June. A close correlation was found between these indicators ($R = 0.748$), but the 56% variation in the corn yield was provided by the average air temperature during this month. Medium-strength relations were established between the yield and the temperature in August ($R = 0.588$), as well as the amount of precipitations in May ($R = 0.481$), when the coefficient of determination was $D = 34.6$ and 23.1%. The weather conditions in all the other months of the vegetation season of corn had practically no effect upon the formation of the crop yields.

The same approach to the assessment of the influence of the weather conditions of a certain month of the season was applied by Maitah et al. when growing corn (maize) for grain and silage in the Czech Republic (Maitah et al., 2021).

It is known that the genetic potential of hybrids significantly affects the level of economic productivity. Thus, hybrids with a longer vegetation season tend to be more productive. At the same time the cultivation of forms with a short vegetation period makes it possible to achieve guaranteed maturation and reduce the material costs for drying down the grain to the standard moisture.

In order to determine the dependence level of the productivity of the corn hybrids of the early ripening (FAO < 199) and medium early (FAO 200–299) maturity groups upon the meteorological factors, a correlation-regression analysis of these indicators was carried out. For the early-ripening hybrids a close correlation was established between the June air temperature and the crop yields ($R = 0.905$) with a determination coefficient $D = 81.9\%$, but with respect to the mid-early forms, a close relation was confirmed between the crop yields and temperature in June, as well as the crop yield and the total rainfall in May (respectively, $R = 0.718$ and 0.811). This regularity can be explained by the need to consume more moisture to form the dry matter of the biomass of hybrids with a longer vegetation season.

Accordingly, the analysis of correlations made it possible to determine the critical period for the development of the corn plants, which is June, and, using the regression analysis, to build mathematical models that describe the dependence of the corn yield upon the average monthly air temperature and precipitations (Table 3).

By means of these models for determination of the agro-climatic conditions at a high level of reliability, it is possible to predict the yield of corn even before the start of the generative phase of the plant development, which is especially important for the management of the crop production systems and, in general, for planning the economic and managerial strategy of agricultural enterprises.

Analyzing the obtained models, it should be noted that the closest relationship between yield and weather conditions was observed in early ripe corn hybrids with FAO 100–199. This is confirmed by the multiple correlation coefficient ($R = 0.910$), indicating the tightness of the relationship and the value of the coefficient of determination

Table 3. Mathematical dependence of corn yield on weather

Number of the FAO hybrid	Regression equation	Multiple correlation coefficient, R	Determination coefficient, D, %
100–299	$Y = 33.3682-2.8139X_1+0.0739X_1^2+0.0187X_2-0.0002X_2^2$	0.818	66.9
100–199	$Y = 19.1398-1.4299X_1+0.0403X_1^2+0.0054X_2-0.0001X_2^2$	0.910	82.8
200–299	$Y = 0.7283+0.3914X_1-0.0036X_1^2-0.0333X_2+0.0003X_2^2$	0.893	79.7

Note: Y – the crop yield the corn grain, t ha^{-1}; X_1 – the average air temperature in June, °C; X_2 – the amount of precipitations in June, mm.

(D = 82.8%), which is a criterion for the influence of the factor. In mid-early hybrids with FAO 200-299, the dependence on weather conditions was weaker, as evidenced by the corresponding coefficients – R = 0.893 and D = 79.7%. That is, it can be argued that the influence of weather conditions on the yield of early-ripening hybrids is 82.8%, and in mid-early 79.9%. It should be noted that the developed predictive models will come true in the absence of other anomalous biotic and abiotic factors that affect the development of the corn plants in ontogeny.

CONCLUSIONS

With the help of mathematical modeling the possibility of predicting the yield of corn for grain was proved, using the available meteorological indicators (average monthly air temperature and the total amount of precipitations) in June, that is, before the start of the flowering macrostage

The frequency of occurrence of atypical and extreme weather conditions in the Forest-Steppe zone of Ukraine according to the average monthly air temperature in June of Ukraine, upon which the corn yield most depends, is 56%, including abnormally high temperatures, observed in five out of 16 years. An essential decrease in precipitations, which took place over four years out of 16 - in May and September, five years – in April, six – in June, nine – in July and 11 – in August, had little effect on the crop yields, except for medium-early hybrids with FAO 200–299, the crop yield of which depended on the summary precipitations of May.

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