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RESEARCH ARTICLE

Forecasting of winter wheat (*Triticum aestivum* L.) yield for the Southern Steppe of Ukraine using meteorological indices

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Wheat is one of the leading agricultural crops grown in all countries of the world and is a major source of calories and nutrients for millions of people. Ukraine is one of the world's leading winter wheat grain producers being one of the top ten producer countries. However, in terms of crop yields, Ukraine is far behind most developed countries. The main limiting factor in winter wheat yield increase is stressful weather conditions during the growing season, especially in the Southern Steppe, characterized by significant aridity of the territory. Timely forecast of winter wheat yield at the regional level is a key element in ensuring food security of the state. The article evaluates the expediency of forecasting winter wheat yield depending on the effect of certain environmental factors. The statistical data on winter wheat yield sown after five predecessor crops using the same cultivation technology and meteorological data of Melitopol meteorological station for 2010-2019 were used for the analysis. Based on the correlation analysis, a number of factors had a significant effect on crop yield, both direct and inverse. It was determined that during the pre-sowing period the conditions of humectation in July (r=0.82) and August (r=-0.76) had the greatest influence on future yield formation. In the autumn period of growing season, the amount of precipitation in November had a significant effect on the increase of the yield (r=0.67). During the winter and restoration of spring vegetation, the formation of the crop was positively influenced by air temperatures in February (r=0.54) and March (r=0.53). High temperatures in May had a significant negative correlation (r=-0.69) on plant productivity. Based on the obtained data, a model for predicting the yield of winter wheat in arid conditions of the Southern Steppe of Ukraine with a high level of significance (0.00009) was developed using power regression method.

Keywords: Agroclimatic factors; *Triticum*; regression; yield; forecast model

Introduction

Population growth and increased food consumption put increased requirements for agriculture, including crop production, to ensure food security (Foley et al., 2011). Godfray et al. (2010) predicts that by 2050 the demand for agricultural products will almost double, which requires a corresponding increase in gross grain production. FAO analysts identify three main sources of increased crop production - the increase in the number of sown areas, the introduction of irrigation and yield increase of major crops (World agriculture, 2002). However, it is believed that most countries in the world have already reached their maximum on all of these sources. Given that the agriculture is extremely sensitive to changing environmental factors, it is projected that by 2030, due to climate change observed in recent decades, most countries will decline in crop yields (Finger, 2010).

Climate change is expected to have a significant impact on natural resources, the global economy and the health of the world's population. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Pachauri et al., 2014), near-Earth temperatures are rising over each next decade, and rainfall is becoming more unpredictable, with prolonged droughts followed by heavy rains. It is suggested that such changes will only intensify in the coming years, which will accordingly affect the development of all sectors of the economy, including agriculture, which is a strategic and most efficient sector of Ukraine's economy. These changes will mainly affect the growth and development of agricultural crops, the cultivation of which is the basis for food security formation. The variability of weather conditions affects the process of photosynthesis and its balance with plant respiration, accelerates the passage of interstage periods, and consequently the vegetation of crops, reduces the efficiency of water use by the crops, leads to plant damage due to disruption of cellular structures and metabolic processes (Gourdji, Sibley & Lobell, 2013; Rezaei, Webber, Gaiser, Naab & Ewert, 2015; Webber et al., 2016). All this complicates acquiring high stable yields of leading crops and requires a more detailed study of the influence of individual weather factors on the yield.

In the structure of agricultural crops in Ukraine, cereals have the largest share (over 50%), more than 40% of them being winter wheat (according to the Department of Agricultural and Environmental Statistics of Ukraine). Annually, the total area of winter wheat fields ranges from 6.0 to 6.7 million hectares, depending on the conditions prevailing at the time of sowing. The Steppe zone of Ukraine is an important region for crop cultivation, accounting for more than 50% of the sown area and more than 45% of the country's gross grain production. Climatic conditions and fertile soils of the zone contribute to the cultivation of winter wheat and allow to obtain high-quality grain in volumes sufficient to meet both domestic needs and formation of the country's export potential.

At the same time, the south of Ukraine belongs to the zone of risky agriculture, which is most exposed to environmental stressors (Adamenko, 2014).

During its growing season, winter wheat plants are influenced by many environmental factors of abiotic, biotic and anthropogenic nature. Among abiotic factors, temperature, humidity and solar radiation of the territory have the most significant effect on the growth and development of crops. According to the World Meteorological Organization (State of Climate Services, 2019), precipitation determines 75% of wheat yield variability in India, 36 to 80% in the prairies of the United States, and 36 to 62% in the prairies of Canada (Saskatchewan). Studies by Lesk, Rowhani & Ramankutty (2016) found that droughts and high temperatures in the period of 1964-2007 reduced yields by 9-10%. Lack of moisture in the soil during seed germination causes damage to future crop, reducing stem density, during tillering - general, and later productive amount of stems per plant, during flowering – amount of grains in the inflorescece, and during grain ripening - mass of 1000 grains. Effects of extreme climate change are particularly harmful in the reproductive period of plant development (Deryng, Conway, Ramankutty, Price & Warren, 2014).

Forecasting the yield of agricultural crops, including winter wheat, is becoming increasingly important in order to predict gross grain production, ensure food security and optimize agricultural management methods (Lecerf, Ceglar, López-Lozano, van Der Velde & Baruth, 2019).

Yield monitoring and forecasting can be performed using a variety of information sources, which may include direct observations of crop growth processes in the field (Bolton & Friedl, 2013), meteorological data for the growing season of the studied crop (Lobell, Nicholas & Field, 2006; Iizumi, Shin, Kim, Kim & Choi, 2018), use of NDVI vegetation indices (Petersen, 2018), FAPAR biophysical parameter (López-Lozano et al., 2015), etc. For example, Joint Research Center of the European Commission (Van den Berg & Baruth, 2020) provides timely forecasting of crop yields for EU member states using the MARS-Crop (MCYFS) system since 1993 (Van der Velde & Nisini, 2019). In addition, said system allows assessing the impact of climate change on agricultural production by modelling different climate scenarios using Biophysical Models Applications (BioMA) program (Shrestha, Ciaian, Himics, & Van Doorslaer, 2013).

WOFOST simulation model, which calculates the daily accumulation of biomass by crops based on temperature data, daylight duration, solar radiation, and genetic characteristics of the crop, has also become widespread (Boogaard, Wolf, Supitc, Niemeyerd, & Van Ittersum, 2013). US scientists have developed another model for forecasting crop yields - EPIC (Balkovičac et al., 2013), which is based on the use of the data on soil and climatic conditions of the region and the efficiency of photosynthetically active radiation uptake by plants.

Given the fact that access to the above forecasting systems is still limited for most countries of the world, statistical modelling based on building multidimensional regression models is still actively used (Parviz, & Paymai, 2017; Panwar et al., 2018).

The purpose of the study was to identify the main agrometeorological factors that may explain the change in winter wheat yield in the Southern Steppe of Ukraine and build a mathematical model of crop yield based on the identified stressors.

Materials and Methods

The main material for the study were the annual reports on winter wheat yield of the Department of Agro-Industrial Development of Melitopol District State Administration of Zaporizhzhya region, data from the State Statistical Service of Ukraine (www.ukrstat.gov.ua) for the period from 2011 to 2019 and meteorological data of Melitopol meteorological station for 2010-2019.

Grain yield of Shestopalivka winter wheat cultivar, cultivated in agricultural enterprises of Melitopol district according to the same technology generally accepted for the Southern Steppe zone of Ukraine, was studied. Predecessor crops were bare fallow, vets-oats mixture (occupied fallow), peas, winter wheat and sunflower, making it possible to identify the peculiarities of the reaction of the studied crop to both weather conditions of the growing season and agronomic factors of cultivation technology.

To achieve the goal of the research, correlation and regression analyses were performed: the strength of correlation between agroclimatic indicators and crop yield was calculated; weather factors that have a significant impact on the yield of winter wheat were determined; a model of dependence of winter wheat yield on weather conditions in Zaporizhzhya region in 2010-2019 was established; a regression equation was obtained which can be used to create statistical predictions.

Weather factors studied were: air temperature (minimum, mean, maximum), the sum of active air temperatures, the amount of precipitation, relative air humidity (minimum, mean), hydrothermal coefficient (HTC) and humidification coefficient (HC).

Hydrothermal coefficient was calculated according to the method of G.T. Selyaninov according to the formula:

$$\mathrm{HTC} = \frac{\mathrm{R} \times 10}{\sum \mathrm{t}}$$

where R – The amount of precipitation for the period with air temperatures higher than +10°C, mm; ∑t – the sum of air temperatures above +10°C for the same period, °C.

Humidification coefficient was calculated according to N.M. Ivanov using the formula:

$$\mathrm{HC} = \frac{\mathrm{R}}{\mathrm{E}}$$

where R – The amount of precipitation for the period, mm;E – evaporation for the same period, mm.

Evaporation was calculated according to a modified empirical formula (Kolpakov & Sukharev, 1988):

$$\mathrm{E} = 0.0018 \times (25 + \mathrm{t})^2 \times (100 - \alpha)$$

where t – Mean air temperature for a certain period, °C; ɑ – mean air humidity for the same period, %.

In order to build a model of the dependence of winter wheat yield on weather factors, the function of linear dependence was used (Pearson, 1901):

$$y = a_0 + a_1x_1 + a_2x_2 + \cdots + a_nx_n$$

where y – winter wheat yield, t/ha; a0, a1, a2, an – linear regression coefficients. x1, x2, xn – weather factors.

For statistical evaluation of the constructed model the coefficient of multiple correlation, coefficient of determination, adjusted coefficient of determination, t-criterion and F-criterion were calculated. The level of significance and standard error of estimation were established. Statistical data processing was performed using Microsoft Office Excel and Gretl software.

Results.

Ukraine ranks seventh in the world in winter wheat grain production - its contribution to global gross production is almost 4% (Grain: world markets and trade, 2020). The average grain yield in the world reaches 3.1 t/ha, and in developed European countries - within 5.6 t/ha. As for Ukraine, the average yield for the last ten years is within 3.73 t/ha (Figure 1), which corresponds to world values, but is far behind the European level.
Regarding Zaporizhzhya region and Melitopol district, the average yield for said period was 2.94 and 3.15 t/ha, respectively. Moreover, the correlation analysis revealed a strong relationship between the yield in the region and the average in Ukraine (r = 0.79). That is, the analysis of winter wheat yield by years in the conditions of Melitopol district will fully reflect its general trend in Ukraine.
Considering that Shestopalivka cultivar is the leader in terms of sown areas in Melitopol district (22-53% of the total sown area) (Bilousova, 2018), the yield of which strongly correlates with the district average (r = 0.99) and in Ukraine as a whole (r = 0.77), then to assess the impact of meteorological factors on the yield of winter wheat and its subsequent forecasting, the dynamics of changes in yield of this cultivar were used.

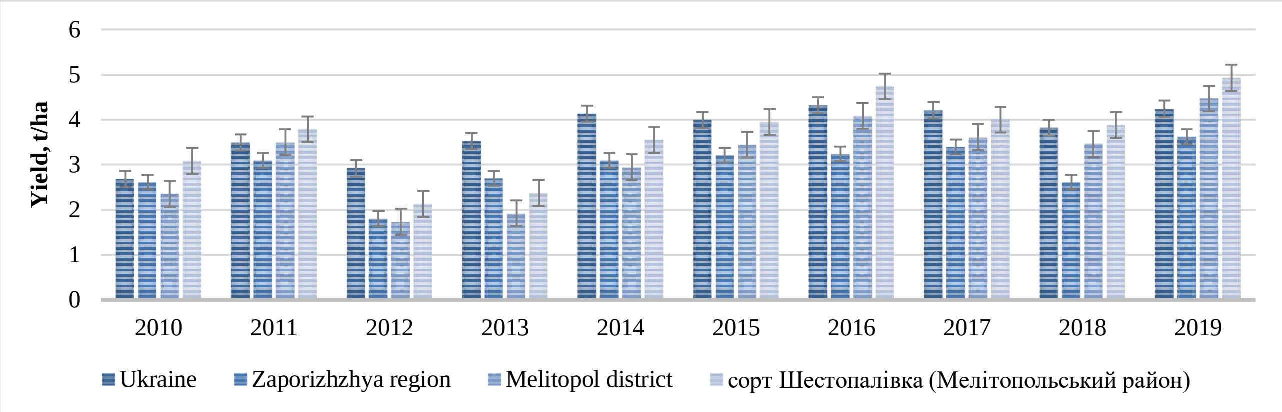

Figure 1. Fluctuations in winter wheat yield over the years.

In recent years, most agricultural enterprises in southern Ukraine have begun to use energy-saving technology of winter wheat cultivation, which is the most acceptable under stressful conditions in the region. Crop rotation is especially important for such technologies, as the correct selection of predecessors reduces the use of pesticides by improving phytosanitary conditions of the crop (Ekström, & Ekbom, 2011). The main predecessors of winter wheat in the Southern Steppe of Ukraine today are bare fallow, occupied fallow, peas, repeated wheat sowing and sunflower (Table 1).

Table 1. Yield of Shestopalivka winter wheat cultivar depending on the effect of the predecessor, t/ha.

Predecessor	Yield year										Mean for the years
	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	
bare fallow	3.31	4.47	3.46	3.67	3.96	4.42	5.42	4.94	4.25	5.31	4.32
occupied fallow	3.57	4.04	1.72	2.39	4.67	4.47	5.21	3.50	4.99	5.30	3.99
peas	3.23	3.33	2.80	2.88	4.03	4.22	5.08	4.20	3.98	5.02	3.88
winter wheat	2.89	3.54	1.22	1.39	2.78	3.40	3.65	2.54	2.67	4.85	2.89
sunflower	2.39	3.59	1.43	1.51	2.33	3.25	4.33	3.30	3.53	4.15	2.98
Mean for predecessors	3.08	3.79	2.13	2.37	3.55	3.95	4.74	3.70	3.88	4.93	3.61
LSD05 for Year factor 0.40, for Predecessor factor 0.57											

Obtained results show that only fallow predecessors and peas ensure high yields (at the level of the world average) in the studied region. With regard to repeated wheat sowing and sunflower as predecessors, it was established that under favourable weather conditions during the growing season (2011 and 2015-2019) the yield decreased by 20-30% compared to fallow predecessors, and under stressful conditions (2012-2013) - by 60-65%. That is, in addition to agrotechnical factors of cultivation technology, weather conditions during the growing season have a significant impact on winter wheat yield in the studied region, which is confirmed by statistical analysis of the results (Figure 2). Similar data was obtained in our other studies (Klipakova & Bilousova, 2018).
Correlation analysis was performed to identify weather factors that have a significant impact on the formation of winter wheat yield. Among all the studied indices, an average (noticeable) and high linear correlation dependence was established for 18 indices according to the Chaddock scale (Sobolev, & Babichenko, 2013) (Table 2).
Given that the indices of amount of precipitation, air temperature and relative air humidity are components in the calculation of humidification coefficient (HC) and hydrothermal coefficient (HTC), further evaluation excluded the following indices: mean and average of the maximum air temperatures in July; amount of precipitation in August, mean and average of the maximum and minimum air temperatures in August, mean relative air humidity in August; amount of precipitation in April; average of the minimum and maximum air temperatures in May, and HC in November, which have less impact on winter wheat yield compared with the complex index for the month.

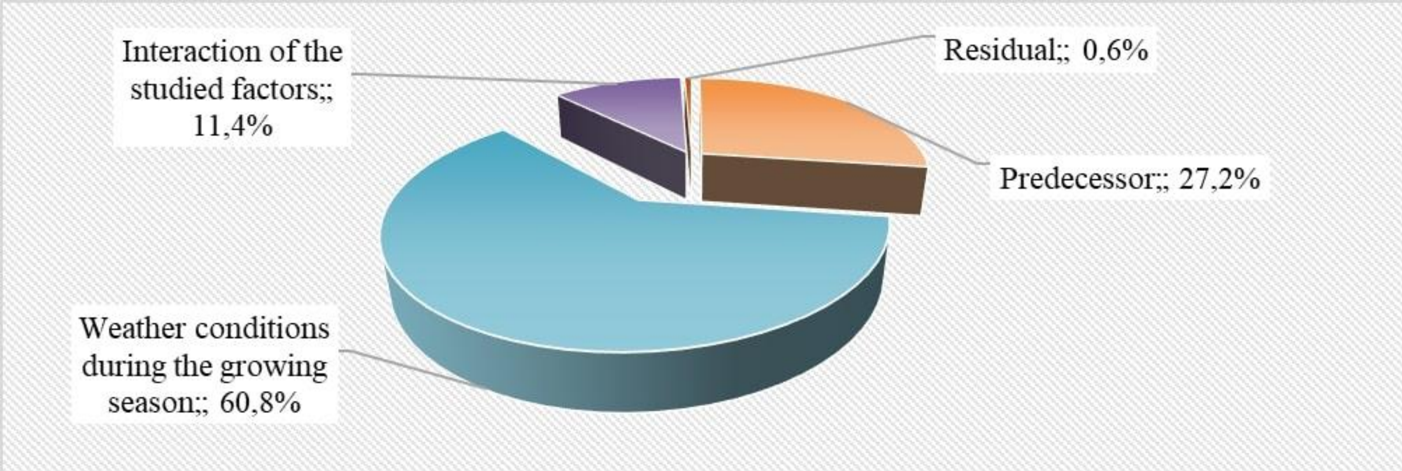

Figure 2. The share of influence of the studied factors on the yield of Shestopalivka winter wheat.

Table 2. Correlation analysis results of the influence of weather indices on winter wheat yield, 2010-2019.

Index	Correlation coefficient	Index	Correlation coefficient	Index	Correlation coefficient
Amount of precipitation in August	-0.61	Mean t за August	0.63	Average of tmin in March	0.53
Amount of precipitation in November	0.67	Mean t in May	-0.69	Average of tmin in May	-0.62
Amount of precipitation in April	0.51	HC in July	0.82	Average of tmax*** in July	-0.60
HTC in April	0.58	HC in August	-0.76	Average of tmax in August	0.67
Relative air humidity in August	-0.79	HC in November	0.57	Average of tmax in February	0.54
Mean t* in July	-0.66	Average of tmin** in August	0.57	Average of tmax in May	-0.69

Note. *t – Air temperature; **t_{min} – Minimum air temperature; ***t_{max} – Maximum air temperature

The analysis shows that during the pre-sowing period, HC in July and August has the most significant effect on the formation of future yield (Figure 3). That is, the ratio of precipitation to evaporation, which reflects the moisture content, affects natural ecosystems more than the absolute amount of precipitation itself.

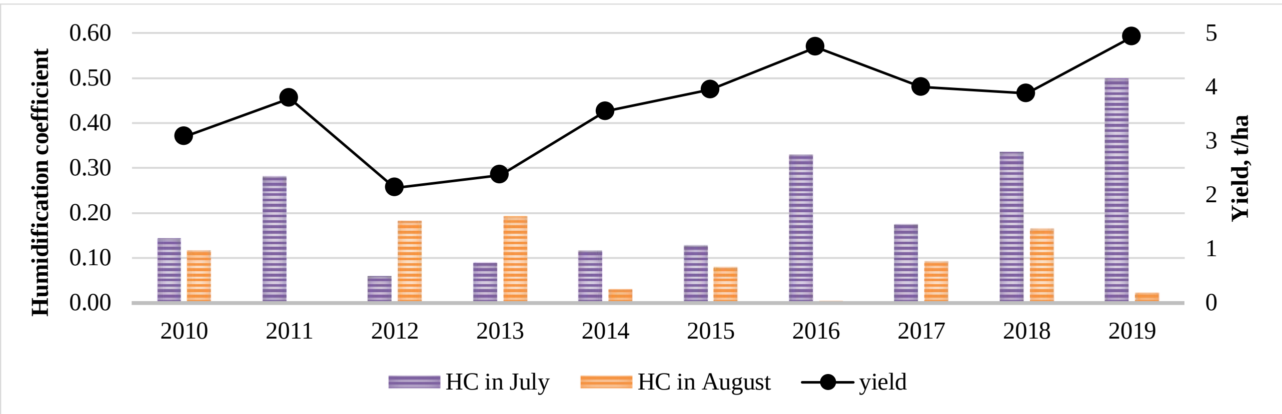

Figure 3. Yield of Shestopalivka winter wheat cultivar and humidification coefficient in July and August.

As seen from Figure 3, the highest yield of winter wheat was observed in 2016 and 2019 at 4.74 and 4.93 t/ha, respectively, which coincides with the highest values of HC in July (0.33-0.50) and the lowest in August (0.00-0.02). The lowest yield for the studied period was observed in 2012 and 2013 (2.13 and 2.37 t/ha, respectively), when the lowest values of HC were observed in July (0.06-0.09) and the highest in August (0.18-0.19).

It should be noted that based on HC values in the second half of the summer, the studied region is characterized by poor humectation, except for July 2019 (insufficient humectation), which is one of the reasons for the lack of yields in the Southern Steppe of Ukraine.

In the autumn period of development of winter wheat plants, the amount of precipitation in November had the most significant impact (Figure 4), which in the studied region is a period of plant hardening before winter. The highest amount of precipitation for said month was recorded in 2016 - 71.1 mm, which is almost twice the average of the norm and coincides with one of the highest yields of winter wheat. Data analysis indicates that the increase in precipitation in November is accompanied by an increase in wheat yields. In general, for the formation of yields over 3.8 t/ha, the amount of precipitation in November should exceed 34 mm.

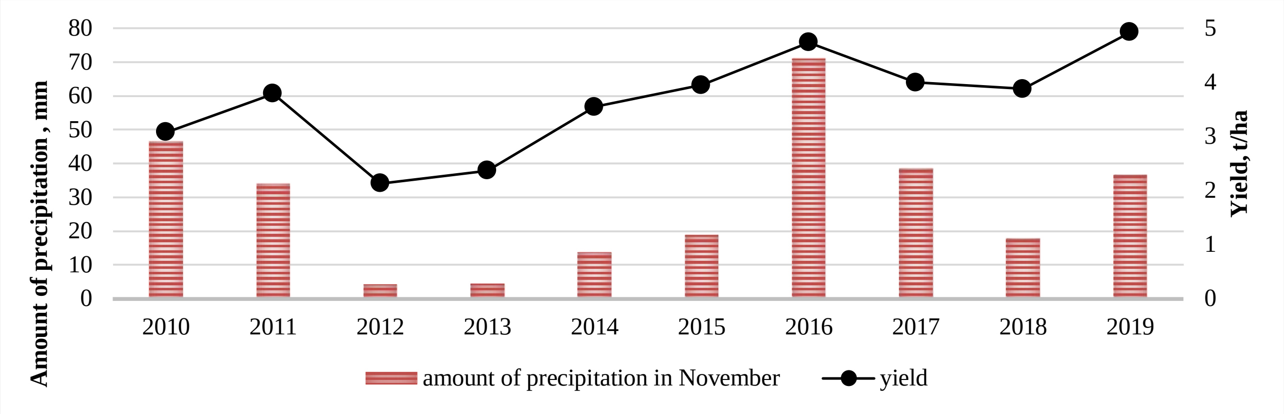

Figure 4. Yield of Shestopalivka winter wheat cultivar and the amount of precipitation in November.

During the restoration of winter wheat vegetation, which in the last 10 years in the studied region occurs on the period from March the 5th to April the 1st, the average of maximum air temperatures in February and the average of minimum air temperatures in March had a significant impact on plant regeneration after winter (Figure 5). It is during this period that the II-III stages of organogenesis occur, accompanied by the formation of the second-order axes and the differentiation of the inflorescence axis on the rachis joints, so there is active formation of the rudiments of the future inglorescence.

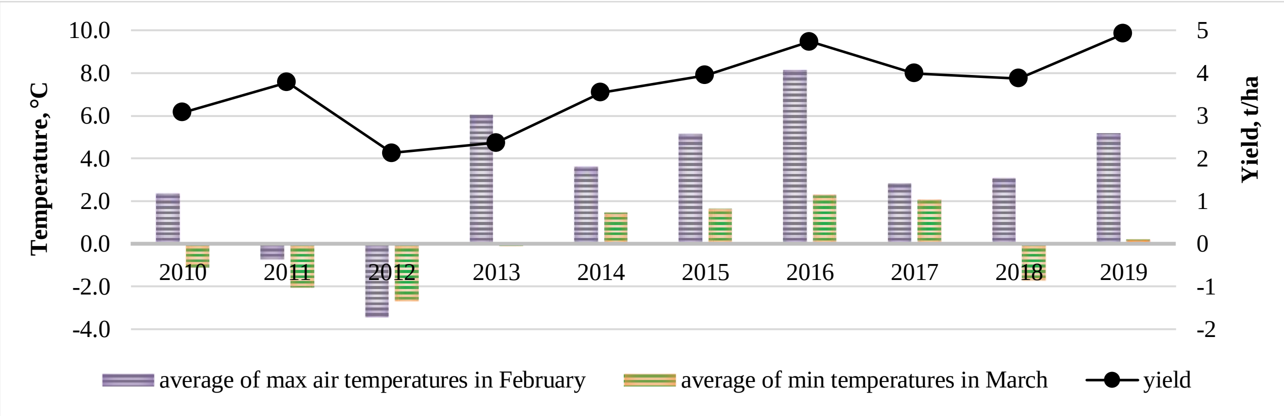

Figure 5. Yield of Shestopalivka winter wheat cultivar and average of maximum air temperatures in February and average of minimum air temperatures in March.

Evaluation of thermal resources for the February-March period shows that high yields within the years can be obtained in the absence of long periods of sub-zero temperatures in February and sharp temperature fluctuations in March, which allows the plants to actively absorb nutrients introduced into the first regenerative fertilization.

During the spring period of development, the hydrothermal conditions of April (Figure 6) and mean air temperature in May (Figure 7) are of great importance for the yield formation of the studied crop, as it is during this period the phases of active vegetative mass growth and the transition from vegetative to reproductive development of plants occur (Bilousova, Klipakova, Keneva & Kulieshov, 2019). The processes of formation and maturation of all organs of the inflorescence, pollination and fertilization of the grain characterize this period.

Analysis of the generalized characteristics of heat and moisture supply in April showed that in order to obtain the yield of winter wheat at the level of 3.55-4.74 t/ha, the value of HTC should be in the range from 0.8 (mild drought) to 1.4 (sufficient moisture supply). For further increase in yield (up to 5.0 t/ha), the hydrothermal conditions of April should be characterized as excessively moist (HTC=1.8).

High air temperatures in May have a negative effect on plant productivity by reducing the intensity of growth processes, premature death of the lower tiers of leaves and reducing the interstage periods of heading - flowering - grain ripening. High temperatures in the heading stage cause damage to the flowers in the inflorescence, resulting in the ear drying very quickly and whitening - the so-called phenomenon of the white ear. Exposure to high temperatures during flowering causes the flowers to become sterile and the ovaries to fall off, leading to lower grain yields.

Analysis of the temperature regime in May for the period from 2010 to 2019 showed that the most comfortable conditions for the growth and development of winter wheat plants in the reproductive period are at the average daily temperature in May at 16.4-19.8°C. In general, the analysis confirms the significant impact of the selected indices on the value of the yield of Shestopalivka winter wheat.

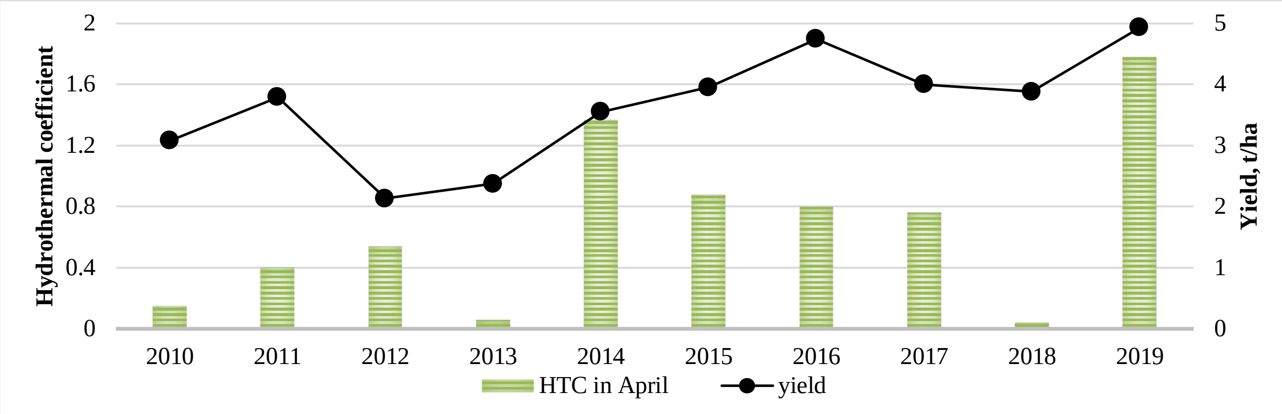

Figure 6. Yield of Shestopalivka winter wheat cultivar and hydrothermal coefficient in April.

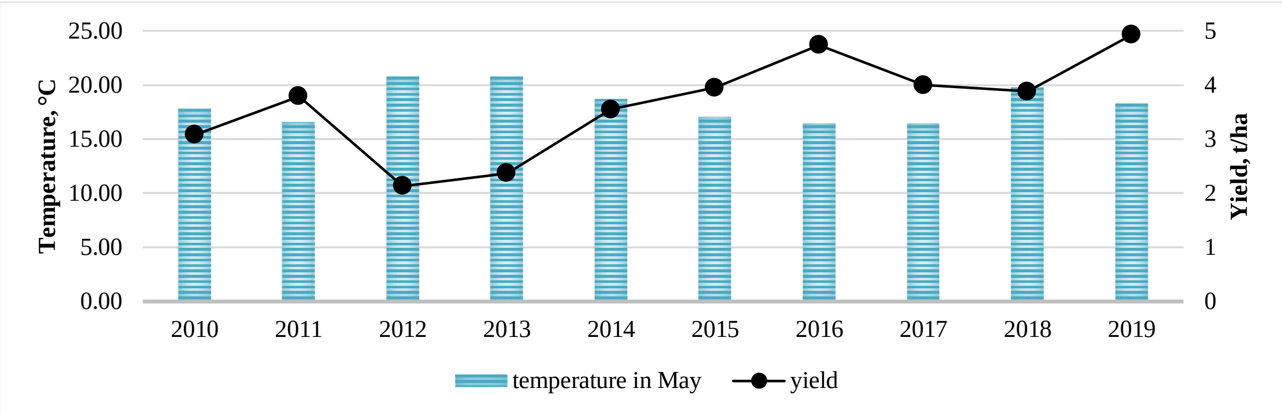

Figure 7. Yield of winter wheat and mean air temperature in May.

To identify the combined effect of the studied factors, a multiple correlation analysis was performed and a matrix of paired correlation coefficients was constructed (Table 3).

Table 3. Correlation matrix, N=50.

Variables	**y**	**x 1**	**x 2**	**x 3**	**x 4**	**x 5**	**x 6**	**x 7**
y	1.0	0.82	-0.76	0.67	0.54	0.53	0.58	-0.69
x 1	0.82	1.0	-0.52	0.52	0.33	0.05	0.39	-0.31
x 2	-0.76	-0.52	1.0	-0.63	-0.27	-0.45	-0.64	0.77
x 3	0.67	0.52	-0.63	1.0	0.40	0.40	0.16	-0.77
x 4	0.54	0.33	-0.27	0.40	1.0	0.75	0.24	-0.25
x 5	0.53	0.05	-0.45	0.40	0.75	1.0	0.50	-0.53
x 6	0.58	0.39	-0.64	0.16	0.24	0.50	1.0	-0.28
x 7	-0.69	-0.31	0.77	-0.77	-0.25	-0.53	-0.28	1.0

where y – winter wheat yield, t/ha; x1 – humidification coefficient in July; x2 – humidification coefficient in August
x3 – Amount of precipitation in November, mm; x4 – Average of the maximum air temperatures in February, °C;
x5 – Average of the minimum air temperatures in March, °C; x6 – HTC in April; x7 – Mean air temperature in May, °C.

Subsequently, multiple regression analysis was performed for the selected factors, the results of which gave the following equation of the dependence of winter wheat yield (y) on the weather conditions of the growing season:

$$y=6.3258 + 4.9618 x 1 + 0.0234 x 2 – 0.0062 x 3 – 0.0124 x 4 + 0.1930 x 5 + 0.0230 x 6 – 0.1946 x 7$$

The main indicators of multiple regression with selected factors are as follows: multiple correlation coefficient R=0.9873; coefficient of determination R2=0.9748; adjusted coefficient of determination R2*=0.8868; standard estimation error S=0.3050; the value of the Fisher criterion F (7.2)=11.0694 at Ft=4.74; significance level p <0.0853, Bayesian information criterion=6.9568, Akaike information criterion=4.5361, Hannan-Quinn information criterion = 1.8806.
Despite the high values of the coefficients of multiple correlation and determination, some of the coefficients of the above equation are statistically insignificant. This means that the described dependence of winter wheat yield on weather factors may be the basis for some management decisions, but the resulting regression equation cannot be used to accurately predict crop yields. The relationship equation is recognized as a model and can be used to predict if both individual parameters and the equation as a whole are statistically significant, so we have made a reasonable selection of factors for inclusion in the equation.
Further analysis of the obtained equation was evaluated for the presence of multicollinearity effect as the inclusion of multicollinear factors in the model leads to instability of the estimate. The stronger the multicollinearity of the factors, the less reliable the

estimate of the distribution of the sum of the explained variation by individual factors using the least squares method is. The variance-inflation factor (VIF) can be used in order to conditionally determine the level of multicollinearity (Akinwande, Dikko, & Samson, 2015) (Table 4).

Table 4. The results of the test for collinearity by the method of inflationary factors.

Factors	x 1	x 2	x 3	x 4	x 5	x 6	x 7
VIF	4.287	6.781	3.697	8.415	14.723	6.415	9.251

As seen, the value of the VIF criterion for x 5 (average of the minimum air temperatures in March) is more than 10, which indicates the presence of a multicollinearity effect. Therefore, for further selection of regressors, the gradual elimination of redundant variables was carried out. Thus, factors such as the humidity coefficient in August (x 2), the amount of precipitation in November (x 3), the average of the maximum air temperatures in February (x 4) and HTC in April (x 6) were excluded from the model. As a result, after excluding collinear and statistically insignificant factors, a model for forcasting of winter wheat yield was obtained:

$y = 5.4349 + 4.5845\ x\ 1 + 0.1729\ x\ 5 – 0.1524\ x\ 7$

The main indicators of multiple regression with the remaining factors are as follows: multiple correlation coefficient R = 0.9824; coefficient of determination R2 = 0,9651; adjusted coefficient of determination R2* = 0.94766; standard estimation error S = 0.2075; the value of Fisher's criterion F (3.6) = 55.2578 at Ft = 8.94; significance level p <0.00009, Bayesian information criterion = 1.0265, Akaike information criterion = -0.1838, Hannan-Quinn information criterion = -1.5115.

As seen from the obtained data, after the exclusion of redundant variables, the model has a higher adjusted coefficient of determination, lower values of Schwartz, Akaike and Hannan-Quinn information criteria. Regressors x 1 and x 5 are 99% significant, and x 7 is 95% significant. The obtained regression model is consistent with the results of studies by other scientists (Argha, & Ahmed, 2019) and its accuracy is not inferior to other models obtained from NDVI data (Kogan et al., 2013).

Conclusion

Study has shown that weather conditions during the growing season significantly affect winter wheat yield formation in the Southern Steppe of Ukraine. The share of their influence significantly exceeds the influence of agrotechnical elements of cultivation technology and reaches almost 61%. The correlation analysis on the influence of weather factors revealed a medium (noticeable) and high linear correlation between 18 weather factors and winter wheat yield in the range of correlation coefficient values between -0.79 and 0.82. In winter wheat cultivation in unstable climatic conditions of the Southern Steppe of Ukraine, the main factors determining the yield are humidification coefficient in July, humidification coefficient in August, the amount of precipitation in November, the average of maximum air temperatures in February, the average of minimum air temperatures in March, hydrothermal coefficient in April and mean air temperature in May. Based on the regression analysis, the effect of multicollinearity between factors was investigated, the significance of the influence of each factor was analysed separately and a linear regression model was built. The built model of forecasting the grain yield of winter wheat can be an effective tool for making adequate decisions on planning activities for the implementation or storage of the yield.

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