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Assessment of Agrocenosis Factors Impact on Winter Wheat Yield and Grain Quality in the Northern Steppe Zone of Ukraine

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Wheat is one of humanity's leading food crops, and ensuring high, sustainable yields is the key to food security. The yield of the crop depends on the agrophytocenosis conditions, including meteorological factors, the number of weeds, pathogens and pests, which change from year to year. Crop yield forecasts are becoming necessary to make informed crop management decisions. The paper presents the results of the multiple regression analysis of actual field data in the system of integrated protection of winter wheat crops in the conditions of the Northern Steppe zone of Ukraine. The predictive value of the models that linked yield and gluten content in grain with the number of pathogens and pests was reduced due to the statistical insignificance of correlations between indicators. In order to overcome the shortcomings of modeling, it is probably necessary to use a more reliable algorithm and a larger sample of data. Regression models reflecting the correlation of yield and gluten content in grain with relative air humidity during the phase of milky ripeness of winter wheat grain showed predictive value (R^2 = 91.9–99.7%) and made it possible to determine the necessary limits of the meteorological parameter to achieve high quantitative and qualitative yield indicators.

Keywords: winter wheat, productivity, grain quality, integrated protection, forecasting.

Introduction

Wheat has remained one of the most widely distributed food crops in the world for many centuries, playing a prominent role in improving global food security and constituting a major component of the human diet along with rice and maize (Erenstein et al., 2022). Winter wheat has advantages over other crops under conditions of current climate change and projected decrease in precipitation, as the crop matures earlier than summer heat and drought (Stratonovich and Semenov, 2015). Numerous high-yielding varieties of wheat created by selection are grown in the world, but today the increase in the crop productivity is slow or static (Shiferaw et al., 2013). In Ukraine, winter wheat crops occupy 7 million hectares (almost half of the grain crop area) with a gross harvest of 32.4 million tons of grain in 2021 (State Statistics Service, 2021).

Obstacles to increasing the winter wheat yield arise both due to unfavorable agro-climatic conditions and the culture sensitivity to the presence of weeds (Tkalich et al., 2014) and a wide range of fungal and other diseases in agrophytocenoses. The most noticeable damage in winter wheat is caused by yellow and brown rust, septoria, fusariosis and powdery mildew, caused by fungi of the genera *Puccinia*, *Septoria*, *Fusarium* and the species *Erysiphe graminis*, respectively (Mazzili et al., 2016; Bebronne et al., 2020). Pathogenic fungi affect seedlings, leaves, stems and roots of wheat, as a result of which there is a decrease in the assimilation surface, the destruction of chlorophyll and other pigments, a decrease in the intensity of photosynthesis, a violation of physiological and biochemical processes in plants and a loss of up to 20% of the harvest (Capo and Blandino, 2021). Pests, among which the frit fly (*Osinosoma frit* L.), ground beetle (*Zabrus tenebricides* Goeze), and corn bug (*Eurygaster integriceps* Put) are the most common in the winter wheat crops, damage plant seedlings and leaves, as well as grain on various formation phases, including full maturity. The consequence of the pests activity in agrophytocenoses can be the loss of the winter wheat harvest in the range of 1–3 t/ha and the grain quality deterioration (Nazarenko et al., 2019; Demenko et al., 2022).

In Ukraine, the average yield of winter wheat over the last ten years was 3.73 t/ha; even in the successful year of 2021, the yield at the level of 4.65 t/ha was lower than potentially possible (Derzhavna sluzhba statystyky Ukrainy, 2022). It is obvious that overcoming various negative impacts on the process of high crop yields forming is impossible without integrated crop protection through the rational use of pesticides and their mixtures (Pysarenko et al., 2021). However, the cultivated plants productivity depends on the interaction with numerical of agrophytocenosis factors (Norodyska et al., 2021), including the dynamics of weather conditions, the type of previous culture in the crop rotation (Mazzili et al., 2016), the soil quality, as well as the number of weeds, pathogens and pests, which change from year to year (Bankina et al, 2018).

Therefore, the existing need to ensure sustained high yields requires analysis of the effects of many changing factors on the crop over long periods. The results of such studies can reveal patterns of perturbations in the plant-harmful factor system and become the basis for forecasting the future crop harvest using a regression model. Nowadays, crop forecasting in the current season and long-term crop yield forecasts are becoming increasingly important for agricultural producers to make informed decisions about crop management, resource mobilization, and crop insurance (Togliattiet al., 2017; Dhakar et al., 2022). A significant part of the created simulation models use satellite remote sensing databases of the state of crops to predict the future harvest (Jin et al., 2018). The purpose of our work was to identify the dependence of the winter wheat harvest on the complex influence of weather conditions and components of integrated crop protection in the agrophytocenoses using a multifactorial analysis of the actual field data.

Methods

Study area

The research was conducted during 2010–2016 in the Northern Steppe zone of Ukraine at the experimental fields of the Institute of Grain Crops of the National Academy of Agrarian Sciences of Ukraine (Dnipropetrovsk region, 48°23'8" N, 35°1'54" E) (*Fig. 1*). The climate of the region has continental features, such as a high annual amplitude of temperatures (27.3°C on average), frequent seasonal droughts together with high air temperature and dry winds, low precipitation (472 mm on average) and high evaporation, which is much higher than the annual amount of precipitation (Ekolohichnyi pasport mista Dnipro, 2016).

The soil of the experimental fields is the ordinary medium-loamy low-humus chernozems, containing in the plowing layer humus 3.1–3.2%, gross nitrogen 0.16–0.17%, phosphorus 0.12–0.13%, and potassium 2.1–2.2%. The preceding crops in the rotation were the sunflower, alfalfa or vetch-oat mixture. Soil infestation was caused by the seeds of annual and biennial weeds (*Setaria glauca*, *Setaria viridis*, *Echinochloa crus-galli*, *Chenioidium album*, *Ambrosia artemisiifolia*, *Amaranthus retroflexus*, *Descurainia Sophia*, *Convolvulus arvensis* etc.) at the level of 310–460 million pcs/ha in the arable soil layer (Matyukha, 2012).

Fig. 1. *Location of the experimental fields*

Design of the field experiments

The planning of field experiments was carried out taking into account the accepted methodological recommendations for conducting field work in the Dnipropetrovsk region (Lyubovych, 2005; Lebid', 2008). The test object was the winter wheat (*Triticum aestivum* L.) mid-early drought-resistant Podolyanka variety, originated in Ukraine in 2003 (Perelik sortiv, 2023). During the research years, the culture was sown in the interval from September 12 to 18, using "C3-36" seed drill and observing the norm of 5.0 mln per ha (250 kg/ha) of conditional seeds with the simultaneous application of $N_{10}P_{10}$; for the fertilization, N_{35} was applied in the tillering phase of wheat. Shallow disk tillage of the soil was carried out before the winter wheat sowing.

Experimental plots with an area of 42 m^2 (10.5 m × 4.0 m) for each variant of pesticide treatment were chosen completely randomly, with three replicates. Herbicide single foliar treatment in the phase of winter wheat complete tillering was done using a small-sized rod sprayer "OM-6" observing the norm of 250–300 L/ ha of the herbicide working solutions (Yashchuk et al., 2016). Herbicides Granstar Pro 75 (active substance tribenuron-methyl, 750 g/kg) and Ellai Super (active substances methylsulfuron-methyl, 200 g/kg and tribenuron-methyl, 500 g/kg) are systemic preparations of the DuPont Company (USA) from the class sulfonylureas, which stop cell division in sensitive weeds and inhibit their linear growth.

The winter wheat crops treatment with insecticide and fungicide was carried out in the phase of two leaves of the crop in dry weather in accordance with (Yashchuk et al., 2016). Falcon fungicide (active substances spiroxamine, tebuconazole and triadimenol aimed at the destruction of powdery mildew, alternaria, fomosis and brown rust) was obtained from Bayer CropScience for approval and was applied at a dose of 0.6 L/ha. The insecticide-acaricide Nurel D (Syngenta), which contains synthetic pyrethroids cypermethrin and chlorpyrifos, inhibits the sterols biosynthesis and damages the nervous system in insects, was applied at a dose of 0.75 L/ha.

Data collection

The spread of pathogenic fungi and pests in the winter wheat crops was assessed before the application of pesticides and 25 days after treatment according to recommendations (Pokoziy et al., 2010). To do this, the sum prevalence of fusariosis, septoria, powdery mildew, tan spot (drechslera tritici-repentis) and brown rust was calculated as a share (percentage) of affected plants from the total number of examined plants.

We also determined the total number of larvae and adults of corn bug (*Eurygaster integriceps* Put), leaf beetle (*Oulema melanopus* L.), Swedish fly (*Osinosoma frit* L.), ground beetle (*Zabrus tenebricides* Goeze), wheat fly (*Phorbia fumigata*), and winter scoop (*Agrotis segetum*) in terms of one m^2 of surveyed plots.

The yield of winter wheat in the years of the study was harvested in 02–08 July in the phase of grain complete ripeness and moisture content of 12–14%. The quantitative and qualitative parameters of winter wheat grain were determined in accordance with accepted methods (DSTU, 2003).

Data on weather conditions in the research region during the growing season of winter wheat in 2010–2016 were taken from the database (Meteopost, 2023), including air temperature, amount of precipitation, and relative humidity.

Statistical processing

The field experiments data and weather conditions data were proceeded using Microsoft Excel 2010 and expressed as the mean ± standard deviation. The differences between the means were compared with the Tukey HSD; all differences were considered statistically significant at $P < 0.05$. Multiple linear regression was calculated using Statgraphics Centurion XV Version 15.1.02 package.

Results and Discussion

Quantitative data (yield) and qualitative characteristics (gluten content) of winter wheat grain of the Podolyanka variety obtained during the crop growing seasons in 2010-2016 in areas without the use of chemical crop protection agents (control) and areas treated with herbicides, fungicides and insecticides were used to create the regression models (*Table 1*).

The effects of pests and diseases on the yield and quality of winter wheat grain were also taken into account in the regression models. These data are presented as the total number of larvae and adults of all investigated pest species and the total prevalence of all identified fungal diseases, calculated before treatment and 25 days after the application of fungicide and insecticide (*Table 2*).

A comparative analysis of meteorological conditions during the growing season of winter wheat in field experiments from 2010 to 2016 revealed differences in all indicators in a significant range. In particular, the average amount of precipitation during the growing season of winter wheat ranged from 277.3 to 506.6 mm; the average relative humidity of the air varied in the range of 68.0–78.3 mm. The average air temperature varied in the range of 7.7–12.5°C during the period of emergence of seedlings, from 0.2°C to 6.1°C during the period of recovery of spring vegetation, and within the range of 17.9–21.8°C during the period of grain filling.

The relationship between the quantitative (yield) and qualitative (gluten content) parameters of the winter wheat harvest with various meteorological characteristics and agrophytocenoses factors was analyzed by the method of multiple linear regression, and numerical regression models were obtained. Unfortunately, the vast majority of these models had a sufficiently low level of approximation of the data, so they were not taken into account in the further analysis.

The regression models, in which the meteorological factor was represented by the level of relative air humidity

Table 1. *Yield and gluten content in winter wheat grains (Podolyanka variety) on control plots (untreated) and treated with pesticides (x ± SD)*

Growing period, years	Yield, t/ha			Gluten content, %		
	Control	Granstar Pro, Falcon, Nurel D	Ellai Super, Falcon, Nurel D	Control	Granstar Pro, Falcon, Nurel D	Ellai Super, Falcon, Nurel D
2010–11	3.61 ± 0.045[a]	4.11 ± 0.012[b]	4.11 ± 0.015[b]	9.68 ± 0.43[a]	12.0 ± 0.52[b]	11.5 ± 0.93[b]
2011–12	0.91 ± 0.015[a]	1.81 ± 0.025[b]	1.91 ± 0.03[c]	9.02 ± 0.27[a]	11.6 ± 0.92[b]	11.0 ± 0.93[b]
2012–13	2.71 ± 0.036[a]	3.92 ± 0.035[b]	3.82 ± 0.015[c]	10.0 ± 0.49[a]	13.2 ± 0.81[b]	15.0 ± 1.27[b]
2013–14	5.72 ± 0.075[a]	7.41 ± 0.021[b]	7.12 ± 0.02[c]	10.0 ± 0.63[a]	14.3 ± 0.69[b]	13.5 ± 0.82[b]
2014–15	3.42 ± 0.047[a]	4.05 ± 0.046[b]	3.71 ± 0.02[c]	9.15 ± 0.44[a]	14.0 ± 0.68[b]	12.9 ± 0.77[b]
2015–16	3.17 ± 0.091[a]	3.62 ± 0.03[b]	3.61 ± 0.036[b]	8.00 ± 0.41[a]	13.1 ± 0.57[b]	14.0 ± 1.05[b]

Note. Different letters in a row after numbers indicate statistically significant differences in means (by the Tukey test, $P < 0.05$).

Table 2. *Prevalence of fungal diseases and insect pests in crops of winter wheat (Podolyanka variety) before the treatment with pesticides and 25 days after treatment (x ± SD)*

Growing period, years	Sum fungal incidence, %				Total pest number, pcs/m^2			
	Granstar Pro, Falcon		Ellai Super, Falcon		Granstar Pro, Nurel D		Ellai Super, Nurel D	
	before	25 d after	before	25 d after	before	25 d after	before	25 d after
2010–11	24.0 ± 1.2	4.0 ± 0.1	21.0 ± 0.9	4.0 ± 0.12	17.2 ± 1.2	0.6 ± 0.15	16.9 ± 0.6	1.9 ± 0.25
2011–12	17.0 ± 0.5	3.0 ± 0.1	18.0 ± 1.3	6.4 ± 0.49	16.4 ± 1.2	1.5 ± 0.50	14.8 ± 0.7	4.5 ± 1.3
2012–13	12.0 ± 0.7	1.7 ± 0.27	10.0 ± 0.6	3.8 ± 0.18	8.0 ± 0.45	0.6 ± 0.20	9.0 ± 0.7	4.0 ± 0.45
2013–14	6.4 ± 0.23	0.9 ± 0.07	5.5 ± 0.2	1.3 ± 0.07	3.3 ± 0.2	0.2 ± 0.01	4.0 ± 0.15	2.3 ± 0.12
2014–15	2.1 ± 0.15	0.4 ± 0.03	1.7 ± 0.11	0.8 ± 0.04	2.2 ± 0.35	0.3 ± 0.1	1.7 ± 0.45	0.6 ± 0.15
2015–16	2.3 ± 0.1	0.3 ± 0.02	2.7 ± 0.19	1.5 ± 0.12	1.8 ± 0.30	0.4 ± 0.15	2.1 ± 0.35	0.3 ± 0.06

in the period of milky ripeness of winter wheat grain, turned out to be the most efficient. These models also took into account the effects of the total number of insect pests and the total prevalence of fungal diseases in winter wheat crops. As a result, the workable regression models obtained in our study had the following form:

$$y = ax_1 - bx_2 - cx_3 \quad (1)$$

where y is yield (t/ha) or gluten content (%) of winter wheat grains; x_1 is relative air humidity (%) during the period of milky grain ripeness; x_2 is total damage (%) of wheat by pathogens 25 days after fungicide treatment; x_3 is total number (pc/m^2) of insect pests 25 days after insecticide treatment.

The analytical dependence of the winter wheat yield on the combined effect of Falcon fungicide and Nurel D insecticide in Podolyanka variety crops treated with Granstar Pro herbicide was described by the following equation:

$$y = 0.0969x_1 - 0.433x_2 - 2.234x_3 \ (R^2 = 91.9\ \%) \quad (2)$$

A statistically significant ($P = 0.050$) coefficient in the regression equation was near the x_1 factor, which indicates a positive influence of the relative humidity indicator during the period of milk maturity on the level of winter wheat grain yield. Other coefficients turned out to be insignificant and did not make it possible to predict the impact of changes in factors x_2 and x_3 on the yield of winter wheat. The obtained mathematical model is workable (adjusted $R^2 = 86.5\%$) and adequate ($P = 0.038$).

The regression equation of the analytical dependence of gluten content in winter wheat grains on the combined effect of Falcon fungicide and Nurel D insecticide in crops treated with Granstar Pro herbicide had the following form:

$$y = 0.202x_1 - 0.432x_2 - 1.061x_3 \ (R^2 = 99.7\ \%) \quad (3)$$

A statistically significant ($P = 0.0003$) coefficient in the regression equation is also associated with the relative humidity indicator, so the level of gluten in winter wheat grain was positively correlated with the change in this meteorological factor; both other coefficients in the regression equation turned out to be insignificant. The constructed mathematical model is workable (adjusted $R^2 = 99.5\%$) and adequate ($P = 0.0003$).

The regression equation, which reflected the analytical dependence of the winter wheat yield on the combined effect of Ellai Super herbicide, Falcon fungicide and Nurel D insecticide in agrophytocenoses, had the following form:

$$y = 0.0741x_1 - 0.913x_2 - 0.873x_3 \ (R^2 = 96.0\ \%) \quad (4)$$

Statistically significant ($P = 0.010$) coefficient in the regression equation was near the relative humidity indicator; other coefficients turned out to be insignificant and did not significantly affect the yield change. The developed mathematical model is workable (adjusted $R^2 = 93.3\%$) and adequate ($P = 0.013$).

Analytical dependence of the gluten content in winter wheat grains on the combined effect of Falcon fungicide and Nurel D insecticide in crops treated with Ellai Super herbicide was described by the following equation:

$$y = 0.192x_1 - 0.631x_2 - 1.040x_3 \ (R^2 = 99.3\ \%) \quad (5)$$

A statistically significant (P = 0.0014) coefficient in the regression equation was near the relative humidity indicator; other coefficients turned out to be insignificant and did not significantly affect the change in gluten content. The obtained mathematical model is workable (adjusted R^2 = 98.8%) and adequate (P = 0.0011).

Therefore, under both variants of integrated protection of winter wheat crops of the Podolyanka variety, the dynamics of the indicator of crop yield during 2010–2016 was positively correlated with the indicator of relative air humidity during the phase of milky grain ripeness. Crop yield, as an integral indicator, reflects the successful manifestation of varietal qualities of cultivated plants. The potential yield of the Podolyanka variety, depending on the growing conditions, can be 5.3–7.8 t/ha (Perelik sortiv, 2023), but the average level achieved so far is in the range of 5.3–6.5 t/ha. One of the reasons is that the degree of realization of the genetic potential of yield of cultivated plants is determined by the influence of a complex of abiotic and biotic factors in agrophytocenoses (Norodyska et al., 2021).

The regression analysis of actual field data allows us to predict that in order to obtain potentially possible harvests of winter wheat of the Podolyanka variety in the Northern Steppe of Ukraine, a relative air humidity within the range of 75–81% is required during the period of milky grain ripeness in the presence of other favorable conditions of agrophytocenosis. In our work, the highest yield of 7.4 ± 0.02 t/ha and 7.1 ± 0.02 t/ha, respectively, in the first and second variants of integrated crop protection, and in the control plot as well was obtained in 2014 at the highest level of air humidity in the phase of milky grain ripeness according to the entire period of research.

In the regression models we obtained, the statistically insignificant coefficients near the factors x_2 and x_3 in the regression equations make prognostic assessments impossible, but indicate a negative relationship between the winter wheat harvest and the number of pathogens and pests that remained viable 25 days after the application of fungicide and insecticide. Therefore, the selection of components of chemical protection of winter wheat crops is an important component in ensuring a high yield of winter wheat. The effectiveness of our combination of sulfonylurea herbicides with Falcon and Nurel D was further confirmed in the 2016–2017 field experiment, where the highest yield of winter wheat was obtained by combining another herbicide from the same class with the same fungicide and insecticide (Nazarenko, 2019).

The level of gluten in the grain is one of the indicators of the quality of the winter wheat harvest and its suitability for baking. Potentially, Podolyanka winter wheat grain can contain 13.5–14.7% crude gluten (Perelik sortiv, 2023). According to the obtained regression equations, in order to achieve such a gluten content in crops treated with the herbicide Granstar Pro, Falcon and Nurel D, a relative air humidity of 66.8–72.8% is required during the milky grain ripeness phase. When crops are treated with the herbicide Ellai Super, Falcon and Nurel D, air humidity should be within 70.3–76.7%. According to the results of field experiments, in the first variant of integrated crop protection, the highest content of gluten in wheat grain was 14.3 ± 0.7%, and in the second variant, it was 15.0 ± 1.3%. Under both variants of herbicide treatment, the level of gluten in grain exceeded the control values by one and a half times, which is caused by metabolic changes in the seeds of plants treated with pesticides. Previously, we indicated such manifestations of the impact of herbicides on Zemlyachka wheat grain as an increase in the content of soluble proteins, an increase in germination energy, and a decrease in seed germination (Matyukha et al., 2012).

The obtained regression equations allow us to determine the optimal changes range of the statistically significant factor of relative air humidity, capable of ensuring high yield and quality of winter wheat grain in agrophytocenoses with an integrated crop protection system. At the same time, our study reflected the general problems that accompany the use of simple predictive models to assess the consequences of complex combinations of phenomena. As noted by Hanspach et al. (2010), when creating temporal or spatial forecasts, uncertainty is inevitable, and forecasting errors may depend not only on the quality of the data and the used modeling algorithm, but also on various characteristics of the studied object. For example, an analysis of the reliability of simulation models based on remote crop survey data showed that the value of yield forecasting in a season is limited by the lack of accurate weather forecast in real time (Jin et al., 2018).

Conclusions

In this work, a multiple regression analysis of the results of field experiments in 2010–2016 was carried out, aimed at identifying the possibility of forecasting the yield of winter wheat in the system of integrated crop protection in the conditions of the Northern Steppe of Ukraine. The regression models obtained based on actual field data made it possible to reveal regularities linking the yield and gluten content of winter wheat grains with the level of relative humidity during the milky grain ripeness phase and the prevalence of pathogens and pests 25 days after pesticide treatment. Regression models reflecting the correlation of quantitative and qualitative indicators of the harvest with relative air humidity showed predictive value and made it possible to determine the necessary limits of the meteorological parameter to achieve high quantitative and qualitative indicators of the harvest. The predictive value of the models is reduced due to the statistical insignificance of the correlations between yield and gluten content on the one hand and the number of pathogens and pests on the other hand. In order to overcome the shortcomings of modeling, it is probably necessary to use a more reliable algorithm and a larger sample of data.

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