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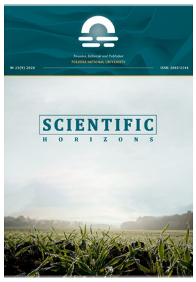

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Patterns of winter wheat ear productivity formation depending on the content of trace elements in the soil

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Abstract. The study of patterns of the formation of ear productivity depending on the content of potentially bioavailable Fe, Mn, Zn, Cu in the soil, the stochastic formalization of such patterns are important for a more profound understanding of the conceptual and mechanistic aspects of the dependence of yield development on the levels of nutrient supply of winter wheat under the conditions of environmentally friendly fertilization systems. The purpose of this study was to find statistically significant interdependencies, significant and relevant univariate or multivariate

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regression equations of the dependence of the mass of grains of ear^{-1} of winter wheat on the content of potentially bioavailable Fe, Mn, Zn, Cu in the soil, arguments and explanations of such subordinations under the conditions of environmentally friendly fertilization systems. The following methods were used in the study: field, laboratory-analytical, mass-spectrometric, mathematical-statistical (Student's *t*-test, *ANOVA*, correlational, single- and multivariate regression analyses). The applied green fertilization systems based on pea straw or pea straw + $N_{30}P_{45}K_{45}$, or $N_{60}P_{90}K_{90}$, only $N_{60}P_{90}K_{90}$ caused an increase in the weight of grains of one ear of winter wheat, the content of mobile forms of Fe, Mn, Zn, Cu in the grey forest soil under this culture (earing phase), compared to the control (without fertilizers). Substantial and significant Pearson correlation coefficients between the mass of grains of an ear of wheat and the content of mobile Fe, Mn, Zn, Cu in the soil, the corresponding contents of Mn and Zn, Cu and Zn, as well as the coefficients of partial correlation of the mass of grains of ear^{-1} of wheat – Cu, Mn – Zn testified to the complex structure of interdependencies between the traits under study. Reliable, relevant single- and multifactorial regression dependences of the mass of grains of ear^{-1} on linear combinations of products of independent variables (the content of mobile Fe, Mn, Zn, Cu in the soil) and/or such variables in indicators of natural powers 2-4 (fragments of the Kolmogorov-Gabor polynomial) were found. The coverage of regularities in the formation of the productivity of the ear of winter wheat depending on the content of potentially bioavailable microelements in the soil under the conditions of environmentally friendly fertilization systems will enable the theoretical substantiation and development of the latest strategies of mineral and ecological engineering of agricultural systems to maintain prominent levels and biological safety of the harvest of the specified crop

Keywords: ecological fertilization systems; winter wheat; trace elements; correlation; regression

INTRODUCTION

The problem of unbalanced management of soil resources, the use of intensive technologies without proper replenishment of nutrients and limitations of biological approaches has led to nutrient deficiencies and imbalances in soils of various genesis, as well as to stagnation of productivity in many countries. Special problems are observed in grey forest podzolized soils of Ukraine due to soil-forming processes that cause glaciation and leaching of trace elements. Solving these problems involves the development of "soft" approaches to increasing the efficiency of ecosystem services of agrophytocenoses using eco-friendly fertilizer systems (EFS). EFSs include moderate rates of mineral fertilizers with bio-effectors and/or trace elements to improve the yield of agricultural crops. Currently, it is important to investigate the patterns of formation of the final productivity of winter wheat depending on the content of mobile forms of essential microelements in the soil when using EFS on grey forest podzolized soils.

According to established ideas, conceptualized, specifically, by A.K. Shukla *et al.* (2018), the need of plants, including cereals, for micronutrients for optimal growth and development is undeniable, while the problem of deficiency of such chemical elements has been significant in many agricultural lands of the world for at least the last seventy years. According to the theoretical and methodological approaches that proceed from the above, A. Jalal *et al.* (2020) found that the number of days to flowering, productive shoots, plant height, wheat yield components were significantly dependent on the rates of application of $ZnSO_4 \cdot 7H_2O$ or $FeSO_4 \cdot 7H_2O$ to the soil (interactive effects occurred several days before flowering). However, in recent years, the frontier of scientific questions concerning the aspects of mineral nutrition of plants has shifted towards harmfulness and dualistic role (e.g., hormesis) of micronutrients in the life of plants, bioremediation, as stated, specifically, in the studies by E. Muszyńska and M. Labudda (2019), A. Rizvi *et al.* (2020). A considerable alternative to the above-listed areas of scientific research, as well as established organic, integrated agriculture, etc., are developed by German authors B. Zimmermann *et al.* (2021) approaches of Mineral-Ecological Cropping Systems (MECS), in which new and existing technologies are combined with agro-ecological practices to stimulate natural regulatory processes, non-chemical plant protection (generally, complete rejection of pesticides), as well as optimization of mineral fertilizer rates. It is advisable to casually apply the components of precision farming and/or treatment of soil, plants with bio-effectors, microelements with the specified set of measures. In this context, it is important to use microbiological fertilizers (e.g., soil inoculation), which contain cellulose-destroying (generally, biodegrading) microorganisms, with the aim of accelerated decomposition of crop residues (Yadav & Sarkar, 2019).

It is also known that the systematic involvement of various crop rotations in organic farming practices leads to increased inoculation of the root system with arbuscular mycorrhizal fungi (AMF), and the subsequent increase in the amount of absorption of nutrients by plants (AMF, as an alternative to chemical fertilizers) (Kaur & Purewal, 2019). It is appropriate to note the arguments of Y. Su *et al.* (2021) regarding the ambiguous influence of straw return on the accumulation of heavy metals and trace elements in soils. According to these authors, "dissolution effects" caused by a decrease or differential changes in soil pH, a transient decrease in the redox potential, and the formation of considerable amounts of dissolved organic matter (DOM) after the introduction of straw, as well as complex formation between DOM and metal ions, microbial methylation of metals in the soil lead to the release of macro- and microelements from the indicated plant residues, which can affect the physiological, biochemical, and biometric indicators of plants. The stated positions partially contradict the previous notion that the return of straw has the properties of mainly reducing the bioavailability of metals in the soil, however, it is consistent with the analysis performed by S.S. Dhaliwal *et al*. (2019) towards the ability of soil OM (SOM), namely plant residues, to increase the levels of mobility and bioavailability of trace elements. It is worth reminding that micronutrients and heavy metals can enter the soil from impurities contained in commercial mineral fertilizers (Ali *et al*., 2020).

An alternative to the bioeffectors listed above in MECS, EFSs are biostimulants (BS), which, according to the du Jardin classification, include humic substances (HS), compositions of proteinogenic and non-protein amino acids (AA), growth stimulants (microorganisms or phytohormones), etc., which have properties aimed at increasing the level of plant tolerance to abiotic stress (Halpern *et al*., 2015). Under the conditions of both applications to the soil and treatment of plants, HS cause a considerable improvement in the absorption of macro- and microelements (e.g., N, P, Fe, Mn, Zn, Cu) due to, among other things, an increase in their solubility, chelation, other signs of bioavailability, auxin-like activity of stimulating the development of root hairs, roots, including lateral ones (Halpern *et al*., 2015). AA, which are part of BS, are often directly or indirectly involved in the regulation of the redox state of plants and play an important role in protecting the growth of these organisms from oxidative stress and detoxification of heavy metals (García-García *et al*., 2020). Cytokinins (CK), which are part of BS or, e.g., biohumus, take part in many key events and functions at all levels of plant organization, specifically, activation of the cell cycle, the possibility of which depends on the level of providing plants with nutrients; also CKs play a crucial role in the control mechanisms of bacterial pathogenesis and contribute to mitigating the adverse effects of abiotic stress in plants (Wong *et al*., 2020).

Thus, all the components, their combinations, based on which the ESFs proposed in this study are built, have real or potential properties towards changes in the levels of providing agricultural crops with macro- and microelements. However, the formation patterns of the final productivity of winter wheat depending on the content of the necessary bioavailable microelements in the substrates depleted by them under the conditions of EFSs, the corresponding mathematical and statistical formalizations and interpretations resulting from them, still lack coverage in the scientific literature.

The purpose of this study was to investigate the regularities of formation of (1) the productivity of the ear of winter wheat, (2) the content of potentially bioavailable Fe, Mn, Zn, Cu in the grey forest podzolized soil under these plants; to formalize the dependence of wheat traits (1) on soil properties (2) and to find relevant interpretations of such dependences using the methods of two- and multivariate statistics.

MATERIALS AND METHODS

The field experiment was conducted in 2019-2020 under the conditions of an experiment to investigate the productivity of crop rotations of the Institute of Agriculture of the Carpathian Region, Stavchany village, Lviv district, Lviv region. Micro-plot experiment, plot area – 1 m^2, distance between plots – 1 m, repetition – 6 times. The scheme of the field experiment was as follows: 1) control – without fertilizers; 2) pea straw; 3) pea straw + $N_{30}P_{45}K_{45}$; 4) pea straw + $N_{30}P_{45}K_{45}$ + BS (biological stimulator); 5) pea straw + $N_{30}P_{45}K_{45}$ + BS + HF (humus fertilizer); 6) pea straw + $N_{30}P_{45}K_{45}$ + BS + MF (microbiological fertilizer); 7) pea straw + $N_{30}P_{45}K_{45}$ + CF (chelated fertilizer); 8) $N_{60}P_{90}K_{90}$; 9) $N_{60}P_{90}K_{90}$+ BS; 10) $N_{60}P_{90}K_{90}$ + BS + manure (afteraction); 11) $N_{60}P_{90}K_{90}$ + BS + HF; 12) $N_{60}P_{90}K_{90}$ + BS + MF; 13) $N_{60}P_{90}K_{90}$ + HF. On the listed micro-plots, winter wheat (*Triticum aestivum* L.) of the Benefis variety was grown after field peas (*Pisum sativum* L.). Therefore, experimental fertilization systems were composed on the basis of pea straw, pea straw + $N_{30}P_{45}K_{45}$ (variants – var. 2, 3-7) or $N_{60}P_{90}K_{90}$ and $N_{60}P_{90}K_{90}$ with the addition of BS, HF, MF, CF (var. 8, 9-13).

The soil of the experimental plots was grey forest with a superficial glaciation, light loam. Physical and chemical and agrochemical parameters of the soil (depth 0-30 cm) before the experiment, characteristics of biological preparations, methods of their use were described earlier (Dubytskyi *et al*., 2022).

Climatic conditions in the autumn of 2018 and 2019 were characterized by a uniform distribution of the sums of active temperatures (average – 0.3-0.5°C higher than the long-term annual average – LAA), precipitation amounts (PA; close to LAA). In April 2019, 2020, there was a 27-38% decrease in PA, in May – an increase of 1.3-1.6 times, compared to LAA. In the phase of earing and filling of grain, there was a 10-12% lack of moisture (2019) or overmoistening with temperatures, on average, 2.6°C higher, relative to LAA (2020). In general, the vegetation conditions ensured satisfactory growth and development of winter wheat.

The selection of soil samples (depth 0-30 cm) from experimental variants and their preparation for laboratory and analytical work was carried out pursuant to DSTU ISO 11464-2001 (2003) after the onset of the earing phase of winter wheat. The contents of mobile forms of trace elements MF-Fe, MF-Mn, MF-Zn, MF-Cu were determined according to DSTU 4770.6:2007

(2005): by extracting from air-dry soil with 1 M ammonium acetate buffer solution (AAB, pH 4.8), and in the following – measuring the absorption values of the obtained extracts at λ = 248.3, 279.5, 2 13.9, 324.7 nm, respectively, using a C-115M1 atomic absorption spectrophotometer (3 repetitions, 2 analytical parallels, *n*=6). The mass of ears of grain^{-1} per plant was determined in the phase of wax maturity (analytical balance Radwag AS 220/R2, Poland (±0.0001 g); 3 repetitions, 4 plants per repetition, *n*=12). The specified indicator was calculated according to certain principles of generally accepted approaches (Yeshchenko, 2014) and their specifications. The final values of each characteristic were obtained by averaging their values over 2 years of research (2019-2020).

Group analysis of statistical significance of differences in results was performed using *ANOVA* (α=0.05) in Excel 11.0.6560.0. In addition, in the specified program, estimates of the standard errors of the differences between the means (*SEDM*), Student's *t*-test, *df*, according to the formulas given in (Woodward, 2014), of the corresponding P values were calculated. Data were tested for normal distribution in Gretl 2021b. The Pearson correlation coefficients, partial correlation, and their significance levels were calculated in STATISTICA Version 10. The parameterization of linear univariate and multivariate regression equations using the method of ordinary least squares (OLS) (dependent variable y is the mass of grains per ear^{-1} per plant; independent variables x_1, x_2, x_3, x_4 are the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu, respectively, in soil), as well as principal component analysis (PCA, the *PC* number = number of independent variables) were performed in Gretl 2021b. OLS regression on *PC* (PCR), iterative Ridge regression methods (IRR, number of λ values = 100), ILASSO (Iterative Least Absolute Shrinkage Regression and Selection Operator, number of λ values = 100) on standardized x_{s_1}, ..., x_{s_4} were performed in the same program. To calculate the empirical OLS-regression coefficients ($b_{j(OLS\_PC)}$) from the PCR coefficients ($\beta_{j(PCR)}$), the authors of this study used the ratios of the corresponding matrices given by W.F. Massy (1965) and G. Sanchez and E. Marzban (2020). Briefly: the equation of the multiple regression of y_s on the standardized x_{s_1}, ..., x_{s_4} was substituted into the OLS regression expression of the standardized y_s on PC_1 in symbolic form, where the coefficients were the loads p_{11}, ..., p_{14} of the eigenvector P_1. – the algorithm according to K.O. Ekvall (2022). Grouping the terms in the last equation helped find expressions for $b_{j(OLS\_PC)}$.

The general expression of the Kolmogorov-Gabor polynomial (KGP) for the dependences of *y* on x_1, ..., x_4 was constructed according to R. Brito *et al.* (2016), H. Moosanezhad-Kermani *et al.* (2021):

$$y = b_0 + \sum_{i=1}^{n=4} b_i x_i + \sum_{i=1}^{n=4}\sum_{j=1}^{n=4} b_{ij} x_i x_j + \sum_{i=1}^{n=4}\sum_{j=1}^{n=4}\sum_{k=1}^{n=4} b_{ijk} x_i x_j x_k + \sum_{i=1}^{n=4}\sum_{j=1}^{n=4}\sum_{k=1}^{n=4}\sum_{l=1}^{n=4} b_{ijkl} x_i x_j x_k x_l, \quad (1)$$

where b_0, b_i, b_{ij}, b_{ijk}, b_{ijkl} are coefficients, *n*=4 is the number of independent variables. OLS-regression of *y* on fragments of the Kolmogorov-Gabor polynomial was performed according to the rules that determined the formation of *y* dependencies from: 1) 2nd-order interactions – sums of $b_{ij}x_ix_j$ + $b_{1234}x_1x_2x_3x_4$, both with and without x_i^2, x_j^2; 2) 3rd-order interaction – sums of $b_{1jk}x_1x_jx_k$, $b_{2jk}x_2x_jx_k$, $b_{3jk}x_3x_jx_k$; 3) 4th-order interaction – sums of $b_{11kl}x_1x_1x_{kxl}$, $b_{12kl}x_1x_2x_{kxl}$, $b_{13kl}x_1x_3x_{kxl}$; 4) $b_{1234}x_1x_2x_3x_4$; 5) sums of x_i and x_k or x_j and x_l, in which each variable was in natural powers 2-4; 6) dependence of *y* on only x_i^2, x_i^3, x_i^4. In items (2), (3) permutations with repetitions and x_{111}, x_{222}, x_{333}, x_{444}, x_{1111}, x_{2222}, x_{3333}, x_{4444} were excluded. The latter – because they caused a significant deterioration of the performance metrics of OLS-regression models.

The main performance metrics of OLS-regression models, specifically, the significance values of regression coefficients, factual F_a-ratios, standard errors of regressions (S), adjusted R^2 (R^2_{adj}), mean absolute percentage errors (*MAPE*), log-likelihoods, information criteria of Akaike, Schwarz, Hannan-Quinn (*logL*, AIC, BIC, HQC, respectively), Theil coefficients *U1*, *UM* displacement proportions, regressions *UR*, *UD* perturbations were obtained from Gretl 2021b. In addition, this program performed a typical set of analyses and tests for models for multicollinearity, leverage, linearity, heteroscedasticity, normal distribution of residuals, Chow test. The Durbin-Watson (*DW*) statistic was calculated according to O.I. Cherniak (2009), P. Turner (2020). The corresponding critical values (*dL*, *dU*, *P*=0.05) were obtained in Gretl 2021b. The presence or absence of autocorrelations was assessed according to a generally accepted algorithm (Cherniak, 2009). F_a-ratios and *MAPE* for PCR, IRR, ILASSO were calculated in Excel 11.0.6560.0 according to (Ahmadi & Rodehutscord, 2017) and (Levine *et al.*, 2019), respectively. The model was considered significant if F_a-ratio ⩾ *F* standard (*P*⩽0.05) and *MAPE*⩽5.0-6.0%.

RESULTS

The obtained results (Figure 1) showed an increase in the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu in the soil of variants 2, 8 by 2.3-12.2% and 16.7-24.1% (*P*<0.001), respectively, compared to the control (var. 1; earing phase of winter wheat). In addition, MF-Mn, MF-Zn experienced an increase in var. 3-7 by 12.7-22.6%, 4.8-10.8% and on var. 10-13 by 1.3-7.7%, 3.4-19.5% (*P*<0.001-0.01), relative to var. 2 and var. 8, respectively. Therewith, on var. 9, the content of MF-Zn in the soil was 1.1% (*P*<0.01) higher, while the content of MF-Mn did not differ significantly from the value of this indicator in var. 8. Ambiguous patterns of changes in MF-Fe, MF-Cu were found on var. 3-7, 9-13, relative to var. 2,

8. Admittedly, MF-Fe underwent growth on var. 3-5, 7 by 2.3-9.5%, while MF-Cu – on var. 5-7 – by 0.4-11.2% (*P*<0.001-0.01), compared to var. 3. Conversely, on var. 6, and var. 3, 4, a decrease in MF-Fe, MF-Cu by 1.3% and 1.1-2.2% (*P*<0.001-0.01) was noted, relative to var. 3. Furthermore, an increase in the values of MF-Fe was observed on var. 9 by 0.9%, and MF-Cu on var. 9-13 by 6.1-14.3% (*P*<0.001-0.05), compared to var. 8.

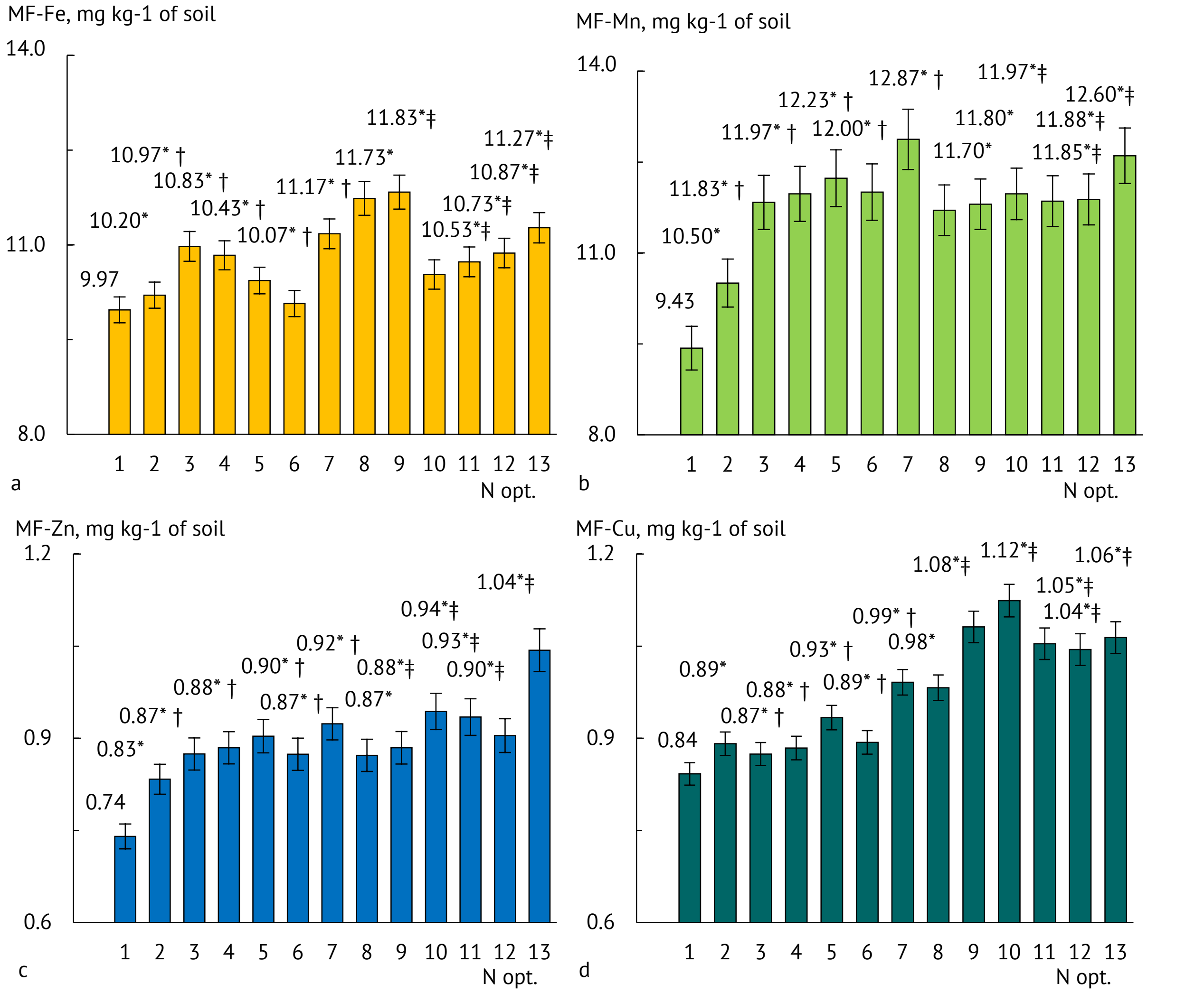

Figure 1. *Changes in the content of mobile forms of trace elements MF-Fe (a), MF-Mn (b), MF-Zn (c), MF-Cu (d) in the soil under winter wheat under the EFS conditions based on pea straw (var. 2), pea straw +* $N_{30}P_{45}K_{45}$ *(var. 3-7),* $N_{60}P_{90}K_{90}$ *(var. 9-13), including the control (var. 1 – without fertilizers) and solely* $N_{60}P_{90}K_{90}$ *(var. 8) (wheat earing phase, 2019-2020)*
Note: *For var. 1-13 significance levels of differences between means according to ANOVA data a, b, c, d – P<0.001, for var. 1-7 – P<0.01, P<0.001, P<0.001, P<0.001, var. 8-13 – P<0.001; Symbols *, †, ‡ – significance levels of differences (Student's t-test on means) relative to variants 1, 2, 8, respectively, P<0.001-0.05*
Source: *developed by the authors of this study*

Thus, EFS based on pea straw (var. 2), pea straw + $N_{30}P_{45}K_{45}$ (var. 3-7), $N_{60}P_{90}K_{90}$ (var. 9-13), and solely $N_{60}P_{90}K_{90}$ (var. 8) undoubtedly caused an increase in the content of mobile forms of Fe, Mn, Zn, Cu in the grey forest soil under winter wheat (earing phase), compared to the variant without fertilizers (var. 1). Therewith, the patterns of formation of MF-Fe, MF-Mn, MF-Zn, MF-Cu increments, relative to var. 1, 2, 8, significantly depended on the applied basic elements of fertilization systems (pea straw or $N_{60}P_{90}K_{90}$) and the type of particular fertilization system. To compare MF-Fe, MF-Mn, MF-Zn, MF-Cu with productivity, the pattern of changes in the mass of grains of ear^{-1} per one plant of winter wheat under the conditions of the fertilization systems under study was investigated (Fig. 2, waxy ripeness phase). On var. 2, 8 there was an increase in the specified indicator by 5.4%, 55.9% (*P*<0.01-0.001), respectively, compared to var. 1. The mass of grains of ear-1 increased on var. 3-7 by 19.4-35.7% and on var. 9-11, 13 by 4.8-11.0% (*P*<0.001-0.05), relative to var. 2 and var. 8, respectively. No significant differences were found between the values of this indicator for var. 8 and var. 12 (*P*=0.130).

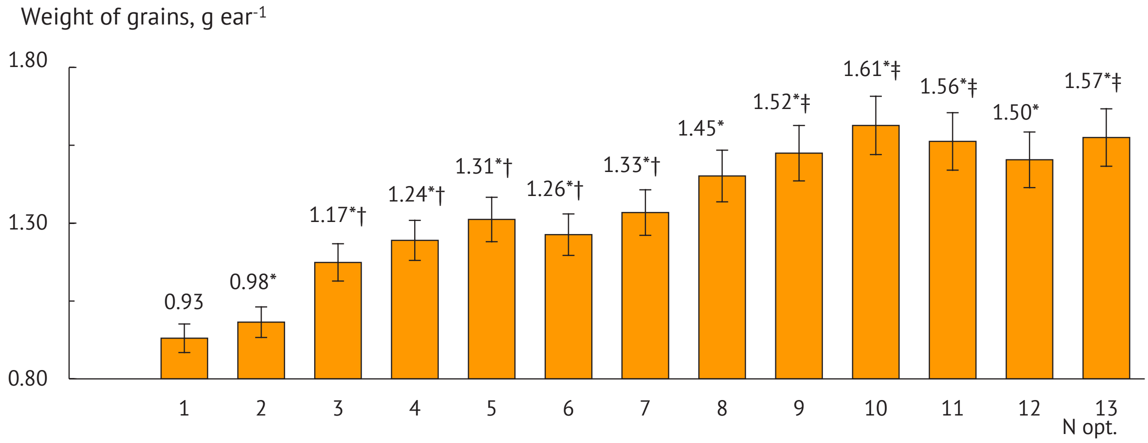

Figure 2. *Variation of the weight of ears of grain^{-1} based on one plant of winter wheat under the EFS conditions based on pea straw (var. 2), pea straw + $N_{30}P_{45}K_{45}$ (var. 3-7), $N_{60}P_{90}K_{90}$ (var. 9-13), including the control (var. 1 – without fertilizers) and solely $N_{60}P_{90}K_{90}$ (var. 8) (waxy ripeness phase, 2019-2020)*

Note: *For var. 1-13, 1-7, 8-13 significance levels of differences between means according to ANOVA data were P<0.001; Symbols *, †, ‡ – significance levels of differences (Student's t-test on means) relative to variants 1, 2, 8, respectively, P<0.001-0.05*

Source: *developed by the authors of this study*

It was established that the Pearson correlation coefficients *r* for the interdependencies between the mass of grains of ear^{-1} (*y*) and MF-Fe, MF-Mn, MF-Zn, MF-Cu (x_1, x_2, x_3, x_4, respectively) were 0.5837-0.9191 (P<0.001-0.05) (Table 1). Close two-dimensional correlations x_2-x_3, x_3-x_4 were also found: r=0.8347, 0.6989, P<0.001-0.01, respectively. Among the significant partial correlations were only the following: $r_{(yx4.x1x2x3)}$=0.8532, $r_{(x2x3.yx1x4)}$=0.6946, P<0.001-0.05. The fact that there was r>0.4, 0.7 ≈ r>0.7 among *r* between independent variables indicates the presence of multicollinearity between predictors. Since all partial correlation coefficients were smaller compared to the corresponding *r*, the effect of variable suppression was absent. Conversely, *y* and x_i depend on several unaccounted factors.

Table 1. *Pearson's correlation coefficients and partial correlation coefficients between the mass of grain ear^{-1} (per plant) of winter wheat and MF-Fe, MF-Mn, MF-Zn, MF-Cu*

Pearson correlation coefficients					
	y	x_1	x_2	x_3	x_4
y					
x_1	0.5837[a]				
x_2	0.6936[b]	0.4998			
x_3	0.7957[c]	0.4296	0.8347[c]		
x_4	0.9191[c]	0.5160	0.4996	0.6989[b]	
Partial correlation coefficients					
y					
x_1	0.1537				
x_2	0.4313	0.2773			
x_3	0.0509	-0.2482	0.6946[a]		
x_4	0.8532[b]	0.0859	-0.5282	0.2808	

Note: *y, x_1, x_2, x_3, x_4 are mass of grains of ear^{-1} based on one plant of winter wheat (g), MF-Fe, MF-Mn, MF-Zn, MF-Cu (mg kg^{-1} of soil); partial correlations y-x_i were calculated under the conditions of invariance x_j, x_l, x_k, partial correlations x_i-x_j – under the conditions of invariance y, x_l, x_k; indices a, b, c are the significance level of the correlation coefficient P<0.05, P<0.01, P<0.001, respectively*

Source*: developed by the authors of this study*

Given the significant r>0 between y and each of x_1-x_4 (Table 1), a search was made for univariate OLS regression models among the following specifications: linear, semi-logarithmic, linearized exponential, power, modified sigmoid logistic $ln\ ((2\cdot 1/y) - 0) = b_0 + b_1 x_{1i}$, modified lognormal $ln\ (10\cdot 1/y) = b_0 + b_1 ln x_{1i}$ (0, 2, 10, and 1 were empirical constants selected "by hand" using OLS and y_{max}, respectively; for a general derivation of the last 2 functions, see, e.g., (Yahya *et al.*, 2019)), as well as power polynomials. No equations were found that were characterized by both sufficient levels of significance of F_a-ratios, *MAPE* values, on the one hand, and adequate test scores, on the other hand, or relevantly significant F_a-ratios in combination with significant equation coefficients; obtaining models with b_0>0 was also problematic (b_0⩽0 contradicts the definition of ear productivity).

Notably, the samples y, x_1, x_4 were characterized by a normal distribution (*ND*) of the data according to the Doornik-Hansen test, Shapiro-Wilk W-statistics, Lilliefors, Jarque-Bera tests, while x_2 were characterized significant deviations from the *ND*; x_3 was normally distributed according to the second and fourth criteria, and deviated from *ND* according to the remaining tests applied. Data were not logarithmised, given the generally satisfactory values of the correlation coefficients and their significance. In addition, deviation of regression residuals from *ND* among the specifications listed above occurred only once.

Considering the results of the correlation analysis, it is reasonable to assume multivariate dependences of y on x_1-x_4. The following OLS models were created and analysed:

factoring in partial correlations

$$y = -0.833^{**} + 1.704^{**} x_4 + 0.049^{*} x_2 x_3, \quad (2)$$

multivariate additive regression model (MAM)

$$y = -1.483^{**} + 0.021x_1 + 0.068x_2 + 0.108x_3 + 1.740^{**} x_4, \quad (3)$$

sequential exclusion of variables from MAM

$$y = -1.348^{**} + 0.078^{*} x_2 + 1.818^{**} x_4, \quad (4)$$

semi-logarithmic modification of the latter

$$y = 0.571^{**}\ ln\, x_2 + 1.900^{**}\ ln\, x_4. \quad (5)$$

Here "**", "*" – P<0.01-0.05. Corresponding F_a-ratios – 22,956-2592,530 > F standard (P<0.001), R^2_{adj} – 0.880-0.907, *MAPE* – 3.43-3.95%. Evidence of strong multicollinearity was found (Adkins *et al.*, 2015) for the first three models: 2 condition numbers (*CN*)>10 (first), 4 and 1 *CN*>30 (second and third), corresponding variance proportions (*VP*) – 0.999, 1.000, 0.999-1.000. It is possible that multicollinearity is the reason for the insignificance of b_1-b_3 in the second model (Thompson *et al.*, 2017), and b_0<0 in the first three equations (Adeboye *et al.*, 2014). In the fourth among these models, b_0=0.

According to existing ideas, to minimize or eliminate the effects of multicollinearity between endogenous variables in MAM, it is advisable to use regularized multiple regression methods (Çankaya *et al.*, 2019). However, PCR, IRR, ILASSO performed in this study were not successful in the parameterization of the equation $y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4$. The obtained regression coefficients were as follows: 1) PCR (by the first component) – -14.796, 0.398, 0.322, 4.367, 2.880; 2) IRR – $-8.135\cdot 10^{-18}$, 0.097, 0.198, 0.149, 0.610; 3) ILASSO – $-5.872\cdot 10^{-18}$, 0.056, 0.273, 0.033, 0.730, respectively. The values of t-Student, P for these coefficients were not calculated, since the models were insignificant and, therefore, could not be used for a full interpretation of the multivariate dependences of y on x_1-x_4. Corresponding F_a-ratios – 2.011-2.255<F standard = 3.838 (P=0.05), *MAPE* – 111.195-244.783%. For all these regressions, the inequalities *SSR*>*SST*, *MSE*>*MST* were true, which made it impossible to calculate R^2 (Levine *et al.*, 2019), and therefore R^2_{adj}. Due to the insignificance of the PCR equation, as well as to save space, the details of this approach are not given.

The features of the above OLS-multifactor models, PCR, IRR, ILASSO testify, most likely, in favour of the opinion that the considered specifications, namely, simple MAM for the dependences of y on x_1-x_4 are irrelevant and/or ineffective. It is possible that the considered multivariate system of variables can be described by the above-unanalysed nonlinear dependences of y on each x_i or x_1-x_4 (OLS for linearized specifications or nonlinear least squares methods). However, the authors of this study did not find any assumptions about the form of such dependencies in the scientific literature. In this regard, the possibilities of presenting this multidimensional system of variables with OLS-regression models on fragments of the Kolmogorov-Gabor polynomial (KGP) were implemented. The latter includes standard additive and multiplicative models as partial cases, nonlinear terms of higher order. This makes it expedient to solve, using KGP, the tasks of formal and comparative structural-parametric identification of individual models of multifactor evaluation (Skakalina, 2018). For this, the group method of data handling (GMDH) was used according to genetic and several other algorithms (Stepashko, 2018). In this study, the model of the dependences of y on x_1-x_4 was specified as fragments of the KGP, which included partial cases of interactions of factor variables separately of the 2nd, 3rd, and 4th orders, as well as additive combinations of x_1, x_3 or x_2, x_4, in which each variable was raised to powers of 2, 3, 4, the dependence of y on x_i^2, x_i^3, x_i^4. The following were the most relevant (namely, b_0>0, significant values of performance metrics, adequate estimates for all tests, absence of autocorrelations, uncertainty intervals), among such OLS-parameterized models, or their improved versions (logarithmisation of independent variables, transformation into a linearized modified lognormal dependence).

$$y = 1.148^{*} - 0.231^{*}x_1 + 0.007^{*}x_1x_2 + 0.164^{**}x_1x_4\ , \quad (6)$$

$$y = 0.793^{**} + 0.033^{*}x_1^2x_2 - 0.470^{*}x_1^2x_3 + 0.014^{**}x_1^2x_4 - 0.031^{*}x_1x_2^2 + 0.421^{*}x_1x_2x_3\ , \quad (7)$$

$$y = 0.399^{**} - 0.086^{*}x_2x_3^2 + 0.171^{**}x_2x_3x_4, \quad (8)$$

$$y = 1.491^{**} + 0.834^{**}\ ln(x_3x_4^2), \quad (9)$$

$$y = 0.943^{**} + 0.003^{*}x_1^3x_2 - 0.049^{*}x_1^3x_3 + 0.001^{**}x_1^3x_4 - 0.003^{*}x_1^2x_2^2 + 0.044^{*}x_1^2x_2x_3, \quad (10)$$

$$y = 0.527^{**} + 0.007^{**}x_1x_2x_4^2, \quad (11)$$

$$y = 0.580^{**} - 0.100^{*}x_1x_3^3 + 0.181^{**}x_1x_3^2x_4, \quad (12)$$

$$ln(100 \cdot 1/y) = 5.479^{**} - 0.505^{**}x_1x_4^3, \quad (13)$$

$$y = 0.471^{**} + 0.008^{**}x_1x_2x_3x_4, \quad (14)$$

$$y = 20.660^{**} - 1.056^{**}x_2^2 + 0.127^{**}x_2^3 - 0.004^{**}x_2^4 + 4.680^{*}x_4^3 - 3.075^{*}x_4^4, \quad (15)$$

$$y = 1.410^{**} + 1.073^{**}\ ln(x_4^2)\ . \quad (16)$$

In equations (6)-(16), the symbols "*", "**" indicate the significance of coefficients $P<0.05$, $P<0.01$, respectively; in (13) the numbers 100, 1 are the empirical coefficient selected "manually" using OLS, y_{max}, respectively. Individual performance metrics of OLS regression models (6)-(16) are presented in Table 2. Clearly, the best among these models are characterized by equations (15), (10), (7) (the largest R^2_{adj}, combined with sufficiently low levels of *S*, *MAPE*, *U1*, and optimally high *DW*); the worst among them are (14), (16) (smallest R^2_{adj}, combined with high levels of *S*, *MAPE*, *U1*) (Table 2). This quality classification is consistent with the values of *logL*, AIC, BIC, HQC for these models. Admittedly, for (15), (10), (7) the specified characteristics were 21.816-29.071, -46.840–-28.243, while for (14), (16) – 13.416-14.170, -24.572–-21.703, respectively. Strong evidence of multicollinearity of OLS regression models (6), (7), (8), (10), (12), (15) was found: 1-5 *CN*>10, 1-3 *CN*>30, *VP*=0.625-1.000; for (6), (8), (10), (12) Variance Inflation Factor (*VIF*)=2.882-12.401, for the rest among these equations *VIF*>1000. However, sufficient levels of significance of such models, their coefficients, high R^2_{adj}, low *S*, *MAPE*, *U1*, adequate evaluations by all tests, strongly suggest that the corresponding dependencies are close to the variables really existing in the system under study. An overestimation of ear productivity under conditions corresponding to b_i=0 in models (13), (15), and, probably, (6), (9), (16) is not excluded; the above calls into question the use of such dependencies for extrapolations.

Table 2. *Numerical values of efficiency metrics of OLS regression models (6)-(16)*

Number of equation	F_a	R^2_{adj}	S	MAPE	U1	UM	UR	UD	DW
6	31.118*	0.883	0.076	3.65	0.023	0	0	1	2.756
7	29.831*	0.923	0.062	2.88	0.017	0	0	1	2.297
8	47.318*	0.885	0.075	4.08	0.024	0	0	1	2.640
9	97.836*	0.890	0.074	4.26	0.025	0	0	1	2.266
10	30.277*	0.924	0.061	2.79	0.017	0	0	1	2.254
11	87.469*	0.878	0.077	4.76	0.026	0	0	1	2.188
12	34.326*	0.847	0.087	5.32	0.028	0	0	1	1.667
13	54.142*	0.816	0.076	1.30	0.008	0	0	1	1.303
14	56.391*	0.822	0.094	5.27	0.032	0	0	1	2.391
15	93.951*	0.975	0.035	1.50	0.010	0	0	1	3.171

Table 2, Continued

Number of equation	F_a	R^2_{adj}	*S*	*MAPE*	*U1*	*UM*	*UR*	*UD*	*DW*
16	64.675*	0.841	0.088	5.75	0.030	0	0	1	1.574

Note: *F_a, R^2_{adj}, S, MAPE, U1, UM, UR, UD, DW – factual F_a-ratio, adjusted coefficient of determination, standard error of regression, mean absolute percentage error, Theil coefficient, bias proportions, regressions, perturbations, Durbin-Watson statistics, respectively; * – the level of significance of the factual F_a-ratio (> F standard) P<0.001*
Source: *developed by the authors of this study*

Thus, the OLS-regression models represented by equations (6)-(16) proved the presence of dependences *y* (mass of grain ear^{-1} of winter wheat; waxy ripeness phase) on linear combinations of factor variables x_1, x_2, x_3, x_4 (content, respectively, of MF-Fe, MF-Mn, MF-Zn, MF-Cu in grey forest soil; earing phase), each of which is included in a nonlinear mathematical expression. Specifically, in equations (6), (14) or (15), (16), the specified regularities were implemented due to the inclusion, respectively, of products of independent variables or such variables in indicators of natural powers 2-4, while in models (7)-(13) – products of factor variables, some of which are in indicators of natural powers 2-4. Notably, most of the OLS regression models (6)-(16) include x_i^2 and/or x_i^3 and/or x_i^4 in the absence of corresponding x_i (power index = 1). Such forms of equations can be interpreted as the dependence of an exogenous variable on unidentified factors that affect y simultaneously with x_i, and this influence is integrated at the level of the formation of subordination of *y* to the values of x_i^2 and/or x_i^3, and/or x_i^4 with the simultaneous levelling of dependencies on x_i (corresponding b_i=0), namely, according to semi-logarithmic or modified lognormal regularities (for partially similar, but mathematical explanations, see, e.g., (Aguilar *et al.*, 2020).

DISCUSSION

In podzolized, specifically grey forest soils, to which the substrate used in this study belongs, the typical redistribution of the silty fraction leads to the leaching of trace elements from the upper eluvial horizons and their accumulation in the illuvial ones. In turn, the depth of such processes depends on the intensity of podzolization (Fatiiev & Pashchenko, 2003). In general, low total concentrations of microelements, typical for podzolic soils, cause a deficiency of one and/or several elements in these soils. In addition, glaciation, as a result of imperfect drainage under conditions of clay enrichment and, therefore, the development of high adsorption capacity of such soils lead to Mn, Cu, Zn deficiency in the soil (Alloway, 2013). Clearly, the ability to increase the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu in the grey forest surface-glazed soil revealed in this study is an important positive feature of the applied fertilization systems.

According to the existing ideas given in the studies of Schulin *et al.* (2010), partially expanded by Vatansever *et al.* (2017), the conditions of insufficient or excessive supply of plants with trace elements have the properties to substantially change the intensity and direction of several physiological and biochemical processes, morphological features, life cycle, etc., and therefore, the values of the components of the productivity of agricultural crops. It is appropriate to assume that the improvement of the conditions of provision of mobile forms of trace elements can lead to an increase in the level and quality of the final productivity of agricultural crops. An increase in the application rate of $ZnSO_4 \cdot 7H_2O$ caused an increase in Zn-DTPA (diethylenetriaminepentaacetic acid) in the soil, optimization of the distribution of Zn in the roots, an increase in the concentration of Zn in shoots and grain, an increase in yield, elements of wheat productivity (field, vegetation experiments) (Liu *et al.*, 2017). Applying $ZnSO_4$ to the soil led to an increase in the number of ears, thousand kernel weight (TKW), yield, while foliar application of $MnSO_4$ – TKW of wheat during some years of the study (Pahlavan-Rad & Pessarakli, 2009). In the same study, significant interactive effects of Zn and Fe ($FeSO_4$, foliar feeding) caused an increase in the number of grains in the ear, TKW. Application of fertilizers containing Fe-EDDHA (ethylenediamine-N,N′-bis (2-hydroxyphenylacetic acid)), $ZnSO_4 \cdot 7H_2O$, $MnSO_4 \cdot H_2O$, $CuSO_4 \cdot 5H_2O$ caused a significant increase in grain yield, straw yield, TKW, number of seeds per ear of wheat (Ziaeian & Malakouti, 2001). DTPA-extracted micronutrients were identified as, among others, the most likely to explain the variability of wheat grain quality in artificial neural network (ANN) for hilly regions of western Iran (Ayoubi *et al.*, 2014). A significant positive correlation was found between Fe-DTPA and total yield, grain yield, TKW, Cu-DTPA and TKW, Mn-DTPA and total yield, TKW of wheat (*r*=0.21-0.61, *P*<0.01-0.05) (Ajami *et al.*, 2020).

Therewith, the scientific literature holds ambiguous assessments of the interdependencies between the content of mobile forms of micronutrients in the soil and the signs of productivity of grain crops. Admittedly, Menna (2022) documented no significant correlations between soil available Cu, Mn, Fe, Zn concentrations and total aboveground biomass or wheat grain yield. It was demonstrated that chitosan nanoparticles in a complex with Zn caused an increase in the content of Zn in grain, without affecting grain yield, protein content, the number of ears in an ear, TKW, etc. Furthermore, H. Liu *et al.* (2017) found that Fe and Zn concentrations in grain were significantly and negatively correlated with wheat grain yield. It was suggested that interdependencies between productivity and concentrations of mineral elements in the body of agricultural plants can be positive on soils depleted of mineral elements (Gregorio *et al.*, 2002). There are no potential obstacles to formulating assumptions about the presence of interdependencies between the content of mobile forms of trace elements in substrates depleted by them, specifically the considered soil, and signs of the final productivity of winter wheat grown under such conditions.

The coefficients of two-dimensional and partial correlations obtained in this study revealed a complex structure of interdependencies between exogenous (the mass of grains in ear^{-1} of winter wheat; waxy ripeness phase) and endogenous variables (the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu in the grey forest soil; earing phase), the presence of the subordination of the listed variables to factors not considered in this study. in addition, the analysed regression models, including those specified as fragments of KGP equations (6)-(16), proved that the development of winter wheat ear productivity does not depend linearly on the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu as such, in the grey forest soil, taken both separately and in the form of additive combinations. On the other hand, the indicated feature of plants is largely determined by linear combinations of interactions of trace elements among themselves (products of independent variables), as well as a number of predictors not identified in this study (independent variables in indicators of natural powers 2-4). Among other things, the latter may include several soil characteristics (pH, content of mineral components, dissolved and solid phases of organic matter, etc.), components of the rhizosphere, namely the root system of plants.

The formulated assumptions are, at least partially, consistent with experimental results and corresponding concepts existing in the scientific literature. It is known that after entering the soil system, specifically through weathering of primary minerals, trace elements are first absorbed during initial reactions, then slowly adsorbed and, thus, undergo transformations and redistribution into numerous chemical forms with different mobilities, toxicity, and bioavailability (Ali *et al.*, 2020). Some factors, including pH, ORP (Oxidation Reduction Potential), total metal concentrations, properties of trace elements, soil structure, concentrations of complexing agents (organic and inorganic), competing cations, content of organic matter (OM), etc., can affect solubility, bioavailability, uptake by plants, and movement of trace elements in the soil profile (Shukla *et al.*, 2018). Furthermore, soil pH and OM (SOM) have properties to change the direction and depth of metal ion speciation processes in the environment (Schulin *et al.*, 2010).

Partitioning between the solid and liquid phases of the soil environment may be accompanied, among other things, by competition between complexation with dissolved organic matter (DOM) and sorption/deposition, particularly of Cu and Zn, in the solid phase. In addition, ions of trace elements and common metals (e.g., Fe and K) can compete for adsorption sites (Liao *et al.*, 2021). It is known that in soils with a low Zn content (high pH and low Zn) complexation with DOM, controlled by humic and fulvic acid fractions (HA and FA), is important for the formation of available forms of this element (Klinkert & Comans, 2020). This is consistent with the predictions obtained in the same study (NICA-Donnan multisurface model) regarding the preferential binding of Zn to dissolved HA in the soil solution. Typically, Fe and Mn form poorly or insoluble oxides in soil that serve as adsorption surfaces, and yet the aforementioned Fe, Zn, and especially Cu can interact relatively easily with DOM or SOM. Therewith, Zn often stays more "soluble" than Cu (Zahedifar *et al.*, 2017). Controlling the processes of sorption/deposition, the SOM cycle has a positive effect on the solubility of trace elements, namely Fe, Mn, Zn, Cu, the ratio of water-soluble and exchangeable Fe, amorphous and crystalline Fe oxides, specifically adsorbed inorganic Mn oxide. In addition, the cycle of SOM and DOM, playing a key role in the distribution of metal ions between solid particles and the soil solution, contributes to increasing the content of available forms of trace elements, during the decomposition of the first and accumulation of the second among the indicated fractions (Zaragüeta *et al.*, 2021). It is interesting that the bioavailability of Fe, Mn, Zn, Cu correlated positively and significantly with the content of silt, clay, OC, but negatively and significantly with sand, $CaCO_3$, soil pH. Notably, for the interactions of Fe, Mn, Zn, Cu, Mg, in the context of the growth and formation of productivity of agricultural crops, antagonism occurs much more often than synergism (Rietra *et al.*, 2017). At least in part, this can be explained by competition between cations in comparable uptake mechanisms involving root cell transport systems. However, both antagonism and Liebig-synergism can occur between N and certain elements that improve symbiotic nitrogen fixation in plants, specifically Cu. Synergism of macroelements-Zn on calcareous soils, N NH_4-fertilizers-Mn under conditions of Mn-deficiency was also revealed, while the introduction of N-, S-fertilizers stimulated the production of phytosederophores and caused an increase in Zn, Fe in wheat (Rietra et al., 2017).

Considering the above, in general, the authors of this study consider it reasonable to assume that all applied fertilization systems affected the rate of SOM circulation in the grey forest surface-glazed soil under winter wheat in the earing phase. In turn, this led to changes in pH, solubility of microelements, ratios in the accumulation of Fe, Mn, Zn, Cu complexes with DOM, SOM, fine and coarse clay and silty minerals, suspended particles, etc., as well as interactions between themselves, a number of other micro- and macroelements in the soil, transport systems of root cells, rhizosphere microorganisms. Interdependencies of trace elements with the listed and probably several other soil characteristics formed a multidimensional system of predictors of the soil environment in the earing phase, which did not linearly affect the formation of the final productivity of winter wheat, levelling the expected response to the content of MF-Fe, MF-Mn, MF-Zn, MF-Cu as such. In the future, it is advisable to investigate the regularities of the formation of winter wheat productivity depending on the simultaneous influence of the listed trace elements and some agronomically important soil characteristics, specifically, potential, exchangeable, hydrolytic acidity, the degree of saturation with bases, the content of exchangeable Ca^{2+}, Mg^{2+}, easily hydrolyzable N, available P, K, water- and NaOH-soluble labile OC, etc. in the earing phase, and during spring tillering – waxy ripeness.

CONCLUSIONS

The studied ecological fertilization systems based on pea straw, pea straw + $N_{30}P_{45}K_{45}$, $N_{60}P_{90}K_{90}$, as well as solely $N_{60}P_{90}K_{90}$ led to a significant increase in the mass of grains of ear^{-1} of winter wheat (waxy ripeness phase), the content of mobile forms of Fe, Mn, Zn, Cu (earing phase) in grey forest surface-glazed soil under this culture, compared to the control (without fertilizers). There were significant Pearson correlation coefficients between mass of grains of ear^{-1} of wheat and the content of mobile forms of Fe, Mn, Zn, Cu in the soil, the corresponding contents of Mn and Zn, Cu and Zn (0.5837-0.9191, P<0.001-0.05), as well as reliable coefficients of partial correlation between the mass of grains of ear^{-1} – Cu, Mn, Zn (0.6946-0.8532, P<0.001-0.05). There is a number of strong evidences regarding the presence of complications for the presentation of the dependence of mass of grains of ear^{-1} on the content of mobile forms of Fe, Mn, Zn, Cu in the soil by meaningful and/or appropriate single- and multivariate linear and linearized nonlinear (method of least squares) or regularized least squares regression equations. As a result of the specification of such dependencies as fragments of the Kolmogorov-Gabor polynomial, their subsequent parameterization using the method of least squares, reliable, relevant one- and multifactorial regressions of the mass of grains of ear^{-1} on linear combinations of products of independent variables and/or such variables in indices of natural powers 2-4 were found. Therewith, the linear and additive subordination of mass of grains of ear^{-1} to the values of the content, as such, of mobile forms of Fe, Mn, Zn, Cu in the grey forest soil were levelled. The obtained results were interpreted as the dependence of the productivity of the ear of winter wheat on linear combinations of interactions of microelements with each other and/or unidentified in this study predictors in the multidimensional space of soil characteristics under the conditions of eco-friendly fertilization systems. In the future, it is expedient to cover the regularities of the formation of the productivity of the ear of winter wheat depending on the content of trace elements, as such, in combination with the soil characteristics not considered in this study, formed by the actions of the specified fertilization systems.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Закономірності формування продуктивності колоса пшениці озимої залежно від вмісту мікроелементів у ґрунті

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Анотація. Вивчення паттернів формування продуктивності колоса залежно від вмісту потенційно біодоступних Fe, Mn, Zn, Cu у ґрунті, стохастична формалізація таких закономірностей є важливими для поглибленого розуміння концептуальних і механістичних аспектів підпорядкованостей розвитку урожайності рівням забезпечення пшениці озимої поживними речовинами за умов екологізованих систем удобрення. Мета роботи полягала у віднаходженні статистично достовірних взаємозалежностей, значущих і релевантних одно- або багатофакторних регресійних рівнянь залежності маси зерен колос$^{-1}$ пшениці озимої від вмісту потенційно біодоступних Fe, Mn, Zn, Cu у ґрунті, аргументаціях та роз'ясненнях таких підпорядкованостей за умов екологізованих систем удобрення. У дослідженнях використано такі методи: польові, лабораторно-аналітичні, мас-спектрометричний, математико-статистичні (*t*-тест Стьюдента, *ANOVA*, кореляційний, одно- та багатофакторний регресійний аналізи). Застосовані екологізовані системи удобрення на основі *соломи* гороху *або* соломи гороху + $N_{30}P_{45}K_{45}$, або $N_{60}P_{90}K_{90}$, лише $N_{60}P_{90}K_{90}$ *викликали збільшення маси зерен колос*$^{-1}$ *пшениці озимої, вмісту рухомих форм* Fe, Mn, Zn, Cu у сірому лісовому ґрунті під цією культурою (фаза колосіння), порівняно з контролем (без добрив). Істотні й значущі коефіцієнти кореляції Пірсона між масою зерен колос$^{-1}$ пшениці й *вмістом рухомих* Fe, Mn, Zn, Cu у ґрунті, відповідними вмістами Mn і Zn, Cu і Zn, а також коефіцієнти часткової кореляції маса зерен колос$^{-1}$ – Cu, Mn – Zn засвідчили складну структуру взаємозалежностей між вивченими ознаками. Віднайдено достовірні, релевантні одно- й багатофакторні регресійні залежності маси зерен колос$^{-1}$ від лінійних комбінацій добутків незалежних змінних (вміст *рухомих* Fe, Mn, Zn, Cu у ґрунті) і/або таких змінних у показниках натуральних степенів 2-4 (фрагменти полінома Комогорова-Габора). Розкриття закономірностей формування продуктивності колоса пшениці озимої залежно від умісту потенційно біодоступних мікроелементів у ґрунті за умов екологізованих систем удобрення дозволить теоретично обґрунтувати і розробити новітні стратегії мінерально-екологічного інжинірингу систем землеробства з метою підтримання високих рівнів і біологічних безпек урожаю зазначеної культури

Ключові слова: екологізовані системи удобрення; пшениця озима; мікроелементи; кореляція; регресія