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Effects of complex of microelements and ecological factors on winter wheat productivity

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ABSTRACT

Soil properties are the most important environmental factors in the formation of the norms for the use of microelements in winter wheat cultivation. However, specific agroclimatic growing conditions and their combinations often necessitate the use of trace elements in the agroecosystem. Humus substances of different nature enriched with microelements and the content of mobile carbonates can serve as another factor in increasing yields. The micronutrient nutrition of winter wheat in the arid climate of the Northern Steppe of Ukraine on washed out chernozems, which are zonal soils of this territory under current conditions of climate change and intensive farming, has its own characteristics. The aim of the research was to study the influence of soil ecological factors on the yield of winter wheat applying foliar fertilization with microelements (Zn, Cu, B, Mo, Co, P_2O_5, K_2O) at the rate of 2.5 $L \cdot ha^{-1}$ and 5 $L \cdot ha^{-1}$. The research was conducted on ordinary low-humus, slightly and moderately leached chernozems, in the profile of which carbonates were raised due to the leaching of the upper accumulative genetic horizon and the deterioration of soil fertility. The yield of winter wheat on ordinary unwashed chernozem was 15.1% higher when applying the norm of 2.5 $L \cdot ha^{-1}$ of the microelement's preparation compared to the control, while on washed soils the effect was less – 3.6–8.8%. When applying the norm of 5 $L \cdot ha^{-1}$ of the microelements preparation on washed out soils, the yield increase was up to 12.0% on medium washed out, 9.6 on slightly washed out and 0.8% on unwashed out chernozem. The content of microelements in grain increased with the increase in the dose of microelements in the fertilizer. Under dry conditions and a large amount of plant residues from the previous crop, which contributed to an increase in water-soluble phenols and soil fatigue, it is recommended to completely abandon minimal tillage in order to avoid ploughing plant residues into the surface layer of the soil or ploughing. When the rate of microelements use was doubled (5 $L \cdot ha^{-1}$), a positive effect was observed on the eroded ordinary chernozem soils and the yield increase was on average 11.0%. The study emphasizes the importance of adapting fertilizer application practices to soil properties and climate, especially in conditions of drought and high phenol content.

Keywords: ordinary chernozem, plant nutrition, microelements, free carbonates, eroded soils, mobile phenols.

INTRODUCTION

Changes in the typical soil characteristics of the Southern Steppe of Ukraine are the result of erosion and atmospheric pollution. Under such conditions, the capacity of soil genetic horizons decreases and their fertility deteriorates. The negative consequences of such changes include the reaction of plants to micronutrient nutrition. It is very necessary in the Steppe, especially on eroded soils, where the upper genetic horizon is washed away and carbonates are pulled up to the surface (Bondar and Makarenko, 2018; *Hunchak* et al., 2022; Voitovyk et al., 2023).

The functions of each macro- and microelement are specific and no element can be replaced by another, which indicates that they are physiologically equivalent in the process of element metabolism in plants (Kryvenko, 2019; Tsentylo and Tsyuk, 2022; Maliarchuk et al., 2019).

In the context of environmental degradation due to man-made pollution, it is necessary to have the most complete information on the microelement's intake by agricultural plants. An unbalanced supply of microelements to plants is one of the most powerful factors in disrupting the normal functioning of the agroecosystems and it impacts human health (Elad et al., 2021; Derevianko et al. 2022; Yunyk and Harbar, 2022).

Qualitative indicators of public health also depend on environmental conditions, in particular, the geochemical situation. Geochemical research considers the impact of a complex of environmental microelements on the body and the relationship between them. In both humans and animals consuming substandard plant products with a microelement content below or above the standard, physiological health disorders may arise and might be irreversible (Kuzminov and Skaletska, 2015; Pryimak, 2018).

Hypomicroelementosis of exogenous origin is observed in 20% of people living in biogeochemical provinces. Iodine deficiency is the main, but not the only, cause of endemic goiter. Sufficient cobalt content in food is also important (Wong et al., 2017; Kuts et al., 2023).

The use of microelements as biostimulants for the growth and development of cereal plants can significantly increase their yield, taking into account their growing locations and physiological needs (Kaur et al., 2021; Sidorovich, 2022; Vlahoviček-Kahlina, et al., 2021).

Microelements such as Cu, Mo, Mn, Co, Zn, B increase the activity of many enzymatic systems in the plant and improve the absorption of nutrients from soil and fertilizers (Rolka and Wyszkowski, 2021). The introduction of microelements not only promotes the growth of the productive part of plants, but also stimulates root growth, increasing the absorption of moisture from deeper soil layers, especially during drought; providing shade on the soil surface and thus reducing the amount of water that evaporates unproductively. However, the opposite effect of unbalanced fertilization can also be observed, if intensive growth in the early stages of ontogeny is accompanied by drought (Das et al., 2022).

Microelements are found in plants in small amounts. However, insufficient amounts, as well as an excess of many microelements, cause adverse effects on plant growth and productivity, which affects the provision of adequate quality nutrition to humans and animals. In this regard, the problem of providing plants with microelements is increasingly gaining general biological significance (Kalenska et al., *2023;* Tsentylo et al., 2019; Balanda et al., 2022).

Microelements perform important functions in plants: they are part of enzymes, hormones, vitamins or affect their activity. Providing cultivated plants with micronutrient nutrition is one of the most important tasks in crop production, and insufficient amounts of them, especially zinc and copper, are a common problem in Ukrainian soils (Kucher et al., 2023).

Micronutrient deficiencies and the phenomenon of so-called plant 'starvation' are caused by a lack of mobile forms of microelements in soils. The amount and, most importantly, the form in which these elements are present in the soil is of great importance. Some microelements may be present in the soil in sufficient quantities, but in a form that is not available to plants. Increasing the number of microelements in crop production is possible by applying appropriate micronutrient fertilizers to the soil, especially by foliar feeding, i.e. spraying plants with a solution of microelements salts (Gholamhoseinian et al., 2020).

Many factors affect the absorption of microelements by plants, one of which is the calcium content of the soil. The most common and relatively mobile form of calcium carbonate is calcite. It is a dispersed mineral in soils that affects the acidity of the soil solution and the reaction of microelements. Carbonates reduce the mobility of microelements due to their sorption by their own highly dispersed fractions, as well as by iron and manganese oxides that are deposited on the surface of carbonates. This effect of trace elements in carbonate soils negatively affects the mineral nutrition of crops. Without trace elements, it is fundamentally impossible for plants to fully absorb fertilizers (nitrogen, phosphorus and potassium), and their lack disrupts metabolism and physiological processes in plants (Sinchenko et al., 2019).

In the context of anthropogenic soil pollution, the lack of trace elements in eroded soils is aggravated by the fact that they either have similar chemical properties to the most dangerous heavy metals or act as soil pollutants themselves (Kucher et al., 2023; Minkina et al., 2017; Vodyanitskii and Yakovlev, 2011). This disrupts the processes of plants micronutrient nutrition, which decreases the productivity of agrocenoses in general, or yields of individual crops, and provokes yields fluctuations against the background of changes in agrometeorological conditions, which have been changing significantly, especially intensively in recent years (Kucher et al., 2022; Rakhmetov et al., 2023; Osman et al., 2023).

Plant nutrition microelements play a special role on eroded chernozems due to their potentially great importance influencing the state of soil humus substances themselves, and indirectly, the destruction of pesticide residues and the state of the soil absorption complex, and the enzymatic activity of the soil (Akatova et al., 2016). Diverse participation of microelements in certain soil processes is directly related to the formation of their mobile forms (Harper, 2016).

Microfertilizers can be applied in different ways, depending on the content of mobile forms of trace elements in the soil and plants, the form of fertilizer and the biological characteristics of crops. There are three possible ways to use microfertilizers in production: seed treatment before sowing, spraying plants with solutions, and main application. Many studies are devoted to finding the optimal way to apply them (Slobodianyk et al., 2022; Prysiazhniuk et al., 2022).

It is assumed that foliar application of a complex of microelements in chelated form has a positive effect on the yield and content of nutrients in winter wheat grain on ordinary chernozems of varying degrees of erodibility, and the effectiveness of top dressing depends on the content of free carbonates in the soil and its humus content under the conditions of the arid climate of the Steppe zone of Ukraine. The aim of the study was to investigate the effect of foliar nutrition with a complex preparation of microelements in chelated form on the yield of winter wheat during drought on ordinary chernozems with varying degrees of erosion.

MATERIALS AND METHODS

Study area and limiting factors

The research was conducted on ordinary chernozems with varying degrees of erosion in the Kirovohrad Oblast, Kropyvnytskyi Rayon of the Steppe zone of Ukraine: unwashed (48° 1’6.33”N 32°13’36.16”E), weakly (48° 1’50.25”N 32°13’27.16”E) and moderately washed (48° 2’36.01”N 32°13’45.70”E). Sampling plots are shown on the map (Figure 1). Agrochemical parameters in the studied soils were performed according to the generally accepted methods (Soil Analysis Handbook of Reference Methods, 2018) (Table 1). The content of mobile forms of trace elements in the soil was determined in an ammonium acetate buffer extract with pH 4.8 by atomic absorption spectrophotometry on a S-115M1 instrument (JSC Selmi, Sumy, Ukraine). The determination of the content of trace elements (Zn, Mo, Cu, Co, B) in winter wheat grain was carried out after mineralization of plant samples by dry ashing method with subsequent treatment with nitric acid solution on an atomic absorption spectrophotometer S-115M1 with atomization in an air-acetylene flame according to the method described by the Soil and Plant Analysis Council (2018).

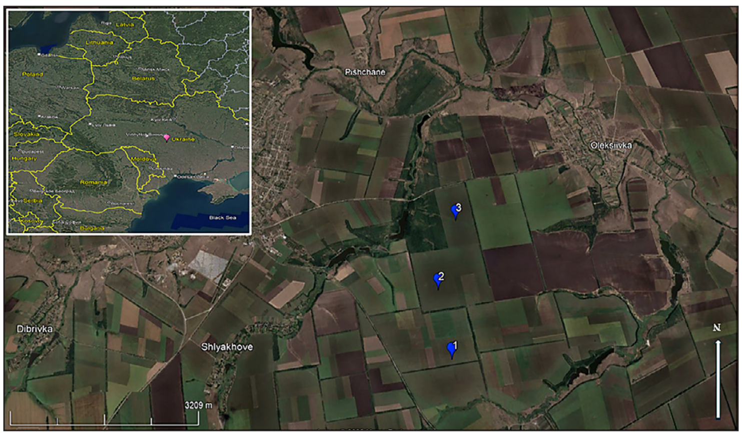

Figure 1. Geographic location of soil and grain sampling sites in the Steppe zone of Ukraine (Google Earth aerial photos): 1 – ordinary low-humus chernozem, 2 – ordinary low-humus, weakly-washed chernozem, 3 – ordinary, low-humus, medium-washed chernozem

Table 1. Agrochemical indicators of ordinary chernozems of varying degrees of erosion in the Kirovohrad Oblast, Kropyvnytskyi Rayon

Indicators	Ordinary chernozem	Ordinary weakly-washed chernozem	Ordinary medium-washed chernozem
Humus, by the Tyurin method, %	4.6	4.2	3.4
Readily hydrolyzed N, mg·kg^{-1}	148	138	112
P_2O_5, by Chirikov's method, mg·kg^{-1}	223	133	124
K_2O, by Chirikov's method, mg·kg^{-1}	235	161	159

The crop under study – winter wheat of the Kuyalnik variety – is a medium-early, drought- and heat-resistant variety. In terms of grain quality, it is one of the best varieties in Ukraine and is classified as a strong wheat variety. Flour strength is 460–510 alveograph units (a.u.), gluten content is 27.5–28.7%, protein content is 13.0–13.7%, and flour yield is 76%. The overall score of the bread is 5.0 points. It is suitable for producing high quality food grain and is one of the most productive varieties in the steppe zone of Ukraine. The previous crop in the rotation was winter rape. Soil cultivation is minimal to a depth of 12 cm.

The winter wheat was fertilized in the earing phase (the earing phase – flag leaf (VVSN 33)) with a complex preparation of microelements in chelated form, produced in Ukraine, with the recommended norms of the current methodological recommendations of Bulygin et al (2003).

The composition of the micronutrient formulation was as follows: Zn – 18.0 g·L^{-1}; Cu – 25.0 g·L^{-1}; B – 4.5 g·L^{-1}; Mo – 0.15 g·L^{-1}; Co – 0.04 g·L^{-1}; P_2O_5 – not less than 45.0 g·L^{-1}; K_2O – not less than 45.0 g·L^{-1}.The use of polysaccharides and surfactants in the preparation allows nutrients to quickly and effectively 'stick' to the leaf surface and be absorbed in full, with a reduced risk of 'running off' from the vegetative part of the plant. All experiments were carried out according to a single scheme by variants: (1) control – no micronutrient preparation was used; (2) foliar application of micronutrient preparation at a rate of 2.5 L·ha^{-1}; (3) foliar application of micronutrient preparation at a rate of 5 L·ha^{-1}. All variants used the main line fertilizer – $N_{50}P4_{0}K_{40}$.

The content of soil carbonates was determined by the method of SSU ISO 10693-2001 (2003).

Agrometeorological conditions are an important environmental factor that determines the development of plants. In year 2019, the air temperature was higher than the long-term average. At the same time, the average excess over 11 months was +2.7 °C, which is a significant value over the past seven years (Figure 2). The conditions of the active growing season of wheat plants can be characterized as drought during the heat.

Precipitation in June and July 2019 determined the accumulation of plant biomass (Figure 3). Reduced precipitation in August, against a background of high air and soil temperatures (air temperature was 2.5 °C above normal), led to the accumulation of precursor plant metabolites and plant residues in the soil in their original state, without transformation into other substances.

In September, precipitation was 3.7 times below normal. The air temperature was 3.0 °C above the long-term average. In October, the weather conditions were slightly better, but also abnormal:

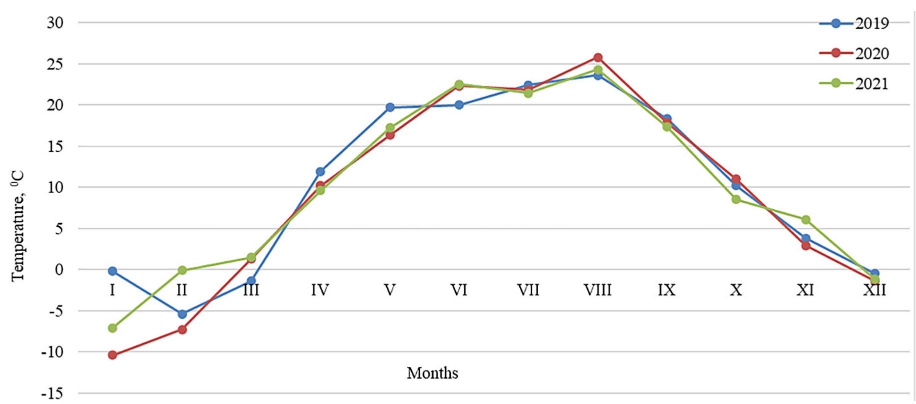

Figure 2. Average monthly air temperature at the Kropyvnytskyi weather station, Kirovohrad Oblast

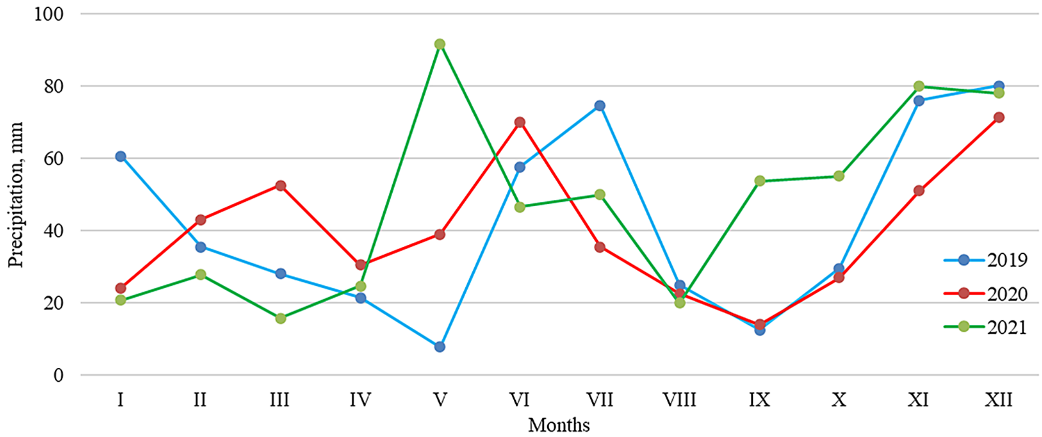

Figure 3. Average monthly precipitation at the Kropyvnytskyi weather station, Kirovohrad Oblast

precipitation was 8.1 mm below normal and the air temperature was 2.1 °C above normal.

The first effective rain fell on 19 November. The winter period was characterized by stable temperatures. In April 2020, the average monthly temperature was +10 °C.

It should be noted that over the past seven years, the value of the hydrothermal coefficient HTCV-VII has fallen below 0.78 four times (with the long-term average value for the area at 0.86). In 2019, the GTCV- VII was 0.43, in 2018 – 0.62, and in 2019 – 0.74. In the Steppe zone of Ukraine, there is a high probability of droughts and water erosion of soils as a result of sudden intense rainfall.

While the average long-term rainfall during the observations (March–August) was 269.3 mm, the rainfall in 2019 was 150.5 mm, which is 44.11% less than the long-term average. In 2020, it was 250 mm, and in 2019, 249 mm, which is 19-29% less than the long-term average, respectively.

A significant portion of precipitation was unproductive, which increased the manifestation of drought during high air temperatures in the years of observations. The pronounced negative manifestations of agrometeorological conditions in 2019–2020 led to the manifestation of soil exhaustion. Among the existing approaches to studying soil fatigue (Grodzinsky, 1991; Boiko and Holovko, 1983; Volosciuc and Josu 2013), the best research option is the direct determination of mobile forms of phenols in the soil. For this purpose, the existing method for determining phenols by Grodzinsky et al. (1983) was used, which was modified to convert them into a mobile state by sorption-exchange reactions on the highly basic cation exchanger KU-2-8, which was converted into the H^+ form. To identify the presence of phenolic compounds, soil samples were collected from areas outside the field and from experimental plots.

The results are expressed as the mean ± standard deviation (SD) of eight analytical replicates. Statistical processing of the data was carried out using ANOVA. The statistical significance of differences between the mean values was assessed using the Tukey test ($p < 0.05$), and significantly different values are indicated by different letters. All statistical calculations were conducted in Microsoft Excel (Microsoft Corporation, Redmond, WA, USA).

RESULTS AND DISCUSSION

It was found that in May there was an increase in the content of decomposition products of plant residues in the form of soluble phenolic compounds (Figure 4). Outside the field ordinary chernozem contained 3.62 mg·kg^{-1} of phenol, and the soil in the experimental fields contained 5.68–5.88 mg·kg^{-1}, which was about 62.4% higher than the healthy soil. These studies were not planned and will be continued in the future.

Studies by Misra et al. (2023) have shown that phenolic metabolites are toxic to plants, and the level determined in the high range also affects the properties of the soil. At low concentrations, phenols can have a positive effect on the availability of mineral elements of plants in the rhizosphere, and at high concentrations – a negative one. According to Grodzinski (1983), when the content of mobile phenols in the soil exceeds 5 mg/kg, microflora is suppressed, enzymes are inhibited,

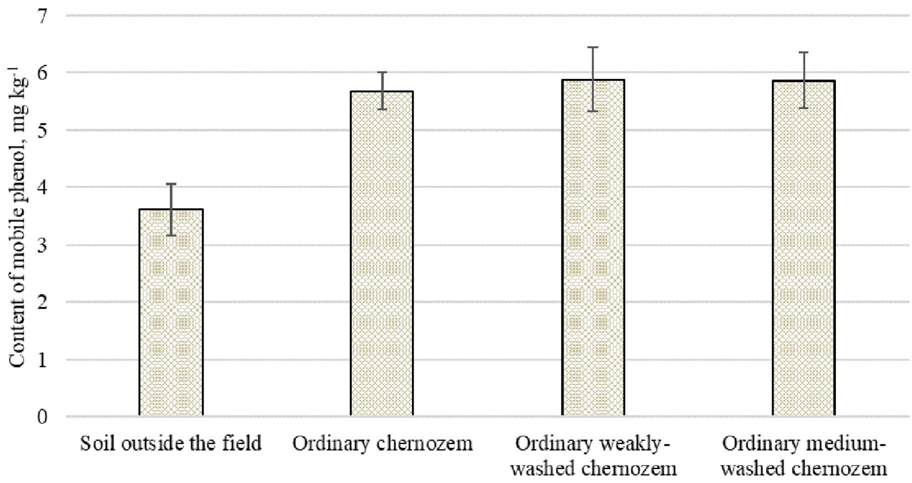

Figure 4. The content of mobile phenol in ordinary chernozems with different erosion degrees of the Steppe zone of Ukraine (x ± SD, n = 8)

and seed germination, plant growth, and fertilizer efficiency are significantly reduced.

In cases where a significant amount of predecessor crop residues remain on the field during drying against a background of high temperatures, shallow tillage should be replaced by plowing, or no tillage should be carried out (No-Till). Periodic deep soil loosening (e.g., once every 5 years) in long-term shallow tillage systems can be a reasonable agrotechnical technique to improve soil physical properties without significant negative impact. However, the effectiveness and feasibility of such a practice depend on specific conditions, such as soil type, climatic conditions and crop rotation characteristics (Peixoto et al., 2019; Bulygin et al., 2025).

Phenolic acids, such as ferulic, salicylic, and p-coumaric, can inhibit the absorption of nutrients by plants, in particular phosphorus, potassium, calcium, magnesium, and iron. These compounds alter the permeability of cell membranes, reduce the activity of ATPases and disrupt the electrochemical potential, which leads to a decrease in the efficiency of micronutrient uptake (Li et al., 2010). Phenolic compounds secreted by plants can alter microbial activity in the soil, which affects the nitrogen cycle. This can lead to a decrease in nitrogen availability to plants, especially under climatic stress conditions such as drought. Thus, phenolic compounds can negatively affect the efficiency of fertilization (Castells, 2008).

Visually, carbonates in the profile of ordinary unwashed chernozem begin to appear from a depth of 68 cm, which is noticeable as a slight boiling from 10% HCl. In eroded varieties, $CaCO_3$ appears from 56 and 40 cm, respectively. The depth of genetic horizons depending on the steepness of the slope is presented in Figure 5.

The yield obtained on the studied soils (Figure 6) varied significantly. The overall low yield of winter wheat indicates a lack of moisture due to meteorological indicators. The amount of yield is also determined by the humus content. Thus, a positive reaction to the use of high rates of the microelement preparation is observed in the experiment carried out on ordinary low-humus, weakly and moderately washed-out chernozem with a relatively low humus content (4.2–3.4%). The yield increase from the use of microelements in the form of chelates at a rate of 5.0 L·ha^{-1} was 12.03%.

On ordinary non-eroded chernozem, the increase from foliar application of a microelement preparation at a rate of 2.5 L·ha^{-1} was 15.1% of the control. At a double rate, a 16.3% increase in yield was observed compared to the control, but the increase compared to the variant with a lower dose was within the experimental error range and amounted to 0.1 t·ha^{-1}. This is explained by the fact that full-profile ordinary chernozem has average humus reserves in the upper layer and a slightly higher content of microelements. Therefore, the yield does not increase significantly compared to the variant with a lower dose of microelements with an increase of the preparation rate. On average, on the three studied soil types with a lower rate of use of the complex of microelements, the effect was positive – the yield of winter wheat increased by 9.2% relative to the control. When the rate of the microelements use was doubled (5 L·ha^{-1}), a positive effect was observed on eroded

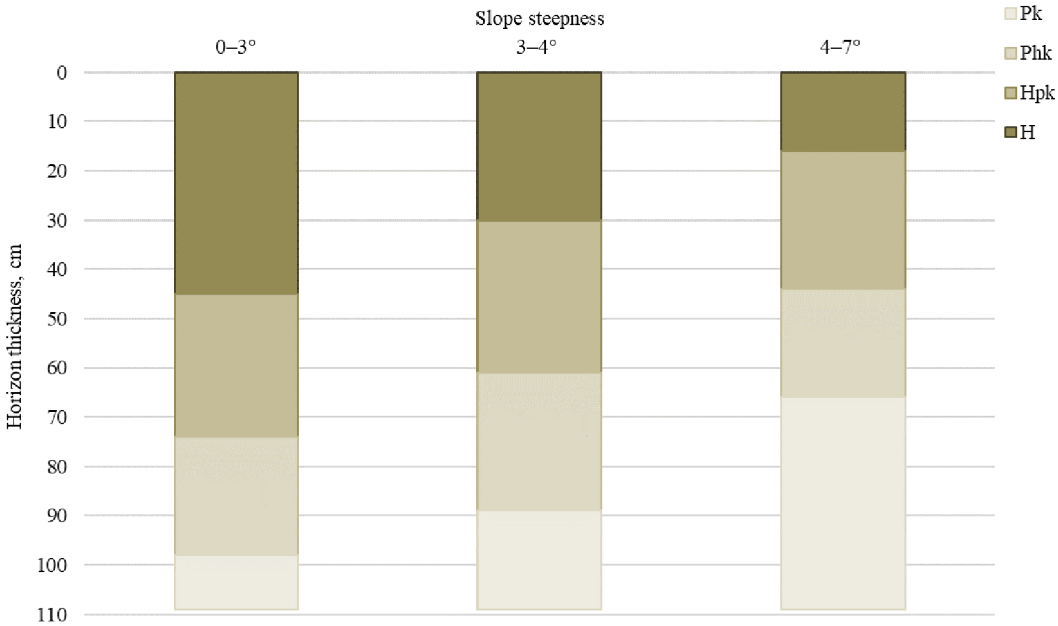

Figure 5. Depth of genetic horizons of ordinary chernozems with varying erosion degrees depending on the steepness of the slope of the Steppe zone of Ukraine

Figure 6. Winter wheat yield at different rates of microelement treatment (x ± SD, n = 8). Different letters indicate values that are significantly different within one column according to the result of the Tukey test ($p < 0.05$).

varieties of ordinary chernozem and the yield increase was on average 11%.

The content of microelements in the studied soils had a significant variation (Figure 7). Most of them were recorded in full-profile soil. With increasing erosion, the content of microelements in the upper soil layer decreased, which is explained by a decrease in the humus content, deterioration of properties and other negative processes that can be observed on eroded soils.

The content of microelements is an important component of product quality, indicating the balance of mineral composition and the value of grain products as a source of microelements in food and livestock feed. However, excessive amounts of microelements can disrupt metabolism. Zinc and copper are essential for all living organisms, but have a toxic effect when accumulated in high concentrations. That is why the content of Zn and Cu is strictly regulated by the State Standard of

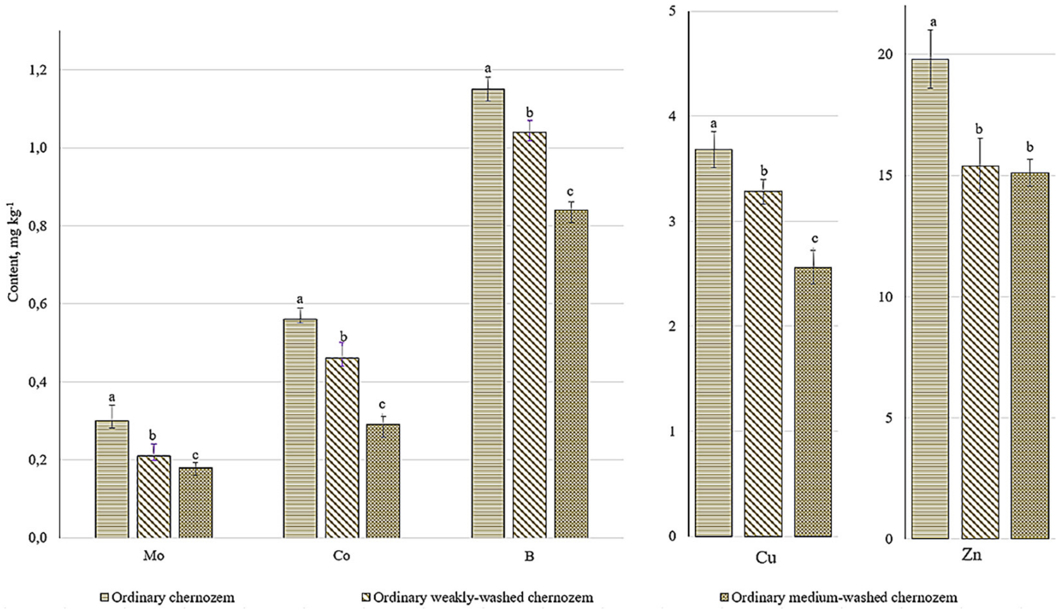

Figure 7. The content of microelements in ordinary chernozems with varying erosion degrees of the Steppe zone of Ukraine (x ± SD, n = 8). Different letters indicate values that are significantly different within one column according to the result of the Tukey test ($p < 0.05$).

Ukraine (SSU) regulations. The content of cobalt in winter wheat grain should not exceed 1 mg kg^{-1}, copper – 10–30 mg·kg^{-1}, and zinc – 50 mg·kg^{-1} (Soil Analysis Handbook of Reference Methods, 2018). The daily requirement of the human body for copper is 0.2–2.0, zinc – 12.0–15.0, molybdenum – 0.15, cobalt (vitamin B12) – 3.0, boron – 1.0–3.0 mg·kg^{-1} (Ali, 2023).

During drought the soil has insufficient amounts of molybdenum, cobalt, sulphur, and potassium (Osokina et al., 2022). The results show that increasing the level of micronutrient nutrition has a positive effect on the content of Zn, Mo, Cu, Co and B in grain (Figure 8). The highest zinc content was recorded in the 3rd fertilisation variant on non-eroded chernozem (25.2 mg·kg^{-1}), which is 27% higher compared to control (19.8 mg·kg^{-1}).

Despite the low demand for cobalt, it performs important physiological functions in plants and the human body. Its main function is related

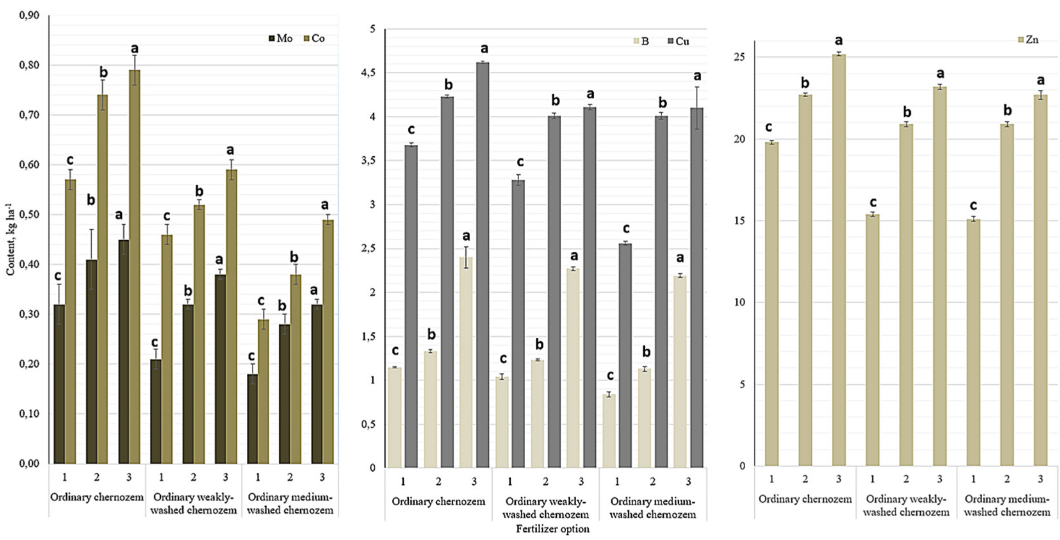

Figure 8. The content of trace elements in winter wheat grain under different rates of trace element processing in the Steppe zone of Ukraine (x ± SD, n = 8**).** Different letters indicate values that are significantly different within one column according to the result of the Tukey test ($p < 0.05$).

to the fact that it is part of the structure of vitamin B12 (cyanocobalamin). Therefore, the main biological role of the element is to participate in hematopoiesis (Genchi et al., 2023). The highest content of the trace element was recorded in the third fertilization option and was 0.81 mg·kg^{-1}, which is 0.25 mg·kg^{-1} more than in the control and 0.07 mg·kg^{-1} more than in the second fertilization option. Winter wheat grain grown on eroded varieties of ordinary chernozem contained less of this trace element and had an average supply in the control. The increase of the trace element in grain under the second fertilization option was 0.06–0.09 mg·kg^{-1}, and under the application of 5 L·ha^{-1} of trace elements – 0.13–0.20 mg·kg^{-1}.

Molybdenum is involved in carbohydrate, nitrogen and phosphorus metabolism, the synthesis of vitamins and chlorophyll, increases the intensity of photosynthesis, and is part of the nitroreductase enzyme, which reduces nitrates to ammonia in plants (Mishra et al., 2024). Molybdenum is involved in oxidative processes in the human body, triggering the conversion of oxygen and nutrients into energy, which is necessary to maintain the functioning of tissues and cells. The concentration of molybdenum varied from 0.18 mg·kg-1 (control, medium-washed chernozem) to 0.45 mg·kg^{-1} (variant 3, non-eroded chernozem). However, the application of a double dose of the micronutrient preparation did not result in any significant increase in the content of microelements due to the pronounced degradation processes in these soils. Foliar application of the micronutrient preparation increased copper content, reaching 4.62 mg·kg^{-1} in variant 3 (non-eroded chernozem) against 2.56 mg·kg^{-1} in the control (medium-washed chernozem). The boron content also increased with increasing fertilization levels, reaching 2.40 mg·kg^{-1} in treatment 3 (non-eroded chernozem), which is more than twice as high as in the control.

When foliar feeding plants under drought conditions, microelements should have a direct positive effect, as evidenced by the accumulated experience (Breus et al., 2022; Bilousova et al., 2021; Litvinova and Dehodiuk, 2020). However, the effect of trace elements can act as an additional stress on plants during the inhibition of photosynthetic processes during soil moisture deficit and high air temperature, as well as in case of non-compliance with the application technology (Pikovska, 2020; Faligowska et al., 2019).

Foliar application is the most effective and safe for the environment. This method of micronutrient fertilization significantly reduces losses compared to soil application. If the technology is followed, losses do not exceed 5% (Fernández and Eichert, 2009). For environmentally safe application, it is necessary to conduct regular soil monitoring, control that the level of micronutrients remains within optimal agronomic and ecological thresholds, and observe crop rotation.

Main element that plays a fundamental role in the theoretical model of the determining factors of the soil agroecosystem is the quantitative distribution of free carbonates in the soil. In arid conditions, the response of plants to the

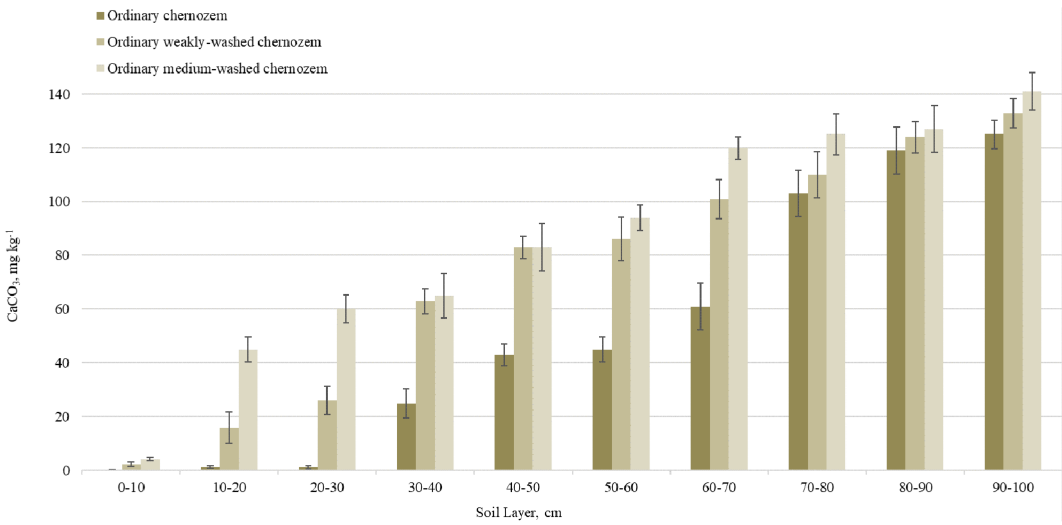

Figure 9. Carbonate content in ordinary chernozem with varying leaching degrees during winter wheat cultivation (x ± SD, n = 8)

use of microelements through foliar feeding had a certain dependence on the content of free-soil carbonates.

Carbonates are compounds that greatly reduce the mobility of trace elements and heavy metals in soils. The mechanism of this action is due to both the sorption properties of highly dispersed carbonate fractions and their indirect effect through the regulation of environment reactions.

The amount of mobile carbonates begins to increase significantly from a depth of 20 cm on slightly washed soils (Figure 9). The positive effect of foliar feeding of plants with microelements at a rate of 5.0 L·ha^{-1} is also observed on these soils. The soil layer of 20–30 cm can be characterized as the physical depth of the first geochemical barrier relative to physiologically important trace elements for plants. However, the overall yield level was higher on the soil, where the carbonate content begins to increase from a greater depth (40 cm). It is important to note that the overall reaction of plants to foliar feeding of plants with microelements, in the latter case, was maximum and the yield increase was +15.1%.

In the 0-20 cm layer, the bulk of the root system of winter wheat is located (Faligowska, 2019). Carbonates of chernozem soils have a ‘dynamic’ nature of origin. They are accumulated through migration from other soil horizons and as newly formed carbonates due to the action of the root system and soil microorganisms. These are the so-called functionally active carbonates in the leaching layer, which smoothly transitions to the horizon of pulsation-migration processes and further to the layer of intensive illuvial processes (Bulygin et al., 2019).

Establishing the relationship between winter wheat yield and carbonate content allows for a more competent crop management policy, taking into account the spatial distribution of carbonates and the significant variation in the content of trace elements in the chernozem of the Ukrainian Steppe (Wyszkowski and Brodowska, 2020).

CONCLUSIONS

In dry years with intense soil and air drought, certain effects of the use of microelement preparations on winter wheat were noted. The yield of winter wheat on unwashed ordinary chernozem was 15.1% higher with the use of 2.5 L·ha^{-1} a of microelements compared to the control, while on washed soils the effect was less – 8.8–3.6%. When applying 5 L·ha^{-1} of the preparation on washed out soils, the yield increase was up to 12.03% on medium washed out, 9.6% on slightly washed out and 0.8% on unwashed out chernozem. Outside the field, ordinary chernozem contained 3.62 mg·kg^{-1} of mobile phenol, and the soil in the experimental fields contained 5.68–5.88 mg·kg^{-1}, which was about 62.4% higher than the healthy soil. Therefore, under such conditions, it is impossible to carry out minimum tillage to a depth of 12 cm. Ploughing or no tillage is recommended. The best way to reduce the negative effects of soil stress on plants was the foliar application of the chelated form of the microelements preparation at a rate of 5 L·ha^{-1} on medium-eroded chernozem, and on poorly eroded and full-profile soil, the application rate of 2.5 L·ha^{-1} was sufficient. The positive effect of foliar nutrition of plants with microelements at a dose of 5.0 L·ha^{-1} was observed in experiments where the carbonate content began to increase sharply from a depth of 20 cm. The overall level of yield was higher on ordinary chernozem where the carbonate content begins to increase from a depth of 40 cm. The research provides a scientific basis for optimizing the use of micronutrient foliar fertilization in erosion-prone agroecosystems. Integrating soil-specific application rates into regional agronomic practices can improve winter wheat productivity and support sustainable land use under climate stress conditions.

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