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THE N:K RATIO IN CHERNOZEM AND CROPS UNDER DIFFERENT FERTILISATION PRACTICES AND CLIMATE CHANGE

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Abstract: Despite nutrient stoichiometry is widely applied to assess plant nutrition, agronomists in Ukraine traditionally use absolute test values. To address this gap, the temporal variability of the N:K ratio in soil and plant tissues was considered in a long-term field experiment (1971–2017) investigating the effects of different potassium fertilisation systems on crop rotation productivity in the northeastern Ukraine (Kharkiv region). The study compared the aftereffect of a high potassium background (1800 kg ha^{-1}) and the systematic application of mineral fertilisers (NPK) at single and double rates within the crop rotation. Available K in Chernozem was positively correlated with annual precipitation, influencing the stoichiometric balance in plant tissues. Under dry conditions, the N:K ratio narrowed significantly, particularly with potassium-only fertilisation. In contrast, balanced NPK application maintained an N:K ratio comparable to that observed under optimal moisture conditions. The relationship between available K and water highlights the need to use stoichiometric relationships, including the N:K ratio, for balanced plant nutrition in the context of climate change. Overall, potassium fertilisation enhanced crop rotation productivity and contributed to a more stable nutrient ratio balance.

Key words: available potassium content, N:K ratio, Chernozem, fertilisers, climate change.

Introduction

Balanced crop nutrition is critical to global food security in the context of climate change, as it strongly influences plants' water use efficiency (Roy et al., 2006). Among the basic nutrients, potassium is as significant as nitrogen and phosphorus, especially for plant enzyme systems (Marschner, 2012; DaCosta and Huang, 2006), transpiration, water balance, and root moisture absorption, which are crucial for increasing plant resistance to droughts or spring frosts (Galmés et al., 2007; Kaldenhoff et al., 2008). Potassium deficiency inhibits protein synthesis, leading to the disrupted nitrogen metabolism.

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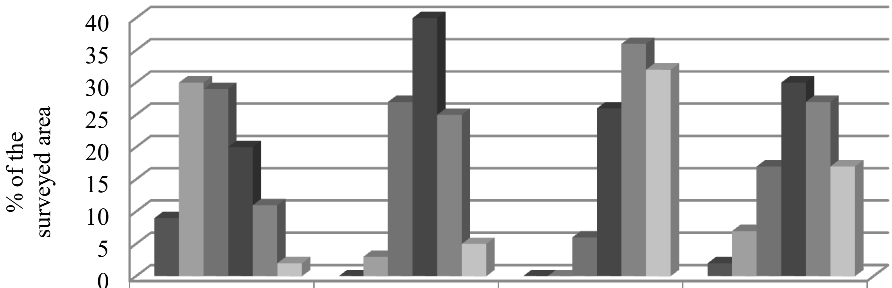
Unfortunately, around 20% of agricultural soils worldwide are potassium deficient, especially in East Asia, Southeast Asia, Latin America and sub-Saharan Africa (Brownlie et al., 2024). Despite varying data reliability, the global trend over recent decades has shown that more potassium is removed from soil than is applied (Zörb et al., 2014). Large agricultural areas are reportedly deficient in 'crop-available' soil potassium (Römheld and Kirkby, 2010). Negative soil potassium balances lead to crop yield losses (Murrell et al., 2021) and to the depletion of crop-available potassium, thereby threatening crop productivity and food security in many countries (Sheldrick et al., 2002).

The available potassium content in soils of Ukraine varies widely due to the different mineralogy and hydrothermal conditions. According to the latest agrochemical survey, more than 55% of the studied area has an increased and high level of available potassium (Figure 1). According to the current Ukrainian gradation system for soil potassium availability, soils are categorised based on their available potassium content (determined by the Chirikov method).



	Polissya	Forest steppe	Steppe	Ukraine as a whole
Very low	9	0	0	2
Low	30	3	0	7
Medium	29	27	6	17
Increased	20	40	26	30
High	11	25	36	27
Very high	2	5	32	17

Figure 1. Distribution of arable land in Ukraine by the available potassium supply, %.
Source: Institute for Soil Protection of Ukraine, 2020.

The following ranges are used: very low (<20 mg/kg of soil), low (21–40 mg/kg), medium (41–80 mg/kg), increased (81–120 mg/kg), high (121–180 mg/kg), and very high (>180 mg/kg). Moisture deficiency, even in soils with a very high potassium content, can limit potassium uptake by plants. As a result, the effectiveness of potassium fertilisers in Ukraine tends to decrease from the more humid western regions toward the drier eastern and south-eastern regions (Khristenko and Istomina, 2013). Overall, the potassium deficit in the arable soils of Ukraine ranges from 11.2 to 43.2 kg per ha (Figure 2).

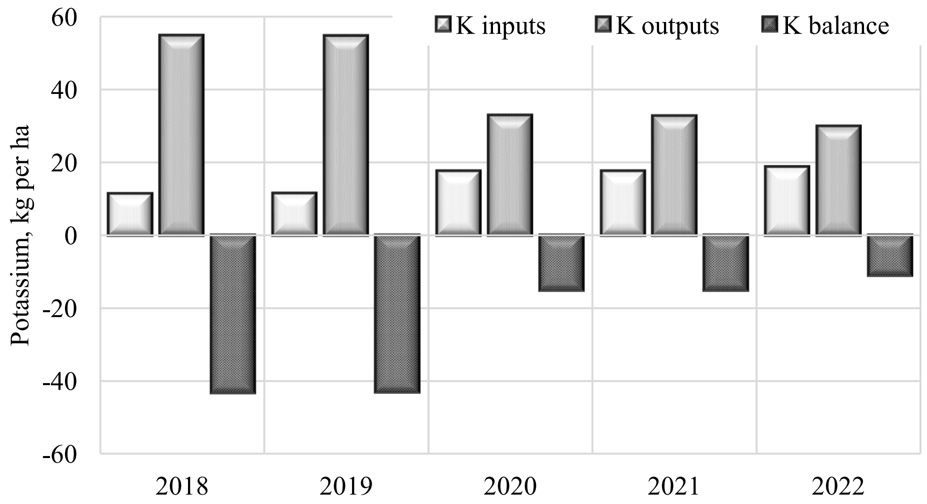


Figure 2. Dynamics of potassium balance in the arable land of Ukraine (2018–2022).
Source: Authors' systematization based on data from the State Statistics Service of Ukraine.

Unfortunately, since 2017, no official information has been available on the supply of potassium fertilisers from domestic producers; therefore, current demand is met entirely through imports. In 2023, the total application of mineral fertilisers in Ukraine amounted to 0.99 million tonnes of nutrients in active substance, including 0.18 million tonnes of K_2O (State Statistics Service of Ukraine, 2023). Nitrogen fertilisers strongly dominate the structure of fertiliser use, resulting in an N:K ratio of 1:0.18. This ratio is considerably wider than the global average (1:0.37) and the average reported for developed countries (1:0.55) (Li et al., 2019).

Previous studies have shown that the balance of nutrients in the soil may exert a stronger influence on plant biomass than their absolute concentrations (Bakare and Osemwota, 2021; Ji et al., 2022). Therefore, investigating the temporal dynamics of the N:K ratio in Ukrainian Chernozems is of particular importance.

A better understanding of how environmental changes affect soil K availability and plant uptake is essential for sustainable soil management. Therefore, we investigated the dynamics of soil potassium in relation to changes in weather conditions, particularly precipitation, as well as temporal variability in the N:K ratio. In addition, we assessed the effects of different potassium fertilisation systems on crop productivity and the N:K ratio across various crops.

Material and Methods

This study was conducted in the long-term field experiments established in 1969 at the Grakivske Experimental Farm, NSC "ISSAR named after O.N. Sokolovsky", in the Kharkiv region of Ukraine. The field experiment was established after ploughing up a 40-year fallow. The coordinates of the field experiment are 49˚46′ N, 39˚40′S. The soil is a *Luvic Chernozem* heavy loam (IUSS Working Group WRB, 2022). Before the experiment began, the arable soil layer had a pH_{KCl} of 5.4, SOC of 2.32%, a clay content of 50–52%, 45 mg per kg available P_2O_5, and 80 mg per kg available K_2O (both determined by the Chirikov method). In 1969–70, medium, elevated, and high levels of nitrogen (N), phosphorus (P), potassium (K), and NPK background were created by applying high rates of mineral fertilisers: three-fold application of 200, 400 and 600 kg/ha. These experimental backgrounds were established to assess the effect and aftereffect of high rates of various mineral fertilisers on chernozem soil fertility indicators, and to determine the duration of these aftereffects. The six-field crop rotation included peas-with-oats for green fodder, winter wheat, sugar beet, barley, maize silage and, again, winter wheat. Further, mineral fertilisers were applied to these backgrounds systematically according to the crop needs: $N_{60}P_{60}K_{60}$ (single dose) or $N_{120}P_{120}K_{120}$ (double dose) for wheat; $N_{90}P_{90}K_{90}$ or $N_{180}P_{180}K_{180}$, respectively, for sugar beet and maize silage. Peas-with-oats and barley were affected by the fertilisers applied to the previous crop. Since 1989, all experimental plots have been divided into two parts: one half continued to be fertilised systematically, and the other half simulated the crop production without fertiliser, studying their aftereffects. Each experimental plot covered 148.5 m², and the study was performed in triplicate.

Soil samples were collected from the 0–20-cm layer in triplicate to determine mineral nitrogen (N) and available potassium (K). Each composite sample consisted of six individual subsamples (1 dm³ each). Available potassium was determined by the Chirikov method following extraction with 0.5 N CH_3COOH. Nitrate nitrogen (NO_3^-–N) was measured photometrically using disulfophenolic acid, while ammonium nitrogen (NH_4^+–N) was determined photometrically with the Nessler's reagent.

Nitrogen and potassium contents in plant material were determined according to the Measurement Method "Plants. Determination of total forms of nitrogen, phosphorus, potassium in a single portion of plant material" (MBB 31-497058-019-2005), which describes the procedure for determining total nitrogen, phosphorus, and potassium in plant samples. The method is based on the digestion of organic matter with boiling sulphuric acid in the presence of a catalyst, resulting in the formation of ammonium salts. Nitrogen and potassium were subsequently quantified in the hydrolysate using a Spekol spectrophotometer. Plant samples were analysed after harvest.

The classification of years as dry or wet in the field experiment was based on the total annual precipitation. Years with less than 500 mm of precipitation were defined as dry, whereas those with more than 500 mm were classified as wet. The threshold of 500 mm was selected because it approximates the long-term climatic norm for large parts of Ukraine, particularly within the forest-steppe and steppe zones, where annual precipitation typically ranges around this value. In these regions, total precipitation below 500 mm is generally associated with soil moisture deficits and an increased risk of drought stress for crops, while precipitation above this level is usually sufficient to ensure favourable moisture conditions during the growing season. This binary classification allowed a clear comparison of soil nutrient dynamics and crop responses under contrasting moisture conditions.

To assess long-term patterns in precipitation distribution between warm and cold periods (1970–2017), the time series data were smoothed using robust regression. This approach was applied to minimise the influence of random extreme precipitation events that could distort trend estimation. Unlike ordinary least squares regression, robust regression reduces the weight of observations with large residuals through an iterative reweighting procedure, thereby limiting the impact of anomalously wet or dry years while retaining all observations in the dataset. This method allowed for a more stable estimation of long-term trends in precipitation distribution between seasonal periods without excluding extreme climatic events. The smoothed values were subsequently used to analyse temporal variability and to compare precipitation patterns between warm and cold seasons.

Statistical analysis was performed using STATISTICA 13.5.0.17. Analysis of variance (ANOVA) was conducted, and treatment means were compared using the least significant difference (LSD) test at $P < 0.05$.

Results and Discussion

Over the 55 years of the experiment, the contents of mineral nitrogen and available potassium in the soil were measured a different number of times – 42 and 99 measurements, respectively. A synthesis of these data indicates a clear relationship with annual precipitation. As shown in Figure 3A, the correlation between precipitation and mineral nitrogen in Chernozem was stronger than that between precipitation and available potassium (Figure 3B).

During periods of increased rainfall, nitrate forms of nitrogen are readily transported with soil moisture, so the total amount of precipitation has a strong influence on the dynamics of mineral nitrogen in the arable layer. In contrast, potassium is subject to non-exchangeable fixation. Depending on soil texture and mineralogical composition, the fixation capacity for potassium can vary widely (Murrell et al., 2021). Although Ukrainian Chernozems are characterised by high natural fertility, they also exhibit intensive fixation of potassium by clay minerals.

Consequently, precipitation dynamics exert a weaker influence on the content of available potassium in Chernozem compared with mineral nitrogen.

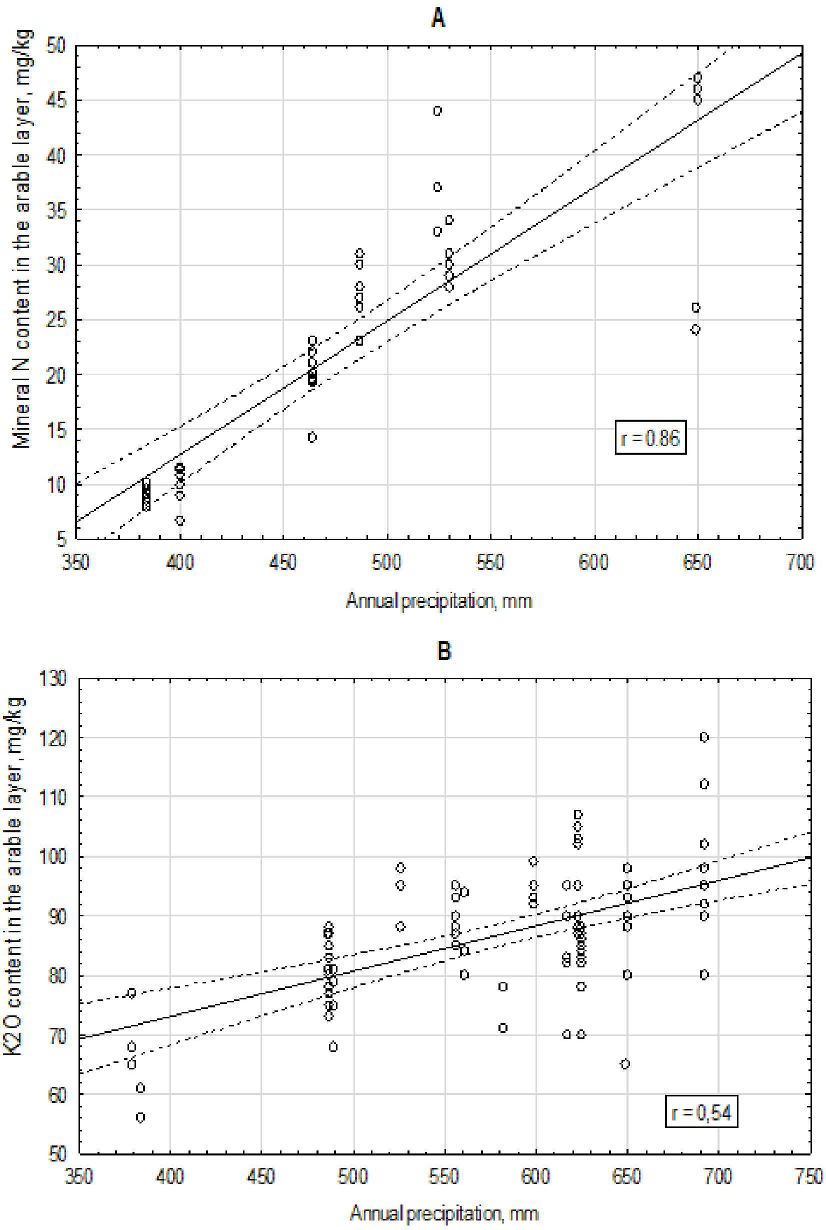


Figure 3. Relationship between the contents of N (A) and K (B) in the arable soil layer and annual precipitation.

Source: Authors' systematization based on own original research.

According to the regression analysis, an increase in annual precipitation of 50 mm was associated with an increase in mineral nitrogen content of 6 mg N kg^{-1}, whereas the content of available potassium increased by only 3.8 mg K_2O kg^{-1}. The relatively large dispersion of the experimental data around the regression line can be explained by the heterogeneity of the dataset, which included measurements obtained under different fertilisation regimes: unfertilised plots, as well as plots receiving single and double doses of NPK fertilisers.

According to Adamenko (2019), the average annual precipitation in Ukraine has decreased by 7–12% over recent decades, mainly during the June–September period. Observations from our long-term field experiment partially support this trend (Figure 4). A robust regression approach was used to smooth random outliers in the dataset. This analysis revealed cyclical fluctuations in annual precipitation. At the same time, an overall decreasing trend was observed, primarily due to reduced precipitation during the warm season. In contrast, precipitation during the cold season tends to increase.

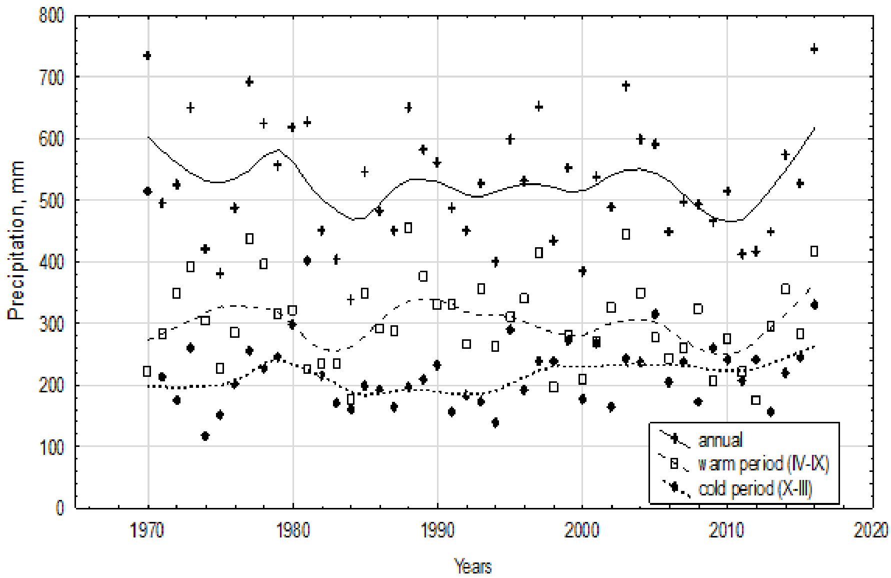


Figure 4. Distribution of precipitation during warm and cold periods (1970–2017).
Source: Authors' systematization based on own original research.

Statistical analysis revealed a significant change in the soil N:K ratio over time (Figure 5). Between 1970 and 1989, when very high fertiliser doses were applied three times to establish the agrochemical background, the average N:K ratio ranged from 0.35 to 0.40. These results demonstrate that a specific nutrient balance in the soil can be deliberately established through the systematic fertiliser application. During this period, the variability of the N:K ratio increased substantially. This reflects the different processes governing nitrogen and potassium in the soil, including plant uptake, fixation, and migration. Since 1989, the soil N:K ratio has declined markedly, mainly due to greater losses of mineral nitrogen compared with potassium.

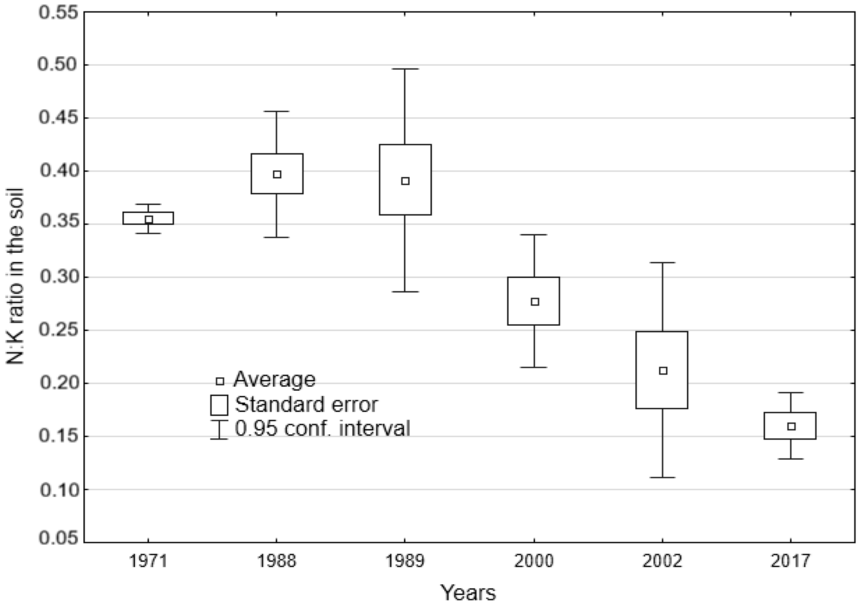


Figure 5. Long-term dynamics of the N:K ratio in the arable layer of Chernozem soil (1971–2017).
Source: Authors' systematization based on own original research.

In recent decades, prolonged droughts during the growing season have become more frequent in Ukraine. This trend negatively affects the efficiency of potassium uptake even in soils with a high content of available potassium (Khristenko and Istomina, 2013). At the same time, results from our long-term experiment indicate a positive crop response to potassium fertilisation (Figure 6). On average, over the period 1971–2017, the yield of cereal grains (barley and wheat) under a high potassium background exceeded that of the unfertilised control but did not surpass 4.5 t per ha. As shown earlier, the high potassium background (1800 kg per ha) significantly increased crop yields at the beginning of the experiment; however, this positive effect gradually diminished over time without annual fertiliser application (Nosko and Hladkikh, 2011). In contrast, the systematic application of single and double doses of mineral fertilisers, including potassium fertilizers, increased the crop rotation yield to 5.5–6.5 t per ha in feed units, in proportion to the applied fertiliser dose (Figure 6).

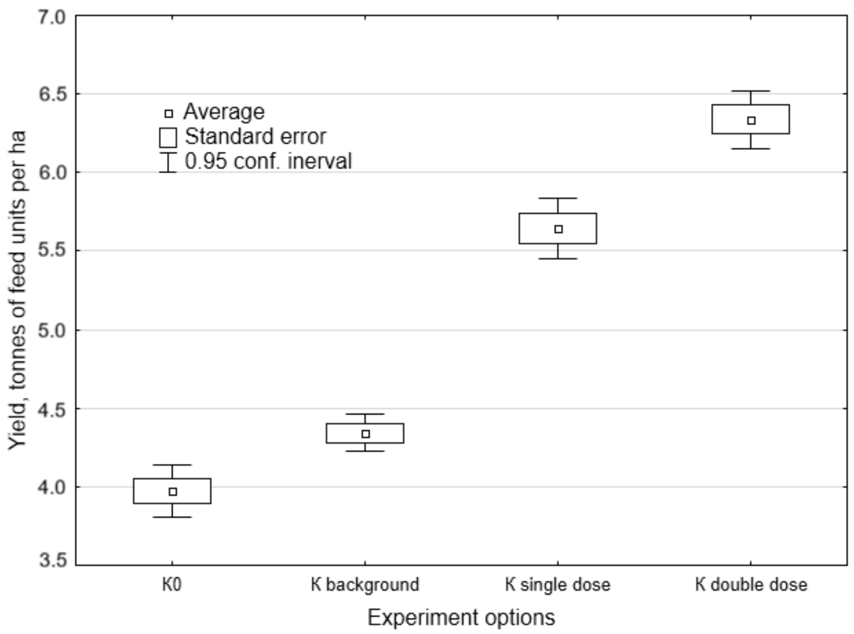


Figure 6. Crop rotation yield depending on the potassium fertiliser options.
Source: Authors' systematization based on own original research.

Our experiment demonstrates a clear dependence of the crop N:K ratio on both the soil N:K ratio and precipitation. To examine this relationship, the dataset for 1971–2017 was divided into years with adequate and insufficient moisture. The results showed that under dry conditions, the N:K ratio in plant tissues of crops was significantly lower in both the K_0 treatment and under the high potassium background (Figure 7). In cereal grains (barley and wheat), the decrease in the N:K ratio in tissues under dry conditions occurred mainly due to reduced nitrogen uptake by plants (by 1.2–1.4 times), while the potassium concentration remained relatively constant. In sugar beet, the decrease in the N:K ratio was caused by a sharp decline in nitrogen concentration (by 3.2–3.5 times) combined with a simultaneous increase in potassium concentration (by 1.8–2.0 times). This pattern likely reflects growth inhibition of sugar beet under insufficient water supply: although potassium concentration increases in plant tissues, the total potassium uptake by the crop remains considerably lower.

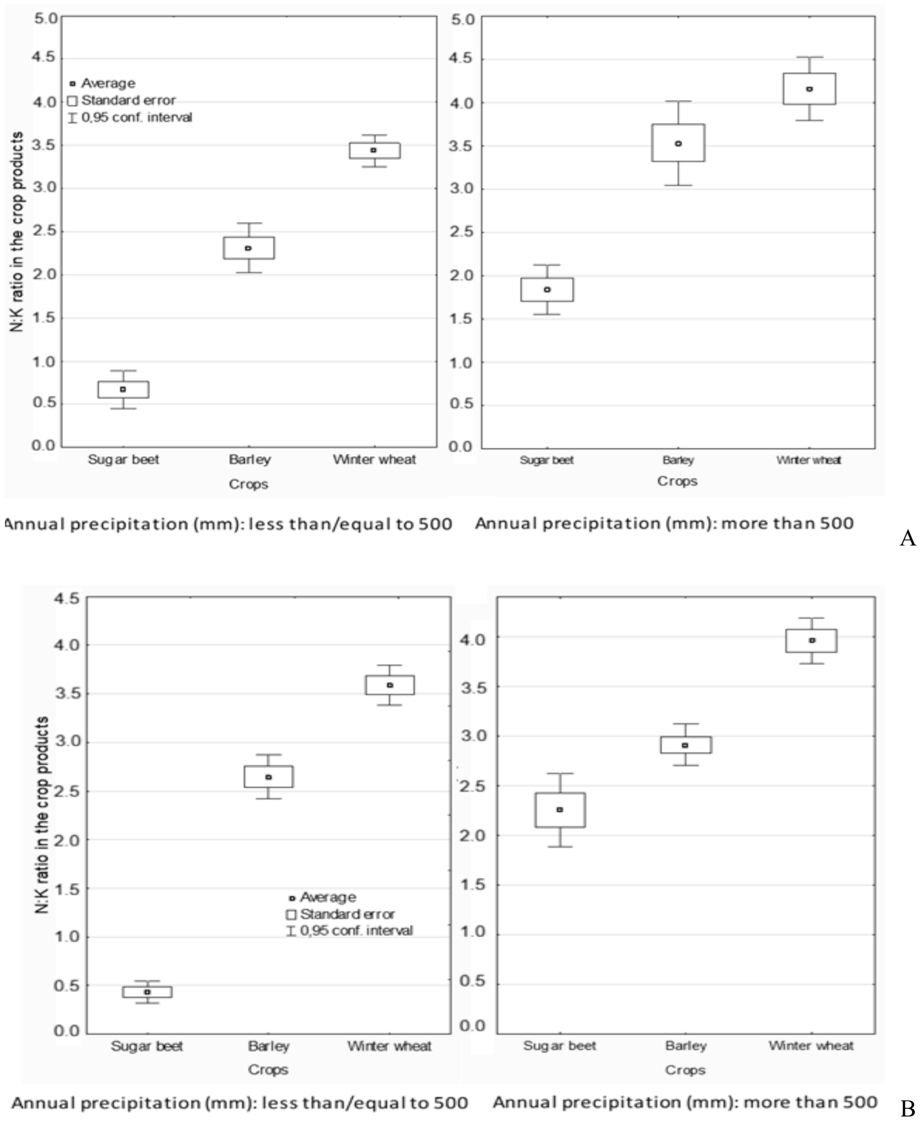


Figure 7. N:K ratio in plant tissues during years with different annual precipitation for the treatments: (A) K0 (no K application) and (B) K background fertilisation.
Source: Authors' systematization based on own original research.

With systematic fertilisation (single and double K rates), the N:K ratio in plant tissues of sugar beet roots and winter wheat grain remained stable regardless of precipitation (Figure 8).

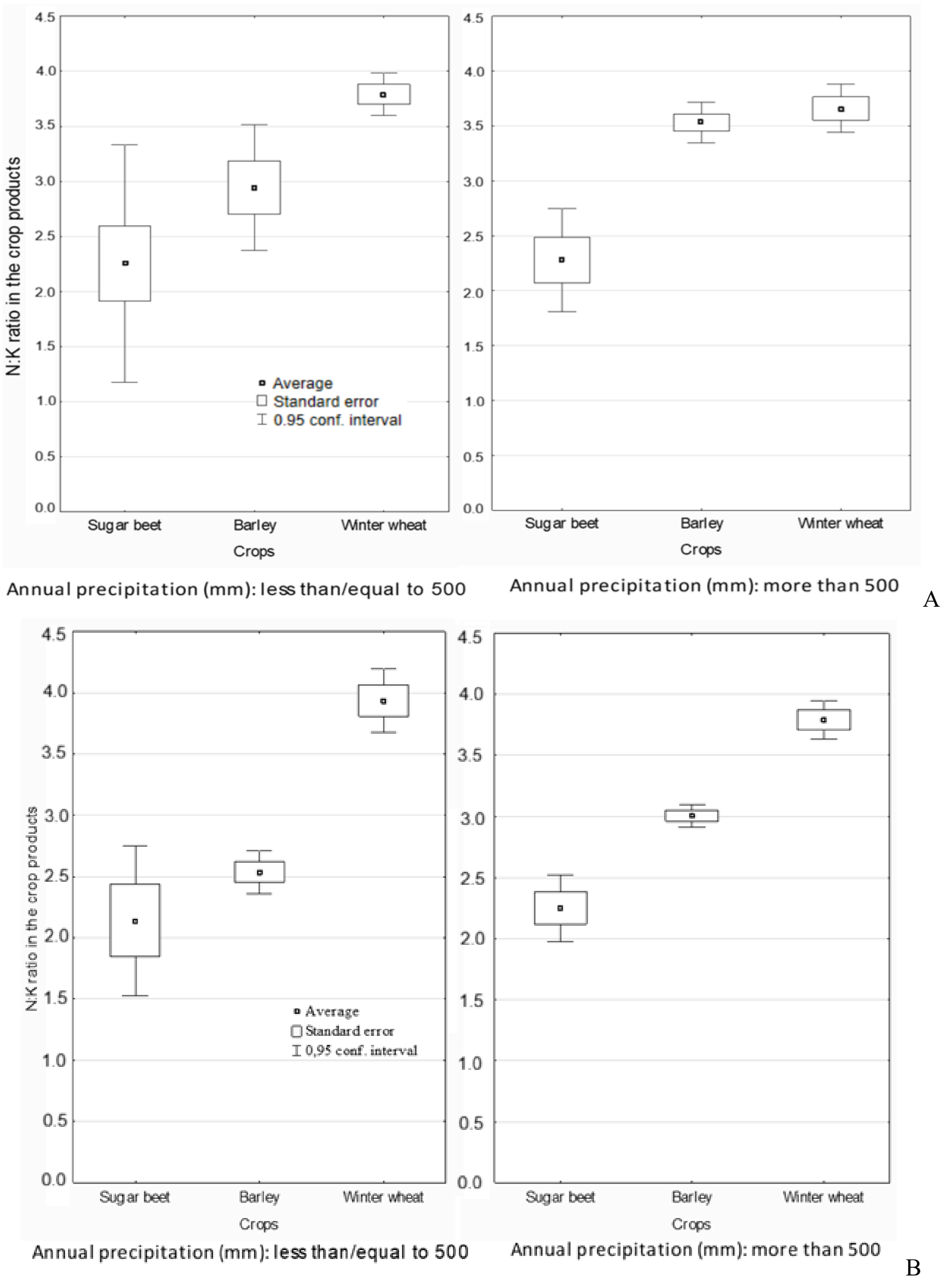


Figure 8. N:K ratio in crops during years with different levels of annual precipitation: (A) single K application and (B) double K application.
Source: Authors' systematization based on own original research.

This finding highlights the importance of balanced plant nutrition, as complete fertilisers (NPK) with a constant N:K ratio were applied in these treatments. Under these conditions, the N:K ratio in plant tissues was close to the standard values reported for nutrient uptake by crops (2.6 for sugar beet, 3.4 for barley, and 4.3 for winter wheat) (Baliuk et al., 2011). In contrast, in the K_0 treatment and under the potassium background without systematic fertilisation, the N:K ratio in crop products corresponded to these standard values only under optimal moisture conditions.

It is known that the broad-scale patterns of soil K reserves are predominantly controlled by climates (Francos et al., 2016; Pogromska, 2021). Temperature and precipitation determine the availability and uptake of essential nutrients, leading to their fluctuations over time (Su et al., 2019). Li et al. (2021) have found that precipitation and temperature affect soil potassium variations both directly and indirectly by influencing key soil properties. Hence, the seasonal dynamics of nutrient content in the soil might be quite high. On the contrary, the study by Kariuki et al. (2010) in eastern Oklahoma concluded that temporal variability did not exist for Mehlich 3 P and K but was significant for nitrogen (NO_3-N).

Our results from the long-term field experiment (Figure 3B) also demonstrate a strong correlation between the content of available soil potassium and precipitation dynamics, with reduced humidity leading to lower potassium concentrations. This is likely related to biological and geochemical processes, such as fixation, release, and weathering, which alter soil K levels (Dixon et al., 2016). Consequently, climate change leading to increased aridity limits nutrient availability and, in turn, alters nutrient ratios in plant tissues (Briat et al., 2020).

In general, numerous studies across different soil types have shown that the soil N:P:K ratio significantly affects the availability and uptake efficiency of these elements by plants, and consequently influences overall crop yield and quality (Ziadi et al., 2008; Luo et al., 2016; Briat et al., 2020; Bakare and Osemwota, 2021; Ji et al., 2022). In particular, Briat et al. (2020) concluded that plant critical levels and potassium uptake dynamics largely depend on soil nitrogen supply, indicating strong N:K interactions. Bakare and Osemwota (2021) also observed that the soil N:P:K ratio affects the availability of N and K in maize. A similar pattern was observed in our field experiment, where the N:K ratio in plant tissues was significantly lower under dry conditions without nitrogen application on a potassium background, compared with optimal moisture (Figure 6). In contrast, systematic NPK fertiliser application brought the N:K ratio in plant tissues closer to standard nutritional values, regardless of annual precipitation (Figure 7). The standard values of nutrient content in plant tissues adopted in Ukraine are given in the publication by Baliuk et al. (2011).

The positive effects of potassium are known not only in terms of plant quality, particularly under weather stress, but also in terms of yield. Mouttaqi et al. (2022)

and Malakouti and Majidi (2019) demonstrated that potassium fertilisation positively influences agronomic performance, including key characteristics of durum wheat, such as yield and thousand-grain weight. Other studies have shown that applying K fertilisers increases seed yield in mung bean and improves important yield components, including thousand-seed weight, plant height, seeds per pod, and first pod height (Eroğlu and Önder, 2023; Chantal et al., 2019). In our long-term field experiment (Figure 5), different potassium fertilisation strategies also had a positive impact on cereal grain productivity (barley and wheat). Even the application of potassium fertilisers alone, as a base dressing or through residual effects, significantly increased yield compared with the control (K0).

Our research highlights the increasing importance of balanced potassium nutrition for plants under conditions of global climate change. The close relationship between plant K status and water availability underscores the need to examine potassium in the context of its stoichiometric relationships with other nutrients. As noted by Sardans and Peñuelas (2015), potassium uptake is strongly dependent on water availability, while at the same time K plays a key role in plant water-use strategies. This creates a paradox: the greater the plant's demand for potassium under drought conditions, the more limited its uptake becomes. In this context, maintaining an adequate supply of available potassium in the root zone may serve as an important buffer against the effects of spring and summer droughts. This statement is consistent with the findings of other researchers regarding the role of potassium fertilisation under conditions of insufficient moisture. Grzebisz et al. (2013) have demonstrated that inadequate K supply during critical growth stages of wheat, maize, and sugar beet reduces the development of yield components. Improving potassium nutrition under water-deficit conditions also enhances plant access to other essential resources, including nitrogen and water. A similar effect of potash fertilisation on legumes was reported by Nisha and Narender (2022).

The need to balance nitrogen and potassium nutrition stems from the physiological roles of these elements in plant growth. Both N and K are highly dynamic in the plant–soil system and play key roles in photosynthesis and the subsequent transport of assimilates. Imbalances in their levels within photosynthetic organelles can lead to excessive or insufficient assimilation, ultimately affecting sugar metabolism and photosynthetic carbon assimilation (Shah et al., 2024). Shu et al. (2024) have reported that net photosynthetic rate, stomatal conductance, and intercellular CO_2 concentration initially increase and then decline with increasing N application, whereas K fertilisation has a positive effect on these parameters. Results from our long-term field experiment clearly demonstrate that systematic NPK fertiliser application prevented imbalances between nitrogen and potassium in both soil and plant tissues.

Conclusion

The content of available potassium in the Chernozem of Ukraine is positively correlated with the annual amount of precipitation. However, over recent decades, average precipitation has declined, contributing to a gradual decrease in the N:K ratio in these soils. Quantitatively, an increase in annual precipitation of 50 mm was associated with an increase in mineral nitrogen of 6 mg/kg, whereas the corresponding rise in K_2O was only 3.8 mg/kg, indicating a more pronounced response of nitrogen availability to improved moisture conditions. Balanced fertilisation was found to stabilise the N:K ratio in plant tissues. Under dry growing-season conditions, the absence of fertilisation or the application of potassium fertilisers alone narrowed the N:K ratio. In contrast, systematic application of NPK fertilisers maintained the N:K ratio within the standard range, and under these conditions the ratio was not affected by annual precipitation variability. Overall, high efficiency was demonstrated for various potassium fertilisation systems, including the application of elevated potassium doses to build up soil reserves. These approaches contributed significantly to enhanced crop rotation productivity, confirming the agronomic and ecological importance of balanced potassium management in Chernozem soils. Studies have shown that improving balanced potassium nutrition in plants is particularly important in the context of global climate change, as it enhances the uptake of other essential resources, including nitrogen and water.

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ODNOS N:K U ČERNOZEMU I USEVIMA PRI RAZLIČITIM PRAKSAMA ĐUBRENJA I U USLOVIMA KLIMATSKIH PROMENA

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R e z i m e

Iako se stehiometrija hranljivih materija široko primenjuje u proceni ishrane biljaka, agronomi u Ukrajini tradicionalno koriste apsolutne rezultate istraživanja. Da bi se prevazišao ovaj jaz, razmatrana je vremenska varijabilnost odnosa N:K u zemljištu i biljnim tkivima u dugoročnom poljskom ogledu (1971–2017) ispitivanjem uticaja različitih sistema đubrenja kalijumom na produktivnost plodoreda u severoistočnoj Ukrajini (Harkovska oblast). U istraživanju je upoređivan rezidualni uticaj visokog početnog nivoa kalijuma (1800 kg ha^{-1}) i sistematske primene mineralnih đubriva (NPK) u jednostrukim i dvostrukim dozama u okviru plodoreda. Dostupni K u černozemu bio je u pozitivnoj korelaciji sa godišnjom količinom padavina, što je uticalo na stehiometrijsku ravnotežu u biljnim tkivima. U sušnim uslovima, odnos N:K se značajno sužavao, posebno pri đubrenju samo kalijumom. Nasuprot tome, uravnotežena primena NPK đubriva održavala je odnos N:K uporedivim sa onim koji se javlja u uslovima optimalne vlažnosti. Odnos između raspoloživog kalijuma i vode ukazuje na potrebu korišćenja stehiometrijskih odnosa, uključujući i odnos N:K, radi uravnotežene ishrane biljaka u kontekstu klimatskih promena. Uopšteno gledano, đubrenje kalijumom poboljšalo je produktivnost plodoreda i doprinelo je stabilnijoj ravnoteži odnosa hranljivih materija.

Ključne reči: sadržaj raspoloživog kalijuma, odnos N:K, černozem, đubriva, klimatske promene.

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