Research Findings

Photo by G. Peskovski.

Efficiency of Potassium Application in Relation to Nitrogen Fertilization Level in Winter Wheat, Grain Maize, and Sugar Beet Cultivated in Western Ukraine

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Abstract

Agricultural production in the countries of the former USSR sharply declined during the end of the 20th century and has only started its recovery during the last 10-15 years. The destruction of the agricultural systems led to the abandonment of well-rooted practices, particularly those of mineral nutrition, the reconstitution of which is currently a major challenge. The objectives of the present study were to reassess, demonstrate, and discuss the efficiency of potassium (K) application in relation to nitrogen (N) fertilization level in winter wheat, maize, and sugar beet production in Western Ukraine. Here, the main results obtained for the three crops during a 3-year research project are reported briefly. Field trials were conducted over three growing seasons (2012-2014) on a shallow, slightly loamy Chernozem, low in organic matter (OM) content. Each trial consisted of

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nine treatments, the first of which was a non-fertilized control. The other eight treatments consisted of four rates of K application on top of two N levels (120 and 180 kg ha^{-1}), and an even phosphorus (P) application within a crop. The yields of the non-fertilized control of winter wheat and sugar beet corresponded with the mean annual yields obtained in recent years, highlighting the existing poor level of basic mineral nutrition in those two crops in Ukraine. On the other hand, the large difference between the non-fertilized control and the mean annual yields in maize demonstrates the significant progress made recently in the cultivation of this crop in Ukraine. Adequate N and P application is a prerequisite for achieving significant yields and improved quality in all three crops. On top of this, increased K application also brought about significant improvement in yield and quality parameters. Interactive relationships occurred between N and K uptake, where increased K application promoted N uptake, and vice versa. In all three crops, maximum yield, produce quality, and net income were obtained at the highest rates of K application tested. However, for winter wheat and sugar beet, the maximum has not yet been achieved, thus a further increase in the annual K dose should be examined from an economic viewpoint. In maize, on the other hand, additional K application is not expected to provide any higher yields. Nevertheless, annual K dose distribution during the season according to the progress of crop developmental stages, particularly in wheat and sugar beet, should be examined to achieve further improvements in yield and quality.

Map 1. Map of Ukraine, Western Polissya, the region where the experimental work took place, is indicated by a red circle. *Source*: https://www.studentnewsdaily.com/.

Introduction

Agricultural production in the countries of the former USSR sharply declined during the end of the 20th century and has only started its recovery during the last 10-15 years. In the context of the current economic and food-price crisis, Russia, Ukraine, and Kazakhstan might be presented with a window of opportunity to reemerge on the global agricultural market, if they succeed in increasing their productivity. However, the future of their agriculture is highly sensitive to a combination of internal and external factors, such as institutional changes, land-use changes, climate variability and change, and global economic trends. The future of this region's grain production is likely to have a significant impact on the global and regional food security over the next decades. (Lioubimtseva and Henebry, 2012).

Winter wheat (*Triticum aestivum*) is the leading crop in Ukraine, which has been historically known as the 'breadbasket of Europe'. Winter wheat is usually sown in the autumn to emerge and establish a vegetative crown before being covered by a thick protective layer of snow throughout the winter. In the spring, the crown evokes tillers that differentiate and elongate later on to carry ears with grains. Harvest takes place during late summer and the yields are determined by the number of reproductive heads, the number of grains per ear, and the grain weight. In spite of the relatively stable area of harvested winter wheat in Ukraine for the previous three decades (5-7 million ha), annual production has fluctuated considerably. On top of normal year-to-year variation, a clear decline can be noticed from 1990 to 2003, with a quite steady increase thereafter (Fig. 1). Linked to the vast political changes and the consequent economic collapse, this pattern is attributed to the dissociation of the previous agricultural systems, and the reorganization of new ones. The decline and the later rise of the mean annual yield may be a good indicator for the changing culture of mineral nutrition. Well-rooted practices were abandoned during the agro-economic crisis, and new concepts and methods are now being examined and adopted. Mineral fertilizer use has been increasing steadily for over 10 years, and the higher application rates have likely contributed to a concurrent increasing trend in wheat yield. Although in recent years, the government has not been providing direct subsidies to grain and oilseed producers, Ministry of Agriculture reports

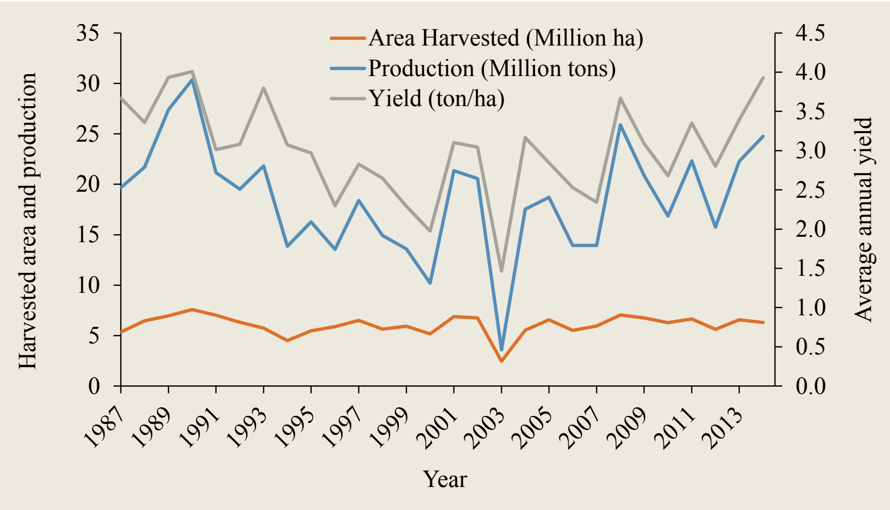

Fig. 1. Wheat production in Ukraine: Harvested area, production, and average wheat grain yields. *Data source:* http://www.indexmundi.com/agriculture/?country=ua&commodity=wheat.

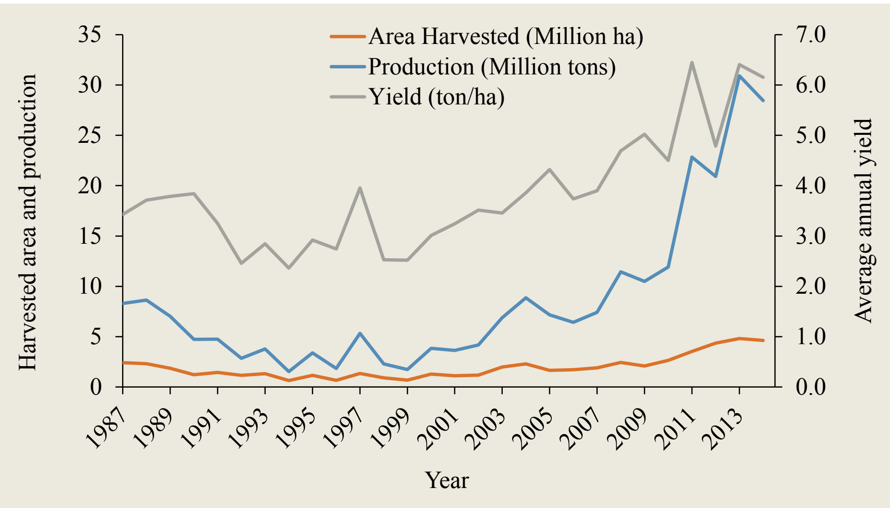

Fig. 2. Maize production in Ukraine: Harvested area, production, and average maize grain yields. *Data source:* http://www.indexmundi.com/agriculture/?country=ua&commodity=corn.

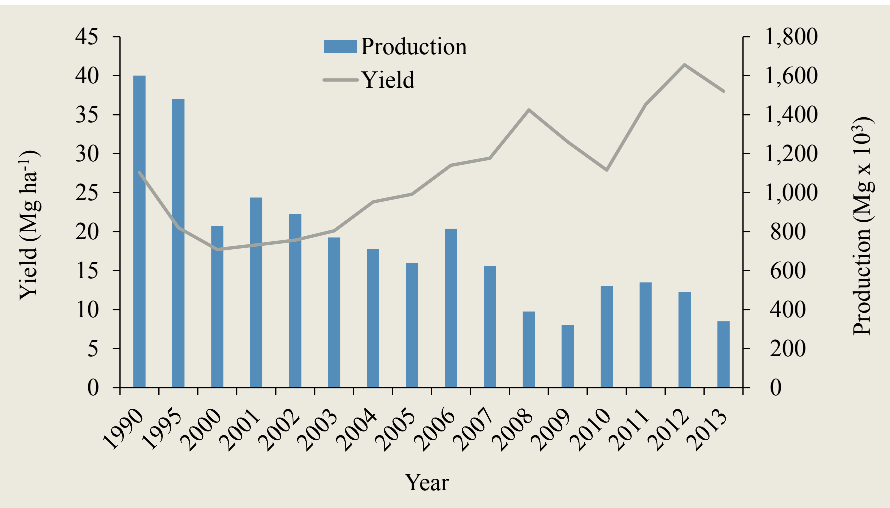

Fig. 3. Sugar beet production in Ukraine: Annual production and yield (Dubinyuk and Hager, 2013).

and private commodity analysts indicate that mineral-fertilizer application will increase again (Lindeman, 2013).

Maize (*Zea mays* subsp. mays) is a relatively new crop in Ukraine. Being cold-intolerant, maize must be planted in the spring in the temperate zones. As a C_4 plant, maize is considerably more water-efficient than C_3 plants like the small grains, alfalfa and soybeans. However, having a shallow root system, maize is very sensitive to drought, particularly at silk emergence, when the flowers are ready for pollination. Silage maize is harvested while the plant is green and the fruit immature. Field maize is left in the field very late in the autumn to thoroughly dry the grain. In the past, maize in Ukraine was grown mainly for animal feed. At present, Ukraine has experienced a remarkable boost in maize production; from 2000 to 2013 the harvested area grew four-fold, and the yield doubled from 3 to about 6 Mg ha^{-1} (Fig. 2). Producing more than 30 million Mg a year with an export rate of 60%, Ukraine was catapulted to the world's second maize exporter, after USA and alongside Argentina and Brazil (Olearchyk and Terazono, 2013).

Ukraine's geographic position, availability of favourable soil and good climatic conditions make it potentially attractive for growing sugar beet (*Beta vulgaris* L.). In recent years, however, sugar beet production has experienced deregulation in Ukraine. Thus, sugar beet production area has been declining over the last two decades (Fig. 3). The main factors stimulating this decline are lack of export markets for Ukrainian refined beet sugar, domestic sugar market oversupply, large stocks, and consequent decline in the domestic market price of sugar (Dubinyuk and Hager, 2013). As a result, producers have lost interest in this crop which is very important in crop rotation, sugar factories are working inefficiently, unemployment in rural areas has increased, and sugar has even been increasingly imported into Ukraine.

There are two issues that might shed more optimistic light on this gloomy situation. The first is associated with the steadily increasing demand of fuel and energy resources, the dependence of Ukraine on the import of natural gas, oil and its derivatives, and a complicated ecological situation, all of which have made biofuel production in Ukraine extremely important and promising. Experience of other countries, such as the US, Brazil, and European countries indicates the effectiveness of processing agricultural raw materials and organic waste into biofuels. Thus, the establishment of bioethanol production based on sugar beet seems an attractive solution to the above mentioned problems, a solution which may reconstruct the declining sugar beet industry in Ukraine (Pryshliak, 2014). The second issue is that in spite of declining production, mean annual yields have steadily increased (Fig. 3), providing evidence of significant improvements in agricultural practices and organization.

Despite the impressive increases in the mean annual yields of the three major crops, these are still related to the lower level of yields, when compared to achievements made in other countries sharing similar climate conditions (Chuan *et al.*, 2013). Further increasing yields and quality is the primary challenge of these crops in Ukraine. Realizing the potential yields is undoubtedly involved with significant improvement of mineral fertilization practices and concepts. While the nitrogen (N) and phosphorus (P) requirements are quite well disseminated to farmers, potassium (K) receives much less attention. The principal contribution of K application to most crops is well-documented (Pettigrew, 2008). Yet, the implementation of this principle always requires experimental work aimed to adapt practices to local conditions, and to demonstrate possible advantages at agricultural as well as economic levels.

The present study objectives were to reassess, demonstrate and discuss the K (MOP) application efficiency in relation to N fertilization level in winter wheat, maize, and sugar beet production in Western Ukraine. Here, the main results obtained for the three crops during a 3-year research project are presented briefly.

Materials and methods

Experimental work was carried out during the growing seasons of 2012, 2013, and 2014 at the Institute of Agriculture of Western Polissya in Western Ukraine. The trials were conducted on a shallow, slightly loamy Chernozem, low in organic matter (OM) content. Over the three growing seasons, the following agrochemical properties were measured in the topsoil: soil pH, OM content, available P_2O_5 and exchangeable K_2O (DSTU, 2005), and hydrolysable N (Cornfield, 1960). Detailed description of the experimental setup is presented in Tables 1 and 2.

Each trial consisted of nine treatments, the first of which was a non-fertilized control. The other eight treatments consisted of four K application rates on top of two N levels and an even P application within a crop (Table 2). Each of the nine treatment was replicated four times. Fertilizer application rates shown in NPK

Table 1. Technical details and soil properties referring to the three experimental sites and crops.

Crop	Cultivar	Preceding crop	Sowing time	Sowing rate	Topsoil properties				
					pH	OM	Avail. P_2O_5	Exch. K_2O	Hydrol. N
				m^{-2}		%	--------$mg\ kg^{-1}$ soil--------		
Wheat	Voloshkova	Winter rapeseed	30-09-2012	5×10^6	6.74	1.71	173	120	139
Maize	Mariin 190 SV	Winter wheat		6×10^5	6.15	1.83	220	107	106
Sugar beet	Shevchenkovsky	Winter wheat	04-2014		6.40	2.13	220	102	111

Table 2. Detailed NPK doses applied in each treatment.

Treatment		Control	N_1PK_1	N_1PK_2	N_1PK_3	N_1PK_4	N_2PK_1	N_2PK_2	N_2PK_3	N_2PK_4
			---------------------------$kg\ ha^{-1}$---------------------------							
Wheat	N	0	120	120	120	120	180	180	180	180
	P	0	70	70	70	70	70	70	70	70
	K	0	0	60	90	120	0	60	90	120
Maize	N	0	120	120	120	120	180	180	180	180
	P	0	90	90	90	90	90	90	90	90
	K	0	0	60	120	180	0	60	120	180
Sugar beet	N	0	120	120	120	120	180	180	180	180
	P	0	160	160	160	160	160	160	160	160
	K	0	0	80	160	240	0	80	160	240

terms refer to N, P_2O_5, and K_2O supply in kg ha^{-1}, respectively. Similarly, nutrient concentrations in plant biomass were recorded in terms of N, P_2O_5, and K_2O percent of dry weight. Plot size was 89 m^2, from which 50 m^2 were harvested. The fertilizers used were ammonium nitrate (AN), mono-ammonium phosphate (MAP), and muriate of potash (MOP), all of which were applied by hand.

In winter wheat, production analyses included mean grain yield, number of productive tillers per m^2, plant height, ear length, grains per ear, grain weight per ear, and the weight of a thousand grains. Nitrogen, P, and K concentrations were determined in the grain and straw. Grain quality was measured in terms of protein and gluten content. Production analyses of maize included the number of productive plants per m^2, plant height, number of cobs per plant, cob weight, number of grains per cob, weight of 1,000 grains, and overall grain yield. Nitrogen, P, and K concentrations were determined in the grain and straw. Protein content was determined in the grains. In sugar beet, N, P, and K contents were determined in the leaves and roots at harvest as well as root yield, root sugar content, and refined sugar yield. Economic efficiency of fertilizer application for each crop was established for the various treatments in terms of net income as UAH (Ukranian Hryvnia). This was calculated using the marginal yield addition obtained due to fertilizer treatment compared to no fertilizer, subtracting the additional expenses required.

Results

Very similar results were obtained each year for the crops studied. To simplify, we report on the findings of 2013 for winter wheat, and those of 2014 for the two other crops.

Winter wheat

Potassium fertilization significantly enhanced uptake of both N and K, as indicated by the increased concentrations of these elements in plant biomass. In comparison to both NP treatments (without K), the application of 60-90 kg K_2O per ha (with N and P) brought about an N increase of 0.7-1.2 mg g^{-1} grains. Nitrogen concentration in the straw was the highest at $N_{180}P_{70}K_{60}$ (4.9 mg N g^{-1}). Potassium concentrations in the grain ranged from 5.3-6.6 mg g^{-1}. Under K application, K concentration in the straw ranged from 9.4-13 mg g^{-1}, with the highest value obtained in the highest N K treatment ($N_{180}P_{70}K_{120}$).

Grain yield analysis (Fig. 4A) demonstrates that N application at rates of 120 and 180 kg ha^{-1} contributed 1.15 and 2 Mg ha^{-1}, respectively (together with P at a rate of 70 kg ha^{-1}), above the basal yield of 4 Mg ha^{-1} obtained with the unfertilized, control treatment. Yield response to K application levels was linear, preserving the primary advantage obtained by the higher N level. Thus, each kg of K application contributed 5.1-5.7 kg grains ha^{-1}, irrespective of the other fertilizers' application rates.

Photo by IPI.

Further analyses revealed the direct influence of fertilizer application on the yield components. It appears that the basal rate of N and P ($N_{120}P_{70}$) had a profound effect on the productive tillers, the number of which up surged from 489 to 569 per m^2 (16.4%). The marginal effect of a further increase in N rate ($N_{180}P_{70}$) was smaller, giving rise to an additional 4% only. Potassium application resulted in a linear effect, in which each kg of K fertilizer yielded an increase of about 2,500 productive tillers per ha (Fig. 4B). The number of grains per ear increased by 5-6% in response to NP fertilization. The effect of K application on this parameter was significant and positive, but it seemed to gradually decline with increasing K rate (Fig. 4C). Thus, while the linear component of the function indicated approximately 3% increase per kg K ha^{-1} applied, the marginal effect would be much smaller at the higher K doses. While NP application gave rise to 11-16% increase in the grain weight, K application did not have any significant influence on this yield component (Fig. 4D). Potassium fertilization did not affect plant height nor ear length.

Grain quality, in terms of protein and gluten content, reached its maximum at the $N_{180}P_{70}K_{60}$ treatment, with 13.2% protein, of which 25.8% was gluten; increasing K rates did not bring about any further improvement in quality. Nevertheless, due to K influence on grain yield, the highest net income was obtained at the highest K rate (treatment $N_{180}P_{70}K_{120}$) - 1067 UAH ha^{-1}.

Maize

Nitrogen uptake, as indicated by N concentration in plant biomass, was increased by K application and ranged from 8.5-11 mg g^{-1}, which was higher by up to 2.6 mg g^{-1} than in the control NPK_0 plants. Potassium uptake also increased, ranging from 13.1-15.7 mg g^{-1} plant biomass, and was higher by 0.8-2.8 mg g^{-1} than in NPK_0 plants. The K application effect was also pronounced in the grains at harvest, with increases of 0.8-1.3, 1.2, and 0.3-1.1 mg of N, P_2O_5, and K_2O, respectively, per g dry weight.

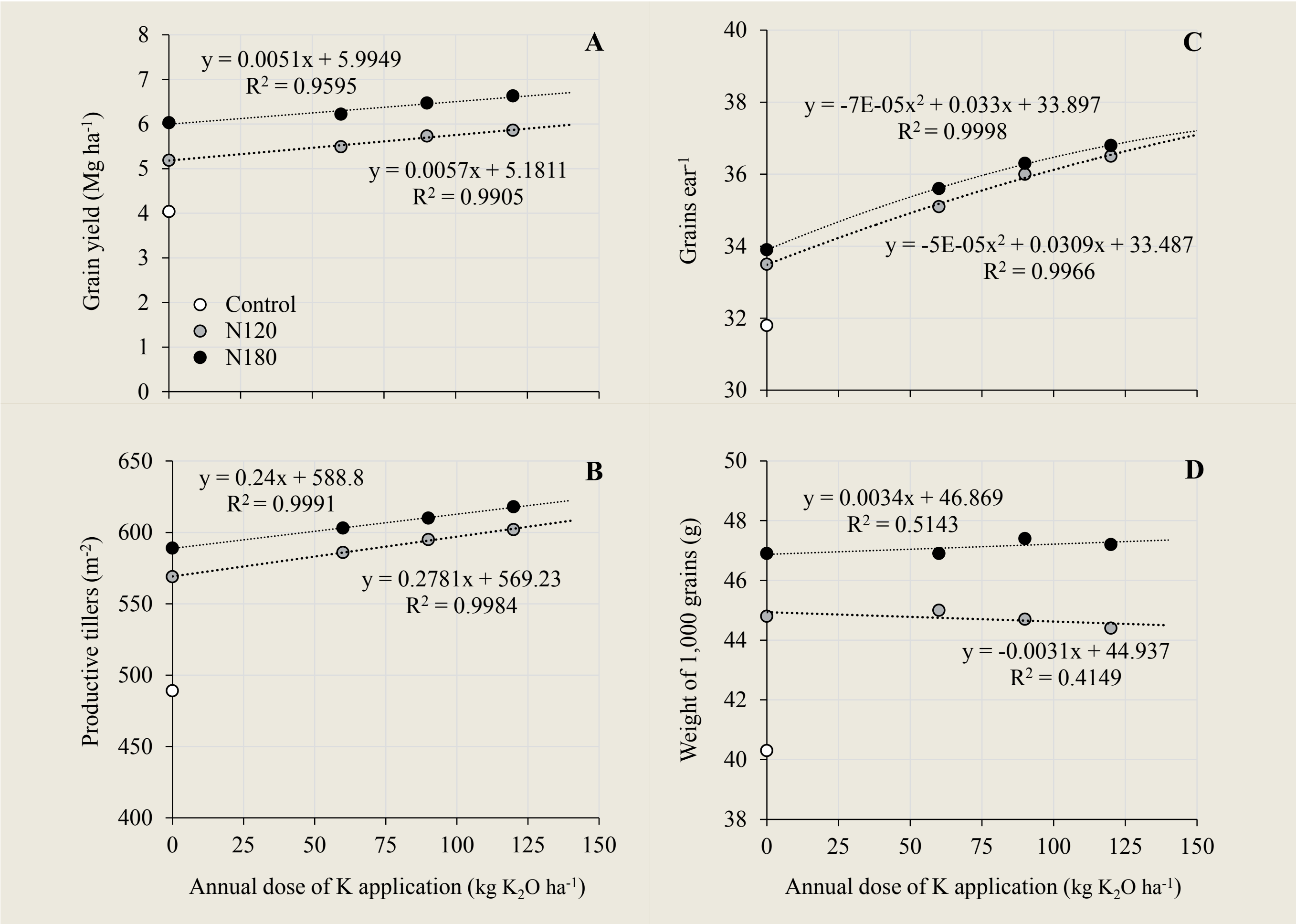

Fig. 4. Effects of fertilizer rates on winter wheat in 2013 with regard to: A) grain yield; B) number of productive tillers; C) number of grains per ear; and d) weight of 1,000 grains.

Nitrogen and P fertilizers had a dramatic effect on maize grain yield. Phosphorus at 90 kg P_2O_5, and at 120 and 180 kg N ha^{-1}, gave rise to grain yield increases of 61 and 84%, respectively, as compared to the non-fertilized control (Fig. 5A). Grain yield increased along with the rising rates of K application, but seemed to be saturated at the higher K rate (180 kg K_2O ha^{-1}). Thus, the highest yields were obtained at the $N_{180}P_{90}K_{180}$ treatment, 11.79 Mg ha^{-1}, 31% more than the $N_{180}P_{90}K_0$ treatment, and 141% more than the non-fertilized control.

Potassium application had a rather small, insignificant effect on the number of plants per m^2 and on plant height (data not shown). Also, no influence on the number of cobs per plant (~1.02) could be observed. However, the mean cob weight was significantly increased as a result of fertilization treatments (Fig. 5B). Whereas, mean cob weight of non-fertilized control plants was about 140 g, it was 187 g and 204 g in the NPK_0 treatments. Potassium application brought about a further increase in cob weight, up to 231 g under the $N_{180}P_{90}K_{180}$ treatment. Most of the increment in cob weight was attributed to a significant increase in the grains share in the cob. In response to the NPK_0 treatments alone, the grains share grew from 64 to 73-76%, and increased further, up to 81%, as a result of raising the K dose to 180 kg K_2O ha^{-1} (Fig. 5C).

The highest grain protein content (9.95%) was reached at $N_{180}P_{90}K_{120\text{-}180}$. Net income was highest (5048 UAH ha^{-1}) under the $N_{180}P_{90}K_{180}$ treatment.

Sugar beet

Nitrogen uptake by sugar beet was significantly increased by K application; N concentration in the above ground organs of the plant increased from 3.32% in the NPK_0 treatments up to 3.93% in the $N_{180}P_{160}K_{240}$ treatment. In the roots, N concentration ranged from 0.97-1.05%, with only a slight K application effect. On the other hand, K_2O concentration in the roots increased from 0.8-0.88% in the NPK_0 treatments up to 0.99% in the $N_{180}P_{160}K_{240}$ treatment.

Nitrogen and P fertilizers considerably affected sugar beet root yield. Phosphorus applied at 160 kg P_2O_5, and nitrogen at 120 and 180 kg ha^{-1}, brought about yield increases of 32 and 39%, respectively, compared to the non-fertilized control (Fig. 6A). Potassium application caused a further yield increase, which displayed a linear response up to 60.3 Mg ha^{-1} in the $N_{180}P_{160}K_{240}$ treatment, about 10% higher than in the respective K_0 treatment.

Sugar concentration in the beets ranged between 17.3-17.6% and did not differ significantly between treatments. Hence, the refined sugar yield corresponded with the fresh root yields, displaying similar responses to the various fertilization treatments (Fig. 6B). Thus, sugar yield increased from about 6.76 Mg ha^{-1} in the non-fertilized control, to 9-9.5 Mg ha^{-1} in the NPK_0 treatments, and rose further up to 10.55 Mg ha^{-1} at the highest applied NPK rates. Consequently, the highest net income of 9450 UAH ha^{-1} was obtained at the highest fertilization rates, $N_{180}P_{160}K_{240}$.

Discussion

The non-fertilized control of winter wheat (Fig. 4) and sugar beet (Fig. 6) yields corresponded with the mean annual yields obtained in recent years in Ukraine, about 4 (Fig. 1) and 38 Mg ha^{-1} (Fig. 3), respectively. These results are highlighting the existing poor level of basic mineral nutrition in those two crops in Ukraine. The large difference between the non-fertilized control and the mean annual yields in maize (Figs. 2 and 5) demonstrates the significant progress made recently in the cultivation of this crop in Ukraine.

The basal N and P fertilization (NPK_0) provided the most significant contribution to yields of all three crops examined in the present study. The first level of N application (N_{120}, 120 kg N ha^{-1}), with the constant basal application of P (70, 90, or 160 kg ha^{-1}, applied to winter wheat, maize, or sugar beet, respectively), gave rise to the highest increase in yield, 28, 61, and 33%, compared to yields of the non-fertilized control of winter wheat, maize, and sugar beet, respectively. When this basal N application level was raised by 50% to 180 kg ha^{-1}, winter wheat grain yield grew further by an additional 21%, displaying a high and stable marginal output. These results are supported by recent findings with winter wheat in China, showing that a rate of 180 kg N ha^{-1} can support no more than a median range of grain yield (about 6 Mg ha^{-1}) and that higher yields require significantly further N inputs (Chuan *et al.*, 2013). Thus, under the circumstances of the present trial, N requirements were still far from being fulfilled. In maize and sugar beet, on the other hand, the marginal outputs provided by the higher N application level decreased, indicating that the crop N requirements were almost satisfied.

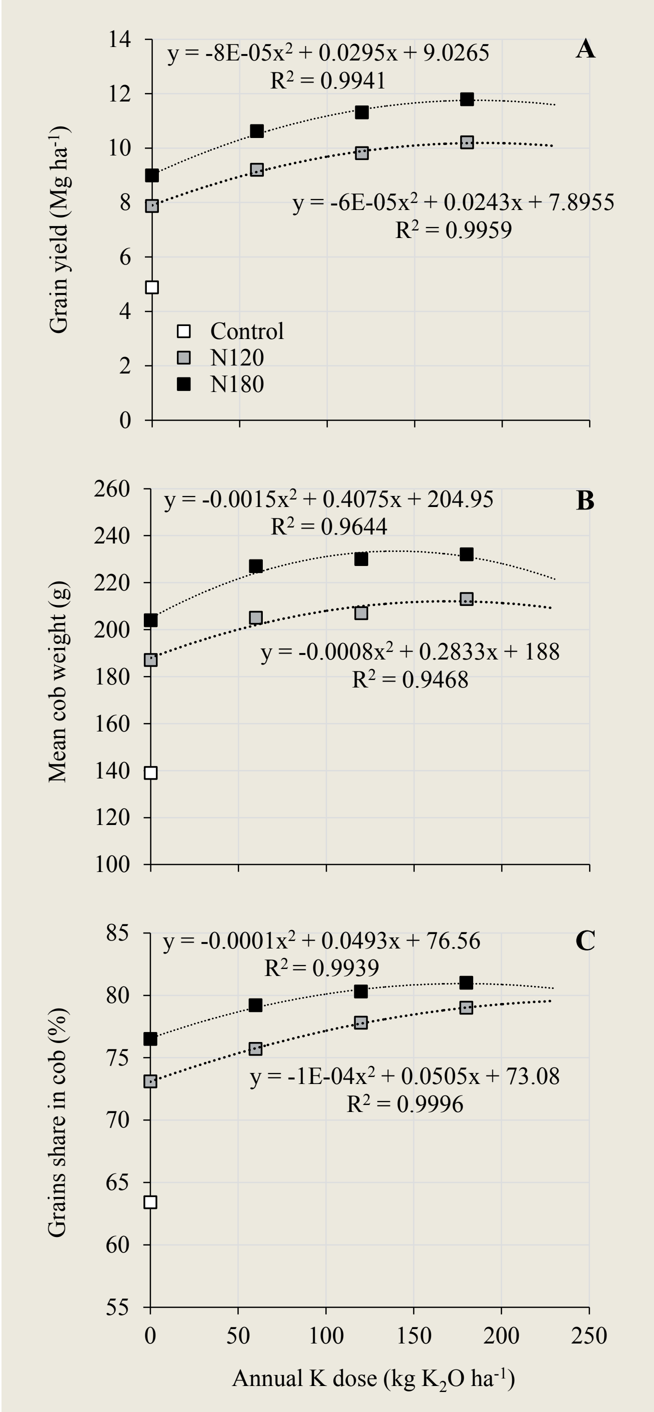

Fig. 5. Effects of fertilizer rates on maize in 2014 with regard to: A) grain yield; B) mean cob weight; and, C) on the grains share in the cob.

Potassium is one of the principle plant nutrients underpinning crop yield production and quality determination. While involved in many physiological processes, K's impact on water relations, photosynthesis, assimilate transport and enzyme activation can have direct consequences on crop productivity. Potassium deficiency can lead to a reduction in the number of leaves produced and the size of individual leaves. Coupling this reduced amount of photosynthetic source material with a reduction in the photosynthetic rate per unit leaf area, the result is an overall reduction in the amount of photosynthetic assimilates available for growth. The production of less photosynthetic assimilates and reduced assimilate transport out of the leaves to the developing fruit greatly contributes to the negative consequences that K deficiencies have on yield and quality production (Pettigrew, 2008). Indeed, amongst all crops examined in this study, K application brought about further increases in yield. In winter wheat, yield response was linear, with a maximum increase of 10 or 13%, depending on the basal N application level, which also indicates a tight dependence of K contribution on plant N status. According to He *et al.* (2012) and Chuan *et al.* (2013), a K application rate of 120 kg ha^{-1} would support much higher yields (about 7 Mg ha^{-1}), but only under elevated N inputs of more than 200 kg ha^{-1}. The greatest contribution of K fertilization to yield was obtained in maize, reaching a maximum of 30%, with no evident dependence on N level. In contrast to winter wheat and sugar beet, the influence of K seemed to be saturated at its highest application rate (180 kg ha^{-1}), hence any further increase of K rate would be ineffective. The maximum increase in sugar beet root and sugar yields ranged at 12%, displaying a linear relationship between K input and beet yield. It appears that further increasing K input might result in elevated yields, and should be considered economically.

Careful attention must be paid to the specific effects of K application on plant development and on the dominant yield components in each crop, trying to understand K role and elucidate practical conclusions (Grzebisz *et al.*, 2013). Among the three crops, winter wheat exhibits the most complex course from seed to yield (Haun, 1973; Zadoks *et al.*, 1974). It is sown in the autumn and the plants must survive the many stresses of winter; plants with well-developed crowns have the best chance of winter survival. Potassium has a primary role in the successful establishment of seedlings as it supports the development of an adequate root system (Weaver, 1926; Ma *et al.*, 2013). Grain yield can be expressed as the product of three variables (yield components) as follows:

Grain yield = (number of heads) x (kernels per head) x (kernel weight)

The impact of each yield component on final grain yield is determined at different stages during the growing season. Successful and timely establishment of seedlings is a pre-requisite to the number of productive tillers produced per plant, which sets the upper limit on the number of heads that can be produced by a wheat crop. In the spring, tiller production is favored by moist, warm weather, and good soil fertility. Tillers must survive to maturity to contribute to grain yield. The developing head and elongating stem generate large demands on the plants' resources, thus relatively weak, poorly developed

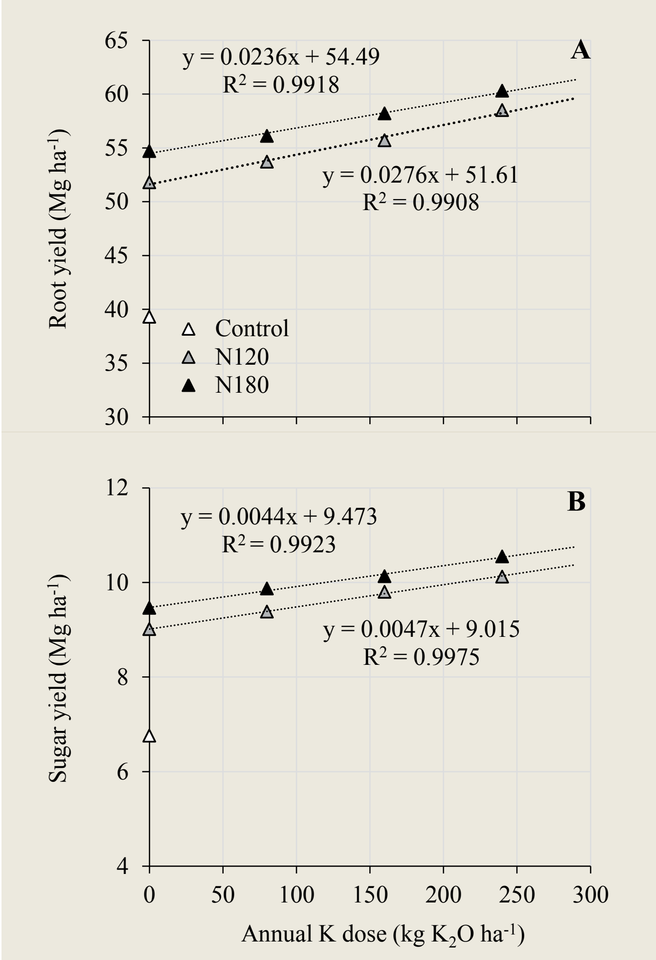

Fig. 6. Effects of fertilizer rates on sugar beet in 2014 with regard to: A) taproots yield; and B) refined sugar yield.

tillers fail to compete and are often lost, particularly under unfavorable environmental conditions (Lopes *et al.*, 2014). The results of the present study demonstrate the pivotal role of K in supporting tiller development, thus increasing the number of productive tillers (Fig. 4B). Potassium, through its constructive effect on root growth and development, might have intensified the ability of the root system (Weaver, 1926) to explore the soil during drought periods. Also, being involved in the plant's water relations (Fischer, 1968; Haeder and Beringer, 1981), an adequate K status would strengthen plant drought tolerance (Grzebisz *et al.*, 2013).

Increased levels of K application brought about a significant rise in the number of grains per ear (Fig. 4C), indicating its influence during the initiation and development of the primary reproductive stage. This effect may be attributed to an improved carbohydrate status of the plant, which allows and supports prolonged activity of basal developmental processes in the ear. Known to promote photosynthetic (Huber, 1985) and carbohydrate translocation (Conti and Geiger, 1982) processes, K impact is not surprising here. Nevertheless, at the later stage of grain filling, no significant effects of K input levels could be observed (Fig. 4D), possibly due to the depletion of this nutrient from the root zone along the season. The timing and distribution of mineral application along the growing season may be crucial, particularly when addressing K, with its combined influences on plant growth and development. In the present study, and according to common practices in the region, the annual K dose was applied basally, prior to sowing. Potassium is very mobile in the plant, but also in the soil; it might be easily leached away from the root zone. The grain yield potential of winter wheat is twice as high as obtained here, reaching about 12 Mg ha^{-1} (Chuan *et al.*, 2013; Dang *et al.*, 2013). Further improvement of winter wheat yields in Ukraine might be achieved by adjustment of K application practices to the dynamic requirements of the plant throughout the season (He *et al.*, 2012; Dang *et al.*, 2013; Ma *et al.*, 2013; Scanlan *et al.*, 2015). In other words, practices using slow-release fertilizers, split K application, or foliar application (Niu *et al.*, 2013; Lu *et al.*, 2014) should be considered well before the emergence of genetically-based solutions (Wang and Wu, 2015). Also, larger N and K doses will be required, as indicated by Chuan *et al.* (2013), as well as in the present study (Fig. 4A).

In contrast to the relatively long and complex pattern of winter wheat growth and development, that of maize for temperate climatic conditions is concentrated in the short summer. Cultivars are selected accordingly, with an ability to grow rapidly and boost the grain yield up as early as possible. Where the numbers of plants and cobs are predetermined at sowing, cob size and grain share are the most effective yield components. Pettigrew (2008) described a cascade of physiological impairments associated with K deficiency in maize (and other plant species). Insufficient K levels reduced leaf area expansion leading to reduced leaf size (Jordan-Meille and Pellerin, 2004). The combination of smaller leaf area and reduced photosynthetic rate under insufficient K levels (Basile *et al.*, 2003) leads to a reduction in the total carbohydrate pool produced in the source tissues (leaves). Coupling that with the restricted assimilate transport characteristic of K-deficient plants (Ashley and Goodson, 1972) results in a smaller total assimilate supply available for sink tissues (cobs), which will ultimately diminish yield and quality produced by those plants. Thus, the significant contribution of K application to maize yield, as found in the present study (Fig. 5A), should be attributed to the general positive effect of K on plant productivity. The majority of K accumulation occurs before silking (Hanway, 1962, Karlen *et al.*, 1988), suggesting an important role of K as the grains set and their further development. Indeed, high levels of K application were associated with larger cobs and greater grain share (Fig. 5), as also shown by Heckman and Kamprath (1992) and Qiu *et al.* (2014).

Potassium requirements of sugar beet are high and comparable to other plants having large storage organs. Also here, given optimum weather conditions, the larger the aboveground biomass (rosette of leaves) obtained the greater the taproot biomass and its sugar content (Kenter *et al.*, 2006). Sugar beet production requires especially fertile soils rich with mineral nutrients and organic matter. While at the early stages of plant development, N would be the major nutrient required for the foliar and taproot growth in terms of fresh weight, K is probably more essential during the later stage of sugar translocation from the leaves, filling the taproot (growth in terms of dry matter) (Giaquinta, 1979). Thus, the effect of elevated K application on sugar beet yields, as shown here, are not surprising. Furthermore, it appears that K requirements are even higher, as indicated by the linear function in Fig. 6. Alternatively, splitting the annual K dose, with more emphasis on the second half of the growing season, may increase the K nutrition efficiency of this crop.

Potassium is an essential mineral in human diet and in animal feed. Increased K application tended to increase the content of this nutrient in grains and stover of wheat and maize, as well as in the sugar beet taproot. Protein content also increased, a fairly well-known phenomenon attributed to K (Mengel *et al.*, 1981; Blevins, 1985), particularly that of gluten, a major quality parameter of wheat flour. Thus, increased K application had positive effects on the produce quality, and hence on the price and revenue of growers.

Interestingly, increased K doses promoted the rise of N uptake, as indicated by the increased N concentration in the biomass of all three crops studied here, and by previous published work (Mengel and Kirkby, 1987; Chuan *et al.*, 2013). From a plant nutrition viewpoint, it is very easy to justify the beneficial effect of K in raising nitrogen use efficiency thereby increasing crop yield and quality (Stromberger *et al.*, 1994). Potassium provides the main cation, and nitrate (NO_3^-) the main anion taken up from soil solution by crop plants in the well-aerated high pH soils at the trial sites. These ions play a dominant balancing role not only in uptake but also in transport within the plant from root to shoot. In most crop plants, the shoot provides the major site of NO_3^- reduction and the synthesis of amino acids and sugars. Potassium is also essential for their transport in supplying developing storage organs that include the grains of winter wheat, cobs of grain maize, and the roots of sugar beet studied in these trials.

Conclusions

Adequate N and P application is prerequisite for considerable performance and yields of three major field crops in Ukraine: winter wheat, maize, and sugar beet. On top of this, increased K application brought about significant improvement in yield and quality parameters. Interactive relationships occurred between N and K uptake, where increased K application seemed to promote N uptake, and vice versa. In all three crops maximum yield, produce quality, and net income were obtained at the highest rates of K application in the trial. However, for winter wheat and sugar beet, the maximum has not yet been achieved, thus further increase of the annual K dose should be examined from an economic viewpoint. In maize, on the other hand, additional K application is not expected to further increase yields. Nevertheless, distribution of the annual K dose during the season according to the progress of crop developmental stages, particularly in wheat and sugar beet, should be examined to achieve further improvements in yield and quality.

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