Nitrogen use efficiency of maize and spring barley under potassium fertilization in long-term field experiment

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ABSTRACT

In the paper, the results of the long-term field experiment on soil depletion from potassium on yields and selected indices of nitrogen use efficiency of maize and spring barley were presented. The factors of the experiment were potassium fertilization (K plus and K minus treatment) and increasing nitrogen rates. Maize responded for soil exhausting from K in yield reduction over all the range of nitrogen rates applied in the experiment, and spring barley only through the highest rates. The greater values of nitrogen use efficiency indices were proven for barley as compared with maize. Potassium fertilization slightly increased agronomic efficiency and physiological efficiency of barley.

Keywords: *Zea mays* L.; *Hordeum vulgare* L.; potassium and nitrogen interaction; NUE indices

Nitrogen (N) and potassium (K) are the major nutrients in crop fertilization. It was proven that moderate N fertilization results in higher yields increment of many crops after K applications as compared to N and K applied separately (Milford and Johnson 2007). The interaction between N and K on crop growth and final yield that occur at the agronomic level are due to their underlying physiological interactions on tissue hydration and osmotic adjustment. In the process of NO_3^- anion uptake and transport within the plant, the monovalent K^+ is an accompanying counter ion (Jiang et al. 2001, Lu et al. 2005, Maathuis 2007).

Efficiency of nitrogen and potassium fertilizer application is affected by numerous factors, including soil type, soil original nitrogen and potassium supplying capacity, crop cultivars, organic matter and the level of other nutrients, which in turn shape the dynamic equilibrium existing among the various forms of nitrogen and potassium (Timsina et al. 2001). Maintaining an adequate level of soil potassium over the long-term is essential because under K deficiency in soil, it is difficult to distribute fresh potash fertilizer sufficiently evenly through the rooting zone in the season it is applied to the roots to access enough potassium to produce optimal yields. Yield response to applied N fertilizers decreased together with diminishing of exchangeable K in soil below a critical level. This critical point seems to be intangible because frequently there is no visual response to potassium fertilizers application.

Enhancement in N uptake through K application ultimately secures increasing of nitrogen use efficiency (Brar et al. 2011). Fixen and West (2001) proved that balanced fertilization with N and K increases first-year recovery with an average of 54% compared with only 21% when nitrogen is applied alone. Yield response to potassium application depends to a great extent on the level of nitrogen fertilization. The new crop cultivars are very responsive to nitrogen; they need much higher N rates to realize their potential than the cultivars a few years ago. It is to be expected that the effect of N × K interaction would be greater at higher yields.

The objective of the long-term field experiment was to access the effect of combine effect of potassium and nitrogen fertilization on yield of maize and spring barley, and selected parameters of nitrogen use efficiency (NUE) – agronomic efficiency (AE_N), physiological efficiency (PE_N) and apparent nitrogen recovery (RE_N).

MATERIAL AND METHODS

A four-course rotation field experiment was carried on in 1985 at the experimental station of the Institute of Soil Science and Plant Cultivation, in Grabów, Poland. In two factorial experiment, four crops were grown each year in the rotation of winter wheat-maize-spring barley-winter rape. For almost 30 years, no manure was applied and no-leguminous crops were grown in this field. From the year 2003, in the split-block layout, the first factor was K fertilization in plus or minus rates, and the second one was six levels of N fertilizers applied in split doses: 0, 30, 60, 90, 120, 150 under barley, and 0, 50, 100, 150, 200 and 250 kg N/ha under maize. Potassium was applied each year, in optimal rates according to the IUNG-PIB recommendations, as follows: for maize – 140 kg K/ha, and for spring barley – 70 kg K/ha.

Soil in field under the experiment was heterogeneous, sandy-loam, Cambisols, and loam. In 2003, soil shows slightly acid reaction (pH 6.1–6.2), medium content of available phosphorus (5.3 mg P/100 g soil), low content of potassium (10 mg K/100 g soil) and magnesium (4.6 mg Mg/100 g soil).

The samples of grain and straw of maize and spring barley were collected at full maturity in the years 2007–2010 and analyzed for the content of N by the Kjeldahl method and for K by the AAS method (atomic absorption method). Nitrogen and potassium uptake by crops as well as NUE indices were calculated as the average for the years 2007–2010.

Nitrogen use efficiency was expressed by the indices: agronomic efficiency, physiological efficiency, and apparent nitrogen recovery (RE_N). These indices were calculated by the following formulas:

$$AE_N = (Y_N - Y_{N0})/N_a \text{ (kg/kg)}$$
$$PE_N = (Y_N - Y_{N0})/(U_N - U_{N0}) \text{ (kg/kg)}$$
$$RE_N = (U_N - U_{N0})/N_a \times 100 \text{ (\%)}$$

Where: Y_N – grain yield in treatment fertilized with N rate (N_a); Y_{N-1} – grain yield treatment without N fertilization; U_N – nitrogen uptake in treatment fertilized with N rate; U_{N0} – nitrogen uptake in treatment without N fertilization.

The data, pooled over the four years, were processed by the analysis of variance (ANOVA). The Tukey's test has been applied to evaluate the significance of differences between the treatments. Statistical processing of the results was performed using the Statgraphic 5 Plus package (Statgraphics Plus, Rockville, USA). Where no significant interaction between K × N fertilization was proven at the 95% confidence level; letters relate to the means of main factors in relevant tables. Where the interaction was significant letters relate to treatments.

RESULTS AND DISCUSSION

Both crops showed high year-to-year variability. Average yields of maize were 7.87, 6.19, 12.0 and 6.45 t/ha in the years 2007, 2008, 2009, 2010 and in barley it was 3.69, 4.20, 2.75 and 4.40, respectively. In spite of the seasonal effect, all experimental factors significantly affected yields

Table 1. Grain yield, total nitrogen uptake and total potassium uptake by maize (kg/ha)

N rate (kg N/ha)	Grain yield			Total N uptake			Total K uptake		
	K plus	K minus	K mean	K plus	K minus	K mean	K plus	K minus	K mean
0	6.45	5.86	a	111.3	107.6	a	102.3	95.2	a
50	7.26	6.54	a	126.9	133.5	a	118.2	95.8	ab
100	9.04	8.18	b	185.7	164.7	b	130.1	114.9	bc
150	9.32	8.77	b	201.1	184.7	bc	135.4	113.0	bc
200	9.10	8.40	b	217.5	182.2	c	147.7	119.1	c
250	9.07	8.38	b	213.5	200.0	c	150.3	114.9	c
Mean	A	B	–	A	B	–	A	B	–

Treatments with the same letter are not significantly different ($P \leq 0.05$)

of maize as well as the total uptake of nitrogen and potassium (Table 1). Maize was more stable in yield increment under nitrogen fertilization as compared with barley (Table 2). Irrespective of the potassium supply, maize yields rose up to the rate of 150 kg N/ha and then slightly dropped. In K plus treatment, nitrogen fertilization in the range between 150–250 kg N/ha, secured corn yield at the level of 9 t/ha, and the yield increment was 84% compared to the control treatment. Yields of barley increased in the whole range of nitrogen rates, and the differences between control treatment without N fertilization and the highest N rate applied in the experiment increased by 125%. However, response of these two crops to potassium fertilization varied considerably.

In K minus treatment maize responded in yield reduction over all the range of nitrogen rates. On the contrary, soil diminishing from potassium caused yield reduction of spring barley only under the rates of 90–120 kg N/ha. It is not an uncommon phenomenon explained by greater demands for potassium because of high-yield potential of maize as compared with barley. Although the average nitrogen uptake per ton of grain with a corresponding yield of straw by maize and barley are comparable and according to Karklins (2001) amount for 28.4 and 21.0 kg/ha, respectively, the average uptake of potassium by maize is 23.3 and by barley only 13.7 kg/ha.

As might be expected, potassium uptake by both crops raised with increasing nitrogen rates. Similarly to yield reaction, maize responded much more steadily for potassium fertilization compared with barley. In K plus treatment, the difference in total potassium uptake by maize between treatments 0 and 250 kg N/ha was 46%, and in K minus it was 22%. The difference in K uptake by barley increased as much as 157% and 100%, respectively. The results proved that potassium is accumulated by cereals in quantities exceeding their nutritional requirements for this element (Leigh and Jones 1984). Nevertheless, in K minus treatment, maize took up significantly less potassium than in K plus one, and no similar effect was proven for barley.

In K plus treatment, the average potassium uptake by maize accounted for 77% of total nitrogen taken up by crop, and in K minus the treatment dropped to 66%. For barley, up to 60 kg N/ha, the ratio of K uptake to N uptake was 62% irrespective of fresh potassium application, and only under the highest N rate it fell to 48% in K minus treatment.

Indexes of nitrogen use efficiency. Nitrogen agronomic efficiency is a parameter representing the ability of the plant to increase yield in response to N applied. Crop physiological nitrogen requirements are controlled by the efficiency with which N in the plant is converted to biomass and grain yield. Potassium application insured the utilization of nitrogen and storage of carbohydrates in roots thus improving NUE. Likewise, the transport of amino acids towards the generative plant organs is enhanced by a higher concentration of this element (Mengel et al. 1981). The increase of NUE is consequence of enhanced uptake and improved utilization by the crop. However, yield response to potassium fertilization depends to a great extent on the level of nitrogen supply (Bruns and Ebelhar 2006, Brennan and Bolland 2007, 2009).

In the experiment, irrespective of potassium fertilization, the largest increase of maize yield was recorded with 100 kg N/ha, which is linked with the highest apparent nitrogen recovery – 75% in K plus treatment and 57% in K minus one, and agronomic efficiency which amounted to 26 and 23 kg grain/kg N applied, respectively (Table 3). Both

Table 2. Grain yield, total nitrogen uptake and total potassium uptake by spring barley (kg/ha)

N rate (kg N/ha)	Grain yield		Total N uptake			Total K uptake	
	K plus	K minus	K plus	K minus	K mean	K plus	K minus
0	2.10^{Aa}	2.19^{Aa}	54.0	53.5	a	35.1^{Aa}	36.5^{Aa}
30	3.02^{Ab}	3.21^{Ab}	76.6	73.6	b	44.2^{Aa}	43.9^{Aa}
60	4.00^{Ac}	4.04^{Ac}	93.5	97.2	c	54.9^{Ab}	57.6^{Ab}
90	4.35^{Ad}	4.19^{Bc}	111	116	d	66.1^{Ac}	58.8^{Bb}
120	4.60^{Ade}	4.29^{Bc}	140	139	e	76.4^{Ad}	65.3^{Bb}
150	4.72^{Ae}	4.33^{Bc}	154	148	f	90.3^{Ae}	73.2^{Bb}
Mean	–	–	A	A	–	–	–

Treatments with the same letter are not significantly different ($P \leq 0.05$)

Table 3. Indices of nitrogen use efficiency for maize

N rate (kg N/ha)	AE_N (kg/kg)			PE_N (kg/kg)			RE_N (%)		
	K plus	K minus	K mean	K plus	K minus	K mean	K plus	K minus	K mean
50	16.2	13.6	a	51.9	26.3	a	31.2	51.8	a
100	25.9	23.1	a	34.8	40.6	a	74.4	57.1	b
150	19.0	19.0	ab	31.9	37.7	ab	59.8	51.4	a
200	12.8	12.5	ab	24.9	34.1	b	53.1	37.3	a
250	10.7	10.4	ac	25.6	27.2	c	40.8	37.7	a
Mean	A	A	–	A	A		A	A	–

Treatments with the same letter are not significantly different ($P \leq 0.05$). AE_N – agronomic efficiency; PE_N – physiological efficiency; RE_N – apparent nitrogen recovery

indexes decreased through the nitrogen rates and the high agronomic efficiency of the rates 200 and 250 kg N/ha was found.

Spring barley showed a relatively high value of apparent recovery efficiency (66% on average), which could be explained by the mean of nitrogen application in small, split doses well-fitted to N requirements and the rate of nitrogen and biomass accumulation (Table 4). This way of application secured better availability of nitrogen from fertilizers for poor-rooting plants; whereby, the other indexes of NUE were also high. In K plus treatment agronomic efficiency reached 30.6 kg grain/kg N for the rate 30 kg N/ha and even 16 kg/kg for the rate 120 kg N/ha.

There was a slight effect of potassium fertilization on agronomic efficiency for the highest rates of nitrogen applied to barley. Because of the capacity of plants to take up considerable amounts of nitrogen and potassium, under K available deficiency in soil, nitrogen from large doses of fertilizers is accumulated in plants in non-protein forms of nitrogen as amides, nitrates, free amino acids and it is not used for biomass production. When soil and plant potassium levels are adequate, K^+ ion having the property of high phloem mobility, and as a result a high degree of the re-utilization by re-translocation via the phloem, it plays an important role in NO_3^- translocation from root to shoot as an accompanying counter (Blevins 1985, Marschner 1995, Marschnert et al. 1997). Potassium fertilization very markedly enhanced pre-anthesis nitrogen accumulation and stored nitrogen translocation through increasing leaf potassium content at anthesis (Jones et al. 1996, Zou et al. 2006). In the experiment application of fresh potassium slightly influenced physiological efficiency of nitrogen of barley. In the range of 0–60 kg N/ha, PE_N increased by 14 kg grain/kg N taken up by crop on average, and over the rates 90–120 kg N/ha by 7 kg/kg.

In conclusion, it was observed that on soil with low K supply class, potassium fertilization increased grain yield of maize in all the ranges of nitrogen rates and in spring barley above the rate of 90 kg N/ha. In K plus treatment, the average potassium uptake by maize accounted for 77% of total nitrogen taken up by crop, and in K minus treatment it dropped to 69%. For barley, up to 30 kg

Table 4. Indices of nitrogen use efficiency for spring barley

N rate (kg N/ha)	AE_N (kg/kg)			PE_N (kg/kg)			RE_N (%)		
	K plus	K minus	K mean	K plus	K minus	K mean	K plus	K minus	K mean
30	30.6	33.9	a	40.8	50.8	a	50.0	66.6	a
60	31.6	30.8	a	57.1	42.3	a	65.8	72.0	ab
90	24.9	20.5	a	39.7	32.0	a	63.0	69.0	ab
120	20.8	17.4	b	29.1	24.5	b	71.6	70.3	b
150	17.4	15.1	b	25.9	22.6	b	66.7	63.5	ab
Mean	A	A	–	A	A	–	A	A	–

Treatments with the same letter are not significantly different ($P \leq 0.05$). AE_N – agronomic efficiency; PE_N – physiological efficiency; RE_N – apparent nitrogen recovery

N/ha, the ratio of K uptake to N uptake was 62% irrespective of fresh potassium application, and only under the highest N rate it fell to 48% in K minus treatment. Under sufficient supply of fresh potassium, a tendency to increasing AE_N and PE_N of barley, particularly in treatments with high nitrogen rates was observed.

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