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Phosphorus-induced zinc deficiency in maize (*Zea mays* L.) on a calcareous chernozem soil

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Abstract

A long-term fertilizer experiment was set up on a calcareous chernozem soil with a wheat-maize-maize-wheat crop rotation, as part of the National Long-Term Fertilization Experiments (NLTFE) Network, set up with the same experimental pattern under different soil and agro-climatic conditions in Hungary. The effect of P fertilization on the soil, on maize yields, and on leaf P and Zn contents in the flowering stage were examined in the trials. In certain years, foliar zinc fertilizer was applied, in order to prove that yield losses due to P-induced Zn deficiency can be compensated by Zn application. Calcium-ammonium nitrate, superphosphate and 60% potassium chloride were used as NPK, and Zn-hexamine (in 1991) and Zn-sulphate (in 2006) as foliar Zn fertilizers.

In the years since 1970, averaged over 36 maize harvests, treatments $N_3P_1K_1$ and $N_4P_1K_1$, involving annual rates of 150 to 200 kg ha^{-1} N, 100 kg ha^{-1} K_2O and 50 kg ha^{-1} P_2O_5, gave the highest yields (8.3 t ha^{-1} grain on average). As the years progressed, treatments exceeding 50 kg ha^{-1} P_2O_5 a year were found to have an increasingly unfavourable effect. Based on the yields of ten cycles (36 maize years), variants P_2, P_3 and P_4 resulted in 16-30-45 t ha^{-1} grain yield losses in comparison to variant P_1.

Investigations carried out in 1987, 1991 and 2006 showed that the leaf Zn content on plots with more than 150 to 200 mg kg^{-1} AL (ammonium lactate)-soluble P_2O_5 (over 30 mg kg^{-1} Olsen-P) dropped below 15 mg kg^{-1} and the P/Zn ratio rose to above 150 or even 250 in the flowering stage in two years. As a consequence of P-induced Zn deficiency, maize grain yields fell by 2 t ha^{-1} in two of the years investigated and by almost 5 t ha^{-1} in one year at the P_4 level (200 kg ha^{-1} P_2O_5 year^{-1}), in comparison to the P_1 variant (50 kg ha^{-1} P_2O_5 year^{-1}).

When 1.2 kg ha^{-1} foliar Zn was applied in the form of zinc hexamine, 1.7 to 1.8 t ha^{-1} maize grain yield surpluses were obtained on plots with higher P levels in 1991. In 2006 the P-induced Zn deficiency caused unexpectedly high

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(almost 5 t ha^{-1}) grain yield losses on plots with higher P levels, so the maize grain yield surpluses obtained in response to 1.2 kg ha^{-1} foliar Zn application, in the form of zinc sulphate, were as high as 1.6 to 3.8 t ha^{-1}.

The data clearly indicate that maize yields are impeded by both poor and excessive P status. Soil and plant analysis may be useful tools for monitoring the nutritional status of plants.

Keywords: long-term field trial, P-induced Zn deficiency, response to Zn application, soil and plant analysis, Hungary

Introduction

Probably, no other crop has changed as dramatically over the last hundred years, in terms of both genetic composition, agronomic/production factors and yield potential, as maize. At the beginning of the 20th century, open-pollinated maize varieties, sown at a density of 20 thousand plants per hectare, were reported to respond better to farmyard manure than to mineral fertilizers (CSERHÁTI 1901, SIGMOND & FLÓDERER 1905). Maize hybrids, however, which entered production in the 1930s in the USA and in the 1950s in Europe, and are now grown at an optimal plant density of 70 to 90 thousand plants per hectare, gave a much better response to mineral fertilizers (BALLA 1960, GYŐRFFY 1979, KÁDÁR 1992, 2013, SARKADI 1975). The effect of fertilization became even more pronounced with increasing plant density (GYŐRFFY 1979, NAGY 2006).

The majority of essential plant micronutrients, including zinc, are more mobile in acidic than in calcareous soils. In crops sensitive to Zn deficiency (maize, sorghum, flax, beans, cotton, etc.), severe Zn deficiency can be detected even visually. Hidden Zn deficiency, however, can only be verified by means of diagnostic plant analysis (MENGEL & KIRKBY 1987). In Hungary, 1/3 of the soils (especially calcareous soils on the north-west to south-east diagonal of the country) are zinc-deficient (BARANYAI et al., 1987; KÁDÁR 2005). The most important limiting factors for Zn availability are high soil pH and excessive phosphorus supplies (MARTENS & LINDSAY 1990). It is generally accepted that P-Zn antagonism is due to plant physiological processes rather than zinc phosphate precipitation in the soil (RAGAB 1980; CAKMAK & MARSCHNER 1986).

Zinc status and phosphorus-zinc antagonism in crops can be characterized using the soluble zinc and phosphorus contents of the soil or the zinc and phosphorus contents and P/Zn ratios of diagnostic plant samples.

Zn supplies to maize in the flowering stage are considered to be poor at leaf Zn contents below 15 mg kg^{-1}, moderate between 16 and 19 mg kg^{-1}, good between 20 and 150 mg kg^{-1}, very good between 151 and 200 mg kg^{-1}, and excessive at over 200 mg kg^{-1} (JONES 1967).

Attention is mainly focused on the connection existing between the soil P-supply and maize grain yields. The yield-reducing effect of repeated P over-fertilization and the beneficial effect of foliar Zn application are also investigated using soil and plant analysis.

Materials and methods

Trials B 18 and B 19, part of the National Long-Term Fertilization Experiments (NLTFE) Network, were set up in autumn 1968 and autumn 1969, respectively, with a winter wheat – maize – maize – winter wheat crop rotation, in the Nagyhörcsök Research Station of the Institute for Soil Sciences and Agricultural Chemistry, Centre for Agricultural Research, Hungarian Academy of Sciences, on a calcareous chernozem soil. The experimental soil had a light loam soil texture (plasticity index according to Arany: 37), a $CaCO_3$ content of about 5%, and a humus content of about 2.5-3% in the ploughed layer. Before the trials were set up, AL-P_2O_5 and AL-K_2O contents of 60 mg kg^{-1} and 160 mg kg^{-1}were detected in trial B 18 and 100 mg kg^{-1} and 160 mg kg^{-1}, respectively, in trial B 19. Soil nutrient analysis indicated poor Zn, poor to medium P, medium N and K, and good Ca, Mg, Cu and Mn supplies (CSATHÓ et al. 1998).

The experiments were set up in an incomplete block design with 20 fertilizer treatments, each in 4 replications (DEBRECZENI & DEBRECZENI, 1994; DEBRECZENI & NÉMETH, 2009).

The maize hybrids sown have changed over the years, with Hungarian hybrids in the first four cycles (Mv 602, Mv Sc 580, Mv 59, Sze Sc 444, KSC 360), and foreign, mostly US Pioneer hybrids from the fifth cycle on. The crop density was 48 thousand plants per hectare in the first two cycles, 57 thousand in the 3rd and 4th cycles and 71 thousand from the fifth cycle on. The amounts of NPK nutrients applied yearly in the experiment are summarized in *Table 1*. The fertilizers used were calcium ammonium nitrate, superphosphate (granules) and 60% potassium chloride. The P and K fertilizers were applied prior to autumn ploughing, while half of the N was applied in autumn and half in the spring, before sowing.

Table 1
Annual fertilizer rates in the trial, kg ha^{-1}

Nutrient level	N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Cycle 1			Cycles 2-10		
kg ha^{-1}						
0	0	0	0	0	0	0
1	40	40	80	50	50	100
2	80	80	160	100	100	200
3	120	120		150	150	
4	160	160		200	200	
5	200			250		

The plots of the increasing P levels were divided into two. Foliar Zn application (0.6 kg ha^{-1} Zn in the 6–8-leaf stage and 0.6 kg ha^{-1} Zn in the 10–12-leaf stage, a total of 1.2 kg ha^{-1} Zn $year^{-1}$) was introduced in 1991 and 2006 in half the plots, while the other half of the plots served as Zn controls (Zn0). The Zn source was Zn-hexamine in 1991 (BARKÓCZI et al., 1989) and Zn-sulphate in 2006.

In the 1^{st} to 10^{th} cycles of the two long-term field trials, between 1970 and 2008, maize was grown in a total of 36 years, all of which were evaluated. Plant and soil samples were taken from selected plots in 1987, 1991 and 2006. To obtain composite plant samples for the purpose of diagnostic plant analysis a single leaf next to the maize cob was taken from 20 plants per plot at the beginning of flowering. Following harvest, composite soil samples were taken from the ploughed layer of the net area of each plot. The composite soil samples consisted of 20 single subsamples from each net plot area. The gross plot size was 88 m^2 and the net plot size 56 m^2.

The plant samples were analysed for P and Zn after wet digestion. The AL-soluble P contents were determined according to EGNÉR et al. (1960), and the EDTA + 0.1 M KCl-soluble soil Zn contents according to the Hungarian Standard (MSZ 20135:1999).

Results and conclusions

The average grain yields of certain selected treatments from cycles 1 to 10 are summarized in *Table 2.* The highest grain yields were obtained in the treatments $N_3K_1P_1$ and $N_4K_1P_1$, where 50 kg ha^{-1} P_2O_5 was given annually. Based on the database of Hungarian P-fertilization trials, maize is considered to have a relatively low phosphorus demand (CSATHÓ, 2003; CSATHÓ et al., 2002; NÉMETH, 2006). With increasing P supplies, the grain yield decreased, at first only as a tendency, but at higher P levels (P_3 and P_4) to a significant degree.

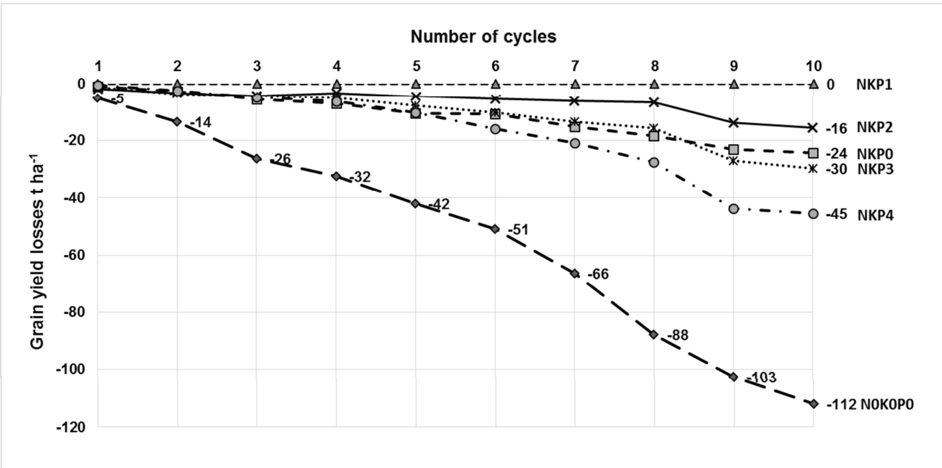

Figure 1
Cumulative losses in maize grain yields due to under- or over-fertilization with P, as compared to the best (NKP_1) variant (annual 22 kg ha^{-1} P or 50 kg ha^{-1} P_2O_5). Calcareous chernozem, Nagyhörcsök, Hungary, 1970 to 2008

Table 2
Effect of fertilization on maize grain yields on a calcareous chernozem soil. Trials B 18 and B 19, Nagyhörcsök, 1970 to 2008

NPK levels[a]	Cycle											
	1	2	3	4	5	6	7	8	9	10	1-10	
	(1970-72)	(1974-76)	(1978-80)	(1982-83)	(1986-88)	(1990-92)	(1994-96)	(1998-2000)	(2002-04)	(2006-08)	(1970-2008)	
	Number of trials											
	4	4	4	3	3	4	4	4	4	2	36	
	Aridity index according to Pálfai (PAI)[b]											
	5.4	4.6	5.8	7.9	5.0	5.8	7.5	5.3	9.2	6.8	6.3	
	Grain yield, t ha^{-1} year^{-1} (86 % d.m.)											
											t ha^{-1}	%
0	4.83	5.44	5.43	5.63	5.31	5.22	5.63	4.00	5.11	5.93	5.20	63
301	5.88	7.09	7.86	7.29	7.31	7.35	8.43	8.56	7.63	9.89	7.63	92
311	6.15	7.19	8.50	7.75	8.48	7.41	9.51	9.35	8.83	10.56	8.26	100
321	5.57	7.30	8.51	8.33	7.97	7.11	9.20	9.44	6.60	9.71	7.87	95
331	5.91	7.08	8.33	7.53	7.76	6.94	8.97	8.97	6.30	9.61	7.64	93
411	6.10	7.86	8.72	7.67	8.46	7.49	9.48	9.42	8.73	10.60	8.36	101
421	5.76	7.00	8.24	7.85	8.10	7.32	9.42	9.10	7.30	9.69	7.88	95
431	5.77	6.70	8.55	7.35	7.43	6.67	8.41	8.76	5.60	8.79	7.33	89
441	5.99	7.08	7.96	7.23	7.21	6.02	8.24	7.71	4.77	9.65	7.05	85
530	5.50	6.44	7.05	6.32	6.23	5.62	8.17	7.52	4.89	8.33	6.53	79
531	5.77	7.30	8.36	7.08	7.36	6.34	8.60	8.38	5.40	9.31	7.29	88
541	5.48	6.67	8.15	6.87	6.82	5.55	8.01	7.86	4.74	7.73	6.73	81
542	5.78	7.11	8.23	6.64	7.12	5.79	7.68	8.09	4.53	7.41	6.80	82
$LSD_{5\%}$	0.58	0.70	0.83	0.78	0.80	0.59	0.81	0.75	0.52	0.79		
Mean	5.73	6.94	7.99	7.19	7.35	6.52	8.44	8.24	6.19	9.02	-	-

[a]: see *Table 1*
[b]: high PAI values indicate dry years or droughts, and low ones favourable years

The yield reduction caused by higher P levels, compared with the yields obtained at the P_1 level, became more and more pronounced as the years passed (*Table 2*). A similar picture was obtained when the cumulated yield reductions of single P treatments were compared with the main yields of all the NKP_1 treatments (averages of the $N_3K_1P_1$ and $N_4K_1P_1$ treatments) (*Figure 1*). The total loss in grain yield over the 10 cycles (36 maize trials in all) was 16 t ha^{-1} at the P_2 level, 30 t ha^{-1} at the P_3 level and 45 t ha^{-1} at the P_4 level. In comparison, the yield loss in the P control (P_1 level) was only 24 t ha^{-1}, less than that found at the P_3 and P_4 levels. Thus, P over-fertilization caused higher yield losses in maize than P deficiency on this calcareous soil, poorly or moderately supplied with P. The smallest yields were obtained on the absolute control ($N_0P_0K_0$) plots, with a total yield loss of 112 t ha^{-1} over 10 cycles, as compared to the NKP_1 treatment (*Figure 1*).

To reveal the causes of the reduction on the higher P levels, an investigation was carried out in 1987, 1991 and 2006, the results of which are shown in *Tables 3* to *5*. It should be noted that the 150 kg ha^{-1} N fertilizer doses applied in the experiments in these years were enough to cover the N demand of even the highest maize yields. To show the effect of P fertilization on the NK base, the yields of treatments that received sufficient amounts of NK fertilizers are given in *Table 3*.

As a result of the P fertilization applied for nearly twenty years, the initial ammonium lactate (AL)-soluble P contents of the soil grew about fivefold and soils with a previously poor P supply became moderately, well or very well supplied with phosphorus. The changes were even more pronounced when Olsen-P values were considered, due to the different P treatments. The sulphate content of the ploughed layer increased with the P doses, i.e. sulphate ions were introduced into the soil when superphosphate was applied, some of which accumulated with the phosphate ions in the upper layer of the soil. The EDTA-soluble Zn content of the soil showed a growing trend, though the increase was not significant.

The weight of the leaves opposite the ears was the highest when AL-P_2O_5 was near to 90 mg kg^{-1}. In general the N, K, Ca, Mg and P% of the leaf also increased parallel with the improved P supply. Among the micronutrients, the Fe, Mn and Cu contents also increased, while the Zn content decreased to about half. Nutrient ratios can also indicate an increase in the P supply. Thus, the N/P, K/P and N/Cu ratios decreased, while the P/Zn ratio increased 2.5 fold (*Table 3*).

In agreement with other authors (JONES, 1967; BERGMANN, 1983; ELEK & KÁDÁR, 1980), it was concluded from earlier studies that the optimum P/Zn ratio in maize leaves is about 80-150 and that Zn deficiency is to be expected if this ratio is larger than 200. In such cases, P fertilizers become ineffective and cause yield depression (ELEK & KÁDÁR, 1980; KÁDÁR 1980). Zn availability was already limited on the calcareous chernozem soil tested and higher P doses could easily induce zinc deficiency in the plants due to P-Zn antagonism. At higher P supplies there may also be unfavourable changes in yield components, such as a decline in the average number of grains per cob, or in the grain number and grain weight per plant.

Table 3
Effect of fertilization on the nutrient content, nutrient ratio and yield components of maize. Calcareous chernozem, Nagyhörcsök, 1987, Pioneer SC 3732

Properties	$N_0P_0K_0$	NKP_0	NKP_{50}	NKP_{100}	NKP_{150}	NKP_{200}	$LSD_{5\%}$
AL-P_2O_5 mg kg^{-1}	62	62	88	156	273	322	28
Olsen-P mg kg^{-1}	10.0	8.6	11.1	28.6	55.8	71.4	8.0
KCl-SO_4 mg kg^{-1}	5.5	5.7	8.5	13.9	18.3	18.4	4.8
EDTA-Zn mg kg^{-1}	1.5	1.7	1.5	1.8	1.9	2	0.6
Leaves at the flowering-stage, 20 $plot^{-1}$							
Weight, g	60	72	73	61	64	58	7
N%	2.22	2.3	2.58	2.5	2.54	2.53	0.15
K%	1.02	1.49	1.66	1.65	1.6	1.71	0.2
Ca%	0.68	0.52	0.58	0.68	0.72	0.75	0.09
Mg%	0.53	0.32	0.4	0.48	0.5	0.49	0.05
P%	0.22	0.24	0.27	0.32	0.37	0.38	0.06
Fe mg kg^{-1}	201	207	230	306	357	402	41 -*
Mn mg kg^{-1}	72	74	105	158	187	203	22
Zn mg kg^{-1}	14.9	20.2	17.4	12	10.4	9.7	2.7
Cu mg kg^{-1}	6.8	7.8	9.2	12.2	13.7	14.4	1.9
N/P	10.2	9.9	9.6	7.7	6.8	6.7	1.5
N/K	2.2	1.6	1.6	1.5	1.6	1.4	0.2
K/P	4.6	6.6	6.2	5.1	4.3	4.5	1
N/Cu	3110	3020	2940	2090	1880	1760	520
P/Zn	154	120	164	273	358	378	73
K/Mg	1.9	4.6	4.1	3.5	3.2	3.5	0.7
Yields and yield elements							
Plant density, 1000 plants ha^{-1}	65.7	69.6	70.2	69.6	68.8	68.8	2.3
Percentage of infertile plants	1.6	0.7	0.8	0.8	0.8	1.1	0.6
Grain number cob^{-1}	418	465	518	522	509	480	58
1000-grain/kernel weight, g	276	300	302	305	300	302	27
Grain number m^{-2}	2940	3100	3620	3640	3260	3020	300
Grain mass, g $plant^{-1}$	134	144	165	163	153	142	10
Efficiency %	69	69	73	73	73	73	3
Stalk yield, t ha^{-1}							
Grain yield, t ha^{-1}	8.69	9.95	11.7	11.27	10.47	9.7	0.45
D±NKP_{50}	-3.01	-1.75	0	0.43	-1.23	-2	0.45

Note: D = Difference from NKP_{50}, grain yield t ha^{-1}

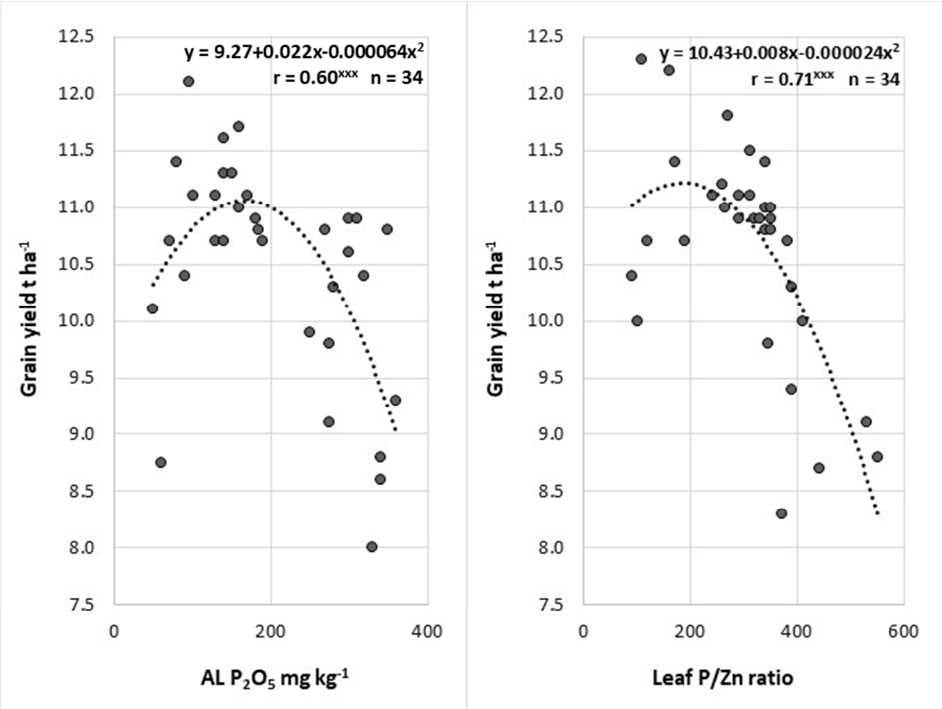

Figure 2
Correlations between the AL-soluble P content of the soil, the leaf P/Zn ratio in the flowering stage and the grain yield of maize. Calcareous chernozem, Nagyhörcsök, 1987

Plant density and the number of grains per cob also determine the number of grains per square metre. In 1987, there was only one fertile cob per plant, with a grain number per cob of 418 in the absolute control, 465 on NK (P-control) plots, 480 in the case of excessive P fertilization and 520 with appropriate P supplies. The average cob length was 16-18 cm on plots treated with deficient or excessive P and 20 cm on plots with satisfactory P supplies. Excessive P fertilization and the resulting Zn deficiency may block the development of cob length and the formation of grains in the cobs. The relationship between soil AL-P_2O_5 content and the maize grain yield shows clearly that both poor and excessive P supplies reduce soil fertility under conditions similar to those in the Nagyhörcsök maize experiment. Leaf analysis can give useful information on P-induced Zn deficiency. Both soil and plant analyses are required to evaluate the plant nutritional status and the danger of under- or over- fertilization (*Figure 2*).

In 1991 and 2006, foliar zinc fertilizer was applied in order to prove that yield losses due to P-induced Zn deficiency can be compensated by Zn application (*Tables 4* and *5*).

In both years, the soil P supply was medium on P0, good on P50, very good on P100 and excessive on P150 and P200 plots. The soil Zn supply was poor on all the plots in both years.

As a consequence of P-induced Zn deficiency, the maize grain yields fell by 2 t ha^{-1} in 1991 and by almost 5 t ha^{-1} in 2006 at the P_4 level (200 kg ha^{-1} P_2O_5 $year^{-1}$) in comparison to the P_1 variant (50 kg ha^{-1} P_2O_5 $year^{-1}$) (*Tables 4 and 5*).

In 1991, in response to the application of 1.2 kg ha^{-1} foliar Zn in the form of zinc hexamine, maize grain yield surpluses were 1.7 to 1.8 t ha^{-1} at the highest P level. In 2006 the P-induced Zn deficiency caused unexpectedly high (almost 5 t ha^{-1}) grain yield losses on plots with higher P levels. The application of 1.2 kg ha^{-1} foliar Zn in the form of zinc sulphate led to maize grain yield surpluses as high as 1.7 to 1.8 in 1991, while 1.0 to 3.8 t ha^{-1} in 2006 (*Tables 4 and 5*).

Table 4

Effect of soil P and foliar Zn application on maize grain yields, leaf P and Zn contents in the flowering stage and leaf P/Zn ratios. Pannónia SC 3737 hybrid.
Calcareous chernozem, Nagyhörcsök, 1991

	NKP_0	NKP_{50}	NKP_{100}	NKP_{150}	NKP_{200}	$LSD_{5\%}$	Mean
AL-P_2O_5 mg kg^{-1}	73	117	208	292	388	69	216
EDTA-Zn mg kg^{-1}	0.7	0.8	0.9	0.9	0.9	0.2	0.8
Zn levels	Grain yield, t ha^{-1} (86 % d.m.)						
Zn 0	9.89	12.51	11.88	10.51	10.40	1.06	10.47
Zn 1	9.70	12.61	12.03	12.32	12.09		11.16
Mean	9.80	12.56	11.95	11.42	11.25	0.90	10.82
	Leaf P % in the flowering stage						
Zn 0	0.19	0.30	0.32	0.42	0.44	0.04	0.31
Zn 1	0.19	0.29	0.30	0.36	0.37		0.28
Mean	0.19	0.30	0.31	0.39	0.40	0.03	0.29
	Leaf Zn mg kg^{-1} in the flowering stage						
Zn 0	39	17	13	12	18	27	20
Zn 1	95	70	59	58	53		68
Mean	67	43	36	35	36	12	44
	Leaf P / Zn ratio in the flowering stage						
Zn 0	50	192	273	349	284	170	205
Zn 1	20	42	53	61	71		46
Mean	35	117	163	205	178	123	125

Note: $LSD_{5\%}$ values were practically identical when determining significant differences between both P and Zn treatments

Such a high maize grain yield loss (4.9 t ha^{-1}) has never before been reported in response to P over-fertilization in Hungarian long-term field trials. Similarly, the application of only 1.2 kg ha^{-1} foliar Zn has never yet resulted in grain yield surpluses as high as 3.8 t ha^{-1} in Hungary (*Tables 4 and 5*).

Over-fertilization with P and foliar Zn application had opposite effects on the leaf P and Zn contents and P/Zn ratios of maize in the flowering stage.

Table 5
Effect of soil P and foliar Zn application on maize grain yields, leaf P and Zn contents in the flowering stage and leaf P/Zn ratios. Pioneer SC 38A24 hybrid.
Calcareous chernozem, Nagyhörcsök, 2006

	NKP_0	NKP_{50}	NKP_{100}	NKP_{150}	NKP_{200}	$LSD_{5\%}$	Mean
AL-P_2O_5 mg kg^{-1}	100	156	252	413	540	87	292
EDTA-Zn mg kg^{-1}	0.7	0.8	0.9	0.9	0.9	0.2	0.8
Zn levels	Grain yield t ha^{-1} (86 % d.m.)						
Zn 0	9.60	10.13	8.34	6.06	5.25		7.88
Zn 1	9.34	10.45	9.97	7.08	9.06	2.16	9.18
$LSD_{5\%}$			2.19				1.05
Mean	9.47	10.29	9.15	6.57	7.16	1.52	8.53
Leaf P % in the flowering stage							
Zn 0	0.26	0.31	0.33	0.33	0.40		0.33
Zn 1	0.26	0.35	0.32	0.30	0.34	0.04	0.31
$LSD_{5\%}$			0.04				0.03
Mean	0.26	0.33	0.32	0.32	0.37	0.03	0.32
Leaf Zn mg kg^{-1} in the flowering stage							
Zn 0	34	18	18	20	14		21
Zn 1	134	155	207	172	212	72	176
$LSD_{5\%}$			77				22
Mean	84	86	113	96	113	54	99
Leaf P / Zn ratio in the flowering stage							
Zn 0	78	185	204	182	328		196
Zn 1	20	75	17	19	18	101	30
$LSD_{5\%}$			102				44
Mean	49	130	111	101	173	72	113

The leaf P supply of maize in the flowering stage is considered to be poor at below 0.15% P, moderate between 0.16 and 0.24%, good between 0.25 and 0.40%, very good between 0.41 and 0.50%, and excessive over 0.51% (JONES, 1967). In 1991, the P supplies of maize in the flowering stage were medium on the P0 plots, good on the P50 and P100 plots, and very good on the P150 and P200 plots. Fifteen years later, in 2006, however, the P supplies were medium to good on P0 plots, and good in all the other treatments (*Tables 4* and *5*).

The leaf Zn supplies of maize in the flowering stage are considered to be poor at below 15 mg kg^{-1} Zn, moderate between 16 and 19 mg kg^{-1}, good between 20 and 150 mg kg^{-1}, very good between 151 and 200 mg kg^{-1}, and excessive over 200 mg kg^{-1} (JONES 1967). Without foliar Zn fertilization, the Zn supplies were good on the P0 plots, both in 1991 and 2006, while on plots given P fertilizer the Zn supplies dropped to poor to medium in 1991 and to medium in 2006. In response to Zn fertilizer the maize Zn supplies increased to good in 1991 and to very good in 2006 (*Tables 4* and *5*).

A maize P/Zn ratio above 150 in the flowering stage may indicate P-induced Zn deficiency, as was the case even in the P50 (50 kg ha P_2O_5 $year^{-1}$) treatment. This phenomenon is even more pronounced at a P/Zn ratio of over 250, as observed in the P100 to P200 treatments in 1991 and in the P200 treatment in 2006. These are the treatments where the highest grain losses occurred due to P over-fertilization. On the P0 plots and all the Zn-treated plots, the P/Zn ratios in the flowering stage remained far below 150, so foliar Zn application is a useful tool for eliminating P-induced zinc deficiency (*Tables 4* and *5*).

In the new, cost-saving, environmentally friendly RISSAC HAS - RIA HAS (Pro Planta) fertilizer recommendation system (CSATHÓ et al., 1998), which is based on correlations found in the database of the Hungarian long-term field NPK fertilization experiments published between 1960 and 2000 (NÉMETH, 2006) and which received the Innovation Grand Prize of Hungary ten years ago, special attention is paid not only to the appropriate NPK levels for field crops, but also to meso- and micronutrient supplies (including zinc) (CSATHÓ et al., 2009).

The data obtained clearly indicate that maize yields are impeded by both poor and excessive P status. Soil and plant analysis may be useful tools for monitoring the nutritional status of plants, including that of P and Zn.

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