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THE MAGNESIUM AND CALCIUM MINERAL STATUS OF MAIZE AT PHYSIOLOGICAL MATURITY AS A TOOL FOR AN EVALUATION OF YIELD FORMING CONDITIONS

Witold Szczepaniak, Witold Grzebisz,
Jarosław Potarzycki, Remigiusz Łukowiak,
Katarzyna Przygocka-Cyna

Chair of Agricultural Chemistry and Environmental Biogeochemistry
Poznan University of Life Sciences

ABSTRACT

Grain yield of maize reflects the extent of nutrient imbalance during the growing period. The key objective of a post-harvest analysis of maize, based on chemical characteristics of each part of plants harvested at physiological maturity, is to determine mineral indices which can serve as indicators of grain yield. This assumption has been validated by a long-term field experiment with four levels of potassium and nitrogen supply (0, 100, 150, and 200 kg N ha^{-1}). The potassium application systems were differentiated by the soil fertility level (medium, high) and K fertilizer (K-, K+). The grain yield of maize was significantly affected by an interaction of the potassium fertilizing systems and years. The importance of this interaction for yield formation manifested itself most distinctly in 2005, when the weather was favourable for plant growth, and in 2004, a season with temporary drought, but not in 2006, when severe drought occurred during the period termed as *the critical window*. The study implicitly showed that stem leaves can be used as indicators of the management of magnesium by maize while the grain content of calcium indicates how the plant manages that element. The limited size of maize's physiological sink, i.e. number of kernels per cob, significantly decreases the flow of magnesium from leaves to kernels. Therefore, an elevated concentration and/or content of magnesium in stem leaves can be considered as an indicator of some disturbance of the yielding performance. The calcium concentration in grain showed the highest year-to-year variability among the maize parts. Any increase of this grain characteristic resulted in a yield decline. The key reason was an imperfect structure of the cob due to the disturbed setting up of kernels.

Keywords: maize parts, potassium fertilizing system, nitrogen rates, nutrient concentration and partitioning, yield performance.

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dr inż. Witold Szczepaniak, Chair of Agricultural Chemistry and Environmental Biogeochemistry, Poznan University of Life Sciences, Wojska Polskiego Street 71F, 60-625 Poznan, Poland, e-mail: witeczek@up.poznan.pl

INTRODUCTION

Being a C_4 plant, maize can achieve its yielding potential provided there is an ample supply of water and nutrients during the critical stages of yield formation (Tollenaar et al. 2002) Under rain-fed conditions, the rate of growth is significantly affected by the distribution of precipitation, which is frequently described as a year-specific effect. It has been well documented that shortage of water during the critical window period (CWP), extending from one week before to the third week after silking, considerably reduces the kernel number per plant – KNP (Ritche, Alagarswamy 2003). The actual degree to which maize yield is reduced depends on the supply of nutrients. As reported by Subedi and Ma (2009), grain yield of maize in a humid temperate environment in Canada is most significantly limited by the absence of a pre-plant application of nitrogen (10-22%). The second most important cause of yield decline in that region is the deficiency of available potassium (13%). The damaging effect of water shortage on maize yield can be ameliorated, at least to some extent, by an adquate supply of nutrients. A good supply of potassium to maize increased the KNP (Szczepaniak et al. 2013). Therefore, in regions exposed to sporadic droughts, potassium can be used as a simple tool to counteract the negative impact of water shortage on maize yield formation (Grzebisz et al. 2013, Heckman, Kamprath 1992).

It is essential to assess the effect of long-term potassium fertilization on the concentration and accumulation of two potentially antagonistic ions, such as magnesium and calcium. Biochemical and physiological functions of both nutrients in plants are well recognized (Maguire, Cowan 2002). Magnesium plays an important role in chlorophyll molecules, where it is the key plant component responsible for carbon dioxide fixation. Early symptoms of magnesium deficiency are not easily discernable, but they can be revealed as changes in carbohydrate distribution among plant tissues. For instance, an early symptom of Mg deficiency in the growth medium is the acceleration of processes favouring root growth (Verbruggen, Hermans 2013, Gerendás, Führs 2013). This probably explains why plants well fed with magnesium are more resistant to abiotic stresses, such as a shortage of water and deficiency of nitrogen. This specific fate of magnesium in plants results in an increase of nitrogen recovery by crops, including maize (Grzebisz et al. 2010, Potarzycki 2011, Szulc 2010, Szulc et al. 2011).

Calcium is a divalent ion, which plays numerous functions during the life cycle of a plant. Its structural functions in the cell walls and membranes are crucial for plant tissue build-up. One of the key functions of calcium is to influence the division of meristematic cells and their subsequent extension, which is necessary for the growth of both roots and stems. In the last two decades, calcium has been recognized as a decisive nutrient responsible for the growth and development of plants. It has been widely documented that calcium concentrations in the cell cytosol are sensitive to signals of different origin, like light, biotic stress, abiotic stress, hormones. Also, it has been evidenced that even small changes in the cytosol calcium concentration result in a specific physiological response, which significantly affects the plant growth rate (Lecourieux et al. 2006, White, Broadley 2003).

Although functions of magnesium and calcium in plants are well documented, there is a wide gap in research on the impact of both nutrients on crop yield performance. Our objective has been to use magnesium and calcium as a diagnostic tool for a post-harvest analysis of growth conditions. It has been assumed that an analysis of the plant's nutritional status at physiological maturity, which takes into account both grain and vegetative parts, will enable us to identify factors responsible for growth disorders during the critical stages of yield performance in maize.

MATERIAL AND METHODS

The response of maize to increasing nitrogen doses was studied at Brody Experimental Station of Poznan University of Life Sciences, Poland (16°28′ E and 52°44′ N), during three consecutive growing seasons of 2004, 2005 and 2006. The long-term experiment was established in 1991 on Albic Luvisol developed from loamy sand underlain by light loam. A field trial was arranged in a two-factorial split-block design, replicated four times and comprised of two sets of factors:

1) potassium fertilizing systems: four treatments;

2) four doses of fertilizer nitrogen: 0, 100, 150 and 200 kg N ha^{-1}.

The tested systems of potassium fertilization are a combination of: i) a medium K fertility soil level without and with an application of fertilizer potassium (acronym MK-, MK+, respectively), ii) a high soil K fertility level without and with an application of fertilizer potassium (HK-, HK+).

Each year, winter wheat preceded maize. The variety Eurostar (FAO 240) was sown in April (the second decade) and harvested in September (the second or third decade). All fertilizers were applied in spring, just before sowing. Doses and forms of the nutrients were as follows: (i) P_2O_5 – 80 kg ha^{-1} as SSP (single superphosphate), (ii) K_2O – 160 kg ha^{-1} as muriate of potash, (iii) nitrogen as ammonium nitrate (34%). The first dose of 100 kg N ha^{-1} was applied before sowing. The remaining N dose was supplied at the stage of 3(5) maize leaf, according to the experimental design. All other technologies were in accordance with standard agricultural practice. A single plot size was 22.4 m^2. At maturity, crops were harvested from an area of 11.2 m^2. Total grain yields were adjusted to 14% moisture content.

Meteorological conditions during the study were highly variable (Table 1). The sum of precipitation during the period from BBCH 15 to BBCH 71 (most of June and July), decisive for yield component formation, was 118.4 mm in

Table 1

Characteristics of meteorological conditions during the study*

Season	January	February	March	April	May	June	July	August	September
Temperature (°C)									
1961-2006	-1.6	-0.5	2.9	7.9	13.2	16.4	18.1	17.5	13.3
2004	-3.5	2.2	5.1	10.0	13.6	16.3	17.3	19.1	13.7
2005	2.1	-1.5	1.8	8.8	12.8	16.4	19.7	16.9	15.6
2006	-6.3	-1.2	0.5	8.7	13.7	19.9	24.4	19.7	16.3
Precipitation (mm)									
1961-2006	40.1	32.6	40.1	38.1	56.7	62.7	77.2	66.7	48.8
2004	73.2	43.4	20.8	23.3	44.3	58.8	59.6	57.4	43.2
2005	48.5	66.4	22.9	19.2	86.2	39.8	126.5	81.6	37.5
2006	17.1	26.8	36.8	47.2	41.4	7.7	9.9	188.7	24.5

* Meteorological Station at Brody

2004, 166.3 mm in 2005, and 17.6 mm in 2006. At the same time, the temperatures were above the long-term average (Table 1).

Plant samples for dry mater partitioning assessment were collected at BBCH 89, from an area of 1.0 m^2 of a plot. The harvested plant sample was divided into sub-samples of leaves (acronym LE), stem (ST), grains (G), cob core (CC) and cob covering leaves (CCL), after which they were dried (65°C). Plant material for mineral element determination was mineralized at 640°C and the ash was dissolved in 33% HNO_3. Magnesium concentrations were measured by flame atomic absorption spectrometry while calcium levels were assessed by flame photometry. Results are expressed per dry matter (DM). The content of each nutrient in every plant part was calculated by multiplying its concentration and the biomass of a given crop part.

The results were subjected to the conventional analysis of variance using the software Statistica® 10. Differences between treatments were evaluated with the Tukey's test. The tables and figures provide results from the *F* test (***, **, * indicate significance at the $P < 0.1\%$, 1%, and 5%, respectively). Path analysis was conducted based on correlation coefficients with grain yield and/or its structural component taken as effects and magnesium, and/or calcium accumulation in plant parts as independent variables. The path diagram, showing direct and indirect path coefficients, was elaborated based on the highest value of the correlation coefficient for a particular set of variables. The second step of the diagnostic procedure consisted of stepwise regression, applied to identify an optimal set of variables for a given crop characteristic. In the computing procedure, consecutive variables were added step-by-step to the multiple linear regressions. The best regression model was chosen based on the highest *F*-value for the entire model and significance of all independent variables (Konys, Wiśniewski 1984).

Acronyms applied in the paper:

Y – yield of grain,

$G_{Mgc/Cac}$ – magnesium/calcium concentration/content in grain,

$LE_{Mgc/Cac}$ – magnesium/calcium concentration/content in leaves,

$SH_{Mgc/Cac}$ – magnesium/calcium concentration/content in stem,

$CCL_{Mgc/Cac}$ – magnesium/calcium concentration/content in cob covering leaves,

$CC_{Mgc/Cac}$ – magnesium/calcium concentration/content in cob core.

RESULTS AND DISCUSSION

Total biomass and grain yield

Among the analyzed factors, the potassium fertilizing system and year interaction was the decisive factor that affected the yield of maize biomass and grain. The effect of nitrogen was of secondary importance. The effect of potassium fertilization on these two maize harvest attributes considerably depended on the weather course during the season (Figure 1). It was demonstrated that the yield of grain (Y) was significantly related to the total biomass (TB) of maize:

$$Y = 0.605TB - 2252 \text{ for } n = 12,\ R^2 = 0.82 \text{ and } P \leq 0.001.$$

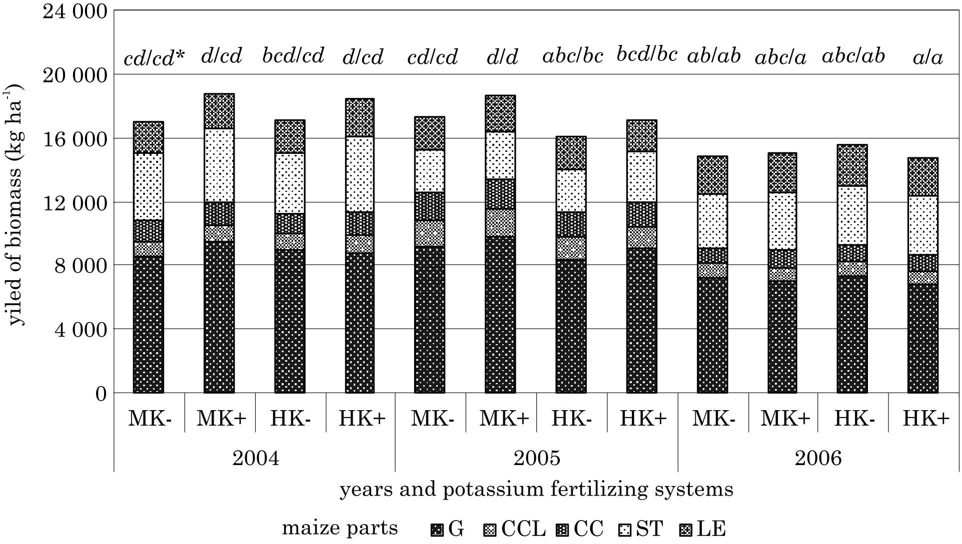

Fig. 1. Effect of potassium fertilizing systems on yield of maize biomass and its structure: G – grain, CCL – cob covering leaves, CC – cob core, ST – stem, LE – leaves,
[a] data marked with the same letters are not significantly different,
* *cd/cd* – statistical evaluation of total biomass and grain yields, respectively

The total biomass components showed significant year-to-year variability. The stem and the cob covering leaves were most sensitive to ambient conditions. Both tissues responded, *albeit* reversely, to the weather course in the consecutive years. In 2005, the biomass of CCL increased at the expense of stem biomass. A contrary situation was observed in years with water shortages. The main reason was the degree and time of water stress. The amount of precipitation during the first season was just 229 mm. Water shortage, resulting in plant stress, was most severe in August, i.e. during the grain filling period. In these conditions, total biomass of maize responded positively to a new dose of potassium (K+ treatments). In contrast, grain yields did not show any response to the potassium fertilizing system. In the second year, environmental conditions were generally favourable to maize growth (361 mm in the season). Nonetheless, the entire yield of biomass showed much stronger variability than in 2004. The crop reached the maximum grain yield, which was harvested from the medium K fertile soil and recently applied potassium (MK+). In 2006, both total biomass and grain yields were the lowest. No response of the whole crop biomass and grain yield to the treatments was recorded. The main reason was the low amount of precipitation (221 mm). A more detailed analysis of the growth conditions showed that the water shortage in July and August seriously affected the KNP. The study implicitly corroborates the key importance of the weather during the CWP for the setting-up of maize kernels. This yield component is recognized as the key predictor of grain yield (OTEGUI et al. 1995, RITCHIE, ALAGARSWAMY 2003, SZCZEPANIAK et al. 2013). The KNP variability depended on the weather course during the growing season and on the potassium fertilizing systems, although no interaction was verified between these two factors. The KNP values, averaged over the experimental treatments, were: 378 in 2004, 473 in 2005, and just 263 in 2006. The impact of the K fertilizing system on KNP was treatment specific. The highest KNP was produced by plants grown on medium K fertile soil, but fertilized with potassium (Figure 2). The KNP trait showed strong impact on the final yield, as presented below:

$$\text{All years: } Y = -0.057\text{KNP}^2 + 50.09\text{KNP} - 3237$$

$$\text{for } n = 12,\ R^2 = 0.88,\ \text{KNP}_{op} = 441 \text{ and } Y_{maks} = 7804 \text{ kg ha}^{-1};$$

$$\text{Years with drought: } Y = 13.87\text{KNP} + 2357 \text{ for } n = 8,\ R^2 = 0.96.$$

The regression model of the 2° degree indirectly indicates optimum growth conditions for yield performance, which occurred in 2005. The highest KNP produced by maize was decisive for attaining the maximum grain yield. The linear model, obtained in years with temporary drought during the CWP, can be considered as an indicator of the physiological sink disturbance. The second yield component, i.e. TKW, showed only year-to-year variability, achieving 288 g in 2004, 299 g in 2005, and 316 g in 2006. Despite a higher weight of kernels in 2006, this trait did not raise the yield due to an insufficient development of the KNP. This study supports the thesis that the ame-

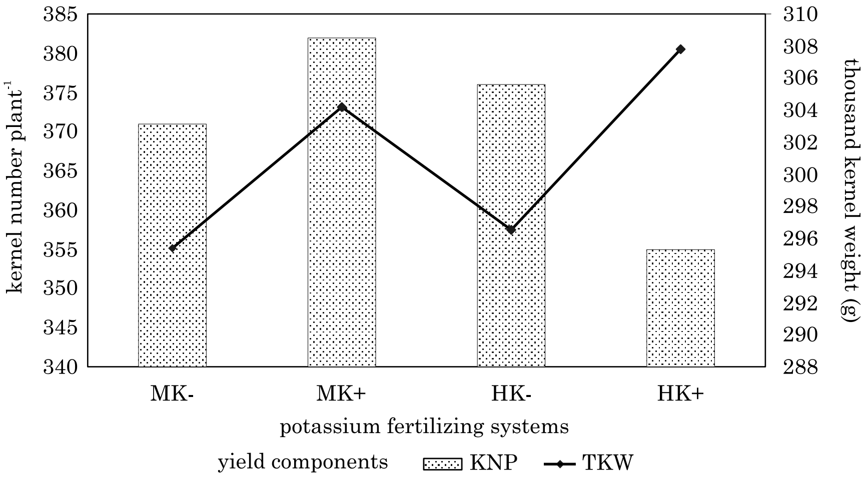

Fig. 2. Response of key yield components to potassium fertilizing systems: KNP – kernel number plant^{-1}, TKW – thousand kernel weight

liorative effect of a good supply of potassium on crops reveals itself only under conditions of mild water stress (Grzebisz et al. 2013, Szczepaniak et al. 2014).

Magnesium concentration in plant parts

Magnesium concentration in maize at physiological maturity was organ-specific, as presented below in the descending order of plant organs: leaves > grain > stem > cob covering leaves > cob core.

The above order of plant parts points to leaves as the most conservative maize organ during the grain filling period. A high concentration of magnesium in this tissue suggests a low magnesium remobilization potential during the kernel growth (Table 2). At the same time, leaves showed the highest sensitivity to the weather. In 2006, Mg concentration in this tissue was twice as high as found in the other years. A slightly different response was observed for the stem and CCL. In these two tissues, the highest Mg concentrations were noted in 2006, being significantly lower in the other two years. The lowest Mg content was found in 2005, when maize yield was the highest. An extremely low Mg concentration in all maize parts observed in 2005 indicates the occurrence of a dilution effect (Brkić et al. 2003). Quite a reverse situation was observed for the cob core. An extremely highly variable magnesium status in leaves due to the impact of external conditions can be used as an indicator of growth disturbances. The effect of the potassium fertilizing systems was significant for the stem and leaves. However, it was only in leaves that the Mg concentration responded antagonistically to the increasing supply of potassium. As reported by Çelik et al. (2010), only high K doses exert a negative impact on magnesium accumulation in leaves. The

Table 2

Magnesium concentration in maize parts at physiological maturity (g kg^{-1} DM)

Main factor	Level of the factor	Grain (G)	Cob covering leaves (CCL)	Cob core (CC)	Stem (ST)	Leaves (LE)
Years	2004	1.34^{b}	0.75^{b}	0.41^{a}	1.00^{b}	1.20^{a}
	2005	0.71^{a}	0.52^{a}	0.76^{b}	0.74^{a}	1.20^{a}
	2006	1.34^{b}	0.96^{c}	0.37^{a}	1.20^{c}	2.54^{b}
	F	114.1***	112.1***	55.8***	70.0***	316.1***
Potassium fertilizing systems	MK-	1.14	0.74	0.54	1.02^{b}	1.79^{b}
	MK+	1.11	0.74	0.53	1.04^{b}	1.75^{b}
	HK-	1.18	0.77	0.50	0.89^{a}	1.56^{a}
	HK+	1.10	0.74	0.49	0.98^{ab}	$1,50^{a}$
	F	1.01	0.39	0.58	4.29**	8.03***
Nitrogen rates	0	1.12	0.68^{a}	0.52	0.83^{a}	1.30^{a}
	100	1.20	0.75^{ab}	0.52	0.98^{b}	1.72^{b}
	150	1.10	0.78^{b}	0.50	1.07^{b}	1.74^{b}
	200	1.11	0.76^{ab}	0.51	1.05^{b}	1.84^{b}
	F	1.27	3.04*	0.135	11.17***	23.02***

^{a} data marked with the same letters are not significantly different;
$^{***, **, *}$ – probability level at 0.001; 0.01; 0.05. respectively

nitrogen doses increasing up to 100 kg ha^{-1} affected positively magnesium concentrations in the leaves, stem and cob covering leaves.

The path analysis method was applied to identify the key maize tissue responsible for the formation of grain yield. Magnesium concentrations in the CCL and LE exerted the strongest impact on grain yield, as documented by the highest correlation coefficients (r = -0.91 for CCL and r = -0.88 for LE). These two variables also produced the strongest direct effect, but the CCL proved to be the key variable for yield determination. Generally, the influence of the other variables on grain yield was indirect (Table 3). The dominant impact of the CCL and LE on grain yield was confirmed by two stepwise regression models:

$$Y = -12.14 - 5.26CCL \text{ for } n = 12,\ R^2 = 0.80 \text{ and } P \leq 0.001;$$

$$Y = 11.85 - 3.24CCL - 0.73LE \text{ for } n = 12,\ R^2 = 0.87 \text{ and } P_{CCL} < 0.001,\ P_{LE} \leq 0.05.$$

The negative value of both coefficients, signifying excessive magnesium concentrations, can be considered as indicators of maize growth disturbances. The main reason of this type of dependence was the insufficient capacity of maize cob to absorb magnesium during the grain filling period. The high Mg concentration in CCL at maize maturity can be explained by its low remobi-

Table 3

Components of path analysis of the Mg impact on maize yield ($n = 12$)

Character type/ Mg variable	Concentration		Accumulation	
	DI*	INDs**	DI*	INDs**
Mg_G	+0.218	-0.903	+0.523	-0.809
Mg_{LE}	-0.534	-0.344	-0.268	-0.615
Mg_{ST}	+0.248	-1.048	+0.046	-0.629
Mg_{CCL}	-0.646	-0.255	-0.123	-0.320
Mg_{CC}	+0.287	+0.445	+1.057	-0.267

* direct effect, ** sum of indirect effects

lization due to inadequate remobilization to kernels, considered as the nutrient physiological sink. This concept was corroborated by an analysis of the relationship between Mg concentration in CCL and KNP. The developed equation clearly demonstrated that magnesium concentration in maize at its maturity depended on the absorption capacity of the cob, related to the number of fixed kernels:

$$KNP = -0.002CCL_{Mg} + 1.49 \text{ for } n = 12,\ R^2 = 0.91 \text{ and } P \leq 0.001.$$

Magnesium accumulation in plant parts

Magnesium accumulation in maize was tissue-specific, but it appeared in a completely different order than its concentrations (Table 4): grain > leaves > stem > cob covering leaves = cob core.

On average, grain contained 45% of total magnesium accumulated in maize at maturity. Magnesium contents in grain and other vegetative tissues were, except for the CCL, significantly affected by the year-to-year variability. In general, the developed trends of magnesium accumulation followed patterns observed for its concentration. The relative distribution of magnesium between maize parts was year-specific (Figure 3). The grain magnesium content, termed as the magnesium harvest index (MgHI), showed a high annual variability. The MgHI exceeded 55% in the semi-dry 2004. In 2005, MgHIs were highly variable due to a significant impact of the potassium regime. It was observed that maize plants grown on the medium K soil (MK) accumulated in grain only 40% of crop magnesium. Plants grown on the K fertile soil (HK) showed much higher Mg content in grain. However, it was dependent on the current K application. In 2006, MgHIs were low, irrespectively of a fertilizing systems, declining to 40% on average. Special attention should also be focused on the maize stem, which can be considered as an Mg internal buffer. This maize organ may play a crucial role in nitrogen management, as suggested by POTARZYCKI (2011). This hypothesis is corroborated by two facts. First is the year-to-year variability of amounts of magnesium in stems. The stem content of Mg was both quantitatively and relatively the

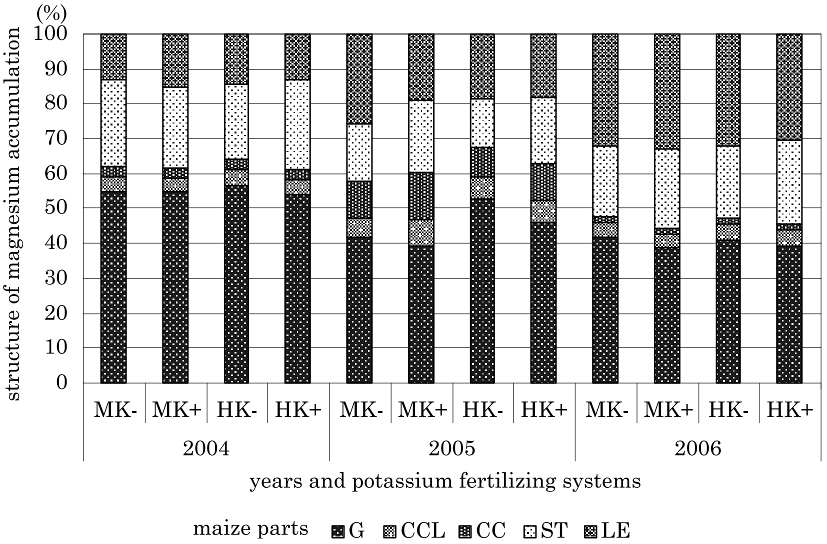

Fig. 3. Impact of K fertilizing systems on magnesium partition among parts of maize: G – grain, CCL – cob covering leaves, CC – cob core, ST – stem, LE – leaves

lowest in 2005, when the yields were higher than in the seasons with temporary water shortages. The second observation was that in 2005 the Mg content in maize tissues proximate to kernels, such as the CCL and CC, increased the highest. In that year, these two tissues were not depleted of magnesium, as observed in years with water stress. The effect of nitrogen doses on the Mg content was generally positive, except for the cob core, and limited to the doses of 100 kg N ha^{-1} for grain, and to 150 kg N ha^{-1} for the cob covering leaves and stem, respectively. In leaves, the Mg increased in accordance to the progressing N doses.

The highest year-to-year fluctuation of magnesium in maize's vegetative parts occurred in leaves, followed by the stem and cob core. However, as results from the conducted path analysis, it is only the magnesium content in leaves that can be used as an indicator of stress growth conditions (Figure 4b). The highest direct impact on grain yield was observed in the cob core, following by the grain Mg content. A positive sign of this index signifies magnesium shortage in both maize tissues. In the case of grain, the sum of indirect effects was high and negative, significantly decreasing the value of the correlation coefficient. Under the growth conditions during our experiment, grain yield (Y) of maize can be determined by two sets of equations, as results from the conducted stepwise analysis:

Grain yield:

$$Y = 1.95 + 0.45G_{Mga} + 3.68CC_{Mga}$$

for $n = 12$, $R^2 = 0.87$ and $P_{GMga} \le 0.001$ and $P_{CCMga} \le 0.000$;

$$Y = 5.08 + 0.27G_{Mga} - 0.21LE_{Mga} + 2.46CC_{Mga}$$

for $n = 12$, $R^2 = 0.92$ and and $P_{GMga} \leq 0.05$; $P_{LEMga} \leq 0.05$; $P_{CCMga} \leq 0.01$.

Kernel number per plant:

$$KNP = 377.9 - 24.28LE_{Mga} + 116.6CC_{Mga}$$

for $n = 12$, $R^2 = 0.93$ and $P_{LEMga} \leq 0{,}001$, $\mathrm{P}_{CCMga} \leq 0.001$.

These two sets of equations demonstrate clearly that the elevated content of magnesium in maize leaves is related to the size of a maize cob. Its yielding capacity is significantly affected by the KNP. Therefore, the development of this crop part is of key importance for magnesium management during the grain filling period. An accurate prediction of maize yield was much easier to achieve when Mg concentrations rather than its accumulation were considered. In short, the magnesium concentration in stem leaves at maize physiological maturity can be considered as an indicative plant trait for yield performance evaluation.

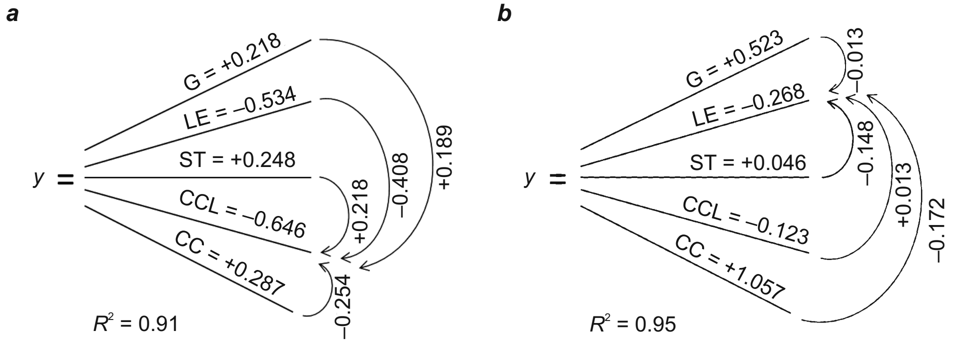

Fig. 4. Path diagram of maize magnesium status at maturity on grain yield: *a* – magnesium concentration, *b* – magnesium accumulation, G – grain, CCL – cob covering leaves, CC – cob core, ST – stem, LE – leaves

Calcium concentration in plant parts

Calcium concentration in maize was tissue-specific, as presented below in the descending order of plant parts: leaves > stem > cob covering leaves ≥ grain > cob core.

The decreased calcium concentration in vegetative tissues proximate of kernels indirectly implicates its high mobility from the cob core and cob covering leaves to developing kernels, considered as a final sink (Table 5). All these three tissues showed the highest year-to-year variability. The lowest calcium concentration in the leaves, stem and grain was observed in 2005. A completely reverse pattern of the weather impact was noted for the cob covering leaves. The effect of the potassium fertilizing systems was significant for the Ca concentration in the stem and leaves. In both tissues, a strong decre-

Table 5

Calcium concentration in maize parts at physiological maturity (g kg^{-1} DM)

Main factor	Level of the factor	Grain (G)	Cob covering leaves (CCL)	Cob core (CC)	Stem (ST)	Leaves (LE)
Years	2004	0.21^{a}	1.02^{a}	0.66^{c}	3.37^{b}	6.90^{b}
	2005	0.17^{a}	1.54^{b}	0.29^{a}	2.80^{a}	6.45^{a}
	2006	0.29^{b}	1.59^{b}	0.45^{b}	2.88^{a}	6.44^{a}
	F	17.97***	81.25***	81.35***	65.81***	7.14**
Potassium fertilizing systems	MK-	0.22	1.40	0.48^{ab}	3.09^{b}	7.04^{c}
	MK+	0.21	1.36	0.42^{a}	3.06^{ab}	6.56^{ab}
	HK-	0.26	1.36	0.53^{b}	2.98^{ab}	6.61^{b}
	HK+	0.21	1.40	0.44^{a}	2.93^{a}	6.18^{a}
	F	1.921	0.274	4.206**	2.94*	9.72***
Nitrogen rates	0	0.25	1.36	0.46	2.72^{a}	0.59^{a}
	100	0.21	1.33	0.44	3.03^{b}	0.67^{b}
	150	0.21	1.42	0.48	3.14^{b}	0.70^{b}
	200	0.21	1.41	0.48	3.16^{b}	0.68^{b}
	F	1.492	1.197	0.659	21.82***	15.99***

[a] sata marked with the same letters are not significantly different;
***, **, * – probability level at 0.001; 0.01; 0.05. respectively

ase of the Ca concentration was observed in plants grown on the K fertile soil. The response suggests antagonism between both nutrients, mainly in years with drought. This conclusion was supported by a high increase in calcium concentrations. The effect of nitrogen increasing doses was positive, but only for vegetative tissues, except the cob core. An increase of calcium concentrations in response to nitrogen application reached the sufficiency level at 100 kg N ha^{-1}.

In order to evaluate the impact of calcium concentration in maize tissues on grain yield, a path analysis diagram was developed (Figure 5*a*). The highest coefficient of correlation was recorded for grain (r = -0.89). The importance of G_{Cac}, as the leading predictor of maize yield was proven by its high direct effect. Much weaker effects were calculated for the cob core and cob covering leaves (Table 6). The impact of G_{Cac} on grain yield was only moderately modified by CC_{Cac}. In the other two tissues, sums of indirect effects were much higher compared to their direct influences. The high variability of the indirect effects indicates an elevated sensitivity of calcium concentrations in maize tissues proximate to grain with respect to external growing conditions. The dominance of grain as an indicator maize tissue was corroborated by the developed stepwise regression model shown below:

$$Y = 11.08 - 16.86G_{Cac} \text{ for } n = 12,\ R^2 = 0.76 \text{ and } P \leq 0.001.$$

This equation proves that calcium concentration variability in grain alone explains 76% of grain yield variability. The effect of other tissues, as demonstrated by the stepwise model, was insignificant. This leads to an obvious conclusion: the higher the Ca concentration in grain, the lower the yield produced by maize plant. The key reason is the low capacity of a physiological sink, i.e. number of kernels on the cob. This conclusion was verified by our analysis G_{Cac} versus KNP:

$$G_{Cac} = -0.0006KNP + 0.43 \text{ for } n = 12,\ R^2 = 0.75 \text{ and } P \leq 0.001.$$

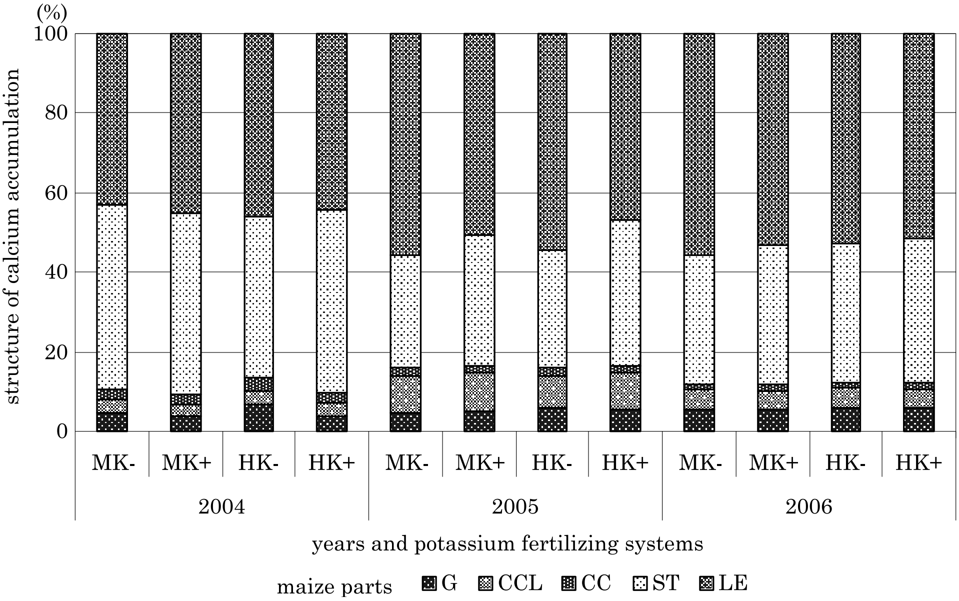

Fig. 5. Impact of K fertilizing systems on calcium partition among parts of maize: G – grain, CCL – cob covering leaves, CC – cob core, ST – stem, LE – leaves

Table 6

Components of path analysis of the Ca impact on maize yield (n = 12)

Character type/ Ca variable	Concentration		Accumulation	
	DI*	INDs**	DI**	INDs**
Ca_G	-1.554	+0.652	-4.815	+4.293
Ca_{LE}	+0.018	+0.132	-0.460	+0.672
Ca_{ST}	-0.254	+0.469	-0.412	+0.717
Ca_{CCL}	+0.835	-1.156	+3.774	-4.209
Ca_{CC}	+1.247	-1.378	+0.804	-0.486

* direct effect, ** sum of indirect effects

Calcium accumulation in plant parts

Calcium partitioning in maize at the stage physiological maturity of maize was most distinctly affected by the season, followed by nitrogen doses (Table 7). The average order of maize tissues was as follows: leaves > stem > cob covering leaves = grain > cob core.

Table 7

Partitioning of calcium accumulation in maize parts at physiological maturity (g m^{-2})

Main factor	Level of the factor	Grain (G)	Cob covering leaves (CCL)	Cob core (CC)	Stem (ST)	Leaves (LE)
Years	2004	0.16^{ab}	0.11^{a}	0.09^{b}	1.47^{c}	1.47^{b}
	2005	0.13^{a}	0.24^{c}	0.05^{a}	0.81^{a}	1.33^{a}
	2006	0.17^{b}	0.14^{b}	0.05^{a}	1.04^{b}	1.60^{c}
	F	3.35*	83.24***	61.24***	118.2***	14.08***
Potassium fertilizing systems	MK-	0.15	0.17	0.06	1.09^{ab}	1.52^{b}
	MK+	0.14	0.17	0.06	1.16^{b}	1.50^{ab}
	HK-	0.18	0.15	0.07	1.03^{a}	1.47^{ab}
	HK+	0.14	0.16	0.06	1.15^{ab}	1.37^{a}
	F	1.526	0.698	0.892	3.053*	2.647
Nitrogen rates	0	0.16	0.13^{a}	0.05^{a}	0.88^{a}	1.15^{a}
	100	0.15	0.15^{a}	0.06^{ab}	1.07^{b}	1.43^{b}
	150	0.15	0.19^{b}	0.07^{b}	1.24^{c}	1.65^{c}
	200	0.16	0.18^{b}	0.07^{b}	1.24^{c}	1.63^{c}
	F	0.037	9.632***	3.947**	22.86***	30.94***

[a] data marked with the same letters are not significantly different;

***, **, * – probability level at 0.001; 0.01; 0.05. respectively

The sensitivity of the calcium content in maize to seasonal weather variability was tissue-specific. The lowest Ca accumulation in maize parts, except for the cob covering leaves (CCLs), was observed in 2005. It is important to stress that the Ca accumulation in CCL in 2005 was on average double that found in the other years. The remaining tissues showed much lower year-to-year variability. The calcium content in leaves was less variable, but the highest result was recorded in the dry year 2006. The effect of the potassium fertilizing systems was documented only for the stem and stem leaves. In leaves, a synergetic effect of recently added potassium fertilizer on calcium accumulation was observed. In the case of leaves, an antagonistic effect of K was recorded on soil reach in potassium, leading to Ca content decrease. The effect of nitrogen doses on calcium accumulation in maize parts was generally positive, but only up to the dose of 150 kg N ha^{-1}. The grain Ca content did not show any response to fertilizer nitrogen.

The path analysis showed elevated variability of both direct and indirect effects of the calcium content in maize tissues on grain yield. Based on the value of the correlation coefficient, grain was chosen as predictive tissue. Its dominant effect was verified by an extremely high but negative value of the direct effect. It was the most strongly corrected by the calcium content in the CCL (Figure 5*b*). This plant tissue also showed an extremely high variability of both direct indirect indices. Therefore, these two tissues can be considered as indicators of calcium management in maize plant.

The relative calcium partitioning between maize particular organs showed the dominance of leaves, followed by the stem (Figure 6). It is important to note that in 2005, a year with ample water supply, the dominance of leaves was the strongest. In addition, positive response to new doses of K was found. In the moderately dry year 2004, the contribution of leaves to total accumulated calcium was the lowest, but it was compensated by an increased stem Ca share. This did not happen in very dry 2006. Therefore, it can be concluded that in a semi-dry year, the stem is a temporary storage organ for calcium.

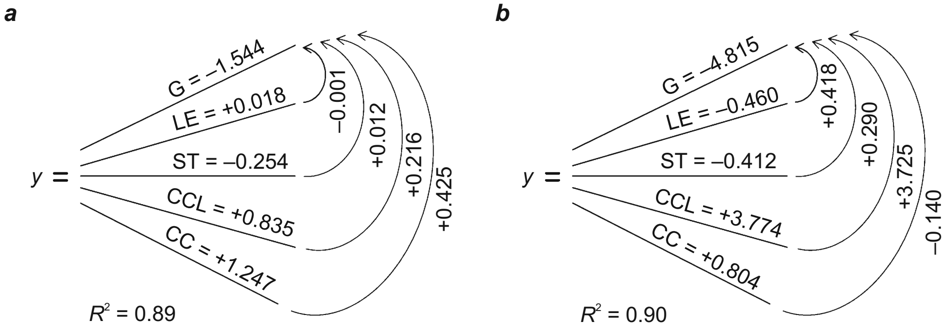

Fig. 6. Path diagram of maize calcium status at maturity on grain yield: *a* – calcium concentration, *b* – calcium accumulation, G – grain, CCL – cob covering leaves, CC – cob core, ST – stem, LE – leaves

CONCLUSION

The yield of maize was significantly depended on the kernel number plant^{-1}, but not on the thousand grain weight. This dependence implicates the Critical Window Period as the decisive time of maize growth and development for the final yield of grain. The magnesium concentration and the content and calcium concentration in maize tissues at physiological maturity can be used as diagnostic tools for an evaluation of yield performance during the growing season. Nutrient-specific tissues were identified, for which the relationship with the final yield of grain was the strongest. The path diagrams and stepwise regression models suggested that magnesium was as a very suitable diagnostic tool. Magnesium concentrations in the stem leaves and cob covering leaves showed the highest response to the weather course during the season. A negative relationship between the magnesium content in stem leaves and kernel number per plant can be considered as an indicator of some disturbance of yield component performance during the Critical Window Period. In the case of calcium, the strongest variability in its content was observed in grain. It was noted that an increase in the calcium concentration resulted in a grain yield decrease. An excessive concentration of magnesium in the stem leaves and calcium in grain at maize physiological maturity were due to the low capacity of maize cob to absorb nutrients stored in the pre-anthesis period in vegetative tissues during the grain filling period. Based on the our results, we can conclude that these two tissues can serve as both a yield predictor and indicator of growth disturbance during the Critical Window Period.

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