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REVIEW PAPER

MAGNESIUM AS A NUTRITIONAL TOOL OF NITROGEN EFFICIENT MANAGEMENT – PLANT PRODUCTION AND ENVIRONMENT

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Abstract

Nowadays, the main objectives of plant crop growers aim at two targets (i) increasing food production and (ii) simultaneously, reducing the environmental impact of increasing fertilizer nitrogen consumption. On a global scale, fertilizer nitrogen recovery ranges from 33 to 50%. The required efforts stimulating production but protecting the environment focus on increasing unit productivity of fertilizer N. Magnesium, owing to its biological functions in plants, should play a much more important role In modern agriculture controlling N economy of crop plants and, consequently, nitrogen dispersion in the environment. In Poland, arable soils are generally poor in total and available magnesium. This state can be considered as indicating the necessity of applying magnesium and then maintaining a well-feed plant nutritional status of growing crops. Crops well supplied with magnesium since the beginning of their growth, as seen from studies on the response of sugar beets and maize, are in a position to increase nitrogen unit productivity. Cereals respond to Mg supply when a dressing treatment takes place just before the onset of flowering. Another factor significantly affecting fertilizer nitrogen recovery in Poland is soil pH. Acid soils fertilized with Mg contain increased soil exchangeable Mg levels, which in turn depress the pressure of toxic aluminum on growing crops. Improvement of the plant Mg nutritional status enables plants to incorporate some of potentially residual N into biomass, increasing

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biomass yield. It can therefore be concluded that magnesium, owing to its ameliorating function in arable soils, meets the main requirement of sustainable nitrogen management, both in agriculture and in the environment.

Key words: sustainable agriculture, nitrogen productivity, crop plants, magnesium, soil fertility, aluminum bio-toxicity, environment protection.

MAGNEZ JAKO CZYNNIK ŻYWIENIOWY EFEKTYWNEGO GOSPODAROWANIA AZOTEM – PRODUKCJA ROŚLINNA I ŚRODOWISKO

Abstrakt

Główne zadania stawiane współcześnie producentom roślin uprawnych skupiają się na dwóch celach: (i) zwiększeniu produkcji żywności, i (ii) jednocześnie zmniejszeniu ujemnego wpływu wzrastającego poziomu nawożenia azotem na środowisko. W skali globalnej wykorzystanie azotu szacuje się od 33 do 50%. Wymagane działania proprodukcyjne i proekologiczne skupiają się na zwiększeniu jednostkowej produkcji azotu stosowanego w nawozach. W nowoczesnym rolnictwie magnez, ze względu na funkcje biologiczne w roślinie, powinien odgrywać dużo większą rolę w kontroli gospodarki azotowej rośliny, a tym samym rozproszenia azotu w środowisku. W Polsce gleby uprawne są ogólnie ubogie w całkowity i przyswajalny magnez, co stwarza konieczność stosowania nawozów magnezowych w sposób zabezpieczający odpowiedni poziom odżywienia rośliny. Rośliny dobrze zaopatrzone w magnez od początkowych faz rozwoju, jak wynika z reakcji buraków lub kukurydzy, są w stanie istotnie zwiększyć jednostkową produktywność azotu. Zboża reagują na nawożenie magnezem wówczas, gdy zabieg odbywa się tuż przed kwitnieniem. Drugim istotnym czynnikiem ograniczającym wykorzystanie azotu przez rośliny uprawiane w Polsce jest odczyn gleb. Traktowanie gleb kwaśnych nawozami magnezowymi, w następstwie wzrostu koncentracji wymiennego magnezu w glebie, istotnie zmniejsza presję toksycznego glinu na rosnącą roślinę. Poprawa stanu odżywienia roślin magnezem umożliwia włączenie części potencjalnie niewykorzystanego N (azot rezydualny) w biomasę, co zwiększa jej plon użytkowy. Można zatem stwierdzić, że stosowanie magnezu, mającego wpływ na poprawę funkcjonowania gleb uprawnych, wypełnia tym samym zadania związane z realizacją zrównoważonej gospodarki azotowej w rolnictwie i środowisku.

Słowa kluczowe: zrównoważone rolnictwo, produktywność azotu, magnez, zasobność gleb, fitotoksyczność glinu, ochrona środowiska.

SUSTAINABLE AGRICULTURE

Despite the enormously high rate of technological progress, food production remains the main concern the world is currently facing. Food production should not only eradicate famine but also eliminate malnutrition. In about 40 years, from 1960 to 1999, the world population doubled from 3 to 6 billion people. At present, however, the number of food consumers suffering insufficient supply of high food quality and experiencing malnutrition-related health problems, ranges from 0.5 to 0.8 billion (ALEXANDRATOS, 1999; DYSON 1999). Short-term demographic prognoses assume the world population will reach 7.5 to 7.8 billion people in 2025. The food demand growth results in two facts: (i) a higher number of people and (ii) shifting consumption patterns boosted by higher incomes of economically growing up societies, especially in Central-Eastern Europe, South America and Asia. Food supply data published at the beginning of the 21st century assumed a 33 and 57% increase (1997 baseline values) in demand for cereals and meat, respectively (ROSEGRANT et al., 2001). In the case of total cereal production, this scenario was achieved in 2008. Within the 10-year period, yields of total cereals increased from 2.994 in 1998 to 3.539 t ha^{-1} in 2008, i.e., by 18.2%, but the harvested area rose just by 1.7% (from 700 to 712 billions ha) (FAOSTAT 2010).

The above statistical data clearly indicate that the global food supply strategy can be successfully realized relying on the yield increase and not on the harvested area increase. However, even this strategy of food supply growth is subjected to criticism due to two aspects. The present pattern of intensive agriculture, immanently resulting from the *Green Revolution* concept (new dwarf varieties, irrigation, pesticides and fertilizers), has reached its *saturation level*. This strategy, dominating in the last 60 years, is the main reason for deep environmental disturbance, caused by uncontrollable inputs of nitrogen and phosphorus to ecosystems near farmlands (SOCOLOW, 1999, TILMAN 1999, TOWNSEN et al. 2003).

The negative environmental consequences of intensification of agriculture observed in the last decades of the 20th century began in western societies (North America, West Europe). This has been pointed out by different ecological organizations, which exert strong pressure on governments. In the 1980s, the first UN global studies on the environment status started. The final report, known as *Our Common Future*, was presented in 1987 during the General Assembly of the UN (www.un-documents.net/a42r187.htm). This document soon became a basis, or even a milestone of the economic and political doctrine nowadays known as sustainable development. In agriculture, this doctrine is referred to as sustainable agriculture. In the European Union, the most important document, significantly affecting the current agricultural development, is the Nitrate Directive (91/676/EEC), which aims at protecting waters against excess of nitrates originating from farming practices.

The present paper deals with magnesium as a factor increasing the efficiency of fertilizer nitrogen in crop production technology. The main hypothesis of the paper assumes that magnesium is part of sustainable development of plant production, considered as a significant component of the food production branch.

MECHANISMS OF NITROGEN UPTAKE BY CROP PLANTS

Harvested yields are generally a function of the quantity and dynamics of nitrogen accumulation by the growing crop during its vegetation. The quantitative requirements of currently grown crops for fertilizer nitrogen are a result of two interacting factors:

1. Crop requirements, including the most important production factors:
   – critical growth periods with respect to development of yield forming components,
   – dynamics of dry matter accumulation,
   – expected yield.

2. Soil potential to supply nitrogen in rates sufficiently high to cover crop plant requirements at critical stages of growth and yield formation.

The first aspect helps to quantify the amount of fertilizer nitrogen required to cover crop plant needs over the growth season and the second one determines the soil capacity to cover these requirements from soil resources. Both create a diagnostic basis for assessing quantitative needs of currently grown crops for fertilizer nitrogen. Plants take up nitrogen in two main inorganic forms, as nitrates (NO_3^-) and ammonium (NH_4^+). The main metabolic core of nitrogen uptake by plant roots is through the transportation of ions from the soil solution through the plasma membrane into the cytoplasm. However, the mechanism of the uptake of each nitrogen form is ion specific. The first difference is the diffusion rate, a prerequisite of the absorption rate, which is *ca* 100-times higher for nitrate ($2.7 \cdot 10^{-6}$ cm^2 s^{-1}) as compared to ammonium ions ($6.1 \cdot 10^{-8}$ cm^2 s^{-1}) (RAYNAUD, LEADLEY 2004). Because of such a big difference, much more nitrate than ammonium ions reach the root surface. Consequently, a plant exploiting the nitrate pool much faster creates a much larger depletion zone in the rhizosphere. With respect to ammonium, four main processes govern ion concentration in the soil solution: (i) plant N demand, (ii) N immobilization/mineralization, (iii) ammonium nitrification rate and (iv) NH_4^+ ion adsorption/desorption by soil particles. This form of nitrogen effectively affects the crop growth rate provided that it is present in small quantities. However, excess of ammonium disturbs significantly the plant growth due to the impairment of basic biochemical and physiological processes such as ATP synthesis, and the uptake of K^+, Mg^{2+} and Ca^{2+} ions (BRITTO, KRONZUCKER et al. 2002, KUBIK-DOBOSZ 1998).

Crop plant nutrition with nitrate nitrogen depends on its concentration in the soil solution, that is the higher the concentration the higher its uptake. Depletion of nitrate from the soil solution is a soil induced signal for a plant to change the pattern of partitioning assimilates in order to increase the roots system size. The response of aerial organs of a plant to insufficient supply of nitrogen is signaled by the appearance of classical symptoms of nitrogen deficiency. This phenomenon is important for a farmer as a diagnostics indicator for an extra plant canopy N requirement, in practice covered by fertilizer application. However, the uptake of negatively charged nitrate ions in comparison to ammonium ions require a double energy expense by a growing plant (CANNEL, THORNLEY 2000). Transport of nitrate ions through the plasma membrane takes place in the protonated form: $2H^+$:NO_3, i.e., a nitrate ion requires preceding protonation, an energy-depended mechanism. This physiological process is directly related to the activity of H^+-ATP-ase, which in turn depends on the plant nutritional status in phosphorus and magnesium. Hypothetically, every cation may participate as a counter-ion for nitrate, but based on the plant nutrient content, the crucial role is played by potassium (K^+), which is accumulated by high yielding crops in the highest amounts (GRZEBISZ 2005). Magnesium ions (Mg^{2+}) do not compete with potassium ones. The latter as well as excessive amounts of protons are antagonistic to the uptake of Mg^{2+} ions (OCHAŁ and MYSZKA, 1984). However, any rise in the Mg^{2+} concentration in the growth solution does not limit the uptake of potassium ions. In spite of these weaknesses, magnesium is considered as a crucial nutrient for the uptake nitrogen, especially nitrates, by high yielding crop plants. The main reason, as mentioned earlier, is the hydrogen pump efficiency, which requires high H^+-ATP-ase activity, depending in turn on Mg^{2+} as an enzyme cofactor. Therefore, the vigorous growth of any plants, particularly crops, requires a good supply of at least three basic elements: phosphorus, magnesium and potassium (FERNANDES, ROSSIELLO 1995, IMSANDE, TOURAINE 1994).

NITROGEN: PLANT PRODUCTION AND ENVIRONMENT

Total fertilizer nitrogen consumption increased many folds between 1960 and 2010, from *ca* 12 in 1960 to 90 mln t y^{-1} at present. This tremendous N use resulted in a significant increase of food production. For example, total wheat production rose from 200 to 700 mln t y^{-1} in this period and its mean yields went up almost three-folds, from 1.1 to 3.1 t ha^{-1} (FAOSTAT, available online, 28.08.10). However, the high rate of wheat yield increase is not directly related to the rate of fertilizer nitrogen consumption. This discrepancy is the main reason to formulate two important questions:

– what part of the applied fertilizer nitrogen does the crop plant use in fact?
– does the non-consumed part of the applied fertilizer nitrogen create any threat to the environment's functionality?

Actually, there is no easy and true answer to the first question. Theoretically, fertilizer nitrogen recovery may reach 100% and even higher. Scientific papers about N fertilizer recovery, presenting field experiment data, are mostly in the broad range from 33 to 75%. However, very high maximal values of N recovery appear seldom, mostly under conditions of extremely low N rates, which do not ensure plant production profitability. The data concerning field conditions show much lower N fertilizer recovery, ranging only from 33% to 50% (DOBERMANN, CASSMAN 2002). Hence, from 45 to 60 mln t of the annually applied fertilizer N is not transformed into plant biomass, but becomes dispersed in soil or in ecosystems neighboring agricultural land (EICKHOUT et al. 2006, GALLOWAY, COWLING 2002).

Nitrate ions move freely both in the soil solution and/or in a stream of transpiration water. Their mobility does not depend on soil pH in the range from 2 to 10. Under conditions of soil water saturation and lack of plant cover, nitrates undergo translocation in accordance with the water gravity movement. The second type of nitrate movement induced physiologically is known as mass flow, and is a process transporting N to roots of growing plants. Therefore, nitrates are mostly subjected to leaching during autumn or winter. In addition, nitrate ions under insufficient oxygen concentration or its low movement in the soil are subjected to reduction, yielding N_2 or N oxides such NO and N_2O. Due to their biological and chemical activity, nitrates and N oxides are termed as active forms of nitrogen (GALLOWAY, COWLING 2002, STRONG, FILLERY 2002, TOWNSEND et al. 2003).

The negative effects of agriculture on the environment, presented above, caused by the low fertilizer nitrogen efficiency are the basic reason for making a significant correction to the current production systems. The main target of fertilization practices is to cover nitrogen requirements of crop plants in the course of their growth, with respect to amounts, forms and time of fertilizer N application. Fulfilling this production induced paradigm is a key to elaborate an efficient system of fertilizer nitrogen management.

Nitrogen applied into soil as N fertilizer (N_f) can be divided into two main fractions (pools): first taken up and consumed by currently growing plants (N_{up}) and second, named as residual nitrogen (N_r), i.e., not taken up by plants. The latter one (N_r) undergoes further biogeochemical changes. Based on the distribution of final products, two sub-groups of residual nitrogen may be distinguished:

– fixed (N_s),
– active (N_a),

$$N_r = N_s + N_a \tag{1}$$

The fixed nitrogen fraction (N_s) represents a pool of applied N_f temporarily unavailable to currently growing crop plants. This part of nitrogen occurs in soil in its primary form or is physically fixed by clay particles and/or incorporated into microbial biomass (immobilized). Potential availability of this previously applied nitrogen depends on the intensity of biogeochemical processes taking place in soil from harvest of the previous crop to the sowing of the subsequent one. The second form of residual nitrogen, (N_a), relates to the part of the fertilizer nitrogen which is lost due to nitrates leaching to underground waters and nitrate oxides and ammonium volatilization to atmosphere. These forms of nitrogen create a real threat to natural ecosystems and in turn to human health (GALLOWAY, COWLING 2002, TOWNSEND et al. 2003).

The classical formula of the apparent fertilizer nitrogen recovery (E_N) by the growing crop plant is as follows:

$$E_N = (N_u/N_f) \cdot 100\% \quad (2)$$

The above formula presents only a general relationship, but its application requires special experimental methodology of gathering data. The main target of any farmer, adhering to the sustainable agriculture rules, is to diminish losses of nitrogen to the environment. Therefore, equation No 2 should be transformed into an index of nitrogen losses (L_N) as presented below:

$$L_N = (1\text{-}N_u/N_f) \cdot 100\% \quad (3)$$

In the light of the ways of fertilizer nitrogen transformation in the soil, as presented above, the key step for farmers to undertake is to work out an effective fertilizing system – a strategy of soil and fertilizer nitrogen management. The production objective of an efficient N application strategy is to cover crop plant nitrogen requirements in critical stages of yield formation by (i) maximizing its yielding potential and (ii) minimizing N losses to neighboring ecosystems. The components of the fertilization system are: (i) crop and its nitrogen requirement, (ii) crop and nutrient requirements others than nitrogen, (iii) soil and its potential to supply nitrogen and other nutrients, (iv) N dressing patterns (amounts, rates, timing), and other nutrients, supporting N efficiency.

ROLES OF MAGNESIUM IN CROP PLANT NITROGEN MANAGEMENT

There are many well recognized biochemical and physiological functions of magnesium in plants. However, farmers have to pay special attention to those which are directly or indirectly related to crop plant N management. The most important functions of magnesium are as follows:

- nitrogen uptake,
- photosynthesis, including:
  - synthesis of chlorophyll,
  - phosphorylation,
  - CO_2 fixation and reduction,
- phloem load of assimilates,
- distribution of carbohydrates among plant parts,
- control of the amounts of reactive oxygen substances (ROS),
- synthesis of organic compounds – starch, proteins, crude fats (CAKMAK, KIRKBY 2008, SHAUL 2002).

The first function of magnesium in the plant body related to plant production is nitrogen uptake (see part 2 of the article). The capacity of the currently cultivated crops to fix CO_2 is generally related to their canopy (expressed as the Leaf Area Index (LAI) or Green Area Index (GAI)), active in solar energy absorption over the growth season. The rate of CO_2 fixation also depends on nitrogen concentration in the aerial biomass (GASTAL, LEMAIRE 2002).

Sugar beet is the most classical crop in which the importance of both indices is evident. This crop is able to express its maximum photosynthetic capacity provided that its LAI is equal 3.0 and the nitrogen concentration in leaves is not lower than 40 g kg^{-1} dry matter. In Europe, nitrogen uptake rate by sugar beet seedlings is the most decisive factor affecting radiation use efficiency by the crop canopy and in turn controlling the rate of aerial biomass growth (ANDRIEU et al. 1997). Phosphorus, magnesium and potassium are of great importance but should be considered as nutrients supporting nitrogen uptake by plants and its further transformation into plant biomass (RUBIO et al. 2003). The same considerations hold true for other crops but maize presents a special case. This crop is extremely sensitive to nitrogen supply during two distinct stages of growth, i.e., the stage of 5(6)-leaves, when plants form the primary yield structure. Insufficient supply of nitrogen negatively affects the potential number of leaves and cobs. The second crucial stage appears from the middle to the end of tasseling. During this particular period insufficient supply of nitrogen decreases the rate of biomass accumulation by the stem, hence depressing the potential number of fertile ovules (GRZEBISZ et al. 2008, SUBEDI, MA 2005).

Biochemical and physiological functions of magnesium in higher plant photosynthetic activity are fairly well recognized (CAKMAK, KIRKBY 2008, SHAUL 2002). However, yield-forming functions of this nutrient are not easily defined, due to its indirect effect, i.e., it can be assessed only *via* nitrogen plant management. The basic features of magnesium, as presented earlier, comprise three consecutive steps. The primary one is the synthesis chlorophyll molecules, which depends on the activity of magnesium chelatase, responsible for the incorporation of Mg^{2+} ion into a proto-porphyrin ring. Any other divalent ions such as Cu^{2+}, Zn^{2+} or Ni^{2+} are not able to replace Mg^{2+} in this specific function. In the first phase of photosynthesis, known as “the light step”, magnesium is the main nutrient limiting the gaining of metabolic energy through the synthesis of compounds such as ATP and NADPH. In the second phase of photosynthesis, termed as “the dark step”, the CO_2 molecule is fixed by the enzyme Ribulose 1,5-bisphopsphate **c**arboxylase/**o**xygenase (RuBisCO). This enzyme requires some kind of preoperational activation and is dependent on Mg^{2+} supply. The key step of CO_2 fixation, i.e., its reduction, is strongly affected by the level of metabolic energy supply, as again related to ATP plant resources. It is well known that the enzyme RuBisCO is strongly related to both CO_2 and O_2. The main enzyme preference does not only depend on the CO_2 concentration in the growth environment but also on the plant magnesium nutritional status. Insufficient plant magnesium content is the main reason for increasing the rate of primary carbon decomposition due to the process known as photorespiration (SHAUL 2002).

The second group of processes, directly resulting form the nutritional status of a given crop plant, but indirectly affecting its nitrogen economy, refers to the partitioning of assimilates among roots and aerial biomass. There are only few experiments, conducted mostly under controlled conditions (hydroponics), reporting this very important process. However, these reports allow us to explain the negative outcome of a limited supply of magnesium to growing plants. As a rule, amounts of assimilates transported to roots significantly decrease, evoking a spiral of plant degradation symptoms. First to appear is the root system size reduction, negatively affecting the water and nutrients uptake; next, the growth rate of aerial parts of plants is impaired (Table 1). The same type of plant behavior has been observed for potassium but not for phosphorus (CAKMAK, KIRKBY 2008, HERMANS et al. 2005).

Table 1

Effect of insufficient supply of magnesium to mulberry plant (*Morus alba* L.) on biomass distribution between shoots and roots and magnesium concentrations (KUMAR TEWARI et al. 2006)

Plant parts	Control		Low Mg supply	
	mean	± SD*	mean	± SD*
Dry matter yield, g plant^{-1}				
Shoots (S)	78.6	4.9	14.5	0.27
Roots (R)	8.2	0.81	1.1	0.01
Shoots/roots ratio (S/R)	9.7	0.37	13.7	0.17
Magnesium concentration, mg g^{-1} dry weight				
Young leaves	1.8	0.0	0.3	0.9
Old leaves	2.9	0.0	0.2	0.1

*SD – standard deviation

The first, mild symptoms of magnesium deficiency are related to accumulation of extra starch and reductive sugars in leaves. The main physiological reason for this storage of compounds in leaf tissue is the low activity of energy compounds such as ATP, responsible for the loading of phloem assimilates and finally for their transport to other plant parts (CAKMAK, KIRKBY 2008, HERMANS et al. 2005). Visible symptoms of magnesium deficiency in an advanced stage, as shown in Photo 1 for a grape plant, such as green veins on the background of yellowing areas, are striking. Emergence of these symptoms on leaves is attributed to the low capability of green tissues to transform the excess of solar radiation into energy compounds. The direct cause of visible symptoms of Mg deficiency is, however, extra production of reactive oxygen substances (ROS) and the generation of compounds such as H_2O_2 (CAKMAK, KIRKBY 2008, TEWARI KUMAR et al. 2006). Under conditions of severe deficiency of magnesium, the production of ROS increases, causing

Photo 1. Classical symptoms of magnesium deficiency on grapevine leaves at ripening (author: W. Grzebisz; no of photo DSCF0036)

leaf tissue damage. As a consequence, crop plants may suffer due to Mg deficiency and are not able to take up enough nitrogen for building their assimilation area. Secondly, this area is permanently reduced under ROS action. Leaf chlorosis, as a particular symptom of advanced magnesium deficiency, appears first on older leaves, exposed to light, i.e., energy saturated. The classical examples are crop plants exposed to light such as potatoes, sugar beets and especially grapes and sunflower.

IMPROVEMENT OF FACTORS LIMITING NITROGEN PRODUCTIVITY BY MEANS OF MAGNESIUM SUPPLY

The dynamics of nitrogen uptake from soil by crop plants depends on their nutritional status with respect to phosphorus, potassium and magnesium. Transportation of the first two nutrients from any point of the soil body to the root surface is related to their diffusion gradients, which are determined not only by physical properties of a given element but also by soil water content and its temperature. Magnesium ions are transported towards roots in a water transpiration stream (mass flow) and therefore the plant supply is related to magnesium soil concentration. Hence, total and especially available magnesium resources (water soluble) are crucial for crop plant nutrition with magnesium as well as nitrogen. An analysis of the total soil magnesium resources in Europe (www:gtk.fi/publ/foregsatlas) underlines low capacity of soils in Poland with respect to this element. The topsoil total magnesium content ranges from 1 to 2.5 g kg^{-1} and for the subsoil it varies from 1 to 3.4 g kg^{-1}. For comparison, the total content of magnesium in the topsoil in the Czech Republic ranges from 7.7 to 10.8 g kg^{-1}. Hence, the presented data stress a significant depletion of topsoil magnesium resources as compared to subsoil ones, which poses a risk of potential deficiency of available magnesium forms. This hypothesis is fully supported by data periodically published by Regional Agrochemical Stations for wole Poland. According to LIPIŃSKI (2005), more than 50% of Polish soils are poor in soil available magnesium.

Under the production conditions in Poland, any choice of a well-defined magnesium fertilization system should be preceded by evaluation of three factors which determin a potential crop plant magnesium nutritional status. They are as follows: (i) quantitative crop plant requirements, (ii) content of soil available magnesium – magnesium content in the soil solution, (iii) timing and form of applied magnesium fertilizer (HUNDT, KERSCHBERGER 1991). Plant magnesium requirements are crop specific, but as a rule dicotyledonous crops are much more sensitive to magnesium deficiency than cereals. Each plant crop accumulates magnesium progressively in the course of vegetation, reaching top values just before full ripening. It is necessary to point out a close relationship between magnesium and phosphorus uptake patterns (Figure 1). In spite of some resemblances among different types of crop plants, they respond differently to fertilizer magnesium application timing. The expected pattern of the response of crop plants to magnesium supply is a prerequisite for selecting a fertilizer magnesium system. Root and tuber crops are best responsive to soil magnesium level. The growth rate of

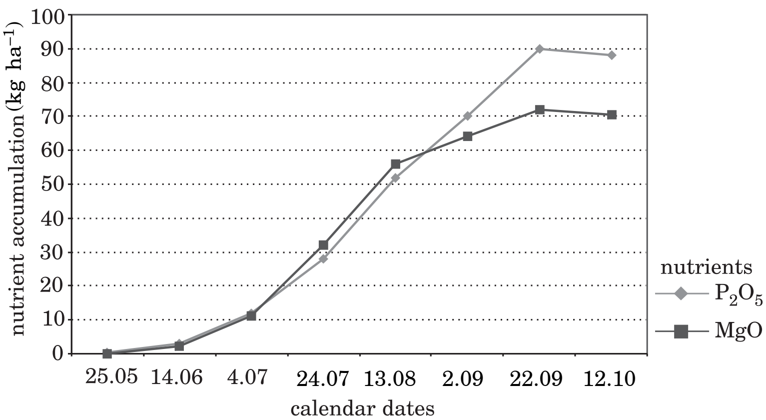

Fig. 1. Magnesium and phosphorus accumulation by sugar beet plantation over the growing season (based on: GRZEBISZ et al. 1998)

beet seedlings required to intercept sufficiently high amount of solar energy at the beginning of the growth season is the main explanation of this type of response (ANDRIEU et al. 1997). Therefore, it should not be surprising that this crop responds to magnesium foliar application performed at early stages of growth but before canopy closing, i.e. the LAI of 3.0 (BARŁÓG, GRZEBISZ 2001). As presented in Figure 2, interactions of soil and foliar magnesium application to sugar beet resulted in a huge increase of fertilizer nitrogen

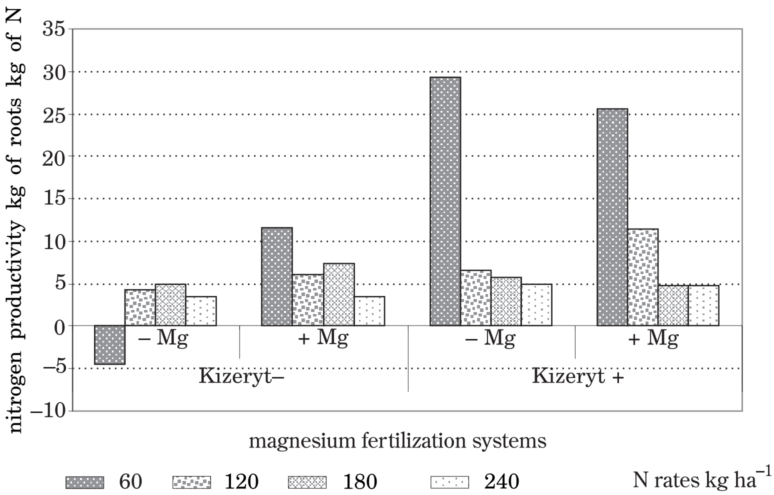

Fig. 2. Partial factor productivity of fertilizer nitrogen index response to systems of magnesium application (based on: GRZEBISZ et al. 2001)

efficiency (one of the factors in fertilizer nitrogen productivity), increasing the final yield of taproots and recoverable sugar. However, the described phenomenon, which also noticeable in other crops, e.g. maize as presented by SZULC (2010), is most pronounced under the conditions of low nitrogen supply (soil + fertilizer nitrogen). It could therefore be supposed that under low N supply, any extra-added magnesium stimulates two independent processes. The first hypothesis assumes an extended growth of plant roots due to raised activity of auxins caused by low N and easily available magnesium. The second hypothesis relies on a higher rate of nitrate uptake, accelerating the canopy growth rate (ANDRIEU et al. 1997). As a result of a higher total uptake of nitrogen, which takes place at the beginning of the vegetative season, some crops are able to produce higher yield, using the applied fertilizer nitrogen more efficiently. Slightly different responses are observed for cereals, which show an increase of magnesium uptake at ripening. Therefore, this group of crops responds significantly to foliar application of fertilizer magnesium, but carried out just before anthesis (Table 2).

Table 2

Effect of the magnesium rate and its timing on grain yield and nitrogen economy of winter cereals

Species Nitrogen economy features	Control	Tillering BBCH28 Mg rates (kg ha^{-1})		HeadingBBCH55 Mg rates (kg ha^{-1})	
		2.5	5.0	2.5	5.0
Rye					
Yield**, t ha^{-1}	4.30	4.50	4.75	4.40	4.75
N in grain, g kg^{-1}	12.8 ± 0.4	12.8 ± 0.4	13.8 ± 0.1	13.3 ± 0.1	14.0 ± 0.2
N uptake, kg ha^{-1}	89.0	94.7	106.2	98.0	128.5
Unit nitrogen uptake*, kg N t^{-1} ****	20.7	21.0	22.4	22.3	27.1
Wheat					
Yield***, t ha^{-1}	5.30	5.50	5.75	5.55	5.90
N in grain, g kg^{-1}	19.0 ± 1.0	19.2 ± 1.1	19.7 ± 0.8	19.5 ± 0.8	20.0 ± 0.7
N uptake, kg ha^{-1}	142.9	149.8	161.6	152.8	168.4
Unit nitrogen uptake*, kg N t^{-1} ****	27.0	27.2	28.1	27.5	28.5

*based on MATŁOSZ (1992), **$LSD_{0.05}$ = 0.15, ***$LSD_{0.05}$ = 0.12,
****grain + respective straw biomass.

The key is the root system, although it can be considered as just a sufficient factor conditioning the uptake of nutrients by crops from the soil body. The size and architecture os the root system are limited by many factors. Soil reaction is one of the main plant production limiting factors (aluminum toxicity) in Poland, where *ca* 60% of arable soils are acid and very acid (LIPIŃSKI 2005b). This level of soil pH is a prerequisite to aluminum bio-toxicity. This phenomenon is the main cause of the reduction of the root system size as it inhibits:

– the division of root cap cells,
– the growth of elongation root zone.

Excess of aluminum in root apoplast, resulting from insufficient supply of calcium, is the main reason for sequentially induced processes such as: (i) synthesis of cellulose – the main component of cell walls, (ii) synthesis of callose (TERAOKA et al. 2002). This organic compound is produced by plant tissues in order to separate healthy part from ill or wounded ones. Allocation of this polysaccharide into the root meristeme of a plant root means the end of its growth, decreasing then the vertical extension of the root system. As a result of these processes, crop plant functions become restricted, with the prevalence of:

– root system size reduction (Figure 3),

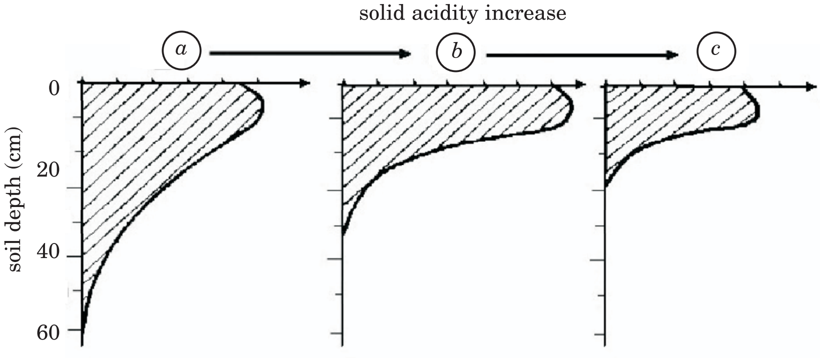

Fig. 3. Size of crop plant root system under growing soil acidification (MARSCHNER 1991): *a* – neutral, *b* – acid, *c* – very acid

– increased threat of nitrate leaching,
– increasing amounts of leached calcium and magnesium (SCHWEIGER, AMBERGER, 1979);
– fixation of available phosphorus by iron and aluminum cations.

The main criterion of water and nutrients uptake, including nitrate-nitrogen uptake, by crop plants is the vertical distribution of their roots and the coefficient of diffusion of nutrients in the soil solution. Plants are able to take up mobile nutrients in the zone extending below 20 cm of the root maximal length (MARSCHNER 1991). Therefore, it can be concluded that the reduced root system of crop plants due to aluminum toxicity is not able to take up nutrients moving downwards, such as nitrates or sulfates. Under acid soil conditions, a substantial amount of fertilizer nitrogen is not taken up by crop plants, thus enlarging the pool of residual nitrogen.

Toxic symptoms caused by aluminum emerge as deficiency symptoms typical of phosphorus, calcium and even magnesium, as presented in Photo 2 (KELTJENS, KEZHENG TAN 1993, SILVA et al. 2010). The deficit of available magnesium appears not only in arable soils, but also in forest and perennial grasses, leading to their degradation (PANNATIER et al. 2004). In fertile soils, the content of exchangeable aluminum should not exceed 36 mg Al_{ex} kg^{-1} soil (SKUBISZEWSKA, DIATTA 2008), but negative effects of elevating the content of toxic aluminum ions was detected even at a level of 9 mg Al_{ex} kg^{-1} soil (DIATTA et al. 2010).

In the light of the above consequences of elevated toxic aluminum levels, a question arises about ameliorative effects of magnesium. So far, scientific reports have been scanty but the main aspects of magnesium presence may be summerised as follows:

1) decreasing accumulation of toxic Al^{3+} ions by crops in the presence of magnesium ions (KINRAIDE et al. 2004, SKUBISZEWSKA, DIATTA 2008);

Photo 2. Maize plants with visible symptoms of magnesium deficiency – aluminum toxicity induced (author: W. GRZEBISZ, no of photo P1010035)

2) a crop well supplied with magnesium excretes to its rhizosphere higher amounts of organic acids and other organic substances exhibiting chelating properties for Al^{3+} (YANG et al. 2007);
3) a crop well supplied with magnesium excretes to its rhizosphere divalent cations, such Ca^{2+} and Mg^{2+}, in turn rising up root apoplast pH above 5.0 supposed to protect a plant root against Al^{3+} toxicity (SILVA et al. 2010).

In today's agricultural practice, magnesium fertilizers represent two main chemical compounds:

– carbonates (dolomite, magnesite);
– sulfates (Kieserite, Epsom salt).

Agrochemical results of carbonate application are easily defined owing to their well-known geochemical transformation pathways. This type of magnesium fertilizers allows us to reach basic targets after a single treatment. The first type of fertilizers causes neutralization of toxic aluminum and the second one is associated with to a huge increase of available magnesium content. Magnesium fertilizers based mostly on sulfates reveal a much more complicated geochemical action, because both ions are involved in toxic Al^{3+} soil solution control (DIATTA et al. 2010).

Yield increase is a result of the amounts of nitrogen taken up by the cultivated crops and incorporated into yield during the growing season. Therefore, as presented in Table 3, yield increase can be considered as an increased temporary potential of crop canopy to accumulate nitrogen. The final production effect of magnesium application, i.e., increased yields, is a result of the agrochemical action of this nutrient, which enables plants to recover some of residual nitrogen in soil, thus dminishing its active pool.

FINAL CONCLUSIONS

Owing to its influence on the plant growth and distribution of assimilates, nitrogen is a yield-forming nutrient (RUBIO et al. 2003). However, today's production technologies cannot exceed a certain level of productivity due to a relatively low fertilizer nitrogen recovery and low unit productivity (DOBERMANN, CASSMAN 2002, GRZEBISZ et al. 2009). One of the most limiting factors is the current system of crop fertilization, guided by three main rules of nitrogen application: the right amount, right form and right timing (JANSSESN 1998). In many parts of the world, including Poland, the applied nitrogen rates are generally badly balanced with phosphorus and potassium (GRZEBISZ et al. 2009). The yield-forming potential of magnesium as a nutrient affecting basic biochemical and physiological plant processes including nitrogen economy is not fully exploited. In Poland, plant production as a natural base for food production is carried out under low natural soil fertility conditions, which does not allow farmers to exploit the yielding potential of crops. The main reasons for low yields harvested by farmers are: (i) low soil pH, a prerequisite for aluminum toxicity, and (ii) low total and available magnesium contents. Application of fertilizer magnesium in agriculture should be therefore considered as one of the most important factors ameliorating both groups of the limiting factors, thus improving the efficiency of the applied fertilizer nitrogen. Therefore, it can be concluded that magnesium is an important component in the sustainable system of farmland management, because it ensures sufficiently high-level plant production and environmental sustainability.

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