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REVIEW PAPERS

MAGNESIUM – FOOD AND HUMAN HEALTH

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Abstract

In the early 21st century, as has been demonstrated by a number of medical reports, human health is seriously threatened by diseases and symptoms related to an insufficient intake of magnesium, independently of country, age and sex. The main causes are deeply rooted in the currently dominant eating habits, mostly based on cereals, i.e. on low concentration of minerals in grain. As it has been lately documented, edible parts of new, high-yielding varieties of cereals and also some vegetables (an important source of magnesium for people) are much poorer in minerals, including magnesium, than the old, low-yielding ones. Magnesium plays many important biochemical and physiological functions in plants, affecting both yield of their biomass and/or edible parts. Hence, fast growing plants require a high supply of magnesium, mainly via externally applied fertilizers, which will sustain their rate of growth. With the evidence of an insufficient content of magnesium in edible plant parts, food producers have now a new objective. Their aim is to increase the concentration of available magnesium in edible parts of plants, including both cereals and vegetables. The growing concern about low magnesium concentrations in plant products can be significantly mitigated through soil and/or foliar application of magnesium fertilizers. In order to produce magnesium-rich food, it is necessary to build up an effective strategy for magnesium management in arable soils, oriented towards providing adequate plant nutrition for sustaining normal human health. This target should be achieved when farmers apply a wide array of magnesium carriers, including fertilizers.

Key words: people, magnesium insufficient intake, diseases, crop plants, magnesium density, magnesium fertilizers, biofortification.

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MAGNEZ – ŻYWNOŚĆ I ZDROWIE CZŁOWIEKA

Abstrakt

Na początku XXI w., jak wynika z wielu ostatnio publikowanych doniesień medycznych, zdrowie człowieka znajduje się w stanie dużego zagrożenia, będącego skutkiem niedostatecznego zaopatrzenia ludzi w magnez, niezależnie od kraju, wieku i płci. Główne przyczyny tego stanu są głęboko osadzone w obecnie dominujących wzorcach odżywienia, zależnych od zbóż, tzn. od koncentracji składników mineralnych w ziarnie. W ostatnim okresie wykazano, że jadalne części współczesnych, wysoko plonujących odmian zbóż, a także niektórych warzyw (ważne źródło magnezu dla ludzi), są dużo uboższe w składniki mineralne, w tym magnez, niż odmiany stare, nisko plonujące. Magnez pełni w roślinach wiele ważnych funkcji biochemicznych i fizjologicznych, istotnie kształtujących zarówno plony biomasy, jak i ich części jadalnych. Zatem współczesne odmiany roślin uprawnych wymagają bardzo dobrego zaopatrzenia w magnez, warunkującego szybkość ich wzrostu, co może być pokryte głównie przez stosowanie nawozów. W świetle faktów wskazujących na niedostateczną zawartość magnezu w żywności pochodzenia roślinnego, pojawił się nowy cel dla producentów żywności. Jest on ukierunkowany na zwiększenie koncentracji magnezu w jadalnych częściach zbóż i warzyw. Narastający problem niedoboru magnezu w produktach roślinnych można istotnie złagodzić przez doglebową lub/i dolistną aplikację nawozów magnezowych. Wyprodukowanie żywności bogatej w magnez wymaga efektywnego systemu gospodarki magnezem w glebie, aby zapewnić odpowiednie odżywienie roślin. Realizacja tego nadrzędnego celu wymaga od rolników korzystania z szerokiej gamy nośników magnezu, włącznie z nawozami.

Słowa kluczowe: człowiek, niedostateczne zaopatrzenie w magnez, choroby, rośliny uprawne, zawartość magnezu w częściach jadalnych, nawozy magnezowe, biofortyfikacja

INTRODUCTION

People's physical growth and mental well-being depend on *ca* 50 externally supplied nutrients such as vitamins, macro- and microelements (referred to as minerals by human physiologists), amino acids or essential fatty acids, which are delivered mainly in food, although some minerals are also supplied in drinking water. The list of elements recognized by physiologists as essential, i.e. vital for life processes in a human body, continues to expand. Generally, animal and human physiologists have accepted so far a much higher number of essential minerals than have more conservative plant physiologists, arriving at the present number of 22. Based on their content in a human body, all minerals are divided into two main groups, presented in the decreasing order:

- macrominerals: Na, K, Ca, Mg, S, P, Cl;
- microminerals: Fe, Zn, Cu, Mn, I, F, B, Se, and Mo, Ni, Cr, Si, As, Li, Sn, V, Co (in vitamin B_{12}).

Most of these minerals are essential both to plants and, through the food chain, to animals and humans. Hence, amounts of soil minerals taken up by plants and subsequently accumulated in plant tissue are important both as fodder for animals and/or as food for humans (WELCH, GRAHAM, 2005).

The history of mankind is closely related to development of agriculture. The first civilization revolution, which took place *ca* 10 000 years ago, changed people's lifestyle from wandering to sedentary one. However, the major change was associated with people's diet, which over millenniums has become more and more dependent on cereals as the most important source of carbohydrates, proteins and also minerals. The industrial revolution, which took place in the early 19th century, was the main reason for increasing the demand of the exponentially growing human population for food. In the second part of the 20th century, long-term work of farmers and plant breeders allowed selecting highly efficient crop plant varieties. However, there are also some negative consequences of both the new, high-yielding varieties and the current diet, based on cereals. The modern varieties of cereals, vegetables and oil crops can produce food in quantities sufficient to meet demands of the current human population (FAOSTAT 2010, available online, March 5, 2011). As a result of the Green Revolution, the world's human population is fairly well supported with carbohydrates and proteins produced from grain, but the content of elements is generally too low. The recognized deficiency refers mainly to an insufficient concentration of elements such as iron, zinc, selenium and also magnesium, calcium, both in edible plant parts and in final food products. The current discrepancy between a high input of carbohydrates, proteins and fat in people's daily diet and a concurrent deficiency of minerals is frequently called *micronutrient malnutrition*, but in fact it could be termed, following medical terminology, *mineral malnutrition* or *hidden hunger* (GRUSAK 2002, WELCH, GRAHAM 2002, WELCH, GRAHAM 2005, ZHAO, SHEWRY 2010).

The main objective of this review paper is best expressed by Dr. Charles Nothern's statement: "*It is simpler to cure sick soils than sick people – which shall we choose?*" (*Modern miracle men* by R. BEACH, U.S. Senate Doc. No. 264, 1936).

MAGNESIUM DECLINE IN PLANT FOOD – REASONS AND CONSEQUENCES

Magnesium recommendations and intake

The amount of magnesium in the human body rises from *ca* 760 mg at birth to 24 g in an adult. In order to keep a sufficient rate of the body growth, both at early stages and during all its life span, a human organism must be regularly supplied with this element. Therefore, any nutrient-level recommendations for humans, known as dietary reference intakes (DRIs), take into account two main factors: age and gender. Among many intake reference guidelines, the Recommended Dietary Allowance (RDA) is the one most frequently used to compare the nutritional status of different societies or groups. It is defined, accordingly to the Food and Nutrition Board of the Institute of Medicine, as "the average daily nutrient intake level sufficient to meet requirement of nearly all (97 to 98%) healthy individuals in a particular life stage and gender group" (MURRPHY 2001, USDA, USDHH 2010). Reference intake guidelines for magnesium in some European countries like Austria, Germany, Switzerland and Poland, i.e. countries characterized by very similar eating patterns, are nearly the same (Table 1). The main differences are attributed to the life stage extending from 10 to 13 years. In Poland, the recommended magnesium intake is much higher than in other countries. In the USA, just 240 mg per day is recommended during this particular life stage, irrespective of gender, whereas in Poland, the level is 300 mg for girls and 290 for boys (VORMANN 2003).

Table 1

Reference intakes for magnesium (mg day^{-1})

Austria, Germany, Switzerland*			Poland**		
Age	females	males	age	females	males
1-4	80		0-1	50-70	
4-7	120		1-3	100-150	
7-10	170		4-6	150	
10-13	230	250	10-12	300	290
13-15	310	310	13-15	300	300
15-19	350	400	16-18	340	400
19-25	310	400	19-25	300	370
25-51	300	350	26-60	300	370
51-65			> 60		
> 65					
Pregnancy	310	-	pregnancy	350	-
Lactation	390	-	lactation	380	-

*D-A-CHReferenzwerte fur die Nahrstoffzufur;
**Instytut Żywności i Żywienia (Institute of Food and Nutrition)

The evaluation of an actual magnesium intake, conducted in many countries, generates a very pessimistic picture for different gender or social groups in western societies. A recent study in Poland has shown that, despite high realization of DRI norms, girls rely much more frequently than boys on diets deficient in magnesium (Figure 1). This negative trend reflects the insufficient intake of magnesium by girls more than 10 years old (WOJTASIK et al. 2009). The presented pattern is significantly influenced by economic conditions of families with children and is probably seriously affected by the dominating eating habits. As reported by USTYMOWICZ-FABISZE-

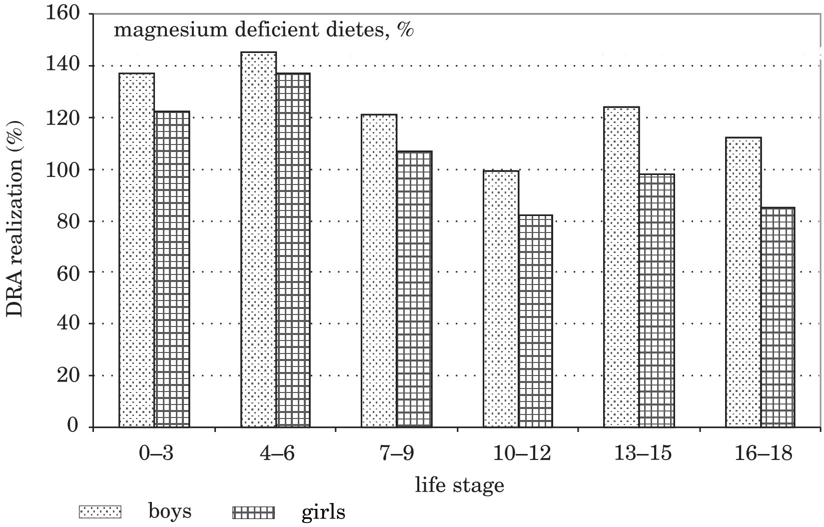

Fig. 1. Magnesium intake norms for children and adolescents in Poland (based on WOJTASIK et al. 2009)

WSKA et al. (2000), the intake of magnesium by 14-year-old children living in Białystok or in villages of the Białystok region was generally below the norms. As a rule, children living in villages made up a higher percentage of insufficient supply of magnesium, reaching 100% among 14-year-old girls. Another study, conducted on a group of 19(20)-year-old students from the same city showed an insufficient intake of magnesium by 63% of women and 60% of men (STEFAŃSKA et al. 2003).

Trends in the dietary magnesium intake in Poland are typical of western societies. In the United States, the average magnesium daily intake decreased from 475-500 mg to *ca* 200 mg day^{-1} from 1900 to 1992 (Figure 2). In the USA, the current RDA ranges for adults are fixed at 420 and 320 mg day^{-1} for men and women, respectively. However, the real magnesium intake is in the range 185-260 mg day^{-1} for men and 172-235 mg day^{-1} for women. The range-curves presented in Figure 2 show two critical timepoints, characterized by a high decline rate of magnesium intake. The first one, from *ca* 500 to 350 mg day^{-1}, took place in the 1920s and the second one, from 300 to 200 mg day^{-1}, occurred in the 1960s (ALTURA, ALTURA 1995, USDA, USDHH 2010).

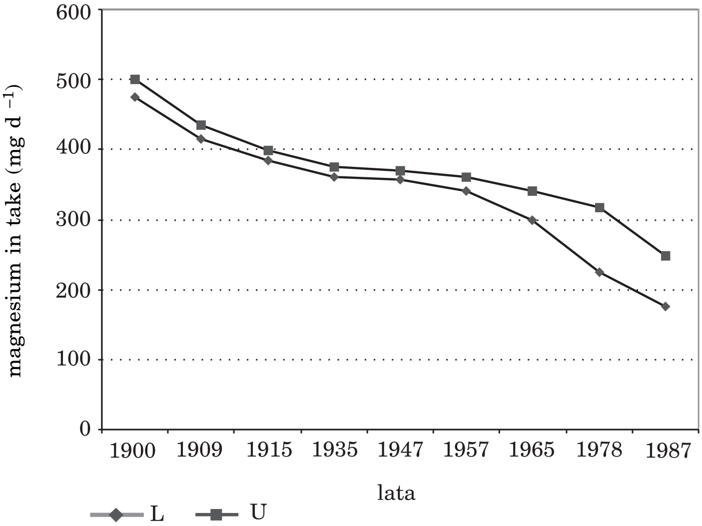

Fig. 2. Trends of magnesium intake in the USA in the 20th century:
L – low, U – upper limits (based on ALTURA, ALTURA 1995)

Evidence of decline

The consumption patterns of minerals, including magnesium, by humans show negative tendencies. In addition, they exhibit quite opposite trends to those presented for energy, fat and protein consumption. The average amount of recommended magnesium for adults in western societies is fixed at the level of *ca* 350 mg day^{-1}, i.e. 70% of its status at the beginning of the 20th century. The currently established RDA standards as compared to the pre-agrarian epoch (the Paleolithic) are 3.5-fold lower (BOYD EATON, BOYD EATON III 2000). There are some fundamental reasons for lower magnesium intake with consumed food, which can be specified in four distinct groups as follows:

1. Economic and social:
   – access to food,
   – changes in eating patterns,
2. Agronomic and technological processing:
   – depletion of soil essential nutrient contents,
   – increasing yielding potential of new varieties,
   – food processing.
3. Metabolic disturbance of magnesium availability to a human organism:
4. others: i) stage of life – fast growth of body; ii) pregnancy and lactation; iii) high physical activity; iv) intense consumption of alcohol.

As described interestingly by BOYD EATON, BOYD EATON III (2000), humans living in the Paleolithic epoch relied in consumption patterns on animal proteins, fat but rich in polyunsaturated fatty acids, and on fruit and vegetables. All these animal and plant products delivered huge amounts of minerals. Current diets in rich western societies are based on plant food, which are rich in carbohydrates and proteins from cereals. People can use magnesium from many different sources, including cereals, meat, vegetables, fruit and also water (Figure 3). Hard water is frequently considered as an important source of this element, positively affecting health of humans dwelling in some areas of the world (DELVA 2003). The intake of magnesium depends, however, on the structure of consumed products, which can be grouped in classes based on magnesium concentration in edible parts (expressed in mg kg^{-1} raw or final product) (GEBHARDT, THOMAS 2002):

1) very high, (> 1000): buckwheat grains, cocoa, almonds, pumpkin seeds, bread from wheat, rye whole grains, oat grains;
2) high (500 – 1000): spinach, soybeans boiled;
3) medium (250 – 500): artichokes, potatoes with skin, green beans;
4) low (< 250): apple, lettuce, potatoes (peeled and boiled).

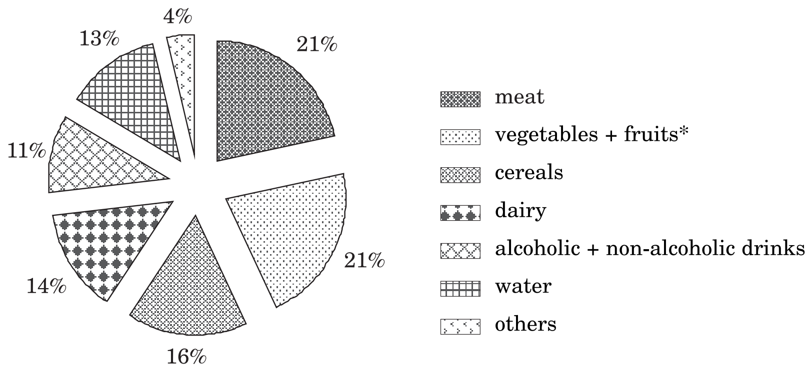

Fig. 3. Structure of magnesium delivery in food in the Spanish diet
(based on JODRAL-SEGADO et al. 2003)

The second factor significantly affecting mineral levels in plant food is related to soil fertility. This view was broadly documented by the evaluation of historical data concerning basic element concentrations in five types of food products in the period extending form 1940 to the end of the 20^{th} century (Table 2). Magnesium decrease was above 20% in cheeses and vegetables and *ca* 15% in fruit and meat. These negative changes are generally related to the quality of fodder and food, relatively poor in nutrients (DAVIS 2009, THOMAS 2003, 2007). The evidence for a decline in the mineral content in plant food has been therefore termed as *soil induced dilution effect*.

The above facts and conclusions are being discussed by scientists. In many areas of intensive food production, like in Europe, no significant evidence for plant available nutrient decline has been observed. Two types

Table 2

The weighted average changes in macronutrient concentration in food products*

Elements	Food products				
	meat***	dairy***	cheeses***	fruit**	vegetables**
Sodium	-24	-47	-9	-29	-49
Potassium	-9	-7	-19	-19	-16
Phosphorus	-21	+34	-8	+2	+9
Calcium	-29	+4	-15	-16	-46
Magnesium	-14	-1	-26	-16	-24

*acc. to THOMAS (2003, 2007); **for years 1940-1991 period;
***for years 1940-2000

of investigations have been carried out to verify this hypothesis. The first one relies on the evaluation of historical food composition data. A classical example is a study performed on wheat grain from the Broadbalk Wheat Experiment, which was established in 1843 at Rothamsted (the UK). An analysis of archived grain samples showed that magnesium concentrations, irrespective of fertilization treatments, were constant over the period from 1845 to the mid-1960s. The concentration of magnesium, averaged over all fertilization treatments, was at the level of 365 mg kg^{-1}. It was, however, found that from 1968 to 2005 Mg concentrations fell significantly, mainly because of the introduction of new type of wheat short-straw cultivars (FAN et al., 2008). Another way for verifying the above hypothesis is based on the *side-by-side comparison* method, which involves comparison of high (modern) and low (old) cultivars grown under the same soil conditions. A case study conducted on broccoli allowed researchers to explain the reasons for a decrease in magnesium and calcium concentrations. It appeared that new, modern cultivars, characterized by a fast rate of growth and high yield of edible parts, are genetically unable to achieve high concentrations of minerals. The detected dilution of most minerals as found for broccoli, wheat and maize has been therefore termed a *genetic dilution effect* (DAVIES 2009).

The impact of food processing on mineral nutrients is highly important for humans, whose diet is based on cereals and potatoes (WATZKE 1998). A classical example is wheat flour, commonly used in bread production. A study on the magnesium content in food products in the USA, as presented by the USDA National Nutrient Database for Standard Reference (2011, based on GEBHARDT, THOMAS 2002) clearly shows that white wheat flour contains *ca* 18% of the original magnesium content. This striking difference is a result of the milling process, causing loss of magnesium into millfeed. The same applies to potato tuber processing. According the same source, the concentration of magnesium in potato baked with flesh and skin is *ca* 280 mg kg^{-1}, but in potatoes boiled or cooked without peelings it is 1/3 lower, i.e., at the level of 200 and 280 mg kg^{-1}, respectively.

Magnesium intake deficiency – health consequences

The above facts support an increasingly popular conclusion that while the *Green Revolution* has combated famine on the global scale, it has also created conditions for an uncontrolled decline of food quality, attributed to a decreasing intake of most minerals, in turn negatively affecting the health of consumers. Magnesium is classical exemplification of this thesis (WELCH and GRAHAM 2002, WHITE, BROADLEY 2005).

An adult human body contains 20-28 g of magnesium, which is not equally distributed in the body. It is shared between bones (60-65% of total Mg), followed by intracellular cells of muscles (27%), other cells (6-7%) and extracellular space (< 1%, serum and red blood cells). The amount of available magnesium, i.e., its potential retention in a human organism, depends on its concentration in the consumed food and on many other factors. It decreases under conditions of high dietary fiber content, excessive consumption of fat, sugar or sodium. High amounts of magnesium not retained in a body are excreted in urine (VORMANN 2003).

Within human cells, magnesium occurs mostly in bonded structures, representing 90% of its total amount. The remaining part is present in ionic forms with the prevalence of Mg^{2+}. The most important bonds are formed with nucleic acids, ATP, negatively charged phospholipids and proteins. The divalent Mg cation activates directly *ca* 350 enzymes and is indirectly involved in thousands of processes in the human body. Bio-physical functions of Mg^{2+} concern the production, storage and use of ATP molecules for any life, energy demanding processes. Other important processes regulated by magnesium are as follows: i) trans-membrane transport of calcium, sodium and potassium, ii) protein synthesis (FAWCETT et al. 1999).

Extended studies have revealed a close relationship between low magnesium consumption by humans and the major risk factors for heart diseases. It is well documented that the heart contains much more magnesium than other muscles. However, under conditions of small but negative changes of Mg^{2+} concentrations, both in the extra-cellular and/or intracellular space, its content in the heart decreases, resulting in some disturbance of its activities. Moreover, it has been reported that the rhythm of the heart depends on gentle balances occurring between Mg^{2+} and other cations (Ca^{2+}, Na^+, K^+). Magnesium deficiency induces several heart dysfunctions such as arrhythmias, high blood pressure, arteriosclerosis, formation of blood clots within blood vessels and finally myocardial infarction (DELVA 2003, DOUBAN et al. 1996, TOUYZ 2003).

MAGNESIUM IN PLANTS – FUNCTIONS AND DEFICIENCY SYMPTOMS

Uptake and redistribution within plant parts

Concentration of magnesium ions in the soil solution ranges from 125 μM to 8.5 Mm. From soil, magnesium ions are transported toward the root surface in water transpiration stream. The permeability of a root to water depends on its age. Young parts of roots consisted of rapidly growing cells, highly permeable to water and transported ions. However, in the course of growth, the anatomical structure of roots undergoes significant differentiation. The most important changes take place in the endodermis surrounding inner tissues of the root stele. In this particular tissue (relative to root maturation processes), synthesis of suberin compounds occurs progressively, creating the Casparian strip. This developing layer becomes the main biological barrier, impeding transportation of divalent cations from the apoplast into the xylem. In addition, most Mg^{2+} cations undergo binding by negatively charged chemical groups naturally present in the root cell walls Therefore, the amount of magnesium reaching the root apoplast to cover plant requirements must be 2(3)-fold higher than the real plant biological requirements. The root apoplast including the endodermis can be considered as an important, partly temporary storehouse of magnesium (CLARKSON 1985, SHAUL 2002).

Amounts of magnesium present in the root apoplast are variable due to the effect of some important factors negatively affecting magnesium supply to crop plants (CLARKSON 1985, HUNDT, KERSCHBERGER 1991, KINRAIDE et al. 2004, METSON 1974):

- low amounts of available magnesium in the soil solution;
- competition with other divalent ions; mostly Ca^{2+} due high soil pH; NH_4^+, K^+ and also by some divalent cations of micronutrients;
- elevated concentration of aluminum, Al^{3+}:
  - directly through ion competition;
  - indirectly through restricted volume of the plant root system;
- all other factors restricting the size of the root system.

The first factor can be considered as the most important one because of the dominance of mass-flow mechanisms of Mg^{2+} ions transport in the soil solution toward the root surface. The second group of factors should be considered with caution because calcium is generally responsible for the rate of root growth, in turn defining the size of the root system at any stage of crop plant growth. Relationships between magnesium and potassium ions are highly complex (HUNDT, KERSCHBERGER 1991). The actual negative effect of potassium excess on magnesium concentrations in plants can be expected only if the supply of potassium is high (WIERZBOWSKA 2006). There is strong antagonism between ammonium and magnesium ions during the uptake by plant roots (BRITTO, KRONZUCKER 2002, KUBIK-DOBOSZ 1998, METSON 1974).

Accumulation of magnesium in aerial plant biomass reaches maximum at the physiological maturity of the crop. The accumulation of phosphorus shows almost the same pattern, irrespective of crop species. The effect of phosphorus application on magnesium concentration in the plant is positive at low but negative at very high rates of fertilizer (WIERZBOWSKA, BOWSZYS 2008). The illustration in Figure 4, showing the accumulation of both nutrients by a high-yielding plantation of sugar beet, indirectly indicates strong biological coherence of both elements. Final redistribution of magnesium among parts of physiologically matured seed crops shows almost the same pattern (Figure 5). Depending on the crop, *ca* 50% of the finally accumulat-

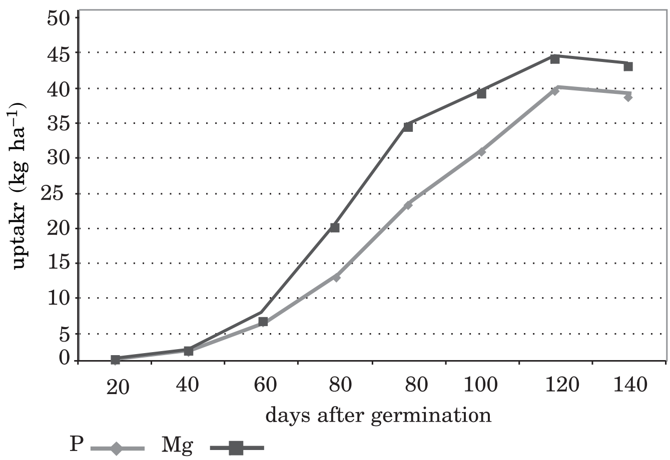

Fig. 4. Dynamics of magnesium and phosphorus accumulation by sugar beet plantation (based on GRZEBISZ et al. 1998)

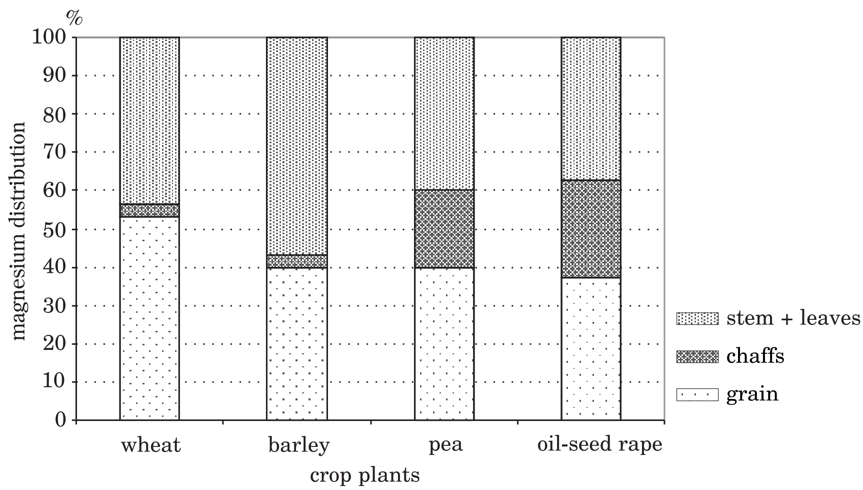

Fig. 5. Magnesium redistribution between plant parts of seeds crops at harvest (GRZEBISZ, non published)

ed magnesium is stored in reproductive organs such as seeds or grain. However, in seeds rich in proteins or fat, this percentage is significantly lower. The same holds true about root crops, such as sugar beets, which accumulate 25-33% of total magnesium in the taproot.

Basic biological functions

Magnesium concentrations in plants vary from 0.1% to almost 2%. Its distribution in plant cells is irregular. In leaves, the most important bonding sites for magnesium are chloroplasts, mitochondria and vacuoles. In cells of well-fed leaves, most magnesium is located in vacuoles, functioning then as the inner cellular buffer. The importance of this buffer increases under an insufficient supply of magnesium from the extracelluar leaf space. Leaf magnesium homeostasis, significantly affecting the activity of chloroplast enzymes, depends on the amounts of this element in chloroplast and its concentration in the cytosol, with optimum at 1 mM. However, free Mg^{2+} represents *ca* 10% of cytosol magnesium. The remaining part is bound by ATP (90%). Decreased concentration of magnesium in the cytosol affects of Mg^{2+} movement from both the vacuole and extracelluar leaf space (KARLEY, WHITE 2009, SHAUL 2002).

Magnesium affects directly or indirectly almost all biochemical and physiological processes occurring within the plant during its course of life. The hierarchy of its biological functions can be presented as follows (MAATHUIS, 2009, SHAUL 2002):

1) photosynthesis:
   – central position in the chlorophyll molecule,
   – light reactions in the chloroplast stroma,
   – photosynthetic enzyme activation,
   – CO_2 molecule binding and reduction,
2) energy production and transformation:
   – ATP molecule synthesis, storage and release,
   – synthesis of carbohydrates, proteins and fat,
3) membrane transport:
4) distribution of carbohydrates among plant parts:
   – phloem load of photosynthetically bound sugars,
   – root system growth,
5) nucleic acids stabilization.

Deficiency symptoms development

Plant magnesium deficiency symptoms seem to be extremely classical as presented in many references. However, the newest scientific facts have revealed some complexity of the development of deficiency symptoms on the cellular level in response to magnesium homeostasis. The hierarchy of the development of deficiency symptoms is as follows:

– excessive sucrose and starch accumulation in fully expanded leaves,

– decreased sugar transport from leaves to other plant organs,
– root system growth inhibition,
– aerial plant part growth inhibition.

The first symptoms of magnesium deficiency are related to the inhibition in loading sucrose to the phloem due to insufficient synthesis of Mg-ATP. There is some scientific evidence that sugar concentration in leaves is inversely correlated with magnesium concentration (CAKMAK 1994, HERMANS et al. 2005). The first biological consequence of inhibited sucrose transportation in the phloem results in decreasing the growth rate of the newest organs such as roots (CAKMAK 1994, HERMANS et al. 2005). Therefore, inhibition of the root system size can be considered as the second symptom of magnesium deficiency. CAKMAK, KIRKBY (2008) reported that a decrease in the root growth rate took place much earlier than any symptoms detected on leaves and on a plant, i.e. related to a decreasing leaf area size, appearance of leaf chlorosis and finally a stunned rate of the plant canopy growth. The most striking symptoms of magnesium deficiency, i.e. leaf chlorosis, is a result of energy transfer disturbance. A magnesium deficient leaf, rich in sucrose and starch, is not able to transfer light energy into biological compounds such as ATP and NADPH; instead it begins to to generate reactive oxygen substances (superoxide radicals, $O_2^{\cdot -}$; hydrogen peroxide, H_2O_2, etc.). These compounds, when not inactivated into a cell, destroy enzymes and chloroplasts, impairing cell photosynthesis and finally causing degeneration of leaf surface tissues. Under low magnesium stress, these visual symptoms are weakly recognizable, but during chronic deficiency, they lead to leaf chlorosis, followed by necrosis. Due to the fact that magnesium concentration increases towards leaf veins, the first visible symptoms are observed as interveinal chlorosis (CAKMAK and KIRKBY 2008, TEWARI et al. 2006).

SOIL MAGNESIUM

Soil magnesium characteristics

The averaged content of magnesium in the lithosphere is *ca* 21 g kg^{-1}, but it is several times lower in soil, i.e. 5 g kg^{-1}. These two figures clearly indicate the high weathering potential of soil magnesium-bearing minerals. Knowledge of the mineral composition of the weathered rock, known as soil parent material, is important to make the first assessment of potential chemical characteristics of any given soil. Hence, the total magnesium content in arable soils reflects to some extent the composition of soil parent material, being the substrate during pedogenesis. Igneous basic rocks (< 66% of SiO_2 represented by basalt, gabbro, norites) show naturally greater weathering potential than acid rocks (> 66% of SiO_2 represented by granite, rhyolite) and at the same time a higher potential for releasing base cations. Therefore, based on mineral composition of soil parent material it may be concluded, that soils formed from mafic igneous rock, containing high amounts of ferromagnesian minerals, serpentine or dolomite, naturally exhibit high concentrations of total magnesium (Metson 1974, Metson, Brooks 1975).

Naturally magnesium deficient soils are:

– sandy soils originated from granites, sandstones,
– sandy soils originated form post-glacial sandy deposits or alluvial sandy deposits,
– organic soils.

Magnesium-bearing minerals represent two basic mineral groups, known as primary and secondary minerals. The first group is represented by silicate minerals such as:

– ferromagnesian minerals: amphiboles, olivines, pyroxenes, hornblendes; important components of igneous rocks and some metamorphic rocks (serpentine, talc);
– micas (muscovite, biotite); specific by a 2:1 layer type silicate structure;

The solubility of magnesium-bearing silicates is a function of pH as presented below for two classical representatives:

1) olivine

$$Mg_{1.6}Fe(II)_{0.4}SiO_4 + 4H^+ \Leftrightarrow 1.6Mg^{2+} + 0.4Fe^{2+} + H_4SiO_4^o \quad \log K^o = 26.18$$

2) serpentine

$$Mg_{1.6}Si_4O_{10}(OH)_8 + 12H^+ \Leftrightarrow 6Mg^{2+} + 4H_4SiO_4^o + 2H_2O \quad \log K^o = 61.75$$

The second group is composed of minerals of different geological origin, which can be simply divided into three main sub-groups such as:

– carbonates,
– secondary clay minerals,
– soluble salts.

The carbonate family of magnesium-bearing minerals is composed mainly of dolomite and magnesite. The main factor affecting solubility is soil pH. The solubility reactions are presented below:

1) dolomite

$$CaMg(CO_3)_2 + 4H^+ \Leftrightarrow Mg^{2+} + Ca^{2+} + 2CO_{2(g)} + 2H_2O \quad \log K^o = 18.46$$

2) magnesite

$$MgCO_3 + 2H^+ \Leftrightarrow Mg^{2+} + CO_{2(g)} + 2H_2O \quad \log K^o = 10.69$$

In spite of its high solubility under natural conditions, dolomite is dissolved much faster than magnesite, but both are less soluble than calcite. All minerals belonging to soluble magnesium salts, for example sulfates, chlorides or nitrates are nor detectable in the soil solution. It is highly important in agronomic practice because any addition of these salts to soil results in an increase of the soil solution magnesium concentration.

Soil magnesium deficiency – reasons and assessment

The primary cause of magnesium deficiency in crop plants is the low content of its available supplies in the soil solution, thus a decreased rate of Mg^{2+} ions uptake (HUNDT, KERSCHBERGER 1991). Several methods for soil magnesium deficiency assessment can be distinguished, but three are the most important in agronomic practice:

1) available magnesium rating,
2) exchangeable magnesium content and its contribution to the soil cation-exchange capacity,
3) soil magnesium balance:
   - exchangeable magnesium balance,
   - agronomic balance.

The first method refers to the classical agro-chemical rating of plant available magnesium. Magnesium deficiency is defined by a current amount of plant available magnesium in the soil body as an indicator of a potential crop response to the applied magnesium fertilizer. Therefore, one of the most important agronomic targets is to establish a critical value of exchangeable soil magnesium (Mg_{ex}) with respect to the expected crop plants response. SCHACHTSCHABEL (1954), by means of 0.0125 M $CaCl_2$ extract, defined the critical content of magnesium to *ca* 50, 70 and 1200 mg kg^{-1} soil for light, medium and heavy soils, respectively. These ranges have been generally corraborated by other researches, as reported by METSON (1974), who a year later published magnesium rating methods based on both exchangeable magnesium and reserve magnesium, i.e. hot extracted from soil by 1 M HCl test (METSON, BROOKS 1975). According to the above values, the expected deficiency is related to both an exchangeable magnesium content lower than 120 mg kg^{-1} soil and its reserves below 720 mg kg^{-1} soil (Table 3). One of the most important assumptions in both approaches is the soil textural class as a factor defining the amount of Mg_{ex} in the cation exchangeable complex. It has been agreed that an ideal cation exchange complex (CEC) consists of Ca^{2+} – 65% , Mg^{2+} – 10%, K^+ – 5% and H^+ – 20% of all cations. In some studies, a 6% contribution of Mg_{ex} in the CEC is considered as sufficient to cover the crop's needs in the course of vegetation (METSON, BROOKS 1975).

Table 3

Rating of exchangeable and reserve magnesium in soils* (mg kg^{-1})

Rating	Exchangeable Mg	Reserve
Very high	> 1680	> 7200
High	720-1680	3600-7200
Medium	240-720	1680-3600
Low	120-240	720-1680
Very low	< 120	< 240

*acc. to METSON, BROOKS (1975)

The third method of assessing tendency towards magnesium-deficient soil relies on measuring Mg_{ex} at the beginning and at the end of three- or four-course rotation or an extended period of arable land cultivation. As presented in Table 4, long-term cultivation of rye with a constant rate of applied farmyard manure or NPK fertilizers resulted in high differentiation of the Mg_{ex} content. Plots annually fertilized with NPK become depleted of minerals, irrespective of the method of soil use (crop or fallow). This process can be mitigated by manure application, but the amount of annually produced manure even on a mixed production farm is too low to replenish losses of magnesium. An elevated content of Mg_{ex} found in the 40 to 80 cm soil layer verifies a typical feature of luvisols in temperate climates, such as accumulation of basic cations in deeper soil layers.

Table 4

Plant available magnesium distribution in the soil profiles of long-term static experiment* (mg kg^{-1} soil)

Soil layer (cm)	Black fallow		Winter rye – monoculture		Winter rye – crop rotation	
	FYM**	NPK***	FYM	NPK	FYM	NPK
0-20	52	22	55	17	58	20
21-40	49	21	46	17	58	21
41-60	99	41	72	58	81	18
61-80	66	33	85	52	90	18
81-100	52	28	52	45	56	29
100-120	36	21	40	31	44	31

*acc. to PIECHOTA et al. (2000);
**FYM – annually applied farmyard manure at the rate of 30 t ha^{-1};
***N – 90; P – 26; K – 100 (kg ha^{-1}).

Soil balance of exchangeable magnesium can be also calculated by taking into account its available content at the beginning and the end of an observation period. However, this method does not reveal the causes of Mg_{ex} loss/gain in the investigated soil. As presented in Figure 6, Mg_{ex} balance after 8 years of study was negative despite the application of magnesium fertilizers in the total amount of 288 kg Mg ha^{-1}. The highest losses were recorded in the control treatment, i.e. without any input of NPK fertilizers. Net magnesium losses were significantly related to increasing NPK rates. Applied lime affected positively magnesium management, decreasing its losses. Maximum calculated magnesium losses, including applied magnesium fertilizer, amounted to 50 kg ha^{-1} $year^{-1}$.

The fourth method for assessing potential threat of magnesium deficiency to cultivated crops relies on agronomic magnesium balance, indicating current trends of magnesium soil management (ŁABĘTOWICZ et al. 2004). A classical balance sheet, in accordance to the "field surface balance", should include:

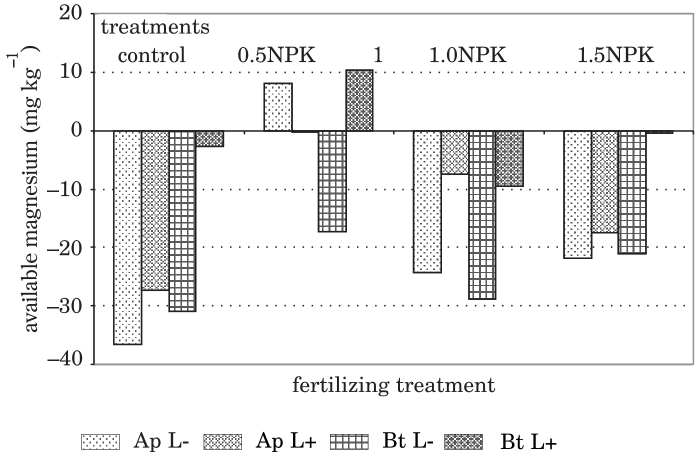

Fig. 6. Effect of liming and mineral fertilizers application on available nitrogen balance (based on KANIUCZAK 1999)

1) input: a) plant residues; b) organic fertilizers; c) mineral fertilizers; d) other sources, for example rainfalls;
2) output: a) crop removal; b) leaching; c) exchangeable Mg^{2+} fixation.

The first step in checking the soil magnesium output is to make a reliable assessment of its removal from the field. These values are mostly evaluated on the basis of utilizable part of crops. Figure 5 shows that just 40 to 60 per cent of magnesium accumulated in final biomass is in utilizable part. The rest remains in crop residues and undergoes different forms of recycling. Another indicator, known as unit nutrient uptake (in the described case: unit magnesium uptake, UMgU), helps to achieve reliable estimation of magnesium removal, as it takes into account the total magnesium in harvested crop biomass, recalculated per unit of harvestable plant part (Table 5). Indices calculated for crops are very useful in determining their sensitivity to total magnesium requirements. Therefore, this assessment must be done carefully.

The second element of a simple magnesium soil balance refers to its leaching. As shown in Figure 6, most of the magnesium lost during the investigated period was leached. SCHWEIGER, AMBERGER (1979), by lysimetric experiments, showed annual losses of Mg_{ex} at the level of 72 kg ha^{-1} for sandy soil and 92 kg ha^{-1} for medium soil during a 36-year-long period. They concluded that the majority of detected losses were due to leaching processes. However, a direct assessment of magnesium leaching by means of its concentration in water outflow from fields showed much smaller values, ranging from 18 to 25 kg Mg ha^{-1}, respectively for medium and light soils (Figure 7). These values can range from less than ten to over 40 kg ha^{-1} (SZYMCZYK et al. 2005). The highest quantitative leaching occurred in winter.

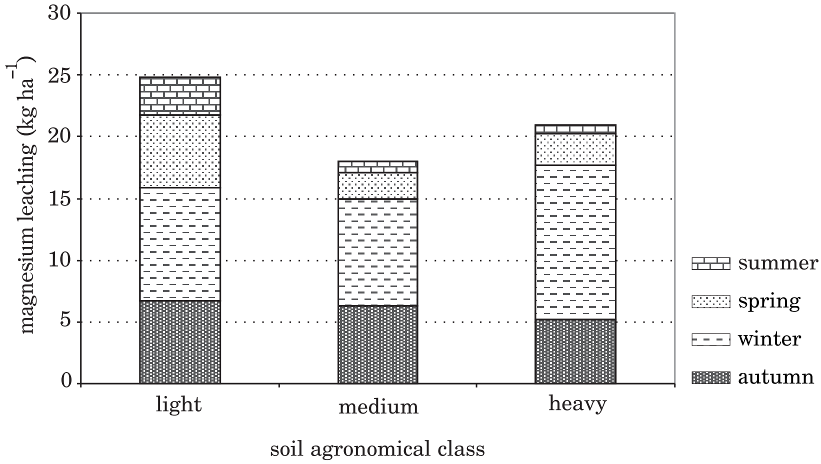

Fig. 7. Effect of soil agronomical class on magnesium leaching in main seasons of the year (based on KOC, SZYMCZYK 2003)

Table 5

Current and potential sources of fertilizer magnesium

Name of magnesium source or fertilizer	Chemical composition	Magnesium content (%)	Water solubility (g dm^{-3})
Water soluble salts			
Magnesium nitrate	$Mg(NO_3)_2 \cdot 6H_2O$	10	1 250
Magnesium chloride	$MgCl_2 \cdot 6H_2O$	25	1570
Epsom salts	$MgSO_4 \cdot 7H_2O$	10	335
Kiserite	$MgSO_4 \cdot H_2O$	18	360
Sulfate of potash magnesia	$2MgSO_4 \cdot K_2SO_4$	12	240
Schoenite	$MgSO_4 \cdot K_2SO_4 \cdot 6H_2O$	6	330
Magnesium chelates	various	3-5	high
Oxides and carbonates			
Magnesium oxide	MgO	50-55	0.009
Dolomite	$MgCO_3CaCO_3$	8-20	0.006
Magnesite	$MgCO_3$	27	0.034
Other sources			
FCMP*		92	90% CAS**
Struvite	$MgNH_4PO_4 \cdot 6H_2O$	10	low
Magnesium ammonium phosphate	$MgNH_4PO_4$	16	0.14
Serpentine	$Mg_3SiO_5(OH)_4$	21	low

*Fused calcium magnesium phosphate; **citric acid soluble

STRATEGIES TO MITIGATE MAGNESIUM DEFICIENCY IN CROP PLANTS

Strategy set-up

The actual daily intake of magnesium from food by human individuals depends on their eating habits. Human nutritionists working out a diet take into account two basic factors: 1) food sources, i.e. food diversification, 2) concentration of minerals, such as magnesium in consumed food and drinking water. At present, there are some alternative options to increase magnesium daily intake. However, the first solution, in fact the easiest way, is to change the structure of consumed products, from low to rich in magnesium content, such as vegetables, some fruit, fish, meat, etc. Another option to cover magnesium daily requirements is to supplement food with mineral magnesium or to take it orally. The second solution is frequently applied during prevention and/or therapy of hypomagnesaemia (well defined signs or symptoms) and also during hospitalization of patients with clinical magnesium deficiency symptoms (Eby, Eby 2006, Douban et al. 1996, Fawcett et al. 1999, Wojtasik et al. 2009).

However, in this part of the review we do not aim to discuss consumption patterns, as being the objective of human nutritionists. It is much more important is to define a simple strategy of magnesium increase, achievable by plant producers, in potentially edible part of currently grown crop plants, as a primary source of food, irrespective of the way of its final consumption. At present, despite high speed of progress in biotechnology, agronomic practices are the only realistic solution for increasing magnesium concentration in plant food. The essence is to find the most effective way of magnesium management in the soil-plant continuum, taking into account three objectives: 1) adequate nutrient supply to a plant during the course of vegetation, 2) increase of its content in edible plant parts, 3) high efficiency of applied magnesium fertilizer as related to low losses via leaching.

Sources of fertilizer magnesium

There are several magnesium carriers that can meet crop plant requirements. They can be divided into different groups, based on selected criteria:

1) chemical origin: a) organic, b) mineral;
2) mineral groups: a) soluble salts, b) oxides and carbonates, c) silicates;
3) solubility: a) water soluble, b) water semi-soluble.

Despite the rate of Mg^{2+} ions release, each of the above specified magnesium-bearing fertilizer sources plays an important role in soil magnesium management. Organic sources of magnesium are of primary or secondary origin. Primary sources are plant residues, which as indicated in Figure 5, contain from 40 to 55(60)% of magnesium accumulated in aerial crop plant biomass at harvest. Plant residues of dicotyledonous crops, such as sugar beets, or oil-seed rape are naturally richer in magnesium than cereals (HUNDT, KERSCHBERGER 1991).

Therefore, such plant residues should be considered as a natural source of basic cations, including magnesium. Farmyard manure contains not only farm recycled plant residues but also other organic fodder or mineral additives used in animal nutrition. Therefore, the content of magnesium in manure is highly variable, depending on the type of farm, method of animals nutrition, type of manure. All organic sources of manure can be classified as slow-release fertilizers irrespective of the type, and the main objective of their application is to increase the total content of soil magnesium.

In practice, minerals such as soluble salts, which are easily dissolved in water, are an important source of magnesium (Table 5). This group of minerals is widely used as magnesium fertilizers in pure or processed forms. These fertilizers enrich directly the concentration of Mg^{2+} ions in the soil solution, in turn increasing the pool of nutrients directly taken up by plants. Another group of minerals, representing by carbonates and/or oxides, are poorly dissolved in water. However, they release Mg^{2+} ions when incorporated into soil. In terms of soil geochemistry, soil can be considered as weakly acid, in turn significantly affecting magnesium minerals dissolution, as presented below for dolomite:

$$(Mg\ Ca)(CO_3)_2 + 4H^+ \rightarrow Mg^{2+} + Ca^{2+} + 2CO_2 + 2H_2O$$

Some other groups of magnesium fertilizers are highly specific, for example fused calcium magnesium phosphate (FCMP), whose production is based on phosphate rock and serpentine, being fused in an electric furnace. The product contains 18-20% of P_2O_5, *ca* 12% of MgO and also silicon and lime. It is very popular in many Asian and South American countries. The main disadvantage of this fertilizer is its high cost of production, 850 kWh per 1 ton of final product (RANAWAT et al. 2009). Another source of magnesium fertilizer source is serpentine ($Mg_3SiO_5(OH)_4$). Although it is not very popular, it was first used make magnesium phosphates in New Zealand 70 years ago, in the 1940s (METSON, BROOKS 1975). Potential sources of magnesium are also ammonium magnesium phosphates, including mineral called struvite. This fertilizer is a product of municipal and animal manure wastewater purification. For all these groups of minerals, the particle size and their degree of crystallization are the most important factors affecting the rate of magnesium release, i.e. defining potential of Mg^{2+} cations to supply cultivated crops.

Critical stage concept – soil versus foliar application

The current nutritional status of commonly grown crop plants can be simply assessed by evaluating their sensitivity to external magnesium supply, i.e. application of magnesium containing fertilizers. The main question refers to the adequate time, amount and form of applied magnesium fertilizer. However, as discussed in chapter two, magnesium is responsible for crop plant metabolism at different stages. An adequate supply of magnesium is important for the distribution of carbohydrates assimilated by leaves, as a prerequisite of an adequate rate of the crop canopy growth (CAKMAK, KIRKBY 2008). Therefore, the first step in any reliable assessment of the nutritional status cultivated crops is to define their critical growth stage(s).

Two main strategies of magnesium fertilizer application can be considered. One relies on magnesium incorporation into soil, depending on the fertilizer solubility or the aim of the treatment. For water soluble fertilizers, the main aim is to achieve a quick increase of the available magnesium content in the soil solution (HARDTER et al. 2004). This method of magnesium application may meet crop plant requirements (GRZEBISZ et al. 2001). However, the application of soluble magnesium salts leads to concurrent leaching of much of the applied magnesium. An alternative solution is to apply slow magnesium releasing fertilizers such as dolomite or serpentine. The release of Mg^{2+} ions to a cultivated crop depends on weathering, whose intensity is controlled mainly by annual precipitation and soil pH.

Agricultural evaluation of main magnesium fertilizers is based on assumed application targets, for example defined by plant magnesium accumu-

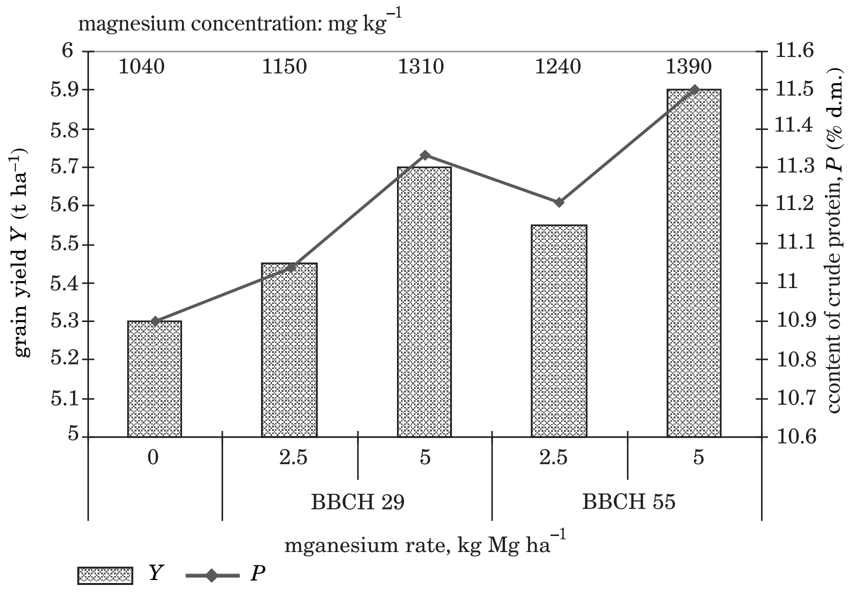

Fig. 8. Effect of timing and magnesium application rate on quantity and quality of winter wheat grain (based on MATŁOSZ 1992)

lation, leaching and crop plant yield and/or quality increase. As shown in Figure 8, in humid regions of the world, leaching of magnesium from soluble salts is high, reaching 50% of the applied Mg rates during 32 months. An effect of pure serpentine rock on both magnesium accumulation and its leaching was weak, demonstrating its low usability as Mg-fertilizer. However, the processed fertilizer called Serp-superA has fulfilled fertilizing and environmental expectations (HANLY et al. 2005, LOGANATHAN et al. 2005).

The highly probability of soil magnesium leaching from soluble salts can be easily overcome by applying lower rates or by splitting the whole rate into sub-rates applied both before and in the course of the growing season (HARDTER et al. 2004). The second option relies on foliar application of water soluble fertilizers. This strategy of magnesium supply to cultivated crops requires adequate determination of three variables affecting the production objectives: 1) time of application adequately related to plant growth and components of yield formation, 2) amount of applied magnesium, 3) salt concentration in the spraying solution. Taking into account the main objective of this review, foliar magnesium spray seems to be the simplest agronomic way of increasing magnesium concentration in edible plant parts. As presented in Figure 9, the application of 5 kg Mg ha^{-1} was able to increase the concentration of magnesium in wheat grain by 33%. This value is at the level of that reported by FAN et al. (2008) for long-stem straw, i.e. before the era of modern short-stem straw varieties.

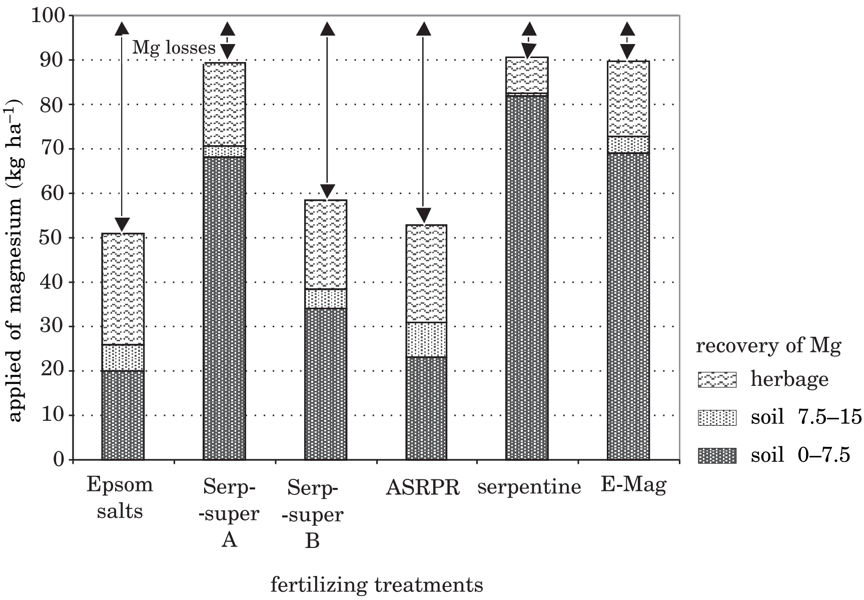

Fig. 9. Structure of fertilizer magnesium recovery (soil + herbage) and losses in soil (based on LOGANATHAN at al. 2005)

FINAL CONCLUSION

The present overview of magnesium importance for the health plants, animals and people in the whole food chain is the best described again dr Northen: "*Minerals are vital to human metabolism and health – and that no plant or animal can appropriate to itself any mineral which is not present in the soil upon which it feeds up*" (BEACH 1936). Agronomic practices consisting of well-tended soil and plant magnesium management seem the best and at the same time the cheapest way to make quick improvement of the quality of edible plant parts with respect to magnesium levels.

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