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Micronutrient Status of Winter Wheat in Poland

Stan Odżywienia Mikroelementami Pszenicy Ozimej Uprawianej w Polsce

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Abstract

The aim of this study was to investigate the scale of the deficiency of the six basic micronutrients: B, Cu, Fe, Mn, Mo and Zn in the fields of wheat grown in Poland. In the years of 2010 – 2011, 357 samples of winter wheat crops were collected from fields located in the averagely intensive farms in 16 provinces of Poland. Plants were collected in the beginning of stem elongation/first node stage (whole aboveground part), and then the contents of individual micronutrients were determined and evaluated on the basis of critical values developed for cereals by Schnug and Haneklaus. It has been shown that the wheat cultivated in Poland is characterized by low Zn (38% of the samples), and Mn (29%) contents, followed by Cu (21%) and B (18%). Almost no deficiencies of Mo (3%), and only few of Fe (11%) were observed in the collected samples. Regional differences in terms of occurrence of deficiencies of the analyzed elements were also quite significant.

Keywords: beginning of stem elongation, microelements, nutritional status, *Triticum aestivum*

Streszczenie

Celem pracy było zbadanie skali deficytu sześciu podstawowych mikroelementów- B, Cu, Fe, Mn, Mo i Zn na polach pszenicy uprawianej w naszym kraju. W latach 2010-2011 pobrano kolekcję 357 prób roślin pszenicy ozimej z pól zlokalizowanych w średnio intensywnych gospodarstwach rolnych, z terenu 16 województw Polski. Rośliny pobierano w fazie początku strzelania w źdźbło/pierwszego kolanka (cała część nadziemna), a następnie oznaczano w nich zawartość poszczególnych mikroelementów i oceniono na podstawie wartości krytycznych opracowanych dla zbóż przez Schnuga i Haneklaus. Wykazano, że w pszenicy uprawianej w naszym kraju najczęściej występuje niska zawartość Zn (38% próbek) i Mn (29 %), a w dalszej kolejności Cu (21%) i B (18%). W zgromadzonych próbkach prawie wcale nie zaobserwowano niedoborów Mo (3%) i tylko nieliczne Fe (11%). Stwierdzono także dość znaczne zróżnicowanie regionalne pod względem występowania niedoborów badanych pierwiastków.

Słowa kluczowe: mikroelementy, początek strzelania w źdźbło, pszenica ozima, stan odżywienia

Streszczenie szczegółowe

Pszenica ozima jest rośliną o największym areale uprawy w Polsce. W 2011 uprawiano ją na powierzchni ponad 2 mln ha. Pomimo pewnego wzrostu plonów tej rośliny w ostatnich latach, są one ciągle znacznie niższe niż potencjalnie możliwości jej plonowania. W roku 2011 średnie plony w Polsce wynosiły 4,1 t/ha, podczas gdy w Niemczech i Francji osiągały poziom 7,5-8,0 t/ha. Ze względu na występujące w Polsce niedobory mikroelementów w glebach można przypuszczać, że jedną z przyczyn uzyskiwania niskich plonów pszenicy w naszym kraju może być jej niewystarczające zaopatrzenie w te składniki. Ocena stanu odżywienia plantacji pszenicy we wcześniejszych fazach wzrostu daje możliwość uzupełnienia ewentualnych niedoborów poprzez nawożenie interwencyjnie. Ocena taka polega na pobraniu prób roślin w odpowiedniej fazie wzrostu, oznaczeniu w nich zawartości mikroelementów i porównaniu z odpowiednimi wartościami krytycznymi. Kompleksową ocenę odżywienia pszenicy opracowaną na dużych zbiorach danych proponują Bergmann (1992), a ogólnie dla zbóż Schnug i Haneklaus (2008). Celem pracy było zbadanie skali deficytu sześciu podstawowych mikroelementów - boru, miedzi, żelaza, manganu, molibdenu i cynku na polach pszenicy uprawianej w naszym kraju.
W ramach współpracy Instytutu Uprawy Nawożenia i Gleboznawstwa w Puławach (IUNG-PIB) i Krajowej Stacji Chemiczno-Rolniczej w Warszawie w latach 2010-2011 pobrano kolekcję 357 prób roślin pszenicy ozimej z terenu 16 województw Polski. Punkty poboru były zlokalizowane w średnio intensywnych gospodarstwach rolnych. W 2010 roku pobrano 165, a w 2011 roku 193 próby. Rośliny pobierano w fazie początku strzelania w źdźbło/pierwszego kolanka (całe pędy ścinane 2 cm nad ziemią). Każda próbka składała się z min. 80 sztuk pędów ściętych z powierzchni 10 m^2. Próbki poddano mineralizacji na sucho w piecu muflowym (500^{o}C) i roztworzeniu kwasem azotowym, a następnie oznaczano w nich zawartość Cu, Mn, Mo, Zn i Fe metodą AAS oraz B metodą ICP. Wszystkie analizy wykonano w akredytowanym laboratorium IUNG-PIB w Puławach. Zbiór wyników analiz chemicznych scharakteryzowano przy pomocy metod statystyki opisowej przy użyciu programu Statgraphics Plus 5.1.
Ocenę stanu odżywienia mikroelementami plantacji pszenic uprawianych w Polsce postanowiono przeprowadzić przy wykorzystaniu wartości krytycznych opracowanych przez Shnuga i Haneklaus (2008). Wydaje się jednak, że opracowane 20 lat temu wartości Bergmana straciły na aktualności i bardziej miarodajne są wartości stosunkowo niedawno opracowane przez Schnuga i Haneklaus. Porównanie wartości opracowanych przez Bergmanna oraz przez Schnuha i Haneklaus wykazało, że były one zbliżone lub identyczne w przypadku Mn

i Zn, natomiast różniły się znacznie dla B, Cu i Mo. Shnug i Haneklaus znacznie złagodzili kryterium niedoboru dla B i Cu, a zaostrzyli dla Mo. Posługując się tymi kryteriami oceniono zawartość mikroelementów w zgromadzonych 357 próbkach pszenicy. Wykazano, że najczęściej w roślinach pszenicy spotykano niską zawartość Zn (38% próbek) i Mn (29%), a w dalszej kolejności Cu (21%) i B (18%). W zgromadzonych próbkach prawie wcale nie zaobserwowano niedoborów Mo (3%) i tylko nieliczne Fe (11%).
W ramach przeprowadzonych badań oceniano również stan odżywienia pszenicy mikroelementami w poszczególnych województwach Polski. Podobnie jak w ocenie niedoborów na poziomie całego kraju posłużono się tu wartościami krytycznymi wg Shnuga i Haneklaus. Zaobserwowano znaczne różnice pomiędzy poszczególnymi województwami. Najczęstsze niedobory odnotowano w województwie małopolskim, pomorskim i świętokrzyskim, a najrzadsze w województwie opolskim.

Introduction

Winter wheat is a plant with the largest area of cultivation in Poland. In 2011, it is grown on the surface of more than 2 million ha. Despite certain increases in yields of this plant in recent years, they are still significantly below its yield potential. In 2011, average wheat yields in Poland amounted to 4.1 t*ha^{-1}, while in Germany and France, they were at the level of 7.5-8.0 t*ha^{-1} (Central Statistical Office, 2011). Due to the micronutrient deficiencies in the soils of Poland, it can be assumed that one of the reasons for low wheat yields in this country may be an insufficient supply of these nutrients. Monitoring of soils carried out from 1987 – 1993 and 1994 – 1999 showed a 70% soil deficiency in boron, 36% in copper, 20% in molybdenum and 10 – 14% in zinc and manganese (Obojski and Straczynski, 1995; Kucharzewski and Debowski, 2000). Also, other authors state that the lack of micronutrients may limit crop yields in Poland (Grzebisz, et al., 2010).

The assessment of nutritional status of wheat plantations in earlier stages of growth provides the opportunity to make up for deficiencies through top dressing. Such an assessment involves collection of plant samples in the appropriate stage of growth, determination of micronutrient content and the comparison of the results with the relevant critical values. In the literature, many researchers have set up critical values for the content of micronutrients in the plants of wheat. However, they were developed on the basis of a small amount of data and pot experiments or solution cultures which do not reflect field conditions (Asad, et al., 2001; Brennan and Bolland, 2002; Brennan and Bolland, 2006). In addition, these values refer mostly to only one micronutrient (Brennan, et al., 2001; Karamanos and Goh, 2004; Karamanos, et al., 2004; Rafique, et al., 2006). The comparison of the critical values with each other is often impossible since they relate to different stages of development (seedlings, tillering, earing) and different organs (flag leaf, the youngest leaves, whole shoots). Comprehensive evaluation of wheat nutrition developed on a large amount of data was provided by Jones, et al. (1991), Bergmann (1992), and generally for cereals, by Schnug and Haneklaus (2008).

The aim of the work was to investigate the scale of the deficiency of the six essential micronutrients: boron, copper, iron, manganese, molybdenum and zinc on the fields of wheat cultivated in Poland.

Materials and Methods

Within the cooperation with the Institute of Soil Science and Plant Cultivation in Pulawy (IUNG-PIB) and National Agrochemical Station in Warsaw in the years of 2010 – 2011, 357 winter wheat samples were collected in 16 Polish provinces (tab.1).

Table 1. Number of samples collected in each province

Lp.	Province	Number of samples
1	Dolnoslaskie	36
2	Kujawsko-pomorskie	35
3	Lubelskie	5
4	Lubuskie	17
5	Lodzkie	3
6	Malopolskie	30
7	Mazowieckie	15
8	Opolskie	18
9	Podkarpackie	35
10	Podlaskie	11
11	Pomorskie	23
12	Slaskie	36
13	Swietokrzyskie	27
14	Warminsko-mazurskie	23
15	Wielkopolskie	36
16	Zachodniopomorskie	7
Total		357

Sampling points were located in medium size farms. In 2010 – 165, and in 2011 – 192 samples were collected. The plants were collected at the beginning of stem elongation/first node stage (whole shoots were cut 2 cm above the ground). Each sample consisted of min. 80 pieces of shoots cut from the area of 10 m^2. The soils, from which plant samples were collected, were characterized by the following features (mean and range): pH_{KCl} – 6.2 (3.8-7.9), fraction < 0.02 mm in % - 27 (2-70), TOC in % - 1.3 (0.4-15.6), P (Egner-Riehm) in mg $100g^{-1}$ – 12.5 (0.7-68.5).

The concentration of micronutrients in plant samples, after ashing in a muffle furnace and diluting with nitrogen acid (PN-R-04014:1991), was determined by the AAS except B, which was determined by ICP-AES. Results were quoted as mg kg^{-1} of dry matter. All analyses were performed in the laboratory of IUNG-PIB, certified by Polish Centre of Accreditation (certificate no. AB 339) according to PN-EN ISO/IEC 17025. A standard reference material IPE B211 (International Plant-Analytical Exchange) from Wageningen (Netherlands) was used for quality control purposes.

Total organic carbon in soil was determined by Tiurin's method using potassium dichromate (PN-ISO14235: 2003), pH was established potentiometrically in KCl solution (ISO10390: 2005), P was determined using Enger-Riehm method (PN-R-04023:1996 and PN-R-04022:1996 adequately), and texture was evaluated by the aerometric method (PN-R-04033: 1998).

Data sets of micronutrient concentrations were characterized by descriptive statistics including mean, median, standard error, range, classical skewness, kurtosis and variability coefficient. All statistical calculation were performed using Statgraphics Plus 5.1software.

Results and Discussion

Characteristics of data set

Concentration values of Fe and Zn were characterized by the highest variability of all studied micronutrients (tab. 2). These elements had the largest range of concentration value, and the highest coefficient of variability. Despite these facts, the kurtosis indicated a large concentration of results around the mean, which for Fe was 170.9 mg kg^{-1}, and for Zn 37.0 mg kg^{-1}. In addition, the skewness show a strong right-sided asymmetry. Such a distribution was caused by the presence of a small number of samples with the content of elements high above the mean, which can be treated as the samples contaminated with these elements.

The contents of Mo and Mn were characterized by significantly smaller coefficients of variability than Fe and Zn, but at the same time by a lower concentration around the mean. Mean concentration values of these elements in wheat plants were 0.87 mg kg^{-1} Mo and 44.5 mg kg^{-1} Mn. Distribution of concentration values for these elements was also right-skewed, but with a lower strength of asymmetry than for Fe and Zn.

The concentration values of B and Cu were characterized by the smallest variation, as well as by the largest symmetry, similar to the normal distribution. Mean concentration values of these elements were respectively 3.93 and 5.31 mg kg^{-1}.

Table 2. Mean concentration of micronutrients in 357 sample collection of wheat plants (mg kg^{-1})

Element	Mean	Median	Standard error	Range	Skewness	Kurtosis	Coefficient of variability %
B	3.93	3.79	0.06	1.64-10.10	1.39	3.78	29
Cu	5.31	5.05	0.09	1.68-16.00	1.47	5.33	34
Fe	170.9	105.0	11.13	37.2-1820.0	4.12	21.52	123
Mn	44.55	35.80	1.53	11.2-239.0	2.81	11.50	65
Mo	0.87	0.66	0.04	0.09-7.23	3.45	19.71	87
Zn	37.0	27.4	2.00	10.5-376.0	5.03	30.45	102

In addition, simple correlation between the examined micronutrients were determined (tab. 3). No negative correlations were found. The biggest positive correlation coefficients were found for the concentration values of Cu-Fe and Cu-Mo. A similar relationship, though expressed by a far lower correlation coefficient, could be observed for Cu-Mn, Fe-Mn and Fe-Mo. The content of Zn was correlated only, and to a small degree, with the content of Mn. Kabata-Pendias and Pendias (2001) and Jones, et al. (1991) confirm the existence of the aforementioned relation between elements, but according to them, they have the nature of antagonisms. The positive correlation in our research is perhaps the result of the application by farmers on wheat field the multicomponent foliar fertilizer, which include several micronutrients.

Table 3. Correlation matrix- concentration of micronutrients

Element	B	Cu	Fe	Mn	Mo
Cu	ns				
Fe	ns	0.615***			
Mn	0.109*	0.236***	0.204***		
Mo	0.113*	0.534***	0.315***	ns	
Zn	ns	ns	ns	0.122*	ns

* , ** , *** - significant level for p≤ 0.05, 0.01, 0.001 respectively; ns-not significant

Assessment of micronutrient deficiency at the national level

The assessment of the nutritional status of wheat plantations in Poland with regard to micronutrients was carried out using the critical values developed by Schnug and Haneklaus (2008). The values proposed by Jones, et al. (1991) relate to other stages of development or other organs of plants than used in our research. Jones provided the values for the 2 upper leaves just before the earing or for entire shoots in early earing, when in our research, the shoots were collected in the stage of first node. Critical values proposed by Schnug and Haneklaus (2008) and by Bergmann (1992) concern identical stages and organs as in our research and could be used for the purposes of this work. It seems, however, that Bergman's values, which were developed 20 years ago, are no longer valid, while the values which were recently developed by Schnug and Haneklaus are more accurate. Murphy, et al. (2008) have shown that currently grown cultivars are characterized by a lower mineral content compared to the cultivars grown in the past, which could be related to their lower demand for these components, including micronutrients. Schnug and Haneklaus's values are increasingly being used in research instead of the Bergmann's values (Barlog, 2009; Gaj, 2010).

The comparison of the values developed by Bergmann and by Schnug and Haneklaus showed that they were similar or identical in the case of Mn and Zn, but differed significantly for B, Cu and Mo (tab. 4).

Table 4. Critical values of micronutrients in cereals in the beginning of stem elongation/first node stage (mg kg^{-1})

Element	Bergmann 1992 (winter wheat)	Schnug and Haneklaus 2008 (cereals)
B	6	3
Cu	7	4
Fe	-	60
Mn	35	28
Mo	0.10	0.20
Zn	25	25

Schnug and Haneklaus significantly lowered their criterion for B and Cu deficiency, and increased it for Mo. The need to reduce the critical values for B, and Cu is confirmed by own experiments. Korzeniowska (2008a, b), in her field experiments, found that significant increases in yields as a result of fertilization with copper occurred at Cu content in wheat shoots amounting to 4.0 – 4.4, and boron in the range of 1.9 – 2.4 mg kg^{-1} depending on the cultivar. At higher contents, there was no increase in yields as a result of the application of Cu and B, which suggests that Bergmann's critical values of respectively 7.0 and 5.0 mg kg^{-1} are too high.

The content of micronutrients in the collected 357 wheat samples was evaluated using the critical values of Schnug and Haneklaus (fig. 1).

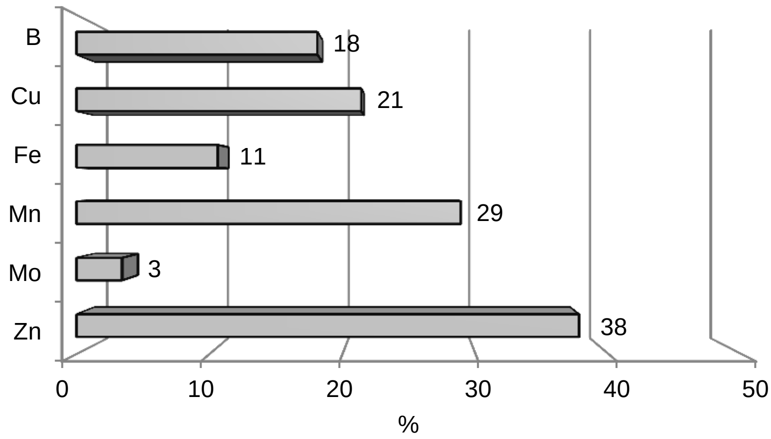

Figure 1. Percentage of samples with micronutrients deficiency in the 357 samples collection according to the critical values of Schnug and Haneklaus (2008).

Rysunek 1. Procent próbek niedoborowych w poszczególne mikroelementy w kolekcji 357 próbek według wartości krytycznych opracowanych przez Schnuga and Haneklaus (2008).

It has been shown that wheat plants were most frequently characterized by low contents of Zn (38% of the samples) and Mn (29%), followed by Cu (21%) and B (18%). Deficiencies of Mo (3%) and Fe (11%) were rarely observed in the collected samples.

These results differ greatly from the evaluation carried out in previous years using the values developed by Bergmann. According to Gembarzewski (2000) and Gembarzewski, et al. (1995), based on 200 fields of winter wheat, the deficiency of B and Cu were the most common in Poland, while Mn and Zn deficiency occurred much less frequently. Such a discrepancy between the current evaluation of the nutritional status of wheat and the evaluation carried out nearly 20 years ago can be related to different nutritional needs of current and older cultivars. Perhaps, current cultivars have lower needs for B and Cu compared to older cultivars.

The difference between the assessment of micronutrient deficiency in the soils of Poland (monitoring in the years of 1987 – 1993 and 1994 – 1999) and their current content in wheat plants shows the need to develop critical values to assess the content of the micronutrients in the soil specifically for wheat, taking into account the currently grown cultivars. This is a very important issue as wheat is the primary arable crop of Poland.

Assessment of deficiencies at province's level

Micronutrient status of wheat in every province was shown as a percentage of deficient samples in all collected samples for a given province (fig. 2). Lubelskie, Lodzkie and Zachodniopomorskie provinces were not included due to an insufficient amount of data (tab. 1). Similarly as in the assessment of deficiency at the national level, critical values of Schnug and Haneklaus were used. Boron deficiency in the plants of wheat were mainly found in Dolnoslaskie (78%) as well as Pomorskie (35%) and Warminsko-mazurskie Province (30% of the samples). In the other 10 provinces, deficiencies did not exceed 25%, and in the six of them deficiencies did not occur at all. It should be noted that 78% of samples with B deficiency were found in Dolnoslaskie Province, which was the largest among all the micronutrients deficits. Copper deficiency in wheat plants were commonly found in the Swietokrzyskie (44% of the samples), while they did not occur in Opolskie and Podlaskie Provinces. Manganese deficiency were most frequently found in Pomorskie (48%) and Wielkopolskie Province (44%), while they were least frequent in Opolskie and Podkarpackie (6% of the samples). Zinc deficiency was frequently found in Dolnoslaskie (67%), Pomorskie (61%) and Swietokrzyskie Province (56% of the samples), while it occurred in sufficient amounts in the southwestern provinces area, such as Slaskie, Opolskie and Dolnoslaskie. Iron deficiency was generally rare. A more frequent occurrence of its deficit was observed only in Swietokrzyskie Province (48% of the samples). Molybdenum deficiency was not found virtually for any of the provinces, with the exception of Dolnoslaskie, where it was reported at 17% of the samples.

Conclusions

To assess the micronutrients status of winter wheat in Poland the critical values developed by Schnug and Haneklaus were used. The comparison of newer Schnug and Haneklaus's values with older Bergmann's values showed that they were similar or identical in the case of Mn and Zn, and significantly different for B, Cu and Mo. Based on the Schnug and Haneklaus limits it was show that wheat grown in Poland in 2010-2011 is characterized by low Zn and Mn contents (38% and 29% of the samples), followed by Cu (21%) and B (18%). Almost no deficiencies of Mo (3%), and only few of Fe (11%) were observed in the collected samples. Significant differences in regional occurrence of deficiencies was also noted. Małopolskie, Pomorskie and Swietokrzyskie provinces experienced most deficiencies, while Opolskie the least.

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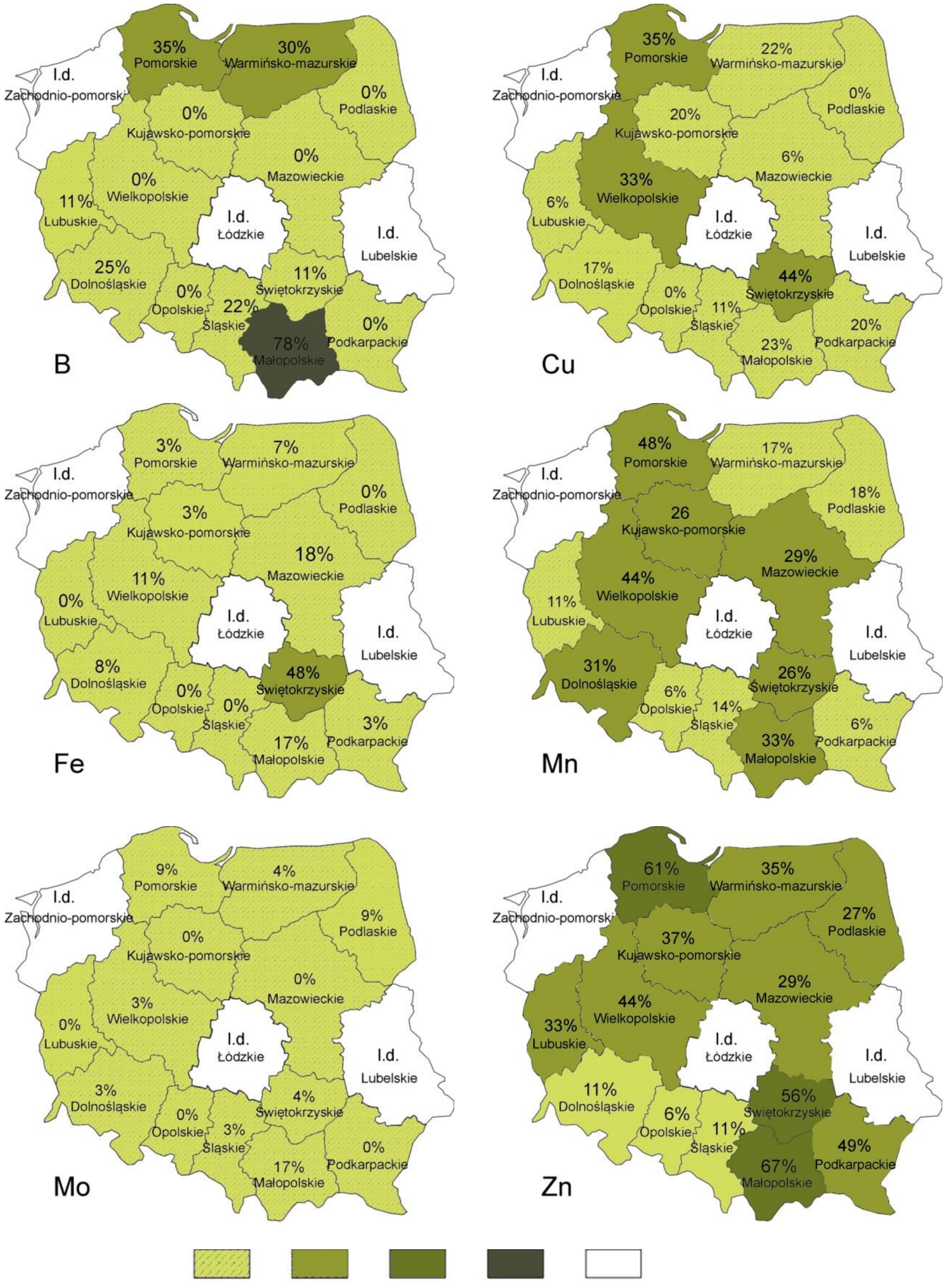

Figure 2. Deficiency of micronutrients in various Polish provinces (in %).

Rysunek 2. Niedobory mikroelementów w poszczególnych województwach Polski (w %).

References

Asad, A., Bell, R.W., Dell, B. (2001) A critical comparison of the external and internal boron requirements for contrasting species in boron-buffered solution culture. Plant and Soil, 233(1), 31-45. DOI: 10.1023/A:1010372430137

Barlog, P. (2009) Studies on nutrition of sugar beet with particular attention paid to sodium. Nawozy i Nawozenie, 35, 1-147 (in Polish).

Bergmann, W. (1992) Nutritional disorders of plants - development, visual and analytical diagnosis. Gustav Fischer Verlag, Jena, Stuttgart, New York

Brennan, R.F., Bolland, M.D.A. (2002) Relative effectiveness of soil - applied zinc for four crop species. Australian Journal of Experimental Agriculture, 42, 985–993. DOI:10.1071/EA01154

Brennan, R.F., Bolland, M.D.A. (2006) Zinc sulfate is more effective at producing wheat shoots than zinc oxide in an alkaline soil but both sources are equally effective in an acid soil. Australian Journal of Experimental Agriculture, 46,1615-1620. DOI:10.1071/EA05071

Brennan, R.F., Bolland, M.D.A., Siddique, K.H.M. (2001) Responses of cool-season grain legumes and wheat to soil-applied zinc. Journal of Plant Nutrition, 24(4/5), 727-741. DOI:10.1081/PLN-100103666

Central Statistical Office. (2011) Statistical Yearbook of the Republic of Poland, Warszawa

Gaj, R. (2010) Influence of different potassium fertilization level on nutritional status of winter wheat and on yield during critical growth stage. Journal of Elementology 15(4), 629-637.

Gembarzewski, H. (2000) Microelement contents and tendencies of their changing in soils and plants from arable fields in Poland. Zeszyty Problemowe Postepow Nauk Rolniczych, 471, 171-179 (in Polish).

Gembarzewski, H., Obojski, J., Straczynsk,i S., Sienkiewicz, U. (1995) The content of macro-and micronutrients in soils and plants of potato and winter wheat in the fields of high productivity. Wydawnictwo IUNG Pulawy, S(80), 1-38 (in Polish).

Grzebisz, W., Lukowiak, R., Biber, M., Przygocka-Cyna, K. (2010) Effect of multi-micronutrient fertilizers applied to foliage on nutritional status of winter oilseed rape and development of yield forming elements. Journal of Elementology, 15(3), 477-491.

Jones, J.B., Wolf, B., Mills, H.A. (1991) Plant Analysis Handbook - Micro-Macro Publishing Inc., Georgia, USA

Kabata-Pendias, A., Pendias, H. (2001) Trace Elements in Soils and Plants. CRC Press, Boca Raton, Fla., USA

Karamanos, R.E., Goh, T.B. (2004) Effect of rate of copper application on yield of hard red spring wheat. Communications in Soil Science and Plant Analysis, 35(13-14), 2037-2047. DOI: 10.1081/LCSS-200026834

Karamanos, R.E., Pomarenski, Q., Goh T.B., Flore, N.A. (2004) The effect of foliar copper application on grain yield and quality of wheat. Canadian Journal of Plant Science, 84 (1), 47-56.

Korzeniowska, J. (2008a) Response of ten winter wheat cultivars to boron foliar application in a temperate climate (South West Poland). Agronomy Research, 6(2), 471-476.

Korzeniowska, J. (2008b) Zinc, copper and boron requirements of wheat in the soil and climate conditions in Poland. Monografie i Rozprawy Naukowe, Wydawnictwo IUNG-PIB Puławy, 20, 1-92 (in Polish).

Kucharzewski, A., Debowski, M. (2000) Reaction and content of micronutrients in Polish soils. Zeszyty Problemowe Postepow Nauk Rolniczych, 471, 627-635 (in Polish).

Murphy, K.M., Reeves, P.G., Jones, S.S. (2008) Relationship between yield and mineral nutrient concentrations in historical and modern spring wheat cultivars. Euphytica, 163, 381-390. DOI:10.1007/s10681-008-9681-x

Obojski, J., Straczynski, S. (1995) Acidity and the content of macro- and micronutrients in Polish soils. Wydawnictwo IUNG Pulawy (in Polish).

Rafique, E., Rashid, A., Ryan, J., Bhatti, A.U. (2006) Zinc deficiency in rainfed wheat in Pakistan: magnitude, spatial variability, management, and plant analysis diagnostic norms. Communications in Soil Science and Plant Analysis, 37(1-2), 181-197. DOI:10.1080/00103620500403176

Schnug, E., Haneklaus, S. (2008) Evaluation of the relative significance of sulfur and other essential mineral elements in oilseed rape, cereals, and sugar beet production. In: J., Jez, ed. (2008) Sulfur: A missing link between soils, crops, and nutrition. CSSA-ASA-SSSA Publishing, Madison, WI, pp. 219-233