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SULPHUR BALANCE IN POLAND – REGIONAL ANALYSIS

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Abstract. Sulphur (S) is one of the main and most essential nutrients for crops. Strict administrative regulations regarding reduction of gas emissions into the atmosphere, introduced by the end of the 20 th century, caused deficiency in sulphur supply for crops. Due to that, there is a need to determine the current status of sulfur demand for cultivated plants as well as the latest content levels of that component. The total requirement of sulphur for crops has been established based on the nutrient's accumulation level in the yield. The regional analysis for the sulphur demand in Poland was carried out between 2013 and 2015 for eight groups of plants: winter cereals (WCS), spring cereals (SCS), oilseed rape (OSR), grain maize (MAI), legumes (GLE), root and tuber crops (RaT), fodder crops (FOD) and vegetables (VEG). Winter cereals and oilseed rape dominated, as far as their sulphur demand was concerned, accumulating approximately $^2/_3$ of their total sulfur requirements. The first group with high stability of the sown area can be treated as the sulfur total requirement indicator for cultivated crops in the entire country. The index for the average sulphur unit accumulation (PP_S) at the level of 20 kg S·ha^{-1} has been adopted as a benchmark to divide Poland into two macro regions, which differ in the sulphur demand level: *Eastern* and *Western*. PP_S index was getting higher along with the increase of sulphur accumulation in oilseed rape and lower as the sulphur accumulation grew in winter cereals. The main natural source channels of sulphur for cultivated crops, in the balance carried out here, were rainfall and manure. An average content of sulphur in the rainfall was 4,8 kg S·ha^{-1}, which varied from 3,5 (Podlaskie voivodeship) to 6,1 kg S·ha^{-1} (Śląskie voivodeship). The average quantity of sulphur supplied by manure was 3,6 kg S·ha^{-1} and varied from 1,1 (Dolnośląskie voivodeship) to 7,0 kg S·ha^{-1} (Podlaskie voivodeship). The average balance value, considering both sources for the given period, was – 11,3 kg S·ha^{-1}. The sulphur balance significantly depended on the type of the tested plants. A decreasing balance value, indicating higher requirements, was recorded for the oilseed rape, whereas for the winter cereals the value increased. The negative balance value for the nutrient along with its negative relation with the winter cereal yield may point at soil as the main sulphur supply source for crops.

Key words: crops, sulphur, voivodeships, accumulation structure, nutrition requirements, sources

INTRODUCTION

Sulphur is one of the key mineral nutrients, significantly influencing the nitrogen balance, yield and the technological quality of crops [Zhao 2008]. As far as the agricultural production is concerned, the sulphur supply level crop plants have a significant influence on the effective use of nitrogen. The deficiency of that component causes a lower plants' nitrogen intake from the soil. That, in turn, increases the residual nitrogen level, which poses a threat to the environment [Hawkesford 2012]. Equally important is the role of sulphur as a nutritional factor, which increases the crops' resistance to pathogens [Jamal et al. 2010, Haneklaus et al. 2007].

No longer than 20 years ago in Poland, the need of fertilizing plants with sulphur was not even being taken into consideration. The main reason for that was the substantial fall down of

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sulphur from the atmosphere, which used to cover the requirements of the most sensitive of plants, such as winter oilseed rape [Podleśna 2013]. The first mention of the deficiency of that particular element in Poland, appeared in the mid-90s of the 20th century and referred to oilseed rape cultivated in the north-west regions of the country [Grzebisz and Fotyma 1996]. The crops' sulphur requirement assessment can be carried out based on the plant and soil tests. However, the obtained results determine only the element content of the particular field or the nutritional state of the crop at a given time [Szulc 2008]. The significant part of the fertilization diagnostics is the nutrient balance carried out using the "soil surface" method, which is normally used for nitrogen or phosphorus [Oenema 2003].

In the classic procedure of the soil surface balance, the quantity of nutrient brought to the field as part of the mineral fertilizers is taken into account. As far as sulphur is concerned, there is no statistical data; therefore, the element balance gives a chance to estimate the quantity of S fertilizer needs for crops [Grzebisz and Cyna 2003]. The most recent assessment of the sulphur balance in Poland was carried out by Podleśna [2013], which showed a substantial deficiency of that component, which consequently results in a harvest, which reaches only 50–60% of the potential yield. This is a highly controversial result, because of the crucial as well as quantifiable deficiencies of other nutrients, such as potassium [Grzebisz et al. 2010]. The realistic assessment of the sulphur balance status in the farm, region or the whole country, should consider the realistic level of the yield of cultivated crops.

The main purpose of this article is to determine the present state of the crops' sulphur requirements as well as the balance value of sulphur, based on the statistics for the period of 2013–2015. The research objective was carried out based on the analysis of the plants yield cultivated on the arable land in Poland, livestock population and the rainfall recordings. The focal point of this paper was to establish the current state of the regional diversification of sulphur balance indexes in Poland.

MATERIALS AND METHODS

The sulphur balance analysis in Polish agriculture was carried out based on the period of 2013–2015. The sulphur balance was calculated based on the following equation:

$$S = I - O$$

The outcome side (O, output) reflects the quantity of sulphur accumulated in the main crop and the supplemental (cover/inter) crop at the time of harvest, taking into account the production specifics for the given group of crops. The income side (I, input) embodies two sources: the quantity of the nutrient carried into the soil from the atmosphere (rainfall) and natural fertilizers.

The basic data regarding the crop area and structure as well as plant yield are obtained from the statistical yearbooks (GUS, 2014–2016). The crop structure analysis takes into account eight plant groups: winter cereals (WCS), spring cereals (SCS), grain maize (MAI), winter oilseed rape (OSR), legumes (GLE), root and tuber plants (RaT), fodder crops (FOD) and vegetables (VEG). The total quantity of the sulphur accumulation in the crop yield was established based on the crop area, yield and the nutrient's accumulation unit value of the crop (S_j) (Table 1):

$$TA_S = CA \cdot S_j$$

where:

TA_S – sulphur total accumulation, t,

CA – crop area for different plant groups, ha · 1000,

S_j – sulphur unit accumulation for a given plant group, $kg \cdot t^{-1}$.

Table 1. Indices of unit sulphur accumulation by selected crops

Crop	$kg\ S \cdot t^{-1}$	Crop	$kg \cdot S\ t^{-1}$
Winter cereals – WCS			
Winter wheat	4.5	Winter triticale	3.5
Winter rye	3.0	Winter barley	3.5
Spring cereals – SCS			
Spring wheat	4.5	Cereals mixture	3.5
Spring barley	4.0	Other cereals	3.0
Oats	3.5	Buckwheat	5.0
Winter oilseed rape – OSR		Maize – MAI	
Winter oilseed rape	20.0	Grain maize	4.0
Legumes – GLE			
Seed legumes	7.0		
Root and tuber crops – RaT			
Sugar beets	0.8	Potatoes	0.5
Fodder crops – FOD			
Clover - fodder	0.8	Alfalfa - fodder	0.8
Fodder maize	0.25	Fodder grasses	0.4
Fodder legumes	0.7	Other legumes – fodder	0.6
Others fodder	0.6	Root crops	0.5
Vegetables – VEG			
Table legumes	7.0	Cabbage	4.0
Califlower	1.5	Onion	2.0
Carrot	0.5	Beetroots	0.5
Tomato	0.5	Cucumber	0.25
Other vegetables	0.25		

Index, determining the quantity of the sulfur average requirement for cultivated crops (PP_S) has been calculated with following equation:

$$PP_S = \Sigma TA_S(WCS + SCS + MAI + OSR + GLE + RaT + FOD + VEG) / \Sigma CA(WCS + SCS + MAI + OSR + GLE + RaT + FOD + VEG)$$

where:

PP_S – the average nutritional requirements of crop plants in relation to sulphur, $kg\ S \cdot ha^{-1}$,

ΣTA_S – total sulphur quantity accumulated in the biomass of the cultivated crop, t

ΣCA – total crop area, ha · 1000.

Data regarding the sulphur content in the rainfall has been obtained from the regional study carried out by the Inspection of Environmental Protection ("Rainfall Chemistry Recordings" for 2013–2015). The sulphur income quantity from the natural fertilizers has been calculated based on the livestock population, shown in livestock units (LU) (GUSb, 2014–2016), crop area (CA), unit production of manure per LU, manure sulphur content.

Analytical procedure [Grzebisz, 2015]:

$$PMa = LU \cdot 12{,}5$$
$$S_{Ma} = PMa \cdot 0{,}72$$

where:

PMa – production of manure, t·ha^{-1},

LU – livestock units, ha^{-1},

12,5 – unit production of manure per LU, t·year^{-1},

S_{Ma} – sulphur content in manure, kg·ha^{-1},

0,72 – sulphur unit content in manure, kg·t^{-1}.

The obtained analytical material was statistically examined, adopting voivodeship as a factor and years as repetitions. The research results underwent the single factor ANOVA variance analysis, using the Tukey's test at the materiality level p=0,05, carried out using the STATISTICA 12 programme (StatSoft Polska, Kraków). Correlation dependencies between the analysed features were appointed using the simple linear regression and the stepwise regression.

RESULTS AND DISCUSSION

Structure of sulphur accumulation by the cultivated crop

Sulphur accumulation structure for the cultivated crops, taking into account both the total as well as the particular crop, indicates an explicit domination of winter cereals and oilseed rape (Fig. 1). During the period of 2013–2015, the first group of plants accumulated over $^1/_3$ and the second over ¼ of the total sulphur content accumulated by all the cultivated crops at the moment of harvest. The groups of plants further down the line have a much lower level of the nutrient's accumulation: spring cereals > grain maize > root and tuber crops ≥ fodder crops > vegetables > grain legumes.

The lowest level of accumulation was registered for the grain legumes, which reached only 1% of the total sulphur accumulation for the given period. The regional diversity structure of the total sulphur accumulation in the agricultural crops stems, first of all, from the size of the voivodeship area and secondly from the crop structure (Table 2). The following algorithm clearly defines the above interrelation:

$$TA_S = 21{,}45CA - 723{,}9 \text{ for } n = 48,\ R^2 = 0{,}81 \text{ i } P \leq 0{,}001$$

where:

TA_S - total sulphur accumulation in the crops biomass, t,

CA - crop area, ha · 1000.

The dominating group in the sulphur accumulation were winter cereals (Fig. 1). The regional diversity for that particular group of plants turned out to be quite substantial. The South-Eastern macro region, which shows the lowest level of the nutrient's accumulation, consists of four voivodeships: Małopolskie, Podkarpackie, Śląskie and Świętokrzyskie. Moreover, a low level of sulphur accumulation was also recorded for Lubuskie and Podlaskie voivodeships. The highest level of the crop sulphur requirement, only slightly lower than the total amount of the smallest group, was recorded for Wielkopolskie voivodeship. The recorded status of the regional diversity comes from the varied total accumulation of the element:

$$TA_{S\text{-}WCS} = 0.34TA_S + 312{,}9 \text{ for } n = 48,\ R^2 = 0{,}96 \text{ i } P \leq 0{,}001$$

where: $TA_{S\text{-}WCS}$ – total sulphur accumulation in the winter cereal biomass, t.

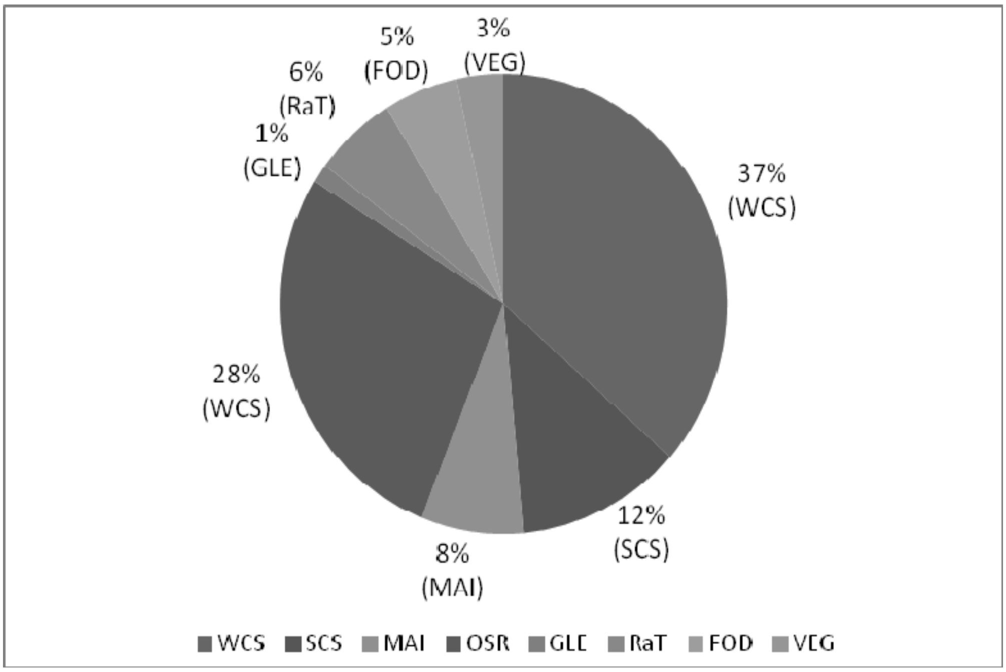

Fig. 1. Structure of sulphur accumulation by the main groups of crops in Poland, years 2013–2015

The obtained interrelation clearly shows a dominant role of the winter cereal in shaping the total sulphur accumulation for a given region. The main factor, which specifies this relationship, is a significant, long-term stability of the winter cereals' participation in the crop structure in different regions within the country. The winter oilseed rape, despite a much smaller crop area and a seriously high-sulphur requirement, constitutes the second dominant crop group in terms of sulphur accumulation (Fig. 1, Table 2).

The regional diversity for the total sulphur accumulation is not smaller than for the winter cereals, however, there are much bigger variations, emphasised by the coefficient of variation value (CV), which is 76% i 56%, for oilseed rape and winter cereals, respectively:

$$TA_{S\text{-}OSR} = 0{,}3TA_S + 287{,}2 \text{ for } n = 48,\ R^2 = 0{,}68 \text{ i } P \leq 0{,}001$$

The reasons for the total sulphur accumulation variation by oilseed rape stems from two factors. The first one is the crop area, significantly determined by the market criteria (seed trading price) [Kapusta 2015]. The second ones are the weather conditions during the autumn-winter vegetation that led, just like in 2012, to a substantial crop yield decline due to a high winterkill of plants. [GUSa 2013, Tys et al. 2003]. The sulphur diversity accumulation by the spring cereal in the researched voivodeships was really high (CV = 80%), however, it is possible to define regions for that group of crops where the element's accumulation diversity is smaller.

The group of a small total sulphur accumulation comprises voivodeship from the South-Eastern macro region as well as, so called *Western Wall* (Dolnośląskie, Lubuskie i Zachodniopomorskie). The highest sulphur requirement within the crop group was recorded for the Lubelskie voivodship. The grain maize is a plant, which, to a large extend, competes with the spring cereals over the stations. The spatial distribution of the total sulphur accumulation by the grain

Table 2. The regional structure of sulphur accumulation by the key groups of crops

Regions	Sowing area ha·1000	Total accumulation	Groups of crops							
			Winter cereals	Spring cereals	Maize	Winter oilseed rape	Legumes	Root and tuber	Fodder	Vegetables
DŚ	730 e	20396 e	7531 de	893 a	2245 e	8082 g	73 ab	1003 d	321 ab	248 ab
KP	847 f	21774 e	6928 c-e	1722 a	2017 e	7223 fg	243 a-c	1891 ef	1087 cd	665 cd
LB	1079 g	21031 e	7727 e	5098 b	942 b-d	3712 cd	257 a-c	1786 e	715 bc	795 de
LS	298 a	6056 ab	2288 a	336 a	473 ab	2365 bc	106 ab	121 a	214 a	154 a
ŁD	710 de	10744 b-d	4686 ab	1892 a	605 a-c	1332 ab	147 a-c	588 a-d	659 a-c	836 de
MP	333 a	5328 ab	1846 a	776 a	607 a-c	491 a	62 a	323 a-c	230 a	994 ef
MZ	1049 g	16204 de	6194 c-e	2719 ab	1211 cd	2310 bc	198 a-c	936 d	1497 e	1139 f
OP	579 c	13960 d	5050 ab	902 a	1344 d	5520 ef	51 a	758 cd	255 ab	80 a
PK	317 a	5326 ab	1997 a	661 a	654 a-c	1133 ab	64 a	478 a-d	186 a	153 a
PD	498 b	7553 a-c	2008 a	2244 ab	521 ab	649 ab	184 a-c	114 a	1746 e	86 a
PM	689 de	12816 cd	5024 ab	1124 a	213 a	4809 de	300 bc	704 b-d	468 ab	174 ab
ŚL	287 a	5055 ab	2068 a	613 a	516 ab	1293 ab	56 a	169 ab	227 a	113 a
ŚW	312 a	4583 a	1899 a	889 a	149 a	523 a	103 ab	311 a-c	274 ab	436 bc
WM	511 b	11934 cd	4584 b	1150 a	299 ab	4146 de	307 bc	225 a-c	1073 cd	150 a
WP	1401 h	30528 f	10846 f	3218 ab	3557 f	7655 g	264 a-c	2397 f	1650 e	940 d-f
ZP	664 de	16178 de	6020 a-c	779 a	201 a	7350 g	353 c	670b cd	632 a-c	172 ab
Mean	644	13092	4793	1564	972	3662	173	780	702	446
SD	325	7574	2674	1247	928	2789	103	686	545	380
CV,%	50	58	56	80	95	76	60	88	78	85

[1] standard deviation; [2]coefficient of variability.
[a]the same letter in the column means the lack of statistical differences

maize showed the highest variety out of the researched crop groups for the given period (CV = 95%). Similarly, just like for the winter cereals, the nutrient's highest requirement was recorded for the maize cultivated in the Wielkopolskie voivodeship, and the lowest in the Pomorskie and Małopolskie voivodeships. For the root and tuber crops, the spatial diversity in sulphur accumulation was very high (CV = 88%). The reason for such a large variety of the researched feature could be explained by the crop analysis structure. The sulphur requirement for the root and tuber crops in the Wielkopolskie voivodeship was 21 times higher compared to the Podlaskie voivodeship. The varied regional sulphur accumulation within the fodder plants was also very high. The Podlaskie voivodeship dominates, whereas the Lubuskie voivodeship is on the opposite far end (7,5% of the Podlaskie voivodeship state). The diversities between the two regions can be explained with the population of the dairy cattle [GUSb 2013–2015, Lipińska and Gajda 2006]. The last but one analysed group were vegetables, where a high accumulation variability was asserted S (CV = 85%). In this crop group, Mazowieckie voivodeship significantly dominates in terms of the requirements of the researched element, which stems from a large crop-land of the Warsaw metropolitan area. Right opposite results were recorded for the Opolskie voivodeship (7% of the Mazowieckie voivodeship). The role of the grain legumes in the regional structure of S accumulation was quite insignificant, less varied, but stable (CV = 60%).

The crop yield analysis as a function of sulphur accumulation in the researched plants' biomass, showed a number of correlations. The main cultivation, which determine the crop yield turned out to be oilseed rape and fodder crops (Fig. 2). In general, crop yield increases along

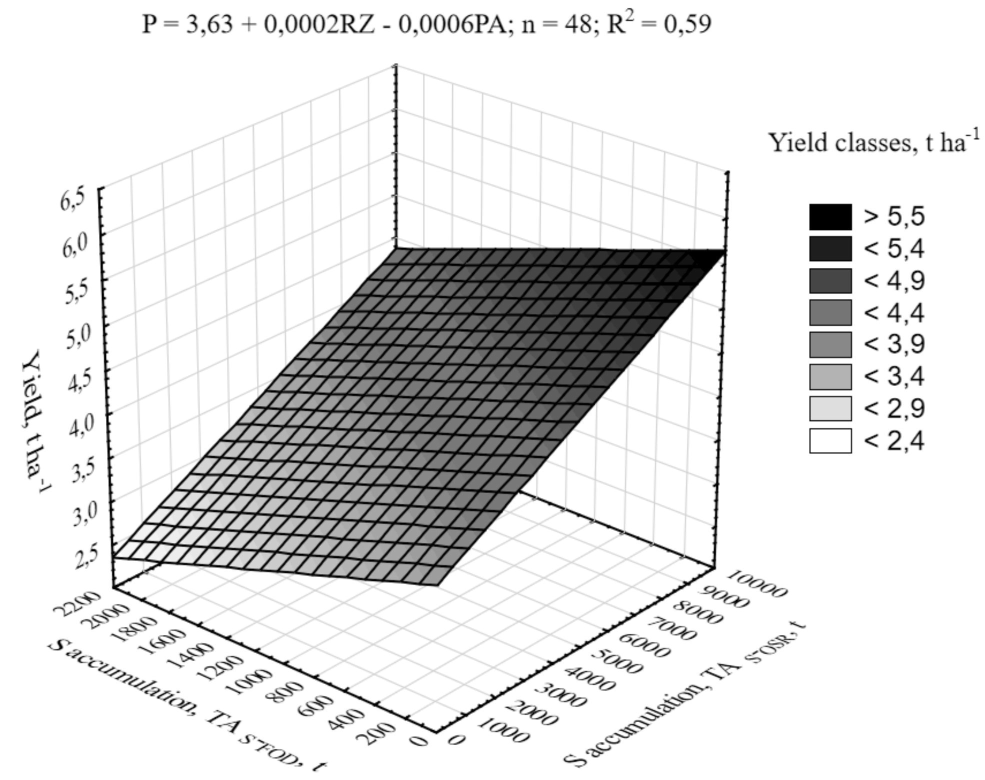

Fig. 2. Yield of cereals as a function of sulfur accumulation by the main groups

with the increased sulphur accumulation in oilseed rape, providing there is a decreased contribution of the fodder plants. The importance of the oilseed rape derives directly from the fact that during the vegetation period, the plant can effectively penetrate deeper soil layers, which leads to a release of many minerals, mainly phosphorus. Those nutrients, in turn, become available to cereals in the following cultivation season. [Łukowiak et al. 2016]. Thanks to that, the oilseed rape cultivation has a stabilizing influence on the future cereal crops.

The index of the average sulphur requirement - PP_S

The basic indicator, which diversifies regions (voivodeships) in terms of their sulphur requirements, is the average unit index for the nutrient requirement (PP_S). The index value for Poland during the period of 2013–2015 was 19,8 kg S·ha^{-1} (Table 3). Based on the calculated average index of nutrient requirements (19,8 kg·ha) and the assumed unit accumulation of sulphur at the level of 4 kg·t^{-1} of grain [Potarzycki et al. 2015], for winter cereals, the size of the

Table 3. Components of sulphur balance in Poland – a regional overview

Region	Output	Input			Balance S1	Balance S2
		Manure	Rainfall	Total		
	kg S·ha^{-1}					
DŚ	27.9 e	1.1 a	5.6 bc	6.7 a-c	-26.8 a	-21.2 a
KP	25.7 de	5.3 g	4.7 a-c	10.0 e-h	-20.4 a-c	-15.7 a-c
LB	19.5 a-d	2.7 c	5.1 a-c	7.8 b-d	-16.9 b-f	-11.8 c-e
LS	20.3 a-d	1.7 bc	4.6 a-c	6.3 ab	-18.6 b-e	-14.0 b-d
ŁD	15.2 a	4.9 fg	4.3 a-c	9.2 d-g	-10.3 fg	-6.0 ef
MP	16.0 a	3.2 de	5.2 a-c	8.5 c-f	-12.8 d-g	-7.5 c-f
MZ	15.5 a	5.0 g	5.3 a-c	10.2 f-h	-10.5 fg	-5.2 ef
OP	24.1 c-e	3.2 de	5.8 c	9.0 d-g	-21.0 a-c	-15.1 a-c
PK	16.8 ab	1.8 c	4.7 a-c	6.6 a-c	-14.9 c-g	-10.2 c-f
PL	15.2 a	7.0 i	3.5 a	10.5 gh	-8.2 g	-4.6 f
PM	18.6 a-d	3.3 e	3.7 ab	7.0 a-c	-15.4 c-g	-11.7 c-e
ŚL	17.6 a-c	3.4 e	6.1 c	9.5 d-g	-14.2 c-g	-8.1 c-f
ŚK	14.7 a	3.5 e	5.1 a-c	8.5 c-f	-11.2 e-g	-6.2 ef
WM	23.4 b-e	4.4 f	3.7 ab	8.1 b-e	-19.0 b-e	-15.3 a-c
WP	21.8 a-e	6.2 h	5.5 a-c	11.7 h	-15.6 ab	-10.1 c-f
ZP	24.4 b-e	1.2 ab	4.4 a-c	5.6 a	-23.1 ab	-18.7 ab
Mean	19.8	3.6	4.8	8.5	-16.2	-11.3
OS[1]	4.3	1.7	0.8	1.7	5.1	5.0
CV[2] (%)	21.7	47.8	15.9	20.3	31.5	44.0

[1]standard deviation; [2]coefficient of variability
[a]the same letter in the column means the lack of statistical differences

achievable yield can be estimated at 4,95 t·ha of grain. The estimated average cereal yield size is larger than the actual yield of the winter cereals, because the calculated average PPs index comprises plants like winter oilseed rape, which has a substantially bigger unit accumulation of sulphur [Grzebisz and Härdter 2006]. The calculated yield, based on the estimated indexes, suggests that crops make an insufficient use of the accumulated sulphur.

The spatial nutrient requirement analysis for crops in Poland, in terms of sulphur, was carried out based on four adopted classes of the PPs index (Fig. 3). The PPs index at the level of

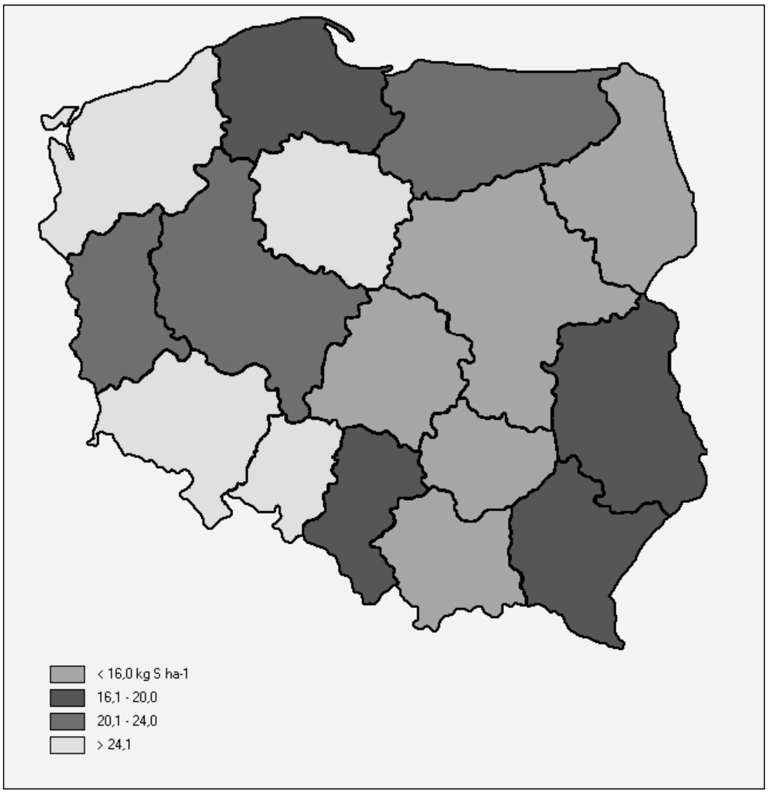

Fig. 3. The regional variability in the average unit S accumulation index, Poland, 2013–2015 years

20 kg·ha^{-1} let differentiate regional discrepancies in terms of the crop nutrient requirements in Poland. The PPs indexes included in classes with values < 20 kg·ha^{-1} S determine the extent of the *Eastern* macro region, which covers the area of the central and eastern parts of Poland. The only exception here is Pomorskie voivodeship, situated in the second macro region, *Western*, with the PPs value over 20 kg S·ha^{-1}. The crop structure and the sulfur accumulation by the dominant crop groups prove (or may prove) the presented regional breakdown of the nutrient requirements in terms of sulphur in Poland [GUS 2014–2016a, Table 1].

The stepwise analysis revealed a significant dependence of the PPs index and the total sulphur accumulation by two plant groups – winter oilseed rape and winter cereals. The analysis concludes Fig. 4 that the bigger share of winter cereals in the cropping area, the greater the decrease of the PPs index value. However, the larger the proportion of the oilseed rape, the higher the PPs index value. The big involvement of oilseed rape in the crop structure, leading to the increase of the index value, significantly increases the total wheat yield, which is usually cultivated in this environment [Kulczycki 2015, Potarzycki et al. 2015].

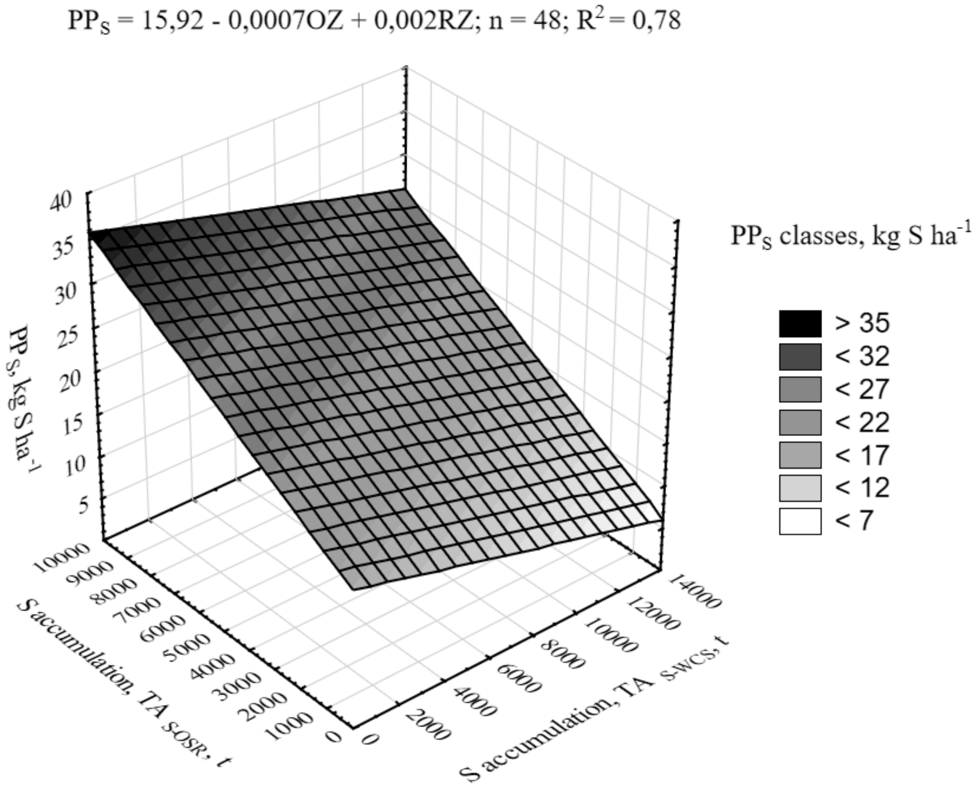

Fig. 4. The unit S accumulation index as a function of sulfur accumulation in the main groups of crops

Sulphur sources and S balance

The main, external source of sulphur for crops is the rainfall. Despite the fact that the importance of this sources is systematically declining, it remains significant for plants, especially for the crop groups, which have low requirements for the element [Grzebisz and Härdter 2006]. The average sulphur income from rainfall to soil in the period of 2013–2015 levelled at approximately 4,8 kg·ha^{-1}, with the regional fluctuations from about 3,5–3,7 kg·ha^{-1} in the north-eastern vivodeships to 6,1 kg·ha^{-1} in Śląskie voivodeship (Table 3). In comparison with the beginning of the 20th century figures, those values are over twice lower [Grzebisz and Cyna 2003]. The scale of the area differentiation of that sulphur source in Poland, as the analysis of Fig. 5 shows, is very small. Most of the country, apart from the earlier mentioned regions, showed an annual growth at the level of 5 kg S·ha^{-1}.

Fig. 5. The regional variability in the sulphur input from precipitation in Poland, 2013–2015 years

The second eligible source of sulphur is manure. The average annual quantity of that nutrient supplied to soil in the given period was about 3,6 kg S·ha^{-1}, demonstrating the average variation of (CV = 48%). The regional diversity is significant enough to differentiate three homogeneous macro regions (Fig. 6). The lowest income of sulphur from that source, below 2 kg S·ha^{-1} was recorded in the macro region called *Western Wall*. The main reason for that is the low livestock density (GUS 2014–2016b). There are six voivodeships in the middle class (2,1–4,0 kg S·ha^{-1}). The compact area in this class comprises of the voivodeships situated in the south-eastern part of Poland. The Central Poland, especially because of the large quantity of pigs or/and milk cattle, the average annual sulphur income from manure levels between 4,1 and 6,0 kg S·ha^{-1}. The largest sulphur income from manure, as a consequence of the intensive cattle production, was recorded in Podlaskie voivodeship. The average values of the sulphur income from manure in the given period as well as their variation scope are comparable with the ones observed at the beginning of the century [Grzebisz and Cyna 2003]. The total income of sulphur from both sources was at the level of 8,5 kg S·ha^{-1} (Table 3). Such quantity of the element has a little potential to cover the nutritional requirements, as its total value reaches the level of 2 t of the quality wheat [Grzebisz and Hardter 2006].

Balance is a straightforward indicator of the variance between income and outcome of the element. The sulphur balance analysis was carried out for the PPs index which represents the outcome (O), which is the average unit value of the sulphur accumulation in the crop mass, as

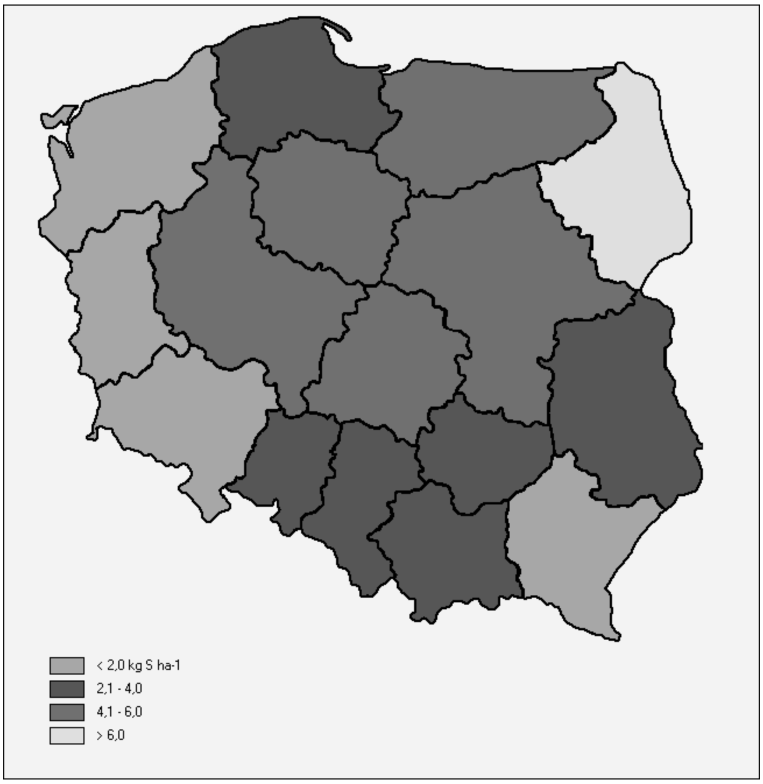

Fig. 6. The regional variability in the sulphur input from manure in Poland, 2013–2015 years

well as the income (I), referred in the first stage of the balance analysis to the direct source, which is manure (balance S1), while in the second, to the total sulphur income from that source and the rainfall (balance S2). The average balance value S1 reached the level of –16,2 kg $S\cdot ha^{-1}$, which indicates the role of manure to cover the fertilization requirements of sulfur at the level of 18% (Tabela 3). The lowest PP_S values, below –20 kg $S\cdot ha^{-1}$ were recorded in most of voivodeships in Western Poland as well as in the Kujawsko-Pomorskie Voivodeship. The highest balance values, however, in other words, higher than –10 kg $S\cdot ha^{-1,}$ were recorded in the Podlaskie voivodeship only. The results of the area diversity of the S2 balance are presented in Fig. 7. The highest negative balance for sulphur was recorded at the *Western Wall*, including the Opolskie voivodeship into that macro region. However, the biggest area in terms of low negative balance (> -8,0 kg $S\cdot ha^{-1}$) spreads from Małopolskie to Podlaskie voivodeships. The balance value for S1 depended, as the stepwise regression showed, on the sulphur accumulation in oilseed rape (OSR) and fodder plants (FOD):

$$S1 = -12{,}82 - 0{,}002OSR + 0{,}004FOD,\ n = 48 \text{ for } R^2 = 0{,}75$$

What comes from the above equation is that the negative sulphur balance increased by the higher contribution of oilseed rape, and decreased by the fodder plants. The balance included the sulphur income from the rainfall, which indicates a slightly different spectrum of the dominant plant group (Fig. 8). The growth in the sulphur accumulation by oilseed rape, analogically,

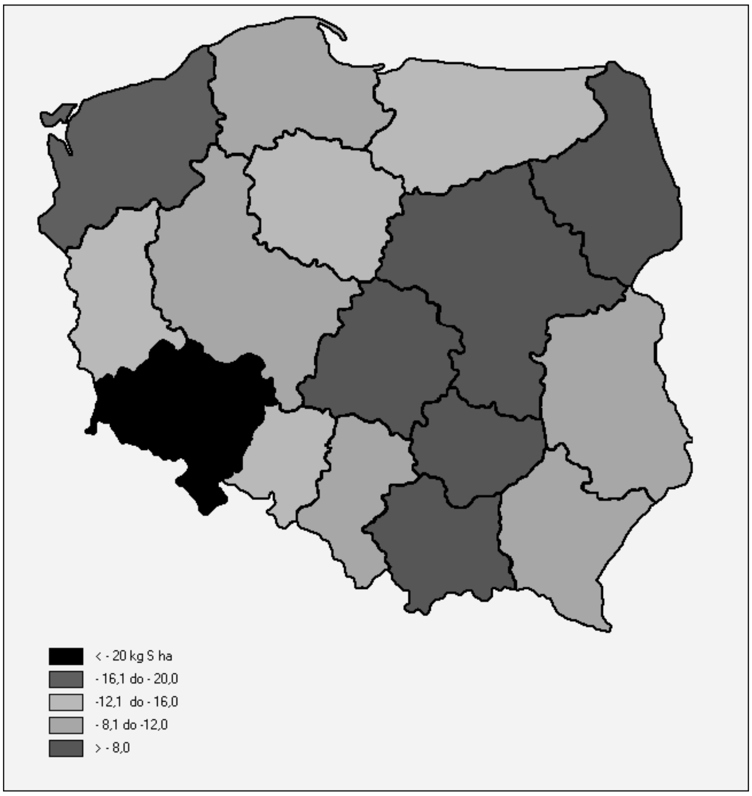

Fig. 7. The regional variability in the sulphur balance in Poland, 2013–2015 years

just like for S1 balance, deepened the negative value of the balance. The bigger proportion of the winter cereals in the crop structure influenced the improvement of the sulphur balance. This may, in turn, help lower the risk of the sulfur deficiency for plants.

The forecast for the influence of the element's deficiency on the crop yield can be estimated by determining their yielding trend. In this analysis, the potential indicator for the element's deficiency is the sulphur balance. The analysis Fig. 9 clearly shows that the winter cereals grew proportionally to the negative values of the sulphur balance. The yielding trend presented by the chart curve plainly shows that the sulphur deficiency is not the basic factor determining the cereal yield in Poland. What follows, even the low level of sulphate sulphur content in the soil, recorded in the monitoring research [Siebielec et al. 2012], satisfies the crop requirements. The obtained yielding trend suggests that the effective use of sulphur accumulated in crops needs to be defined and the production factors that have bigger influence on yield than sulphur, need to be optimized. An example of the fertilization component, which has a great influence on a potential yield is potassium [Grzebisz et al. 2010]. Based on the obtained interrelation, what field vegetation experiments also confirm, [Kulczyki 2015, Potarzycki et al. 2015], it can be assumed that the use of sulphur fertilizers can significantly influence the stability of the cereal crop at a higher level.

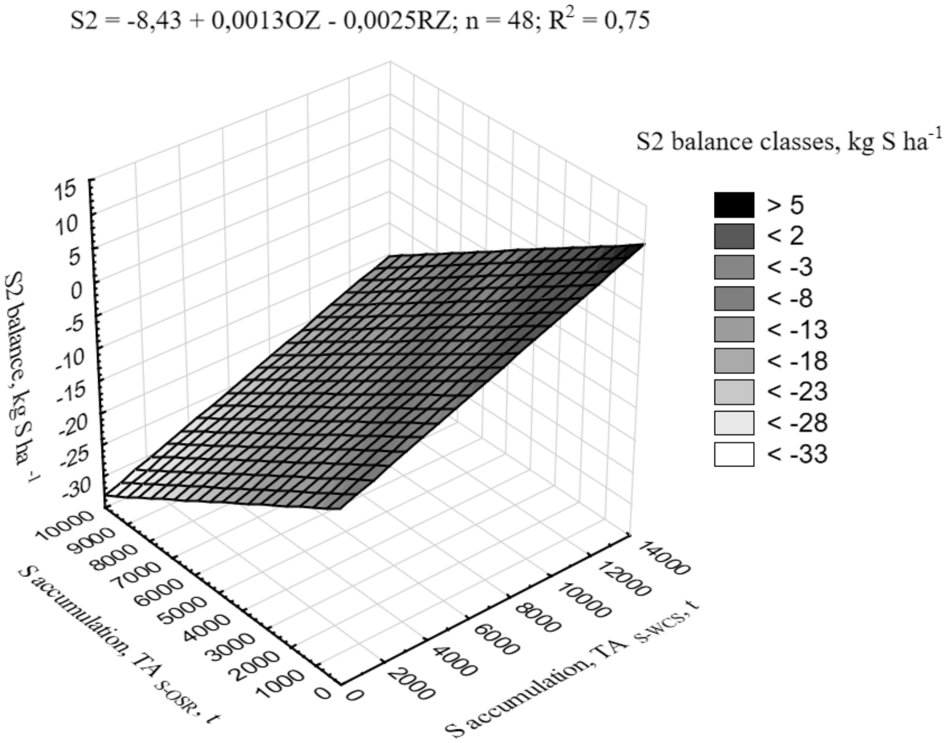

Fig. 8. Sulfur balance as a function of sulphur accumulation by the main groups of crops

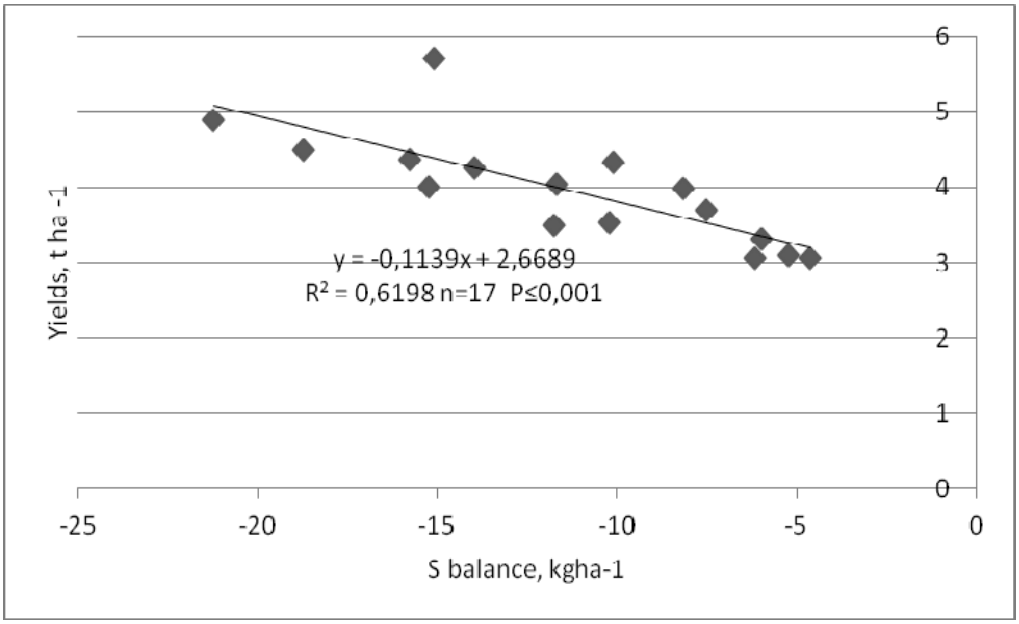

Fig. 9. Yield winter cereals in dependence on the sulphur balance (S2)

CONCLUSIONS

1. The trends of the regional diversity of sulphur balance in Poland were mainly established by the presence of winter cereals and winter oilseed rape in the crop structure in the respective region.
2. The PPs index at the level of 20 kg $S \cdot ha^{-1}$ let divide Poland in terms of crops' sulphur requirements into two macro regions: *Eastern* – with smaller requirements and *Western* with larger requirements for that element.
3. The sulphur income from the rainfall and manure in Poland only slightly levelled the negative balance of sulphur, respectively compensating for the total requirement of that element with 24 and 18%.
4. Sulphur, despite its negative balance, is a secondary factor that determines the yield of winter cereals in Poland.

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SALDO BILANSOWE SIARKI W POLSCE – ANALIZA REGIONALNA

Synopsis. Siarka (S) jest jednym z głównych i niezbędnych składników pokarmowych dla roślin uprawnych. Ponieważ restrykcyjne regulacje administracyjne dotyczące ograniczenia emisji gazów do atmosfery wprowadzone pod koniec XX wieku, wywołały niedobory w zaopatrzeniu roślin w siarkę, wystąpiła potrzeba określenia aktualnego stanu zapotrzebowania roślin uprawnych w siarkę oraz wartości salda bilansowego dla tego składnika. Zapotrzebowanie całkowite roślin uprawnych na siarkę określono na podstawie akumulacji składnika w ich plonie. Analizę regionalną zapotrzebowania roślin na siarkę w Polsce przeprowadzono w okresie 2013–2015 dla ośmiu grup roślin: zboża ozime (ZO), zboża jare (ZJ), rzepak (RZ), kukurydza na ziarno (KU), strączkowe na ziarno (ST), okopowe (OK), pastewne (PA) i warzywa (WA). Zboża ozime i rzepak dominowały w strukturze potrzeb względem siarki, akumulując około $^2/_3$ całkowitego zapotrzebowania tego składnika. Pierwsza grupa o dużej stabilności powierzchni zasiewów może być traktowana jako wskaźnik zapotrzebowania całkowitego przez rośliny uprawne na siarkę w kraju. Wskaźnik średniej jednostkowej akumulacji siarki (PP_S) na poziomie 20 kg $S \cdot ha^{-1}$ przyjęto jako kryterium podziału Polski na dwa makroregiony, różniące się poziomem zapotrzebowania na ten pierwiastek: Wschodni i Zachodni. Wskaźnik PP_S wzrastał wraz ze wzrostem akumulacji siarki w rzepaku a malał ze wzrostem akumulacji siarki w zbożach ozimych. Głównymi źródłami przychodu siarki dla roślin uprawnych, w wykonanym bilansie, były opady atmosferyczne i obornik. Średnia zawartość siarki w opadach atmosferycznych wynosiła 4,8 kg $S \cdot ha^{-1}$, wahając się od 3,5 (woj. podlaskie) po 6,1 kg $S \cdot ha^{-1}$ (woj. śląskie). Średnia ilość siarki dostarczana w oborniku wynosiła 3,6 kg $S \cdot ha^{-1}$, wahając się od 1,1 (woj. dolnośląskie) po 7,0 kg $S \cdot ha^{-1}$ (woj. podlaskie). Średnia wartość salda bilansowego, uwzględniając oba źródła, wyniosła w tym okresie -11,3 kg $S \cdot ha^{-1}$. Saldo bilansowe siarki istotnie zależało od udziału w nim badanych gatunków roślin, dla rzepaku odnotowano obniżanie się wartości salda, natomiast w przypadku zbóż ozimych stwierdzono jego wzrost. Ujemna wartość salda bilansowego dla tego składnika przy jednoczesnym ujemnym jego związku z plonem zbóż ozimych może wskazywać na glebę, jako główne źródło zaopatrzenia roślin uprawnych w ten składnik.

Słowa kluczowe: rośliny uprawne, siarka, województwa, struktura akumulacji, potrzeby pokarmowe, źródła

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