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Comparison of the phosphorus balance results based on '*field surface*' and '*farm gate*' methodology in large-scale farms

Jerzy Mirosław Kupiec

Poznań University of Life Sciences, Department of Ecology and Environmental Protection
Piątkowska 94 C, 60-649 Poznań, Poland

Abstract. The aim of the study was the comparative analysis of the results of the phosphorus balance calculated by two methods, in the field scale and the farm scale, and assessment of usefulness of the application of balances in monitoring the agricultural production. Twenty-six large-scale farms were selected for studies with the area from 204.0 to 11391.5 ha. The analyses used data from the years 2002-2006. The spatial scope included the farms located in 33 municipalities, which administratively belonged to three provinces. Twenty six municipalities were located in 7 areas, particularly nitrate vulnerable zones (NVZ's). The evaluation of phosphorous load of the selected farms in different regions was performed based on the calculation of the balance with two methods – *field surface* and *farm gate*. As research has shown although the balance of the phosphorus calculated with *the field surface* method was on average higher by 7.2 kg P_2O_5 ha^{-1} AL, the results obtained based on two different methodical approaches indicate similar trends. The higher balance was mainly affected by manures produced in the own farm. Maximal values of the balance in both methods remained at a similar level, reaching approx. 60 kg P_2O_5 ha^{-1} AL. In the case of *the field surface balance*, 7 farms fitted in the standard, and in the case of *the farm gate balance* 5 met recommendations concerning the acceptable balance for the analysed region.

keywords: phosphorus, agricultural pollution, *field surface balance*, *farm gate balance*, large scale farms

INTRODUCTION

The discussion about the size of the phosphorus emission to the environment from agricultural sources has lasted for many years. As some authors say, in Poland the views are that the level of fertilisation with this nutrient is low (The state…, 2007). Based on these views one can get the impression that agriculture does not have a negative impact on the water quality. Meanwhile, agriculture uses 90% of phosphorus obtained from minerals. They are used mostly for producing mineral fertilisers. However, already small surplus of this nutrient causes its accumulation in the soil, as an added value to the sustainable supply of this nutrient, not entirely defined in Poland (Sapek, 2008). However, the capacity of the soil to retain phosphorus is limited and when the saturation with the nutrient is exceeded, the process of its release into the environment takes place, which can cause the uncontrolled process of eutrophication (Sibbesen and Sharpley, 1997). Another problem is the monitoring of pollution from agricultural sources, which in terms of nutrient dispersing in the environment is often inefficient and unreliable. The main problem is variety of balance methods, which are used to control agricultural production and give incomparable results (Fotyma et al., 2000; Kupiec, 2010; Kupiec and Zbierska, 2012). Using the models for the assessment of size and characteristics of pollution sources cannot be entirely correct and can generate significant mistakes (Ilnicki, 2014). The large problem also involves the belittling possibilities of ways the phosphorus gets to the environment other than fertilising. Poorly stored and kept manures and their inappropriate use is very often a standard in the Polish farms.

The aim of the study was the comparative analysis of the results of the phosphorus balance calculated with methods in the field scale and in the farm scale and the assessment of usefulness of the application of balances in the agricultural production monitoring.

MATERIALS AND METHODS

Twenty six large scale farms were selected for studies. The analyses used data from the years 2002–2006. The spatial scope included the farms located in 33 municipalities, which administratively belonged to three regions

Corresponding author:
Jerzy Mirosław Kupiec
e-mail: jkupiec@up.poznan.pl
phone +48 61 8466524

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Fig. 1. Localization of analysed large area farms.

(Fig. 1). 26 municipalities partially or entirely were located in 7 special areas – nitrate vulnerable zones (NVZ's). The average size of the farm was 1680.3 ha, with the diverse surface from 209.0 to 11391.5 ha. Selected elements of the farm characteristics are shown in Table 1.

The assessment of the phosphorus load of the selected farms was performed based on the balance calculation with two methods:

field surface balance (Isermann, 1991; Oenema, 1999; Rozporządzenie..., 2002):

$$P_{\text{field surface balance}} = \Sigma P_{DEP} + \Sigma P_{MF} + \Sigma P_{M} + \Sigma P_{SM} + \Sigma P_{CCp} - \Sigma P_{MC} - \Sigma P_{CCh}$$

where:

DEP – deposition, MF – mineral fertilizers, M – manures,
SM – sowing material, CCp – by-product and catch crops plowed,
MC – main crops,
CCh – by-product and catch crops harvested from the field

farm gate balance (Barszczewski, 2004; Kaczyńska et al., 2004) – the method takes into account elements only to a large extent dependent on the farmer, meaning those, which were brought in or out from the farm by the farmer:

$$P_{\text{farm gate balance}} = \Sigma P_{MF} + \Sigma P_{PM} + \Sigma P_{PA} + \Sigma P_{CF} + \Sigma P_{SM} - \Sigma P_{C} - \Sigma P_{F} - \Sigma P_{AP} - \Sigma P_{A} - \Sigma P_{AD}$$

where:

MF – mineral fertilisers, PM – purchased manures,
PA – purchased animals for breeding, CF – concentrates and feeds,
SM – purchased sowing material, C – sold commodity crop,
F – sold feed plants, AP – sold animal products,
A – sold animals, AD – animal death

Both these methods are known and used in many countries around the world under the same name but in different modifications. Calculations of particular elements of both balances were performed according to Kupiec and Zbierska (2010) and Kupiec (2010). Utilisation of nutrient was calculated using the formula:

$$U = \frac{\text{output}}{\text{input}} \cdot 100$$

RESULTS AND DISCUSSION

Characteristics of farms

The arable lands accounted for 86.5% of total farmland. The area occupied by the grassland, was on average 12%. Crops pattern was dominated by grain (Table 2). They occupied 52.3% area of agricultural land. Among the cereals the largest surface was occupied by the winter wheat. Cereal yields were higher than provided for the country by the GUS (Rocznik..., 2005). In addition to cereals, a considerable area of fields was sown to industrial plants – mostly rapeseed, and fodder.

Among the special branches occurring in the farms we should distinguish the horticultural production, aimed mainly at fruit-growing and cultivation of vegetables (farms no.: 1, 2, 7, 16, 20). A small acreage (1 ha) of the farm no. 18 was devoted to the cultivation of willow. Moreover, farm no. 2 in the area of 0.21 ha conducted cultivation of plants under covers, mostly cucumbers and tomatoes under glass and foil. Farm no. 1 has a significant area of orchards and berries – 405 ha. Apart from farm no. 1 the orchard was also run by farms no. 7, 8, 18, 20.

The level of mineral fertilisation in the farms was very high (Table 1). The NPK input was, on average, 204 kg per 1 ha AL, ranging from 0 to 317 kg ha^{-1} AL, which is considerably more than the country's and the region's averages. Farm no. 24 did not buy any mineral fertilisers in the studied period. Deficiencies of nutrients were supplemented only by the purchased manures and those produced in the farm. Nitrogen accounted for 54%, phosphorus (P_2O_5) for 15% and potassium (K_2O) for 31% of the applied fertilizers. In the analysed period the average use of the phosphorus in the group of the studied farms was 29.8 kg P_2O_5 ha^{-1}. The high level of fertilisation of phosphorus (over 50 kg P_2O_5 ha^{-1} AL) was recorded in farms no. 4, 8, and 21. In the period, 26 farms did not purchase any mineral fertilizers.

The possession of livestock was a characteristic feature of all selected large scale farms in the study, giving a steady income from the sale of livestock or livestock products. The amount of livestock units (LSU) in farms ranged from 0.25 to 1.23 LSU ha^{-1} AL (on average 0.64, Table 1). Rearing of the cattle was conducted in each farm, and its share in the inventory structure was on average as much as 81.4%. The cattle load of 1 ha AL was on average 0.52 LSU (0.1–1.0 LSU ha^{-1} AL). Rearing of the cattle

Table 1. Selected elements of the large-scale farms.

Farm No.	Area of AL [ha]	Specialisation		Other animals	$LSU \cdot ha^{-1}$ AL	Mineral fertilisers	
		plant production on arable land	animal production			NPK summary [$kg \cdot ha^{-1}$ AL]	ratio# $N:P_2O_5:K_2O$
1	2254.0	cereals	dairy cattle	-	0.29	208.1	1:0.25:0.60
2	343.7	cereals	dairy cattle/pigs	-	0.25	184.9	1:0.27:0.58
3	1713.0	cereals	dairy cattle	horses	0.47	232.6	1:0.31:0.63
4	350.0	cereals	dairy cattle	horses	0.70	288.3	1:0.52:0.83
5	589.0	cereals	dairy cattle	horses	0.64	146.7	1:0.17:0.42
6	1447.5	cereals/feed plants	dairy cattle	horses	0.53	133.1	1:0.52:0.79
7	3395.5	cereals	dairy cattle/pigs	-	0.71	192.3	1:0.28:0.65
8	887.9	cereals	dairy cattle	pigs, poultry	0.37	244.5	1:0.36:0.59
9	381.5	cereals	dairy cattle	-	0.40	111.1	1:0.13:1.07
10	1168.5	cereals	dairy cattle	-	0.34	158.4	1:0.20:0.41
11	1891.0	cereals	pigs/dairy cattle	horses, sheep	1.23	276.5	1:0.45:0.93
12	316.0	cereals	dairy cattle	-	0.76	237.0	1:0.07:0.58
13	2042.0	cereals	dairy cattle	-	0.53	179.0	1:0.14:0.54
14	528.1	cereals	dairy cattle	pigs, sheep	0.62	150.8	1:0.36:0.44
15	364.5	cereals	dairy cattle	pigs, sheep	0.77	194.2	1:0.18:0.40
16	988.0	cereals	dairy cattle	pigs	0.47	153.2	1:0.19:0.33
17	2806.9	cereals	dairy cattle	pigs, horses, sheep	0.76	272.1	1:0.24:1.00
18	10887.0	cereals	dairy cattle	horses	0.29	246.2	1:0.22:0.58
19	614.0	cereals	dairy cattle	-	0.42	282.0	1:0.31:0.66
20	3150.8	cereals	dairy cattle/pigs	horses, sheep	0.94	303.6	1:0.29:0.79
21	373.2	cereals	dairy cattle	pigs	0.79	317.0	1:0.27:0.73
22	292.5	cereals	dairy cattle/pigs	-	0.95	162.0	1:0.41:0.41
23	3535.4	cereals/feed plants	dairy cattle	-	1.00	257.1	1:0.27:0.66
24	233.0	cereals	dairy cattle	pigs	1.08	0.0	0
25	975.9	feed plants	dairy cattle	-	0.52	233.1	1:0.17:0.39
26	195.0	cereals/feed plants	dairy cattle	-	0.81	140.8	1:0.34:0.44

nitrogen as 1

Table 2. Structure of sown area in analysed large area farms.

Crop pattern [%]					
cereals	root plants	papilionaceous plants	industrial plants	feed plants	others
52.3	9.5	5.9	16.6	15.5	0.2

in most cases was oriented to the production of milk. Fattening of animals and sale of the beef livestock resulted from the possession of calves from in-house livestock, or removing culled pieces from the herd, and was rather an additional activity. The pigs in the inventory structure was 15.9%. In farm no. 11 the production of the pork was dominant, and in farms no. 2, 7, 20, 22, next to the cattle, it constituted the second important direction of animal production, and represented a similar level of intensity. The pig stocking rate calculated from the average annual figures in the farms conducting the breeding of pigs was quite low and ranged from 0 to 0.73 LSU per 1 ha AL (on average 0.1 LSU ha^{-1} AL).

Besides cattle and swine, the large scale farms also reared sheep and horses. Flocks of sheep were held in 19.2%, and horses in 30.8% of farms. The size of sheep herd in farms having this group of animals was on average annually from 3.6 (farm no. 15) to 167.3 LSU (farm no. 17), while horses from 1.3 (farm no. 6) to 117.2 LSU (farm no. 5). Farm no. 5 run the breeding of thoroughbred saddle horses and only in this farm the breeding of horses was on a very high level. In other farms the horse herds were of no importance in the general livestock turnover. Considering all studied large scale farms, one farm averaged 6.6 LSU of these animals.

In addition to the above-mentioned animals one of the farms (no. 8) run the breeding of poultry. The average amount of poultry per year, per 1 ha in this farm, was

0.1 LSU. Over the years, the animal production was maintained at a constant level, and changes in the inventory occurred in a very short range.

The animal production in the analysed farms was strongly associated with the crop production. Animal husbandry to a large scale modified the structure of crops, in which the large scale farmers had to consider the type and the area of fodder sown. The scale of production affected the economy of fertilisers, as well as the amount of purchased feed and fertilisers. Keeping livestock in agricultural farms entails the formation of large amounts of excrements, which in the form of manure can be a valuable complement of mineral nutrients in the soil. The amount of the produced solid manure per 1 ha of agricultural land (AL) averaged 6.7 t ha^{-1} per farm, and that of liquid manure 3.2 t ha^{-1}.

Because natural fertilisers, apart from nutrients, enrich the soil with organic matter, the total amount of natural fertilizers produced by large farms was used to raise their own crops. Some farms bought manure, limiting or completely reducing the purchase of mineral fertilisers (farm no. 24).

Analysis of the phosphorus balance

The average value of the phosphorus balance obtained based on *the field surface balance* stood at the level of 15.3 kg P_2O_5 ha^{-1} AL, with fluctuations from -13.4 to 59.6 kg P_2O_5 ha^{-1} AL (Table 3). The highest percentage of the results (53.8%) ranged from 0–30 kg P_2O_5 ha^{-1} AL. 23.1% of the results was in the range of 30–60 kg P_2O_5 ha^{-1} AL and the same number of farms showed the negative balance. The amount of phosphorus added to the soil with mineral fertilisers were much lower than nitrogen or potassium, which could affect the nutrient balance. According to the Code of Good Agricultural Practice (Kodeks…, 2004) the phosphorus balance can be balanced in soils with the average content of available forms of this nutrient. In soils with a low and very low content of phosphorus it is recommended to use approx. 50% larger doses of fertilisers in relation to their uptake by crops, and in soils with high and very high content, doses of fertilisers should be reduced by 50% in relation to the uptake. The share of soils with a low and very low content of phosphorus in the studied NVZ's (apart from the catchment of the River Orla) was small, therefore, it can be assumed that the balance of the nutrient should be close to zero.

The utilisation of phosphorus in 6 farms was greater than 100%. This can indicate the insufficient complementation of the macronutrient in soils of these farms and the plants using a certain pool of soil reserves. The average utilisation of phosphorus by the plants was high and stood at the level of 75.8%, with fluctuations from 42.1 to 130.3% (Table 3). Analysing individual elements of the input and output it can be noticed that the largest amounts of phosphorus were brought with mineral fertilisers and manures, and removed with the main crop.

The balance calculated with *the farm gate* method showed more favourable results than *the field surface* (Table 4, Fig.

Table 3. The balance of phosphorus in surveyed large-scale farms by *the field surface* method.

Specification	Value				
	min.	max.	average	standard deviation	[%]
Input [kg P_2O_5 ha^{-1} AL]					
Deposition from atmosphere	0.2	0.9	0.3	0.2	0.4
Mineral fertilisers	0.0	65.2	29.8	15.9	47.1
Manures	5.5	40.2	19.3	8.5	30.5
Sowing material	0.4	1.8	0.8	0.3	1.3
By-product and catch crops plowed	7.8	14.3	13.1	4.0	20.7
Summary input	31.1	102.8	63.2	19.1	100
Output [kg P_2O_5 ha^{-1} AL]					
Main crops	20.1	65.0	41.6	8.7	86.8
By-product and catch crops harvested from the field	2.1	11.4	6.3	2.0	13.2
Summary output	25.7	74.3	47.9	9.8	100
Balance	-13.4	59.6	15.3	19.1	-
Utilisation of nutrient [%]	42.1	130.3	75.8	24.7	-

Table 4. The balance of phosphorus in analysed large-scale farms by *the farm gate* method.

Specification	Value				
	min.	max.	average	standard deviation	[%]
Input [kg P_2O_5 ha^{-1} AL]					
Mineral fertilisers	0.0	65.2	29.5	16.0	77.1
Purchased manures	0.0	18.0	1.1	3.9	2.8
Purchased animals for breeding	0.0	0.02	0.0	0.0	0.0
Concentrates and feeds	0.0	62.5	7.5	13.6	19.6
Purchased sowing material	0.0	1.3	0.2	0.3	0.5
Summary input	5.8	85.7	38.3	20.7	100.0
Output [kg $P_2O_5 \cdot ha^{-1}$ AL]					
Sold commodity crop	0.0	30.5	17.8	7.5	58.9
Sold feed plants	0.0	0.1	0.0	0.0	0.02
Sold animal products	0.0	34.0	8.8	6.3	29.1
Sold animals	0.1	19.2	3.3	4.4	11.0
Animal death	0.0	1.8	0.3	0.3	1.0
Summary output	12.5	60.6	30.2	9.4	100.0
Balance	-36.5	59.5	8.1	22.0	-
Utilisation of nutrient [%]	29.2	396.9	110.1	87.0	-

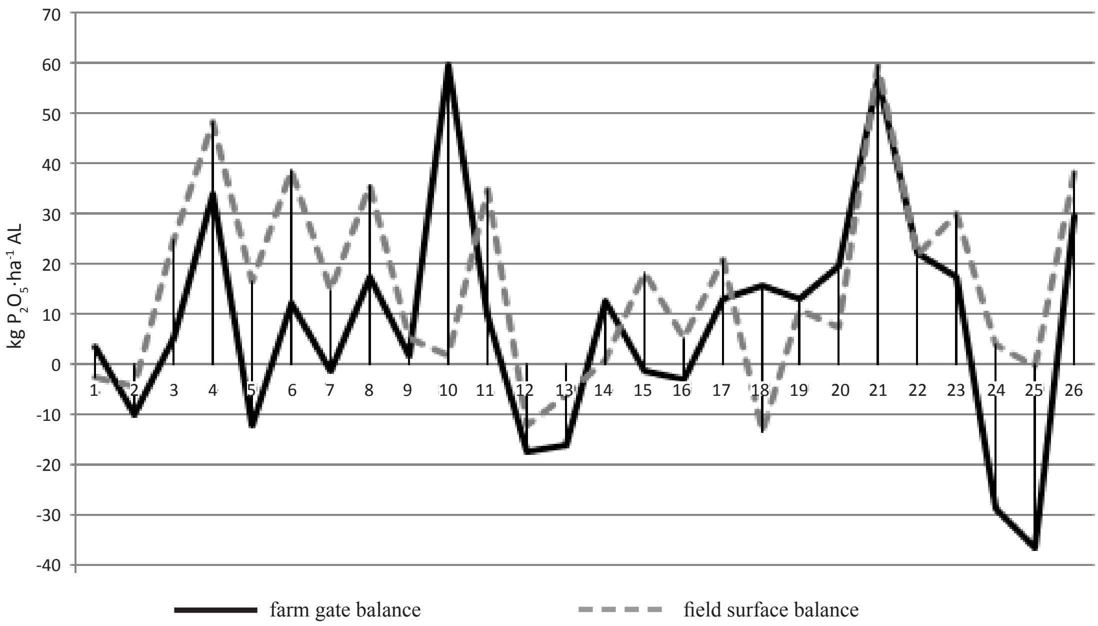

Fig. 2. Formation of the phosphorus balance calculated by two methods.

2). The phosphorus balance in the group of studied farms was close to balanced (8.1 kg P_2O_5 ha^{-1} AL), which confirms similar dependencies in *the field surface balance*. Considering the results it can be noticed that the significant share involved farms where balances were negative (34.6%). In more than half of the farms (53.8%) the results were within the range of 0–30 kg P_2O_5 ha^{-1} AL. Only in 3 farms the balance was greater than 30 but smaller than 60 kg P_2O_5 ha^{-1} AL. The utilisation of phosphorus was from 29.2 to 396.9%, averaging 110.1% (Table 4). The main source of phosphorus input came from mineral fertilisers and purchased concentrates and feeds. Phosphorus in large quantities was removed from farms as sold crops and animal products (mainly milk).

According to Toczyński et al. (2013) the acceptable balance of phosphorus for the Wielkopolska region ranges in the scope -3.5–1.5 kg P·ha^{-1} (-8.0–3.4 P_2O_5), for Dolny Śląsk region -1.1–3.9 kg P·ha^{-1} (-2.5–8.9 P_2O_5) and for Lubuskie -2.1–2.9 kg P·ha^{-1} (-4.8–6.6 P_2O_5). Based on *the field surface balance*, 7 farms fell within this norm, and in the case of *the farm gate balance* – 5 met the requirement. In summary, it can be stated that the balance results obtained with *the farm gate* method presented similar tendencies as those produced by *the field surface* analysis.

Comparing the obtained balances in individual farms it can be observed that the calculated balance using *the farm gate* method most often showed lower values than *the field surface balance* (Fig. 2). In four farms quite a large discrepancy of results was observed. In farms no. 10 and 18 results of *the farm gate balance* were much higher than calculated with *the field surface* method. The differences in balances were mainly influenced by the animal production. These two farms bought considerable amounts of industrial fodder (concentrates), reaching 63 kg P_2O_5 ha^{-1}. The sold animal products, livestock and animal death were in total at the level slightly exceeding 5 kg P_2O_5 ha^{-1}, and thus the amounts of phosphorus taken out of the farm were disproportionate in relation to its income. In the case of farms no. 24 and 25 *the farm gate balances* in turn were much lower than *the field surface balance*. Farm no. 24 did not purchase any mineral fertilisers. The phosphorus input in *the farm gate balance* was small. The sale included approx. half of the collected crops and animal products and livestock. The ratio of input to output in this farm amounted to 1:3. In farm no. 25 the difference between balances resulted from large quantities of the sold animal products, mostly milk. As per 1 ha of the farm 34 kg P_2O_5 ha^{-1} was sold.

The non-parametric analysis was used for the assessment of differences between results of two analysed balances – test of order of the Wilcoxon pairs. The analysis showed that differences between results of two balances were significant (Table 5, Fig. 3). In addition, correlation

Table 5. The results of the test Wilcoxon's sequence pairs.

A pair of variables	Z	p
FSB & FGB	2.908068	0.003637

FSB – the field surface balance, FGB – the farm gate balance

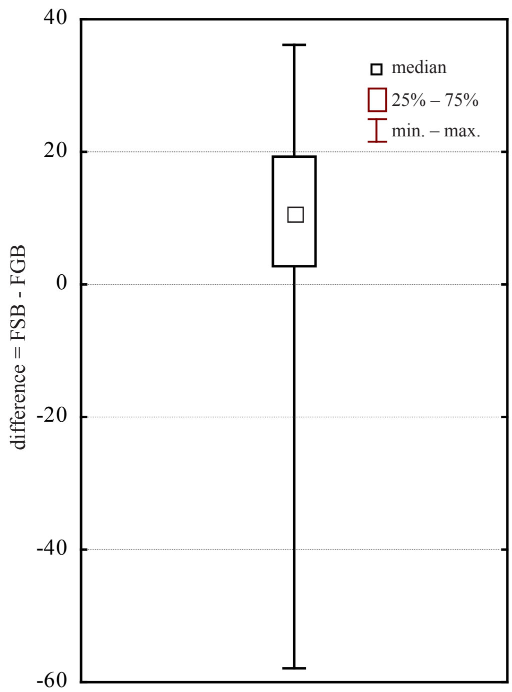

Fig. 3. Box-plot for differences in results based on the two analysed balances – the field surface balance (FSB) and the farm gate balance (FGB).

Table 6. Correlation coefficients (r) Pearson for the field surface balance of phosphorus and elements of input and output and selected characteristics of the farm.

Variable	Balance
AL area	-0.289772
Deposition	0.159602
Mineral fertilizers	**0.760093**
Manures	0.368646
Sowing material	0.045139
Plowed by-product and catch crops	0.335266
Main crops	0.204882
By-product and catch crops harvested from the field	0.337754
The share of cereals	0.424447
The share of papilionaceous	0.099961
The share of root plants	-0.274257
The share of industrial plants	0.203149
The share of feed plants	-0.056259

Marked correlations are significant at $p < 0.05000$

coefficients (r) Pearson were calculated to demonstrate the relationship between the balance of both analysed balance sheets on one side and various elements of input and output, certain characteristics of farms, like agricultural area, stocking density, participation of cereals, legumes,

Table 7. Correlation coefficients (r) Pearson the farm gate balance of phosphorus and elements of input and output and selected characteristics of the farm.

Variable	Balance
AL area	-0.233428
Mineral fertilisers	**0.638950**
Purchased manures	-
Purchased animals for breeding	-
Concentrates and feeds	**0.512538**
Purchased sowing material	0.059903
Sold commodity crops	0.387691
Sold animal products	0.201360
Sold animal	-0.085663
Animal death	0.006080
Animal density	0.165260
The share of cereals	-0.074958
The share of papilionaceous	0.148021
The share of root plants	0.427272
The share of industrial plants	-0.043348
The share of feed plants	-0.172475

Marked correlations are significant at $p < 0.05000$

root crops, industrial and fodder in crop structure on the other. The results of correlation clearly indicate that in the balance sheet of phosphorus in *the field surface* methodology the greatest impact on balance have used mineral fertilisers (Table 6). In *the farm gate balance sheet*, elements which may significantly affect its result are purchased mineral fertilisers and introduced into a farm concentrates and feeds (Table 7).

CONCLUSIONS

1. The comparative analysis showed that the results of the phosphorus balance obtained based on two different methodological approaches, despite significant differences in results, indicate similar trends. Both methods can be used for monitoring agricultural pollution but each of them in different contexts.
2. Due to the statistically significant differences in results the two analysed balance methods should not be used interchangeably. It is necessary to take into account differences between the balance results in the case of comparison results obtained from the different methods.
3. The phosphorus balance calculated using *the field surface* method was on average higher by 7.2 kg P_2O_5 ha^{-1} AL. The higher balance was affected mainly by manures produced and used in-house, which constituted approx. 31% of the input.
4. Results of the phosphorus balance, obtained from *the farm gate balance*, were higher than results of *the field surface balance* in six farms. In two analysed farms, the differences were significant (approx. 29 and 58 kg P_2O_5 ha^{-1}).

The higher balance in the farms was affected by the significant amounts of industrial fodder (concentrates) and feed supplements purchased by farmers. In both cases the primary activity involved the breeding of dairy cattle.

5. The maximum values of the balance in both balances remained at a similar level, reaching approx. 60 kg P_2O_5 ha^{-1} AL. These are values significantly exceeding the recommendations for this region. In the case of *the field surface balance* 7 farms, in the case of *the farm gate balance* 5 farms met the standard.

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Sorpcja fosforu w glebach płowych i czarnych ziemiach w katenie falistej moreny dennej Pojezierza Poznańskiego

Katarzyna Wiatrowska, Jolanta Komisarek

Katedra Gleboznawstwa i Rekultywacji, Uniwersytet Przyrodniczy w Poznaniu
ul. Piątkowska 94, 60-694 Poznań, Polska

Abstrakt. Zachowanie fosforu w glebie jest istotnym zagadnieniem zarówno ze względów produkcyjnych, jak i środowiskowych. Zminimalizowanie presji na środowisko ze strony rolnictwa wymaga między innymi rozpoznania czynników decydujących o procesach sorpcji biogenów w glebie. Celem pracy była analiza zdolności retencyjnych oraz parametrów sorpcji fosforu w glebach płowych i czarnych ziemiach w układzie katenalnym moreny dennej. Korzystając z analizy regresji wstecznej opracowano równania umożliwiające oszacowanie parametrów sorpcji Langmuira w oparciu o podstawowe właściwości gleby. Wykazano, że parametr a (maksymalną ilość fosforu, jaką może zatrzymać faza stała gleby) oszacować można w oparciu o zawartość węgla organicznego, amorficznych tlenków glinu, wapnia wymiennego i fosforu przyswajalnego. Natomiast parametr sorpcji Langmuira „b" kształtowany był przez zawartość frakcji iłowej, tlenków glinu i żelaza oraz amorficznych form żelaza.

Słowa kluczowe: fosfor, sorpcja, izoterma Langmuira

WSTĘP

Intensyfikacja produkcji rolniczej i związane z tym zwiększone zużycie nawozów fosforowych spowodowały istotne zmiany w środowisku rolniczym. Stosowane dawki nawozowe, odbiegające od rzeczywistego zapotrzebowania roślin, przyczyniły się do akumulacji fosforu w glebach i późniejszego jego rozproszenia w środowisku, powodując przyspieszoną eutrofizację wód śródlądowych. Ładunek fosforu wynoszony z gleby wraz z wodami odpływającymi ze zlewni, związany jest z ukształtowaniem terenu, jego użytkowaniem, warunkami meteorologicznymi, zasobnością gleby oraz pojemnością sorpcyjną gleby względem tego biogenu (Jadczyszyn i in., 2014; Sapek, 2014).

Ruchliwość fosforu w środowisku glebowym, a tym samym jego dostępność dla organizmów żywych, jest silnie ograniczana przez szereg zjawisk powierzchniowych zachodzących na granicy fazy stałej i roztworu glebowego. Fosfor wprowadzany do gleby podczas nawożenia ulega szeregowi reakcji zmniejszających jego migrację, poczynając od procesów strącania z jonami Ca^{2+}, Mg^{2+}, Fe^{3+} i Al^{3+}, poprzez procesy adsorpcji elektrostatycznej, jak i specyficznej na powierzchni minerałów ilastych oraz tlenków Al i Fe, kończąc na mechanizmach absorpcji do wnętrza tlenków żelaza i glinu (Sanyal, De Datta, 1991; Reddy i in., 1999; Idris, Ahmed, 2012). Tym samym procesy, w jakich udział biorą jony fosforanowe, znacząco ograniczają przemieszczanie się tego pierwiastka w środowisku, szczególnie w postaci rozpuszczalnej. Spośród komponentów gleby wpływających na proces sorpcji fosforu wymienić należy materię organiczną, amorficzne tlenki żelaza i glinu, węglany, jak i frakcję iłową. Pomimo iż zagadnienie sorpcji fosforu było szeroko analizowane przez wiele ośrodków badawczych, opublikowane dane nie są jednoznaczne. Wielu autorów donosiło o istotnym wpływie węgla organicznego na ilość sorbowanego fosforu (Lopez-Hernandez i Burnham, 1974; Kanabo i in., 1978; Owusu-Bennoah i Acquaye, 1989; Guppy i in.,2005), inni zaś o braku takiej relacji (Borggaard i in., 1990). Podobną rozbieżność w literaturze można znaleźć w odniesieniu do roli frakcji iłowej; jedne źródła wspominają o istotnej i dodatniej korelacji pomiędzy zawartością tej frakcji a sorpcją fosforu (Niskanen, 1990), inne zaś o słabej lub jej braku (Lopez-Hernandez, Burnham, 1974).

Znajomość zarówno poziomu zawartości fosforu przyswajalnego w glebie, jak i parametrów sorpcji tego pierwiastka umożliwi prawidłowe bilansowanie tego biogenu

Autor do kontaktu:
Katarzyna Wiatrowska
e-mail: kawiatr@up.poznan.pl
tel. +48 61 8466442

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uwzględniające potrzeby roślin, ale także zdolności retencyjne środowiska.

Celem niniejszej pracy było określenie zdolności retencyjnych gleb względem fosforu oraz oszacowanie parametrów sorpcji w glebach płowych i czarnych ziemiach w katenie falistej moreny dennej Pojezierza Poznańskiego z wykorzystaniem podstawowych właściwości gleb.

MATERIAŁY I METODY

Badania prowadzono w mikrozlewni rolniczej o powierzchni 220 ha, położonej na terenie Rolniczo-Sadowniczego Gospodarstwa Doświadczalnego w Przybrodzie, należącego do Uniwersytetu Przyrodniczego w Poznaniu. Badaniami objęto gleby zlokalizowane w typowej katenie gleb płowych i czarnych ziem wytworzonych z dennomorenowych glin zwałowych zlodowacenia bałtyckiego fazy poznańskiej. Na potrzeby pracy wytypowano sześć pedonów, które zaklasyfikowano jako: gleba płowa zaciekowa opadowo-glejowa (P1 i P2), gleba płowa gruntowo-glejowa (P3), czarna ziemia z poziomem *cambic* (P4 i P5) oraz czarna ziemia murszasta (P6). Gleby te użytkowane były jako grunty orne. Na glebach reprezentowanych przez profile P1–P4 uprawiano naprzemiennie żyto, rzepak ozimy i jęczmień. Na glebach najniżej położonych w katenie (P5 i P6) uprawiano kukurydzę w monokulturze.

W próbkach gleb oznaczono podstawowe właściwości fizyczno-chemiczne, takie jak: skład granulometryczny metodą areometryczną (PN-R-04032), zawartość węgla organicznego (Nelson, Sommers, 1982), kationową pojemność wymienną (Kociałkowski, Ratajczak, 1984; Thomas, 1982), odczyn (Soil Survey..., 1992). Zawartość całkowitą tlenków żelaza i glinu oznaczono po spaleniu próbek w piecu w temperaturze 850°C i trawieniu w mieszaninie kwasów fluorowodorowego i borowego w zamkniętych naczyniach (Komisarek, 2000). Formy amorficzne tlenków żelaza i glinu ekstrahowano mieszaniną kwasu szczawiowego i szczawianu amonu o pH 3 w stosunku gleba:roztwór 1:40 (McKeague, Day, 1966). Zawartość fosforu dostępnego dla roślin oznaczono w mieszaninie 0,03 M NH_4F + 0,025 M HCl (Bray-P1) w stosunku gleba: roztwór 1:10, czas ekstrakcji wynosił 5 minut (Olsen, Sommers, 1982). Po odwirowaniu próbek w uzyskanym przesączu fosfor oznaczano metodą molibdenianową (Tiessen, Moir, 1993). Wszystkie analizy gleb wykonano w dwóch powtórzeniach.

Krzywe sorpcji fosforu wyznaczono poprzez wprowadzenie do 2 g gleby 30 ml roztworu zawierającego odpowiednio od 0 do 65 mg P·dm^{-3} (1, 5, 15, 25, 35, 45, 55, 65 mg P·dm^{-3}) w postaci KH_2PO_4. Próbki gleb równoważono przez 24 h, a następnie przesączano przez sączki bezfosforanowe Whatman S&S. Zawartość fosforu oznaczono kolorymetrycznie metodą molibdenianową z zastosowaniem kwasu askorbinowego jako reduktora (Tiessen, Moir, 1993). Zdolności sorpcyjne próbek glebowych względem fosforu określono na podstawie równań Langmuira [1] i [2]:

$$S = \frac{a_{max} \cdot b \cdot C_e}{1 + b \cdot C_e} \qquad [1]$$

$$S = \frac{(C_i - C_e) \cdot V}{M} + S_0 \qquad [2]$$

gdzie:

S – ilość fosforu zasorbowanego przez stałą fazę gleby (mg·kg^{-1});
a_{max} – maksymalna ilość fosforu zasorbowanego przez fazę stałą (mg·kg^{-1});
b – współczynnik związany z energią wiązania (dm^3·mg^{-1});
C_e – stężenie fosforu w roztworze zrównoważonym (mg·dm^{-3});
C_i – stężenie początkowe fosforu w roztworze (mg·dm^{-3});
V – objętość roztworu (dm^{-3});
M – masa próbki gleby (kg);
S_0 – początkowa zawartość fosforu w glebie – fosfor dostępny dla roślin (mg·kg^{-1}).

Parametry sorpcji w równaniu Langmuira wyznaczono za pomocą regresji liniowej metodą najmniejszych kwadratów. Ponadto w celu określenia zdolności gleby do wiązania fosforu obliczono również jej maksymalną pojemność buforową [3] (Indiati i in., 1999).

$$MBC = a_{max} \cdot b \qquad [3]$$

gdzie:

MBC – maksymalna pojemność buforowa (dm^3·kg^{-1}).

Parametry takie jak zawartość węgla organicznego, frakcji iłowej, fosforu przyswajalnego, całkowita zawartość tlenków glinu i żelaza oraz ich form amorficznych, wapnia wymiennego, a także stężenie wodoru oraz kationowa pojemność sorpcyjna (PWK) uwzględniono w analizie korelacji i regresji wielokrotnej. Te narzędzia statystyczne wykorzystano do opracowania równań umożliwiających oszacowanie parametrów sorpcji: maksymalnej ilości fosforu zasorbowanego przez fazę stałą (Q_{max}) i współczynnika związanego z energią wiązania (k), oszacowanych na podstawie równań regresji [4] i [5].

WYNIKI I DYSKUSJA

Najwyższe położenie w katenie, w obrębie płaskiego wyniesienia, zajmowały pedony P1 i P2 (rys. 1). Gleby te w poziomach powierzchniowych zbudowane są z piasków gliniastych i glin piaszczystych przechodzących w poziomach eluwialnych oraz *glossic* w gliny piaszczyste. Poziom *agric* charakteryzuje się uziarnieniem glin średnich. Na stoku swobodnym zlokalizowano profil P3, wykazujący cechy oglejenia gruntowego. Powierzchniowy poziom tej gleby z cechami *mollic* zalega na szczątkowym poziomie *luvic*. Nieco niżej w katenie na stoku usypiskowym, gdzie dochodzi do największej akumulacji materiałów denudowanych, wytworzyły się czarne ziemie z poziomem *cambic* – profil P4. Poziomy powierzchniowe i iluwialne zbudowane z gliny piaszczystej zalegają na poziomie gle-