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Effect of long-term slurry application on contents of available forms of soil macronutrients

Abstract: The objective of the study was to assess the effects of long-term application of liquid manure from pig production and digestate from manure fermentation installation for biogas production on chemical changes in the soil, i.e.: soil reaction, accumulation of available forms of phosphorus, potassium, and magnesium in the soil arable layer, as well as the phosphorus balance. The assessment was carried out in two highly productive farms specialising in pig production, located in the Zachodniopomorskie Province. The soils under the study were treated with slurry and digestate annually for subsequent 12 years. The assessment of changes in nutrient content and accumulation was performed twice: after 10 and 12 years of fertiliser treatments. The rate of changes in soil reaction due to slurry and digestate application varied depending on the analysed field. Irrespective of the analysed field, 12-year application of slurry caused a drop in soil pH by an average of half a unit. The direction of changes in the content of available nutrient forms in the soil varied depending on the element evaluated. Notwithstanding the analysed field and the type of slurry used, a decrease in the content of available forms of potassium in the soil was observed. Slurry fertilisation did not affect magnesium contents in the soil. In the study period, the content of magnesium remained unchanged. Among the evaluated nutrients, an increased nutrient content in the soil was only found in the case of phosphorus – as a result of application of liquid manure in combination with mineral fertilisation. In the analysed farms, in the case of fields fertilised with slurry and digestate, the phosphorus balance was positive, and ranged from 15 to 40 kg P·ha^{-1}. The obtained values of the phosphorous balance strongly suggest that regardless of the type of liquid manure used on the farm, measures should be taken to introduce changes in the scope of fertilisation plans, with particular emphasis on the principles of balanced fertilisation.

Keywords: slurry, digestate from biogas plant, phosphorus balance, soil reaction, potassium, magnesium

INTRODUCTION

Natural fertilisers and different kinds of organic waste are a cheap source of nutrients for plants and an important source of organic matter contributing to soil fertility. On the other hand, they cause a risk of emission of biogenes (nitrogen and phosphorus) to waters, and greenhouse gases to the atmosphere (Sapek 2000a). The scale of emission of the aforementioned components to the environment depends on the applied dose of slurry and the way and term of its application (Mogge et al. 1999). In intensive animal production, particularly of pigs, slurry production is to a greater degree perceived in categories of a tedious waste than a valuable source of nutrients for plants (Romaniuk 2000). Due to the changes in animal production involving a transition to indoor breeding, the amount of produced slurry increases at the cost of a reduction of the amount of manure. Classic storage of natural fertilisers (manure pits, manure pads, lagoons) involves considerable losses of organic matter in the form of CO_2 or CH_4 (Maćkowiak 1999; Haussermann et al. 2006; Berg et al. 2006). Improper application of fertilisers, and currently also organic materials of waste origin for fertilisation of soils and plants can additionally cause threats for the natural environment, including cleanliness of waters and soils, and quality of plant yields (Oniszk 2000; Sapek 2000b). The negative effect of slurry on the natural environment particularly results from gas emission occurring during storage and application of the fertiliser (Blanes-Vidal et al. 2008; Philippe and Nicks 2015). According to the report prepared for the European Commission (Foged et al. 1997), 7.8% of produced natural fertilisers are processed in the EU. In Poland, 252 thousand tonnes are processed, constituting 0.3% of the total amount of natural fertilisers produced in the EU (Jurga and Winiarski

2016). The reduction of losses of methane from slurry is implemented in a variety of ways. One of the latest ways is the utilisation of natural fertilisers in agricultural biogas plants (Myczko 2000). Fermentation in an agricultural biogas plant reduces losses of methane emitted to the environment, and therefore reduces the contribution of agriculture in the emission of the gas (Oniszk 2000). Moreover, digestate from the biogas plant emits a considerably smaller amount of odour compounds and is almost completely devoid of pathogenic microorganisms, because they are destroyed in increased temperature in the process of fermentation (Jurga and Winiarski 2016). Replacing fresh fertilisers with fermented mass or composts also reduces leaching of nitrates down the soil profile due to the fact that after the fermentation process the dominant form of mineral nitrogen is $N\text{-}NH_4$ (Paavola and Rintala 2008; Tambone et al. 2009). Controlled methane fermentation is a good solution, particularly due to the protection of waters, soil, and atmospheric air (Bohdziewicz and Kuglarz 2009). The process permits obtaining renewable energy and stabilised organic fertiliser, namely fermented slurry. Danish research showed that fermentation of pig slurry in a biogas plant allows for a reduction of losses of methane and ammonia by 50% (from 3.1 to 1.5 kg t^{-1}) and 20% (by 100g NH_3 t^{-1}), respectively.

Considering the admissible amount of nitrogen applied with natural fertilisers in a dose of 170 kg·ha^{-1}, excessive amounts of phosphorus are frequently introduced to the soil. Regular application of slurry can become the cause of excess accumulation of the element in the soil, leading to a serious water pollution problem (Haneklaus et al. 2016). In the first year of application of natural fertiliser, approximately 35 to 40% of total phosphorus content is available for plants. From the point of view of counteracting water eutrophication, provisions of the Act of 20 July 2017 Water Law are very important. They directly result from the provisions of Council Directive 91/676/EEC on the protection of waters against pollution caused by nitrates from agricultural sources. The application of fertilisers in doses exceeding the nutrient requirements of plants can leads to changes in the ionic balance of the soil solution and causes transfer of the element to groundwaters. The chemical analysis of soil constitutes an important tool of assessment of potential threats resulting from the surplus of phosphorus dispersed from the natural environment (Maguire and Sims 2002). The balance of the element shows the direction of changes of a given element in the soil and provides the basis for the preparation of fertilisation plans. Improper diagnosis can lead to the disturbance of the economic feasibility of production and environmental degradation. One of the commonly recognised methods of investigation of flow of nitrogen and phosphorus and assessment of the degree of environmental load of the elements are their balances prepared by means of the method propose by the OECD (Kopiński 2007). N and P balances are prepared obligatorily at the scale of the country and voivodships. This results from Poland's membership in the OECD from 1996. The paper adopted a research hypothesis stating that long-term application of slurry and digestate from agricultural biogas plant increases the content of macroelements in the soil and leads to a decrease in the pH value.

The objective of the study was the assessment of the effect of long-term application of slurry from pig production and digestate from biogas plants on changes in soil reaction, content of available forms of phosphorus, potassium, and magnesium, and phosphorus balance.

MATERIALS AND METHODS

The study focused on two agricultural farms specialising in pig production located in the Zachodniopomorskie Voivodship. The total area of the farms is 870.62 ha. The assessment covered only arable fields on which digestate from biogas plant (farm A) and slurry from pig production (farm B) has been regularly applied since 2001. On farm A, the total area of fields covered by the study was 552.81 ha, which constituted 11% of the total size of the farm (Table 1). The area of fields covered by the study on farm B was 317.15 ha, constituting 10% of the total size of the farm (Table 2). Approximately 41% of land

TABLE 1. Area of analysed fields and crop structure on farm A

Field numer	Agronomic category	Area ha	Plant
1	medium soil	200.63	corn
2	light soil	108.47	corn
3	light soil	43.48	corn
4	medium soil	124.70	corn
5 (control)	light soil	75.53	corn

TABLE 2. Area of analysed fields and crop structure on farm B

Field number	Agronomic category	Area ha	Plant
1	medium soil	50.81	corn
2	medium soil	25.58	corn
3	medium soil	95.20	corn
4	medium soil	94.69	corn
5	medium soil	51.53	winter triticale

was occupied by medium soils, and 59% by light soils. On each of the farms, the study covered 5 fields (numbered from 1 to 5). Detailed research concerning crop yields, element uptake, and phosphorus balance was performed in 2011 and 2013. Fields fertilised with digestate from biogas plant in 2011 and 2013 were completely used for sawing corn mainly for silage, constituting a substrate for the production of biogas. Moreover, the study considered a control field belonging to farm A, excluded from the application of slurry and digestate. In the crop structure on farm B in 2011 and 2013, two plants were dominant, namely corn and triticale, with a percent contribution of 84% and 16%, respectively.

The characteristics of the chemical composition of slurry and digestate from biogas plant are presented in Table 3. Slurry and digestate were applied by means of spreading hoses coupled with cultivator tines in a two-dose system. An average of 45% was introduced in autumn and 55% in spring. Table 4 presents total amounts of the applied slurry and digestate from biogas plant in 2011 and 2013. Pursuant to the Act on fertiliser and fertilisation of 2007, the determination of the dose of both fertilisers adopted a criterion limiting the amount of the applied fertiliser dose to 170 kg N ha^{-1} in the form of natural or organic fertilisers (Ustawa o Nawozach i Nawożeniu 2007).

Soil samples for chemical analyses concerning the determination of the content of available elements and pH value in selected years were collected after harvests before the application of slurry. The number of oil samples collected from a given field was variable depending on the surface area of a given field. Soil samples were collected in accordance with the methodology of the Chemical-Agricultural Station (PN-R-04031:1997), assuming 1 average sample from an area of 4 ha, comprising 15–20 partial samples. Chemical analyses of soils were performed in three terms:

1) autumn 2001 – before the application of slurry,
2) autumn 2011 – after the crop harvest,
3) autumn 2013 – after the crop harvest.

Mean pH values were calculated after dealgorithmisation of results

For the purpose of determination of potential threat of leaching and effects of excessive accumulation of phosphorus related to a high amount of the element in slurry, phosphorus balance was performed by means the of the field surface method. The balances were prepared separately for each field on a farm. The P balance on the side of revenues considered the amounts of the element introduced with mineral fertilisers and slurry, and on the side of expenditures, the amount of phosphorus expended with crop yields. In the case of slurry, a phosphorus fertiliser equivalent at a level of 70% was adopted, and in the case of digestate from biogas plant 80%. Based on the difference between the dose of the element applied in mineral and natural fertilisers and the total amount of P subject to uptake with crop yield, P balances were determined. Phosphorus uptake with a main crop yield

TABLE 3. Chemical composition of slurry and digestate from biogas plant in the study years

Years	Slurry					Digestate from biogas plant				
	s.m	N	P	K	pH	s.m.	N	P	K	pH
	%	kg m^3				%	kg m^3			
2011	8.81	3.40	1.24	1.48	6.40	3.91	2.20	1.12	1.16	7.58
2013	8.23	3.70	1.38	1.40	7.10	3.75	2.80	1.23	1.93	7.65

TABLE 4. Doses of slurry and digestate from biogas plant applied in the study years, $m^3 \cdot ha^{-1}$

Field number	Type of fertiliser		
	digestate from biogas plant	slurry	
	2011 i 2013	2011	2013
1	50.00	41.80	45.45
2	51.45	41.80	45.45
3	45.45	41.80	45.45
4	46.91	41.80	45.45
5	0	38.20	41.80

unit with the corresponding secondary yield was determined from the product of unitary P uptake according to data included in the Code of Good Agricultural Practices (Kodeks 2002) and yield collected from a given field. The value of unitary uptake for corn was adopted at a level of 0.7 kg P×t^{-1} and triticale 3.8 kg P·t^{-1}. The study results were processed by means of an Excel spreadsheet and STATISTICA 10.0 software.

RESULTS AND DISCUSSION

Soil reaction

Both mineral and organic fertilisation is among important factors modifying soil reaction. The final effect of a fertiliser depends on its type and soil properties (Mazur and Sądej 2002). The study showed that long-term application of slurry from pig production and digestate from biogas plants caused changes both in soil reaction and nutrient accumulation in the arable layer (Table 5, 6, Fig. 1, 2). Among fields subject to the assessment on farm A, the strongest decreasing tendency of pH values due to the application of digestate from biogas plants was observed in the case of field 2 (Table 5). A different direction of changes in soil reaction was observed for field No. 3, because 10 years of application of natural and organic fertiliser had no effect on the pH value. The effect of long-term fertiliser application on changes in soil pH manifested only after 10 years from the moment of application of the fertiliser. The variable response of soils to acidification is a result of the buffer mechanisms of soils. Digestate from biogas plants is characterised by higher pH (7.1–7.4) in comparison to slurry. Literature data (Grzebisz et al. 2009) suggests that the pH value of digestate from biogas plant can be up to 8. The analysis of data concerning the reaction of the analysed soils on farm A in the years 2001–2013 shows that regular application of digestate from biogas plant caused a decrease in the pH value of the analysed soils by an average of 0.5 unit. The decreasing tendency of soil pH was also observed in the case of the control field (field No. 5), excluded from slurry application. Acidification is a natural process occurring in the soil, and agrotechnical measures, including fertilisation, particularly with nitrogen and natural fertilisers, result in an increase in the rate of the processes. Soils belonging to farm B were characterised by low pH throughout the study period with a decreasing tendency of its values with years of slurry application (Table 6). In 2001, the average soil pH value on farm B varied from 4.7 to 5.5, and in 2011 the range was narrowed to

TABLE 5. Changes in soil reaction attributable to the use of digestate from biogas plant on farm A fields

Field number		2001	2011	2013
1	mean	6.54	6.01	5.93
	max	7.70	7.20	7.02
	min	5.00	5.00	5.17
	O. S.[a]	0.61	0.44	0.40
2	mean	6.32	6.16	5.63
	max	7.40	7.00	7.15
	min	5.00	5.40	5.04
	O. S.	0.50	0.47	0.52
3	mean	5.20	5.47	5.36
	max	6.90	6.20	6.27
	min	4.30	5.20	4.89
	O. S.	0.58	0.33	0.43
4	mean	6.18	6.02	5.86
	max	7.40	7.00	7.50
	min	5.10	5.30	5.05
	O. S.	0.53	0.39	0.53
5	mean	6.57	6.17	5.65
	max	6.90	6.80	6.86
	min	6.00	5.80	5.01
	O. S.	0.19	0.28	0.50

a – standard deviation.

TABLE 6. Changes in soil reaction attributable to the use of slurry on farm B fields

Field number		2001	2011	2013
1	mean	4.91	5.14	4.92
	max	6.90	6.66	6.65
	min	4.20	4.62	4.00
	O. S.[a]	0.46	0.72	0.72
2	mean	5.36	4.56	5.05
	max	6.10	5.04	4.40
	min	4.90	4.35	5.87
	O. S.	0.32	0.27	0.55
3	mean	5.50	5.12	5.64
	max	6.90	6.11	6.75
	min	4.20	4.36	4.16
	O. S.	0.47	0.50	0.37
4	mean	4.97	5.19	5.20
	max	6.50	6.10	6.10
	min	4.80	4.52	4.52
	O. S.	0.31	0.37	0.37
5	mean	4.65	4.29	4.64
	max	5.20	4.70	5.90
	min	4.20	4.02	3.60
	O. S.	0.44	0.20	0.66

a – standard deviation.

FIGURE 1. Changes of macronutrient contents in farm A soils on account of long-term use of digestate from biogas plant

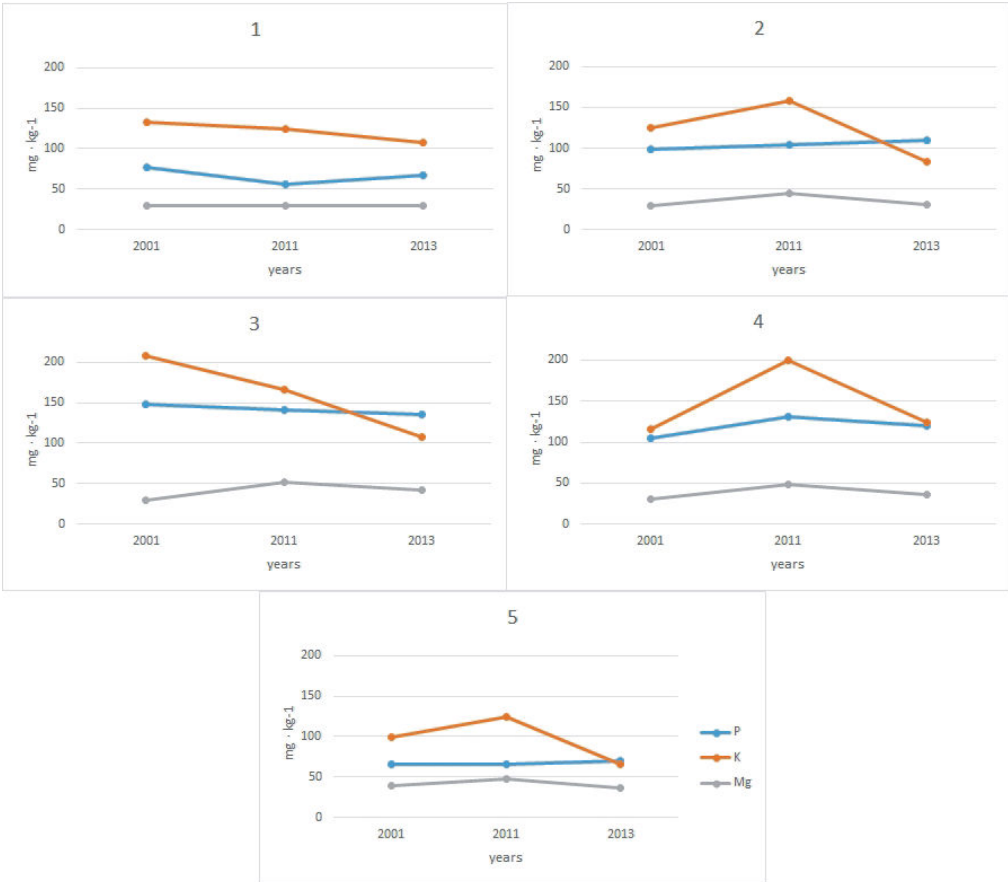
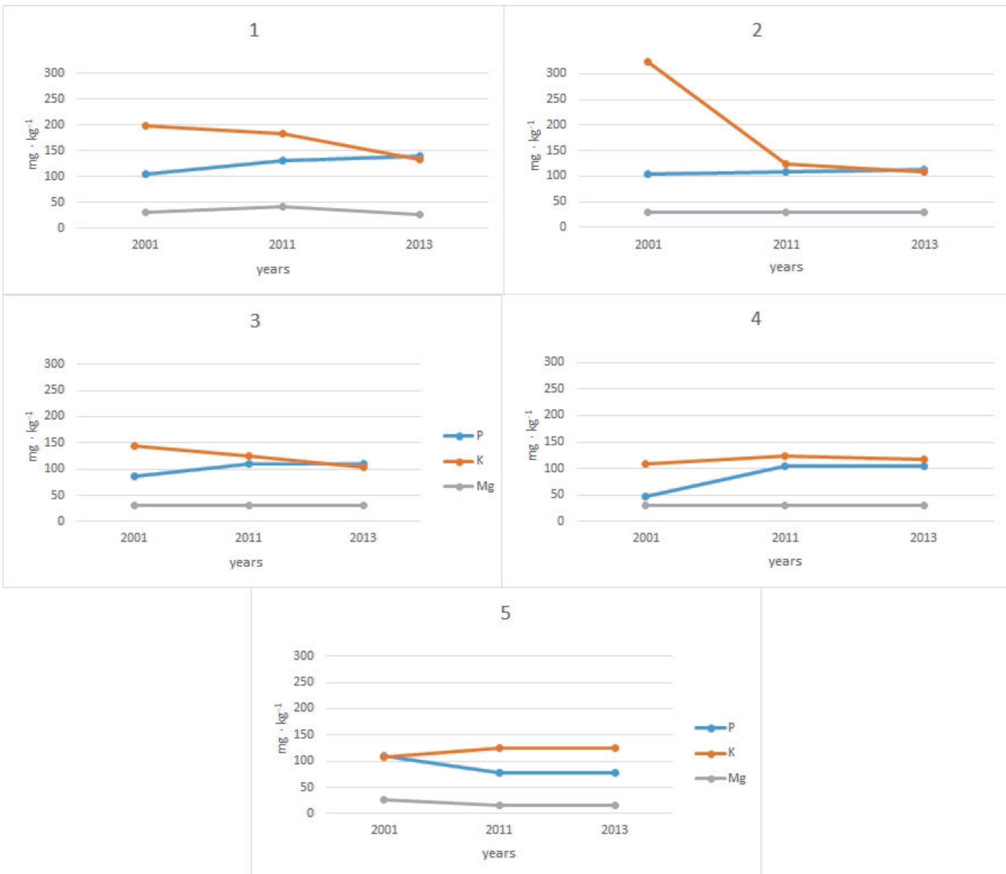


FIGURE 2. Changes of macronutrient contents in farm B soils on account of long-term use of slurry



4.3–5.2. The lowest average soil pH values were recorded in the case of field No. 5 in each of the analysed terms, and the highest pH was observed for field No. 3. Soil reaction was also variable within the analysed field, and the highest variability of the evaluated parameter was observed in reference to field No. 1, as confirmed by high values of the standard deviation and broad range between minimum and maximum values. Soils of field No. 5 in 2011 were characterised by very acidic and acidic reaction. The analysis of changes in average soil pH on a given field on account of long-term application of approximate doses of slurry and digestate from biogas plants suggests that the rate of the occurring pH changes is variable depending on the analysed soil, and does not always lead to a decrease in its value. The issue concerning the effect of long-term slurry fertilisation on the development of soil reaction is extensively documented in Polish and foreign literature, although results by the authors are ambiguous. Mazur and Mazur (2007) point out that annual application of high doses of slurry can contribute to a decrease in soil reaction. Research by Potarzycki (2000) concerning the dynamics of changes in soil reaction on account of fertilisation with bovine slurry showed that 20 years of application of the fertiliser increased soil pH values, and the application in combination with mineral nitrogen fertilisers caused o changes in the assessed index. The knowledge of a farmer on the state of reaction of the cultivated soil and consequences of the conducted production is a very important component of the strategy of management of the factor in plant production. The production and ecological effects of excessive soil acidification present the final effect of a number of largely unidentified processes (Hede et al. 2001; Kidd and Proctor 2001; Marschner 1991; Van Breeman et al. 1983). Soil reaction decreasing below the value optimal for a given element results in a fast decrease in its crop yield effectiveness. Out of three mineral components (N, P, K), phosphorus responds to soil acidification the strongest (Barrow 1984; Hinsinger 1998).

Nutrient accumulation in the soil

Long-term application of digestate from biogas plant and slurry from pig production contributed to changes in the accumulation of available forms of phosphorus and potassium in the analysed soils. A considerable effect of the application of slurry and digestate on an increase in the content of bioavailable forms of phosphorus in soils subject to the study was evidenced. High content of available P suggests a potential threat of dispersal of the component to groundwaters and surface waters. Before the commencement of application of slurry, the content of available phosphorus in soils was variable depending on the field. In the case of farm A it varied from 74 to 148 mg P kg^{-1} of soil, and in soils of farm B from 74 to 109 mg P kg^{-1}. The assessment performed after 10 years confirmed the evident effect of digestate fertilisation on an increase in the content of available phosphorus in all the analysed soils. Although the applied doze of digestate was comparative on all fields subject to the study, an increase in the content of the analysed component at particular sites was variable on account of its application. In 2011, the contribution of soils with very high content of available phosphorus equalled 80%, and the remaining soils were characterised by high content of the component. Another assessment performed after two years showed that soils of all the fields subject to the study on farm A were characterised by high content of available phosphorus. Its content oscillated between 87.2 and 139.5 mg $P \cdot kg^{-1}$ of soil (Fig. 1). A smaller variability of content of available P (61–69 mg $P \cdot kg^{-1}$ of soil) in comparison to the remaining fields was observed in the case of the control object (field No. 5). Considerably greater differences in the content of available P were observed on account of application of slurry in the soils of farm B. An increase in the content of available P was observed in the case of fields 1–4, and in reference to field 5, an evident decrease in the content of phosphorus was determined (from 109 to 82.8 mg $P \cdot kg^{-1}$ of soil), whereas its content was still maintained in the class of soils with high P abundance. High contents of phosphorus in the soil resulting from long-term application of slurry and digestate from biogas plants suggests that the determination of doses of natural fertilisers should consider not only the acceptable criterion of content of N as the component limiting the slurry dose, but also P content. Failure to respect this rule in the long term can cause a serious environmental threat and contribute to the deterioration of the quality of waters. Outflow of phosphorus to surface waters depends on the level of P in the soil, type of soil, and land surface inclination (Sims et al. 1998; Arheimer and Liden 2000). Monitoring research conducted by chemical-agricultural stations shows a considerable increase in the content of available forms of phosphorus in soils (Igras and Fotyma 2013). At sites of monitoring research, the average increase in the content of available phosphorus was approximately 1.4 mg $P \cdot kg \cdot year^{-1}$ (Jadczyszyn et al. 2009). The application of an excessively high dose of slurry in fields and failure to observe agrotechnical periods is often the cause of an ecological threat to soils, waters, and the atmosphere as a result of disturbance of balance, and exceedance of the sorption capacity of the soil and assimilation capacity of plants (Carpenter et al.1998). As a consequence of the occurring processes, nitrogen and phosphorus compounds from slurry are supplied to surface waters and groundwaters, causing eutrophication of water bodies (Fotyma et al. 2006).

The content of available potassium in the soils of farm A before the application of digestate from biogas plants in the majority of case corresponded with the class of medium and low abundance. The data analysis performed after 10 years of application of digestate showed an increase in the contribution of soils with low K content. Changes in the content of the component in years subject to the study were determined by the high contribution of corn in the crop structure. Due to the volume of produced biomass and its purpose, corn contributed to a considerable reduction in available potassium in the soil (Fig. 1). A close relation was also observed between the content of the component in the soil and the pH value. With a decrease in pH, content of available K also decreased. The assessment of the dependency of soil acidity and content of available potassium requires the consideration of the granulometric composition (agronomic category of the soil). This results in a triple pattern of relations: agronomic category – reaction – content of available potassium (Lipiński 2005, Tkaczyk and Bednarek 2011). In the case of all the analysed fields on farm B in the study period in the years 2001–2013, a tendency for a decrease in the content of available forms of potassium is was observed (Fig. 2). Before the application of slurry in 2001, the content of available potassium in soils belonging to farm B was variable within a very broad range of values from 99 to 323 mg $K \cdot kg^{-1}$ of soil. The assessment performed after 12 years of regular application of slurry showed a considerably lower content of available potassium in all the analysed soils, varying from 83 to 182 mg $K \cdot kg^{-1}$ of soil. In 2013 in comparison to seasons evaluated earlier, potassium content was within a narrower range of values from 83 to 141 mg K kg^{-1} of soil. A decrease in potassium content in soils was a result of unbalanced mineral and organic fertilisation. A particularly considerable change in the content of the component in the soil in the analysed period 2001–2013 was observed in the case of field No. 2 (Fig. 2). A reduction of the content of available potassium on the aforementioned field was accompanied by a simultaneous decrease in soil pH. Changes in the content of available potassium were also strongly related to the crop species. In the case of field No. 5, where in vegetative seasons 2011 and 2013 triticale was cultivated, small differences in the content of available potassium in the soil were determined in the analysed study period. The remaining fields were characterised by a considerably greater reduction of potassium content, and the change was a consequence of high expenditure of the component with corn yield.

Long term application of slurry and digestate from biogas plant determined changes in magnesium content to a considerably lower degree in comparison to phosphorus and potassium. Mg content oscillated in a narrow range from 3 to 5 mg Mg kg^{-1} of soil (Fig. 1, 2). In the analysed study period, the content of available magnesium in the soil was maintained on an even level irrespective of the application of slurry or digestate from the biogas plant The obtained results are in accordance with data obtained by Maćkowiak (2001) and Gosek (2002).

Phosphorus balance

The component balance is the basic tool of control of nutrient circulation in agriculture, used in the monitoring of pollutants originating from aerial sources. The result of the balance is the difference between the revenue of the component and its expenditure. Moreover, it permits the assessment of the potential volume of losses of components from agricultural production as a result of specified intensity of management measured by the level of mineral fertilisation and animal stocking (Sapek and Sapek 1993). Results of the P balance gain special importance in comparison with the state of abundance of soils and quality of groundwaters and surface waters (Igras and Lipiński 2005). The study involved the assessment of potential threat to the environment caused by the dispersal of the component introduced in excess of the requirements of the cultivated plants. The P balance prepared for particular fields in the case of the analysed farms showed a positive balance (SB) varying from 16 to 40 kg $P \cdot ha^{-1}$ and dependent on the species of plant cultivated on a given field as well as the obtained harvests (Table 8). The effect of the plant as a factor differentiating the use of phosphorus from fertilisers is presented in research by Gaj (2008). In the current study, higher than average phosphorus balance shows low effectiveness of use of the element from slurry. As a consequence, this can contribute to excessive phosphorus accumulation in the soil. Sharpley (1986) and McLaughlin et al. (1988) evidenced that only 9–23% of phosphorus absorbed by plants originates from current P fertilisation, and the remaining part of phosphorus is absorbed by plants from reserves accumulated in the

TABLE 7. Phosphorus balance on farm A

Field number	Yield	Mineral fertilisers	Organic fertilisers	Fertilisers M+N kg	P uptake	Phosphorus balance
	t·ha^{-1}	kg P·ha^{-1}				
	2011					
1	50.63	20.24	44.80	65.04	35.32	29.72
2	52.93	20.24	46.10	66.34	36.92	29.42
3	39.45	20.24	40.73	60.97	27.52	33.45
4	48.49	20.24	42.03	62.27	33.83	28.44
5	46.06	30.36	0.00	30.36	32.13	-1.77
mean	**47.51**	**22.26**	**34.73**	**57.00**	**33.14**	**23.91**
	2013					
1	44.7	20.24	49.20	69.44	31.18	38.26
2	48.76	20.24	50.63	70.87	34.01	36.86
3	41.70	20.24	44.73	64.97	29.09	35.88
4	44.53	20.24	46.16	66.40	31.06	35.34
5	41.73	30.36	0.00	30.36	29.11	1.25
mean	**44.28**	**22.26**	**38.14**	**60.41**	**30.89**	**29.51**

TABLE 8. Phosphorus balance on farm B

Field number	Yield	Mineral fertilisers	Organic fertilisers	Fertilisers M+N kg	P uptake	Phosphorus balance
	t·ha^{-1}	kg P·ha^{-1}				
	2011					
1	46.00	20.24	36.28	56.52	32.09	24.43
2	38.00	20.24	36.28	56.52	26.51	30.01
3	39.00	20.24	36.28	56.52	27.21	29.32
4	46.00	20.24	36.28	56.52	32.09	24.43
5	4.55	0	40.38	40.38	17.29	23.09
	mean	**16.19**	**35.66**	**51.85**	**27.03**	**26.26**
	2013					
1	35.50	20.24	43.90	64.14	24.76	39.38
2	35.58	20.24	43.90	64.14	24.76	39.38
3	35.20	20.24	43.90	64.14	24.76	39.38
4	34.69	20.24	43.90	64.14	24.76	39.38
5	5.0	0	40.38	40.38	19.0	21.38
	mean	**16.19**	**43.20**	**59.38**	**23.61**	**35.78**

soil. Monitoring research published by Potarzycki (2006) showed that phosphorus accumulation by crop plants to the amount higher than 17 kg P ha^{-1} leads to a negative balance. According to literature data (Fardeau et al. 1997; Tujaka and Gosek 2009;), the use of phosphorus from mineral fertilisers in the first year of application varied from 10 to 20%, and in many cases shows a variability depending on soil conditions, cultivated plant, and even its cultivar (Ozturk et al. 2005). Phosphorus balances prepared for different fields of a farm, or even region, are characterised by a certain simplification, because they ignore changes in the content of the element in the soil in the study period. They are usually primarily based on the calculation of the balance difference between the amount of phosphorus introduced to the soil with fertilisers and the amount absorbed by plants (Ellmer et al. 1999; Sądej 2000). At the scale of the country, however, great regional variability of the amount of phosphorus supplied with manure, slurry, or mineral fertilisers should be considered. Balances assess the accuracy of management of elements, and are one of the most important agro-environmental indicators (Kupiec 2015; Gaj and Bellaloui 2012; Koper et al. 2002; Sassenrath et al. 2013). A positive balance described as surplus or losses constitutes a load of a component unused in agricultural production, subject to accumulation in the soil, or transferred to surface waters (Pietrzak 2013). The average phosphorus surplus for Poland is approximately 3.7 kg $P \cdot ha^{-1}$, and for the Zachodniopomorskie Voivodship 6.7 kg $N \cdot ha^{-1}$ (Kopiński and Tujaka 2009). The comparison of balances presented in the paper with results obtained by Kupiec and Zbierska (2010) for large-area farms shows that balances obtained by the cited authors were considerably lower than those obtained in own research. In the context of the growing threat for the natural environment resulting from the application of slurry from industrial rearing of pigs, it is necessary to constantly monitor changes in the chemical and physical properties of soils, groundwaters, and surface waters in the area of influence of the farms. Particularly strict control is required in areas with regular application of slurry. The study shows that annual application of the fertiliser on a given field results in excessive accumulation of available forms of phosphorus in the soil, and as a consequence constitutes a threat to the environment.

CONCLUSIONS

1. Long-term application of slurry from pig production as well as digestate from biogas plant caused a decrease in the pH of the majority of the analysed soils, although the dynamics of changes in the study period showed a variable rate depending on the analysed field.
2. Long-term application of slurry increased the content of available forms of phosphorus in the soil, and had no effect on the content of available magnesium. A decrease in the content of available forms of potassium in the soil was observed irrespective of the analysed field.
3. The phosphorus balance on both analysed farms in the case of fields fertilised with slurry and digestate from biogas plants was positive, within the range of values from 15 to 40 kg $P \cdot ha^{-1}$.
4. High positive phosphorus balance suggests a high surplus of the element supplied with fertilisers, and constitutes a potential threat to the quality of groundwaters and surface waters.

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Wpływ wieloletniego stosowania gnojowicy i pofermentu na zmiany zawartości przyswajalnych form makroskładników w glebie

Streszczenie: Celem podjętych badań była ocena wpływu wieloletniego stosowania gnojowicy pochodzącej z produkcji trzody chlewnej oraz pofermentu z biogazowni na zmiany odczynu oraz wybrane właściwości gleb, tj. akumulację przyswajalnych form fosforu, potasu i magnezu w warstwie ornej gleby oraz bilans fosforu. Ocenie poddano dwa gospodarstwa wielkotowarowe zlokalizowane w województwie zachodniopomorskim specjalizujące się w produkcji trzody chlewnej. Do analizy wykorzystano gleby, na których każdego roku przez 12 lat stosowano gnojowicę oraz poferment z biogazowi. Ocenę zmian zawartości i akumulacji składników przeprowadzono dwukrotnie: po 10 i 12 latach stosowania nawozów. Tempo zmian odczynu badanych gleb pod wpływem aplikacji gnojowicy oraz pofermentu z biogazowni było zróżnicowane w zależności od analizowanego pola. Dwunastoletnie stosowanie gnojowicy spowodowało obniżenie wartości pH gleby średnio o pół jednostki. Kierunek zmian zawartości przyswajalnych form składników pokarmowych w glebie był zróżnicowany. Niezależnie od analizowanego pola oraz rodzaju zastosowanej gnojowicy odnotowano zmniejszenie zawartości przyswajalnych form potasu w glebie. Nawożenie gnojowicą nie miało wpływu na zmiany zawartości magnezu w glebie. Spośród ocenianych pierwiastków tylko w przypadku fosforu stwierdzono wzrost jego zawartości w glebie pod wpływem zastosowanego nawożenia gnojowicą w połączeniu z nawożeniem mineralnym. Bilans fosforu w analizowanych gospodarstwach w przypadku pól nawożonych gnojowicą i pofermentem z biogazowni był dodatni i kształtował się w zakresie wartości od 15 do 40 kg $P \cdot ha^{-1}$. Otrzymane wartości salda bilansowego P jednoznacznie wskazują, że niezależnie od rodzaju stosowanych nawozów w gospodarstwie, powinny być podjęte działania zmierzające do wprowadzenia zmian w zakresie opracowywanych planów gospodarowania, ze szczególnym uwzględnieniem zasad zbilansowanego nawożenia.

Słowa kluczowe: gnojowica, poferment z biogazowni, gleba, bilans fosforu, odczyn gleby, potas, magnez