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ORIGINAL PAPER

CORRELATION BETWEEN THE QUANTITY OF PHOSPHORUS IN THE SOIL AND ITS QUANTITY IN THE RUNOFF IN A CULTIVATED FIELD AT A SELECTED FARM

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Abstract

Phosphorus losses from agricultural soils due to runoff pose a risk of the eutrophication of surface waters. In recent years, numerous studies dedicated to this problem have been performed. The same question has been investigated in our study as well. Our aim was to determine the relationship between the content of phosphorus in the 0-5 cm layer of arable soil, and the concentration of this element in the naturally formed surface runoff under conditions of ongoing agricultural production. The study was conducted between 2009 and 2014, on an arable field at a selected farm in West Pomerania Province. It included the parallel sampling of surface runoff and soil from an isolated portion of the field, subsequent laboratory analyses and further preparation of balance sheets for phosphorus by the "surface field" approach. The concentration of $P\text{-}PO_{4\text{ in the}}$ runoff samples was determined with the colorimetric method using a flow analyser, and the content of available forms of phosphorus in the soil samples was measured by the Egner-Riehm method. It was established that: a) within the studied period, the content of phosphorus available for plants in the soil and the concentration of phosphate phosphorus in the runoff ranged widely – from 12.6 to 288.2 mg P kg^{-1} and from 0.42 to 17.97 mg $P\text{-}PO_4$ dm^{-3}, respectively; b) the content of available phosphorus in the soil was strongly positively correlated with the concentration of phosphate phosphorus in the runoff. However, the strength of this correlation (expressed as the Pearson product-moment correlation coefficient) was smaller than the degree of correlation of the same variables determined in comparable experimental studies with the use of a rain simulator; c) application of chicken manure was the most probable cause of the occurrence of extremely large quantities of phosphorus in the surface layer of the soil and in the runoff, and could have been a crucial cause of the strong correlation of the analysed factors.

Keywords: phosphorus, cultivable soil, correlation, run-off.

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INTRODUCTION

Phosphorus-enriched runoff from agricultural soils may contribute to the eutrophication of surface waters (ANDRASKI, BUNDY 2003, MILLER et al. 2011). Due to the risk to water bodies, losses of phosphorus in soils caused by rainfall have been the subject of numerous studies in the last decades (LITTLE et al. 2006), mainly experimental studies conducted in small fields or in laboratory conditions with the use of a rain simulator (DOUGHERTY et al. 2004). Their results indicate that there is a strong linear correlation between the soil content of phosphorus and the concentration of dissolved phosphorus in the runoff (POTE et al. 1996, TORBERT et al. 2002, SHARPLEY, KLEINMAN 2003).

Relationships between phosphorus in the soil and phosphorus in the runoff occurring in natural conditions may be of a different nature in comparison to experimental conditions (LITTLE et al. 2006), mainly because the quantity of phosphorus transported in the runoff is strongly affected by the length of its journey (MCDOWELL, SHARPLEY 2002). Thus far, however, there has been too little information to facilitate a comparison of results of studies of chemical compositions of runoffs formed in small experimental fields with data obtained from runoffs formed in natural fields (BOHL BORMANN et al. 2012). Undoubtedly, in the context of the required prevention of eutrophication of surface waters, the knowledge in this respect needs deepening. The present work is an attempt to make a contribution within this scope. Its aim was to recognize, in regard of water protection against eutrophication, the level of phosphate phosphorus concentration in the runoff from arable soil depending on changes in the content of available phosphorus for plants in its top layer, resulting from the agrotechnical activities carried out at a selected farm.

MATERIAL AND METHODS

The study was conducted between 2009 and 2014, in a cultived field on Cambisols lying on a hill with an approx. 5% gradient, and situated in the commune of Stare Czarnowo, in West Pomerania Province. Due to the soil conditions and topography, the above area can be considered as representative for the mesoregion called the Wełtyńska Plains.

The range of research activities included:
- the collection of samples of runoff and soil from the selected part of the field;
- laboratory analyses of the collected samples of water and soil;
- review of the history of the use of the field, including types of crops, doses of mineral and natural fertilisers, the size and type of harvest;
- preparation of a phosphorus balance using the "on the surface of the field" method.

The runoff samples were initially collected using one and later three special gutters (collectors) with the following dimensions: length – 1.000 mm, width – 200 mm, depth – 150 mm, installed on the slope of the field. The soil samples were collected from the 0-5 cm profile (on the basis of SHARPLEY et al. 1985, SCHINDLER et al. 2004, HANSEN et al. 2012) from a part of the field located above the gutters, but a representative (consolidated) sample was formed from seven individual samples. The collection of water and soil samples was performed each time after rainfall that caused runoff. All analyses of the water and soil samples were conducted in the Research Laboratory of Environmental Chemistry of the Institute of Technology and Life Sciences in Falenty. The concentration of P-PO_4 in the water samples was determined using the colorimetric method with a continuous flow analyser. The pH (in KCl) was determined in the soil samples using the potentiometric method, while the soil reaction and content of available forms of phosphorus (P-PO_4) were measured using the Egner-Riehm method with calcium lactate solution (pH~3.55).

Before and during the collection of samples for laboratory tests, data characterising the production activity on the studied agricultural field were collected. On the basis of the data, the history of the use of the field was reviewed and phosphorus balance sheets were developed with "on the surface of the field" method, covering the farming years from 2009/2010 to 2014/2015. In the balances, on the credit side, nutrients transported into the soil from the following sources were considered: sowing material, mineral fertilisers, natural fertilisers, precipitation, and the biological binding of nitrogen by free-living micro-organisms. On the debit side, nutrients transported out of the field with the main crops (grain) and secondary crops (straw) were taken into account. Indicators needed for calculations, i.e. the content of phosphorus in the main and secondary crops, the quantity of nitrogen brought in by soil nitrogen-fixing micro-organisms and the amount of phosphorus brought in with (wet) precipitation in West Pomerania Province, were assumed on the basis of references (PIETRZAK 2013, WIOŚ Zielona Góra 2015). The share of phosphorus in the fresh mass of poultry manure equal 0.70% of P was assessed by laboratory determinations performed in OSChR (a regional chemical and agricultural station) in Gdansk. The mass of the straw collected from the field was calculated assuming that its harvest in relation to the harvest of grain is: 1 – for oliseed rape, 0.7 – for winter barley and 1.13 – for winter triticale (LUDWICKA, GRZYBEK 2010).

RESULTS AND DISCUSSION

In the farm years from 2009/2010 to 2014/2015, winter crops and winter oilseed rape were grown in the studied agricultural field. Mineral fertilisation was performed every year, including phosphorus fertilisation in doses of 15-26 kg P ha^{-1} (Table 1). Natural fertilisation with poultry manure was only

Table 1

Selected components characterising the production activity on the studied agricultural field in the farming years from 2009/2010 to 2014/2015

Specification		Farming year					
		2009/2010	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015
Crop		winter oilseed rape	winter barley	triticale	winter oilseed rape	winter wheat	winter oilseed rape
Dose of sown grains (kg ha^{-1})		3.5	135	250	3.2	280	3.5
Mineral fertiliser (kg ha^{-1})	N	247	75	119	222	210	162
	P	26	17	21	21	15	17
	K	83	50	62	75	50	50
Natural fertiliser (t ha^{-1})		-	-	15	-	-	-
Main crop (dt ha^{-1})		29.6	40	62.3	40	80	42
Management of secondary crop		collected from the field	collected from the field	collected from the field	collected from the field	collected from the field	collected from the field

performed in 2011, after the harvest of winter barley, i.e. in late August. It has to be emphasised that after the manure had been applied, the field was first harrowed and then deep ploughed.

The balances (surpluses) of phosphorus "on the surface of the field" in the studied period ranged from -13.0 to 97.5 kg ha^{-1} (Table 2). The biggest surplus of P was recorded in the farming year when poultry manure rich in phosphorus was spread on the field.

Table 2

P balances "on the surface of the field" in the farming years on the arable land

Specification	Farming year					
	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015
P enrichment (kg ha^{-1})						
- grain	0.02	0.5	0.9	0.02	0.9	0.02
- phosphorus-based fertilisers	26.2	16.6	20.9	20.9	15.3	17.4
- poultry manure	-	-	105.4	-	-	-
- precipitation	0.4	0.4	0.4	0.4	0.4	0.4
P enrichment in total (kg ha^{-1})	26.6	17.5	127.6	21.4	16.6	17.9
P withdrawal (kg ha^{-1})						
- grain	17.8	14.0	22.4	24.0	25.6	25.2
- straw	3.8	3.1	7.7	5.2	4.0	5.5
P withdrawal in total (kg ha^{-1})	21.6	17.1	30.2	29.2	29.6	30.7
P balance, surplus (kg ha^{-1})	5.0	0.4	97.5	-7.8	-13.0	-12.7
P use (%)	81.1	97.7	23.6	136.5	178.6	171.7

During the study, the content of phosphorus available for plants in the five-centimetre-deep topsoil ranged from 12.57 to 288.18 mg P kg^{-1} and the concentration of $P\text{-}PO_4$ in the runoff ranged from 0.42 to 17.97 g m^{-3} (Table 3). The biggest quantities of phosphorus in the soil and in runoff occurred on two days of sample collection directly before the use of poultry manure. In particular years of research, the average amount of phosphorus in the soil ranged from 52.39 to 112.03 mg P kg^{-1} and in runoff – from 1.08 to 9.42 mg $P\text{-}PO_4$ dm^{-3} (Table 4).

Table 3

Results of determinations of phosphorus in the soil and the runoff

No. sampling	Sampling date	Phosphorus content in soil (mg P kg^{-1})	Phosphorus concentration in the runoff (mg $P\text{-}PO_4$ dm^{-3})
1	13.05.2011	36.40	3.73
2	25.05.2011	38.44	4.09
3	10.06.2011	68.04	11.10
4	27.06.2011	52.13	11.41
5	29.09.2011	28.18	16.76
6	14.04.2012	28.56	17.97
7	16.05.2012	62.74	0.68
8	25.06.2012	27.16	0.49
9	03.07.2012	12.57	0.90
10	07.05.2013	68.93	0.55
11	15.05.2013	43.50 (34.17-49.89)*	0.42 (0.34-0.50)*
12	28.05.2013	50.64 (50.9-53.27)*	1.54 (1.11-190)*
13	17.06.2013	57.53 (38.03-89.26)*	1.45 (0.96-1.77)*
14	24.04.2014	147.41 (105.64-202.39)*	1.58 (0.92-2.58)*
15	21.05.2014	79.50 (50.92-99.13)*	1.06 (0.47-1.92)*
16	10.06.2014	9.97 (67.20-107.23)*	8.30 (2.28-17.89)*
17	14.07.2014	129.26 (105.09-151.62)*	7.40 (5.41-9.25)*
Arithmetic mean		90.59	5.26
Median		62.74	1.58
Standard deviation		81.32	5.87

* From 15.05.2013 to 14.07.2014 soil samples and runoff samples were collected from three spots in the field – the results are presented as a mean of the three measurements. Minimum and maximum values are given in brackets. Source: own results.

The content of phosphorus available for plants in the five-centimetre layer of soil with runoff on the surface underwent dynamic changes. According to the limits defined for mineral soils (PN-R-04023 1996), the content most frequently achieved very high values (over 29% cases) and then (after approx. 24% cases) medium or low values (Table 5).

The level of phosphate phosphorus concentration in the runoff is difficult

Table 4

Descriptive statistics of phosphorus content in the soil and concentration of this component in the runoff in 2011-2014

Item	Unit	Year			
		2011	2012	2013	2014
		phosphorus content in soil			
Number of sampling	pieces	5	4	10	12
Arithmetic mean	(mg P kg^{-1})	96.64	97.01	52.39	112.03
Median		52.13	44.95	48.82	105.37
Standard deviation		107.82	127.46	15.94	39.63
Max.		288.18	285.56	89.26	202.39
Min.		36.40	12.57	34.17	50.92
		phosphorus concentration in the runoff			
Number of sampling		5	4	10	12
Arithmetic mean	(mg P-PO$_4$ dm^{-3})	9.42	5.01	1.08	4.59
Median		11.10	0.79	1.03	2.43
Standard deviation		5.51	8.64	0.61	5.05
Max.		16.76	17.97	1.90	17.89
Min.		3.73	0.49	0.34	0.47

Table 5

Evaluation of phosphorus content in selected soil samples in comparison to the evaluation criteria listed in PN-R-04023 (1996)

Range of phosphorus content in soil (mg P kg^{-1})	Contribution of samples in the range of content (%)	Assessment of content
<22	5.9	very low
<22-45)	23.5	low
<45-66)	23.5	medium
<66-88)	17.6	high
≥88	29.4	very high

to evaluate unambiguously due to the lack of reference values. Indirectly, it can be assumed that it was significant, taking into account that:

– the concentration of phosphate phosphorus in all the samples exceeded the limit value of 0.1 g P-PO$_4$·m^{-3} corresponding to good class waters (*Regulation of the Minister of Environment*… 2014);

– all the runoff samples contained over 0.25 g P$_{og}$ m^{-3}, which classified them as sensitive to eutrophication[1] (*Regulation of the Minister of Environment*… 2002).

[1] The limit value of 0.25 mg P dm^{-3} refers to total phosphorus. It can be assumed that if the concentration of phosphorus in water samples was bigger than the limit values for total phosphorus, the concentration of P$_{og}$ was bigger than the defined norm.

– in over 35% of the samples there was over 5 g P_{og} m^{-3}, i.e. more than the acceptable concentration of phosphorus in treated wastewater introduced into surface waters (*Regulation of the Minister of Environment*... 2006).

There was a strong, directly proportional positive correlation between the concentration of phosphate phosphorus in the runoff and the content of mobile phosphorus forms in the top layer of the soil, expressed as the value of the determination coefficient (R^2) amounting to 0.582 (Figure 1).

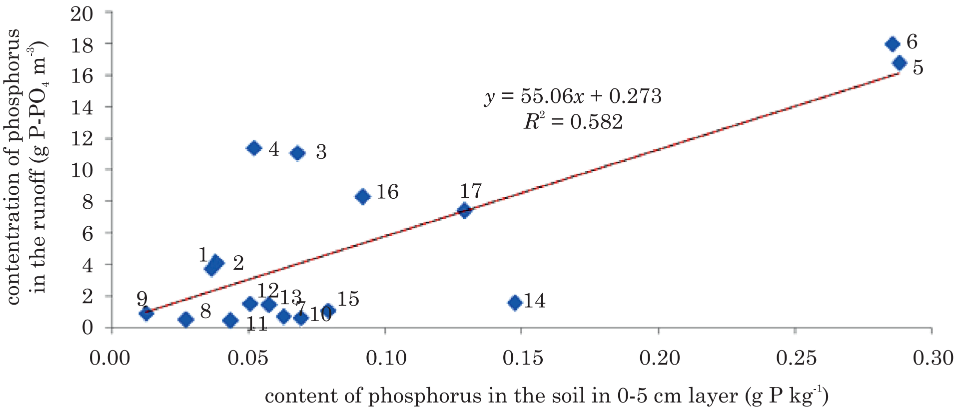

Fig. 1. Correlation between the phosphorus concentration in the runoff and its content in the top five-centimetre layer of the soil (determined using the Egner-Riehm method): 1, 2... no. of sampling

The degree of this correlation was lower than the degree of the correlation of changes in the content of available phosphorus in the soil versus the concentration of this nutrient in the runoff achieved in similar conditions to the ones in the study, but with the use of a rain simulator. In such studies, determination coefficients concerning the studied factors are normally higher than 0.65 (Table 6).

The predominantly extremely high values of determinations of the studied parameters in the soil and runoff samples which were collected in September 2011 and April 2012 resulted in a fairly strong correlation between the concentration of dissolved phosphorus in the runoff and the content of available phosphorus in the soil. Had the results of those determinations been excluded, the correlation between the studied factors would have been statistically insignificant. A significant quantity of phosphorus in the water and the soil on the former sample collection date is undoubtedly related to the preceding application of a large dose of phosphorus in poultry manure and shallow harrowing. Significant accumulation of phosphorus in the top layer of the soil and in the runoff could have been related to the low-depth incorporation of manure (using a harrow). By analogy, GILLEY et al. (2007) posited that when a harrow was used to cover cattle manure (compost), the

Table 6

Determination coefficients defining the strength of correlation between the concentration of dissolved phosphorus in the runoff and the content of available phosphorus in the soil on the basis of studies using a rain simulator according to various authors

Coefficient of determination	Crop type	Depth at which soil samples were collected (cm)	Soil test type	Source
R^2 = 0.715-0.961	green area	0-5	Mehlich-3 and soil water extraction	TORBERT et al. (2002)
R^2 = 0.91-0.92* R^2 = 0.88-0.89**	green area, corn (no tillage), ploughed field	0-5	Mehlich-3	SHARPLEY, KLEINMAN (2003)
R^2 = 0.64-0.96	corn and soybean rotation	0-5	Olsen, Bray-Kurtz, Mehlich III, water extraction, 0.01 m calcium chloride	SCHINDLER et al. (2009)
R^2 = 0.65-0.69	green area	0-5	Mehlich-3 and soil water extraction	SCHROEDER et al. (2004)
R^2 = 0.92-0.95	field with no cover crops	0-15	Mehlich-3	DAVIS et al. (2005)

content of phosphorus (measured with the Bray-1 test) in the top five-centimetre layer of the soil was 200 mg kg^{-1} and the concentration of dissolved phosphorus in the runoff was 1.73 g P m^{-3}, whereas when a plough with mouldboards was employed, the indicators achieved significantly smaller values: 48.0 mg kg^{-1} and 0.03 g P m^{-3}, respectively. The extremely high amounts of phosphorus in the runoff and the soil in April 2012 are more difficult to interpret, at least because the field was ploughed deep in the autumn of 2011. However, they also seem to be a subsequent effect of the application of poultry manure and the consequent surplus of phosphorus "on the surface of the field" in the farming year of 2011/2012 (no implications as to other causes).

On the basis of the above findings, it can be claimed that the use of manure is an especially sensitive treatment due to the risk of phosphorus losses through its withdrawal with runoffs. It can be presumed that if the fertiliser had been covered with soil immediately after its application, the degree of correlation between the concentration of dissolved phosphorus in the runoff and the content of available phosphorus in the soil would have been significantly lower than the one we recorded.

CONCLUSIONS

1. During the study, the content of phosphorus available for plants in the five-centimetre-deep top soil underwent significant changes from approx. 12.6 to approx. 288.2 mg P kg^{-1}, which may be associated especially with the effect of such factors as the type of crops, dose of phosphorus in mineral fertilisers and manure, type of cultivation treaments, and the date of soil sample collection.

2. Runoffs from the studied field were characterised by a significant concentration of phosphorus (0.42-17.97 g P-PO_4 m^{-3}) and thus constituted a potential source of contamination of surface waters with this element.

3. There was a strong, directly proportional correlation (R^2 = 0.582) between the concentration of dissolved phosphorus in the runoff from the cultived soil and the content of phosphorus available for plants in its surface layer. However, it was lower than the level of correlation between the mentioned factors demonstrated in experimental studies using a rain simulator.

4. The use of poultry manure probably had a decisive effect on the correlations between the concentration of phosphorus in the run-off and the content of this element in the soil.

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