Possible phosphorus losses from the top layer of agricultural soils by rainfall simulations in relation to multi-nutrient soil tests

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ABSTRACT

The objective of the study was to examine a possibility of predicting phosphorus leaching from the top layer of agricultural soils by rainfall simulations by means of three multi-nutrient soil tests: Mehlich 3, NH_4-acetate extraction and water extraction (1:5, w/v). Another objective was to determine parameters of maximum phosphorus losses after an extreme load of rainfall on the top layer. Forty soils from different localities of the Czech Republic were used for the experiment. A leaching experiment was conducted in pedological cylinders with a soil layer of about 1 cm and with the bottom from a glass microfibre filter with pores 1.2 μm in size. Within 15 days the soils were flooded ten times with 25 mm of simulated rainfall in a minimum interval of 1 day. The closest regression between the soil test and phosphorus leaching was computed for NH_4-acetate soil test (R^2 = 0.8831) and Mehlich 3 test (R^2 = 0.8572) after the first application of 25 mm of rainfall. In water extraction it was for the mean of 10 simulated rainfalls (R^2 = 0.8674). As leaching proceeded, the closeness of regression diminished due to fluctuations of P concentration in leachates (increases and decreases), mainly in soils with higher *P*-test. The increase in P concentration could be caused by the activation of phosphorus from Fe-phosphates under anaerobic conditions in wet soils. The steepest decrease in P concentration in leachates was observed in light soils with low CEC value and higher initial *P*-test.

Keywords: phosphorus; soils; leaching; soil tests; Mehlich 3; NH_4-acetate extraction; water extraction

After nitrogen, phosphorus is another biogenic element with marked environmental impacts on water quality. This phenomenon was recently emphasized and considered to some extent as superior to the basic importance of phosphorus as an essential nutrient for the provision of sufficient crop production, sufficient foods, for the increasing human population on the Earth (Denison and Kiers 2005, Reid et al. 2005). The reason is that in agricultural areas the long-term intensive applications of phosphoric fertilizers to soils and phosphorus recycling in farmyard manure caused the situation when the soil, originally a strong sink of phosphorus, became a source of its escape to the environs (Sharpley et al. 1992, Sharpley et al. 1996, Haygarth et al. 1998, Sharpley et al. 2001, Sharpley et al. 2004).

For example the uptake of phosphorus converted per 1 t of wheat grain yield from the field is 3.3 kg P/ha, that of winter rapeseed 7 kg/ha (Klír et al. 2008). From the aspect of the long-term strategy of soil fertility conservation for necessary production of foods and feeds for the increasing human population on the Earth phosphorus taken up by the crop yield from the soil must be recompensed (Tilman et al. 2002, Denison and Kiers 2005). It is to note that only the efficient reserve of labile forms of phosphorus should be maintained in agricultural productive soils. This should be ensured by a systematic testing of the nutrient status of soils including agronomic calibration for the present needs of agriculture (Fixen 2005). Raij (1994) considered soil testing as a remarkable and unique activity that synthesises a large amount of research information and scientific knowledge for practical needs of the identification and prevention of the majority of disproportions in plant nutrition in a given field. Soil testing provides

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farmers with the highest quantity of practically applicable information.

Unfortunately, an agronomic approach to the fertilization of farmed lands during its long history, i.e. intensification of crop production, has mainly been used. Due to considerable phosphorus chemosorption in the soil and low phosphorus uptake capacity of crops (e.g. potatoes usually take up 16–20% of the P-fertilizer rate) P fertilization rates were 3–5 times higher than the actual uptake of phosphorus for a good yield. The environmental aspect, i.e. potential contamination of waters by phosphorus with subsequent disturbance of ecological balance in farmed cultural landscape, has been omitted completely.

An assessment of the reserve of labile forms of phosphorus in soil by soil tests has a long tradition. Unfortunately, an erroneous idea, that it is not possible to overfertilize with phosphorus, has also persisted until now that was primarily initiated by the large-scale deficiency of phosphorus in soils and by precipitation of applied water-soluble forms of phosphorus into soil. In the agronomic categorization of phosphorus storage in soils by means of soil tests the upper limit values and their necessity for high yields have not been proved conclusively and experimentally either from the aspect of maximum utilization of phosphorus for crop production or in relation to the potential transport of soluble phosphorus from the soil by water runoff from fields. The application of environmental principles is absolutely missing here. If the aqueous phase of soil were always localized within the soil profile of the given field, everything would be all right. However, in climatic conditions of this country there exist periods when precipitation water exceeds the retention capacity of soil. The aqueous phase of soil leaves the field profile percolating to groundwater or as lateral surface runoff in dependence on the relief of the field and surrounding landscape. It is mainly in the washing period during winter vegetation resting. In addition, when the frequency of events of intensive rainfalls and torrential rainfalls in the growing season increased, the retention capacities of agricultural fields were exceeded. According to the relief, crop and hydro-pedological characteristics of soil water runs off the field and it may result in undesirable contamination of waters by phosphorus. Possible contamination of runoff waters by phosphorus will basically be influenced by the content of labile phosphorus forms in soil and by the easiness of their conversion to water-soluble fractions. But the actual load of phosphorus on watercourses will be different in relation to hydrological characteristics of soil and geography of the terrain of surrounding landscape that are largely variable and locally specific (Johnston and Dawson 2005).

The need for economic use of phosphorus in agriculture is accentuated by the finite supply of economically acceptable P resources (phosphates) for the production of concentrated fertilizers. Sufficient reserves of P resources are estimated to last for about 70 years and maximally for 300 years (Roberts and Stewart 2002, Isherwood 2003).

The objective of our study was to test a possibility of predicting phosphorus mobilization from the top layer of agricultural soils into the aqueous phase after simulation of intensive rainfall on the basis of the knowledge of phosphorus reserve in soils diagnosed by multi-nutrient soil tests: Mehlich 3, NH_4-acetate extraction and water extraction (1:5, w/v). Our study also aimed to determine parameters of maximum possible phosphorus losses after an extreme load of rainfall on the top layer causing water surface runoff in exposed localities.

MATERIAL AND METHODS

Forty soils from the topsoil of agricultural lands from different localities of the Czech Republic were used in the experiment (Table 1). After air-drying, soils samples were homogenized by screening through a 2-mm mesh sieve.

Three soil tests were used to evaluate the nutrient status of soils like in the previous work Matula (2009): Mehlich 3 (Zbíral 2002), water extraction 1:5 w/v (SPAC 1999) and extraction with 0.5M ammonium acetate with addition of ammonium fluoride (Matula 1996). The content of oxidizable organic matter was determined according to Sims and Haby (1971). Selected results are shown in Table 1.

Calibrated pedological stainless cylinders (50 mm in diameter, 51 mm in height; Eijkelkamp, the Netherlands) were used for a leaching experiment. The bottom of the cylinder consisted of a glass microfibre filter with pores 1.2 μm in size. The disk of the glass microfibre filter 9 cm in diameter was covered with permeable garden plastic sheet (Fargilia) and fixed with elastic bands to the outer wall of the pedological cylinder. An amount of 30 g soil was spread on the bottom of the cylinder that made a layer about 1 cm in thickness. A circle of the glass microfibre filter 47 mm in diameter was put on the soil surface to protect the soil surface

Table 1. Information about characteristics of the experimental set of soils

Number of soil	Origin of soils and soil classification	pH (0.2M KCl)	CEC mmols(+)/kg	C_{ox} (%)	*P*-soil tests (mg P/kg)		
					Mehlich 3	NH_4-acetate	water (1:5)
2	Vrchovina, Fluvisols	4.72	41	0.62	261	40.2	10.6
3	Sedlejovice, Cambisols	5.11	77	0.77	184	27.1	8.9
4	Sychrov, Cambisols	5.10	81	0.58	111	18.3	4.4
5	Sychrov, Cambisols	6.31	102	0.99	127	15.7	6.6
6	Opatovice, Cambisols	5.74	114	1.15	97	16.5	8.6
7	Opatovice, Cambisols	5.70	118	1.22	102	20.3	9.5
8	Heltín, Regosols	5.20	84	0.79	79	16.9	6.6
9	Rápošov, Luvisols	5.20	70	0.58	59	12.9	4.1
10	Kateřinky, Podzoluvisols	3.94	113	0.88	63	12.4	3.8
11	Kateřinky, Podzoluvisols	4.73	174	1.27	62	10.0	6.5
12	Petrovice, Cambisols	6.11	133	1.24	82	9.5	6.0
13	Dobříč, Luvisols	6.03	132	1.63	61	9.0	6.0
14	Dobříč, Luvisols	6.03	132	1.47	55	7.5	5.4
15	Hradiště, Podzoluvisols	6.34	120	1.09	91	11.6	5.4
16	Hradiště, Podzoluvisols	5.90	126	1.17	35	6.6	6.0
17	Hradiště, Podzoluvisols	5.68	99	1.11	74	11.2	5.8
18	Úboč, Podzols	4.64	138	1.48	115	19.3	8.3
19	Chocomyšl, Cambisols	5.74	127	1.23	48	9.7	7.0
20	Kaničky, Podzoluvisols	5.58	161	1.31	47	9.1	7.5
21	Přeseky, Gleysols	6.50	71	1.04	372	49.2	19.7
22	Přeseky, Gleysols	6.64	60	0.86	259	32.3	11.1
23	Vranín, Fluvisols	6.52	83	1.76	154	13.7	7.7
24	Drnek, Rendzinas	6.06	161	1.72	111	13.3	10.8
25	Drnek, Rendzinas	5.42	143	1.50	147	17.5	13.3
26	Libovice, Cambisols	5.62	133	1.28	66	9.4	6.4
27	Hrušov, Podzoluvisols	5.96	103	1.29	46	8.1	4.2
28	Bečice, Cambisols	6.05	136	1.43	173	14.1	9.4
29	Stádlec, Cambisols	4.96	102	0.92	36	7.5	4.3
30	Roveň, Regosols	5.86	112	0.91	80	7.8	4.9
31	Příchvoj, Cambisols	5.64	125	0.91	421	51.3	26.3
32	D.Bousov, Xerosols	4.74	220	1.38	57	7.1	5.9
33	Horka, Phaeozems	6.64	145	1.08	70	7.4	4.2
34	Zdětín, Phaeozems	6.66	142	0.91	60	5.4	4.2
35	Senice, Chernozems	6.78	279	3.50	27	6.9	5.5
36	Vidlatá Seč, Vertisols	5.55	128	1.44	225	32.1	17.2
37	Vidlatá Seč, Vertisols	5.68	112	1.15	268	42.0	15.6
38	Vidlatá Seč, Vertisols	5.98	127	1.18	241	31.0	17.4
39	Morašice, Arenosols	6.12	116	1.15	132	17.8	10.2
40	Dolany, Phaeozems	6.89	140	1.48	200	19.6	9.4
41	Staré Ždánice, Greyzems	5.56	84	0.75	110	18.8	12.4

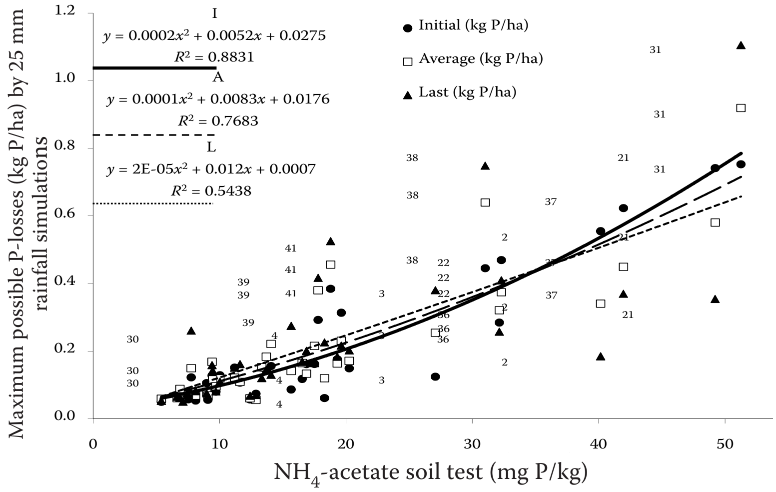

Figure 1. The relationship between the NH_4-acetate soil test and the maximum possible losses of phosphorus from soils by 25 mm rainfall simulation. (Arabic cipher means the number of soil)

from washing away with simulated rainfall water. Before the leaching experiment started, the soil was saturated with distilled water by capillary rise. After capillary saturation of the soil the cylinder with the soil was put into a plastic filter funnel and the application of 50 ml of distilled water with a measuring batcher started. One water dose of 50 ml simulated a rainfall of 25 mm. Simulated rainfall was applied to the soil surface in these daily intervals: day 1, 2, 3, 4, 5, 9, 10, 11, 12 and 15. After the application of the water dose the cylinder was covered with watch glass. The phosphorus concentration was immediately determined in percolates. The ICP-OES technique (Thermo Jarrell Ash Trace Scan Analyzer) was used for the detection of phosphorus and other nutrients.

Experimental results were evaluated by statistical programmes GraphPad PRISM, Ca., USA, version 4 and Microsoft Excel 2003.

RESULTS AND DISCUSSION

Figures 1 to 3 illustrate the relations between soil tests and phosphorus leaching from the soil by simulated doses of 25 mm rainfall. Each graph shows three regression relations between a specific soil test and phosphorus leaching from the soil as converted per phosphorus losses per one-hectare area. Regression (I) represents the reaction of soils to the application of the initial dose of rainfall water. Regression (A) was derived from the mean of the determined values of phosphorus leaching by 10 simulated rainfalls within 15 days of experiment duration. Regression (L) is related to phosphorus leaching by the last dose of simulated rainfall event. The Arabic numeral at the point in the graph identifies the soil number (Table 1). A shift of points (I and L) in the specific soil signals the individual character of the reaction of a given soil to the course

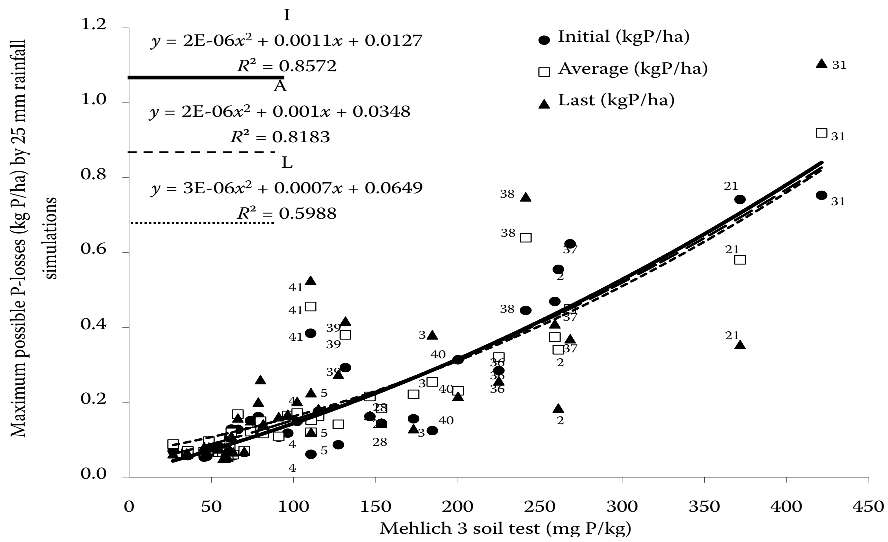

Figure 2. The relationship between the Mehlich 3 soil test and the maximum possible losses of phosphorus from soils by 25 mm rainfall simulation. (Arabic cipher means the number of soil)

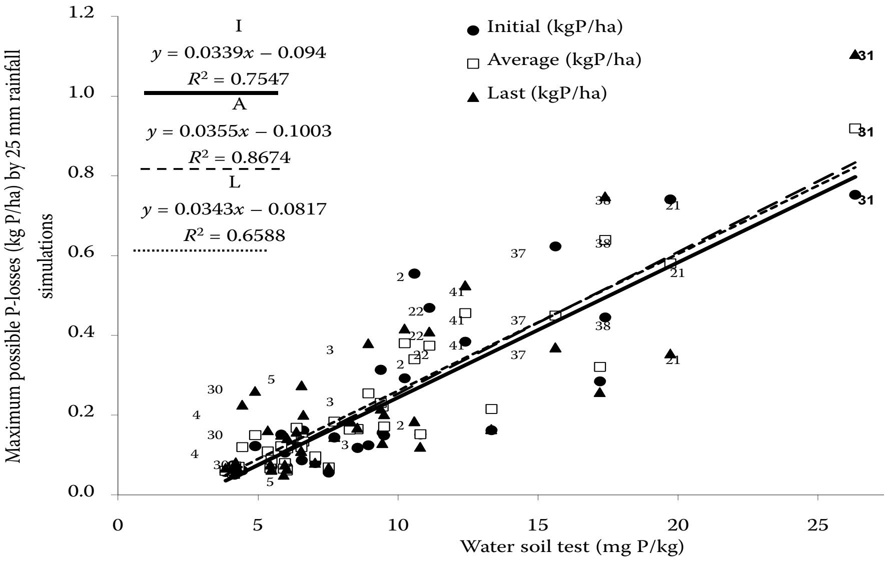

Figure 3. The relationship between the water soil test and the maximum possible losses of phosphorus from soils by 25 mm rainfall simulation. (Arabic cipher means the number of soil)

of intensive soil leaching. A decrease in the concentration of percolate phosphorus was recorded between the first and the last dose of simulated rainfall and an opposite trend of an increase in phosphorus concentration in percolate was also observed during the leaching experiment.

The most marked decrease in phosphorus concentration in leachate was observed between the first and the last dose of simulated rainfall in soil 2 and 21. Both these soils were light sandy soils and had a high value of soil test phosphorus before the start of leaching experiment (Table 1) and at the same time a very low CEC value. On the contrary, in soils 4, 38 and 31 an increase in phosphorus concentration in leachate was recorded at the end of leaching experiment. Soil 4 belonged to the category of the lower phosphorus reserve in soil determined by soil tests. Soil 38 and soil 31 had a medium and a higher reserve of phosphorus, respectively. More detailed information on the dynamics of phosphorus concentration in leachates during the leaching experiment is shown in Figures 4–7.

The closest regression relation of soil test to the prediction of possible phosphorus losses by leaching from the soil was computed in the NH_4-acetate soil test (R^2 = 0.8831) and in Mehlich 3 soil test (R^2 = 0.8572) after the first dose of simulated rainfall of 25 mm. Soils 3, 4 and 41 deviated from the determined regression relation to the largest extent. In soil 3 and 4 the prediction of leaching by NH_4-acetate and Mehlich 3 soil test was higher than the actual leaching while in soil 41 it was lower. In the soil test with water extraction (1:5, w/v) the closest regression relation with phosphorus leaching was determined for the mean of all values of ten doses of simulated rainfall (R^2 = 0.8674).

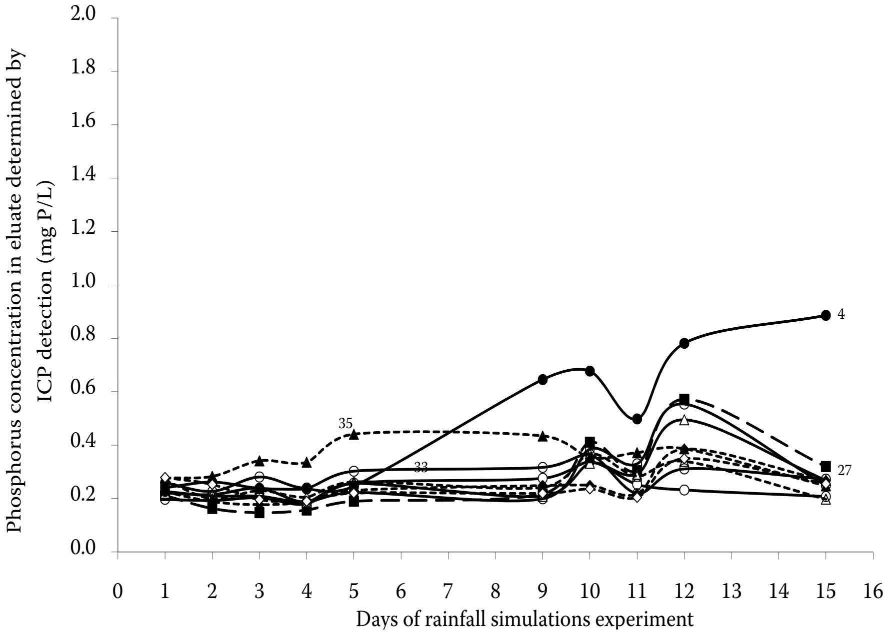

Figure 4. Dynamics of P-concentration in leachates from soils during the rainfall simulations experiment (4, 27, 29, 20, 10. 35, 33, 32, 16, 34)

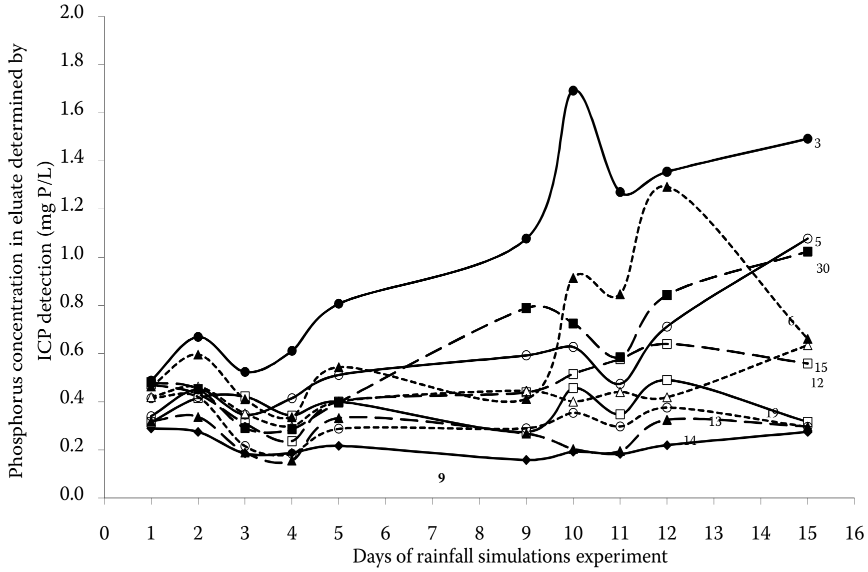

Figure 5. Dynamics of P-concentration in leachates from soils during the rainfall simulations experiment (3, 5, 30, 6, 15, 12, 19, 13, 14, 9)

In all three soil tests the closeness of the relation with the prediction of possible losses by leaching diminished significantly in the last application of simulated rainfall (Figures 1–3). It can be explained by a well-known fact, especially from paddy fields, when the values of phosphorus diagnosed by soil tests before flooding do not correspond to the actual phosphorus nutrition of rice that is mostly better. The concentration of phosphorus in the soil solution increases upon flooding. Such increases are due to the reduction of ferric phosphates into more soluble ferrous phosphates. None of the common soil extractants can detect reductant-soluble phosphorus, which may become available upon flooding. Many of the common extractants do not detect much Fe-P (Sanchez 1976).

Figures 4 to 7 illustrate the dynamics of phosphorus concentration in percolates after the tenfold load of simulated rainfall on soils in the course of fifteen days. For the transparency of the graphical representation of results the set of 40 soils was divided into four subsets of 10 soils according to the initial phosphorus concentration in percolate after the application of the first simulated rainfall.

In soils with the low initial concentration of phosphorus in leachate (0.20–0.28 ppm P) the P concentration did not decrease in subsequent leachates of the leaching experiment. The dynamics of P concentration in leachates is quite stable (Figure 4). Only in soil 35 with a high content of oxidizable organic matter (C_{ox}) a slight increase in P concentration in leachates was recorded from

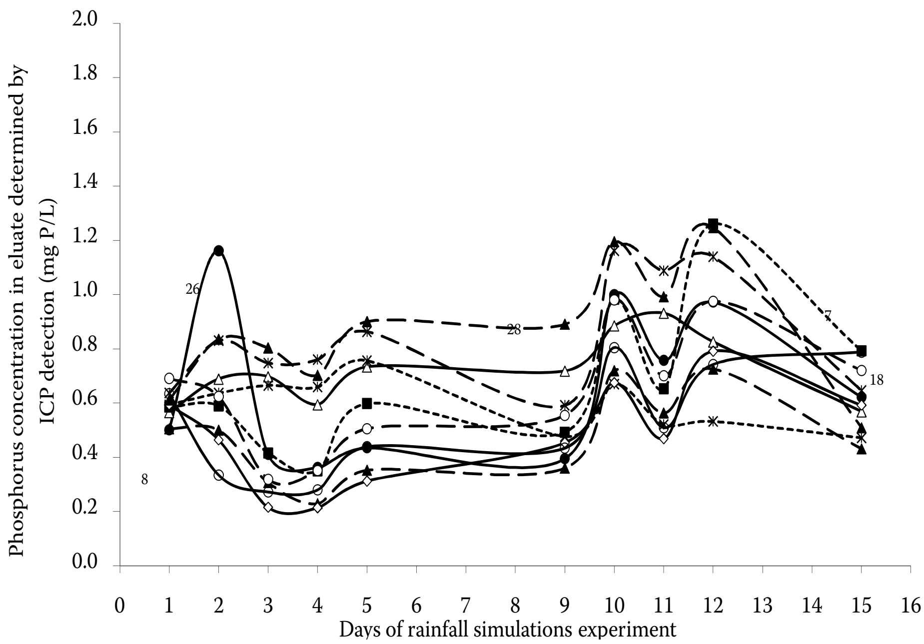

Figure 6. Dynamics of P-concentration in leachates from soils during the rainfall simulations experiment (7, 8, 18, 25, 26, 17, 23, 28, 24, 11)

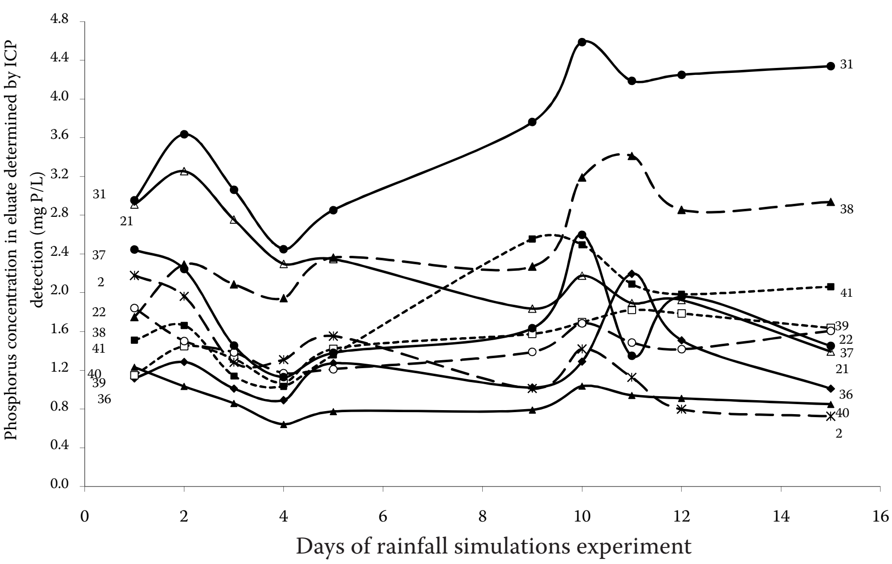

Figure 7. Dynamics of P-concentration in leachates from soils during the rainfall simulations experiment (31, 21, 37, 2, 22, 38, 41, 40, 39, 36)

day 3 to day 12 of the experiment duration. Soil 4 showed higher fluctuations and an increase in P concentration in leachates, which reached 0.89 ppm P at the end of experiment.

In a subsequent subset of ten soils with the initial concentration of 0.29–0.49 ppm P higher fluctuations and an increase in P concentration in leachates from soils 3, 5, 30, 6, 15 and 12 were recorded (Figure 5). In a subsequent subset of ten soils with the higher initial concentration (0.50–0.68 ppm P) marked fluctuations (both increases and decreases) of P concentration in leachates were also determined (Figure 6).

In soils with the highest initial phosphorus concentration in leachates (1.12–2.95 ppm P) we recorded the most marked fluctuations of the dynamics of phosphorus concentration in leachates in the course of 15-day experiment (Figure 7). The soils showed marked individual features documenting different intensity of phosphorus desorption and activation of water-soluble phosphorus from labile forms of phosphorus in the soil in conditions of water saturation of soil. The anaerobic conditions that originate as a result of water saturation of soil and microbial activity create reduction conditions for the activation of water-soluble phosphorus, especially from Fe-phosphates. This well-known phenomenon was recently confirmed by Loeb et al. (2008). In their study during the inundation experiment, concentration of P in the pore water rose 2–90 times compared to the initial concentration. An important predictor variable of P release was found in the ratio between the concentration of iron-bound P and amorphous iron. In our leaching experiment the highest increase in P concentration in leachates was recorded in soil 38 (1.9 times) and in soil 31 (1.6 times) compared to the initial concentration. The steepest decrease in concentration during leaching occurred in soil 2 (3.1 times) and in soil 21 (2.3 times), which was already mentioned above. These are sandy soils with a low CEC value.

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