Technology for Reduction of Phosphorus Leaching and Optimization of Plant P Nutrition in River Basin

E.A. Bocharnikova

Institute Physical-Chemical and Biological Problems in Soil Science Russian Academy of Sciences,
Pushchino, 142290, Russia, e-mail: mswk@rambler.ru

ABSTRACT

Eutrophication of natural waters initiated by P leached from agricultural soils is an urgent problem. Frequent, heavy rainfall and widespread use of irrigation and drainage can lead to leaching 20% to 80% of the nutrients and chemicals added from well-drained soils. A solution of the problem should be founded through an understanding of the chemical and physical-chemical processes in the soil-microorganism-plant system related with P behavior. The movement of P through soil is a complex process, controlled by biological, chemical, and physical soil conditions. Solid Si-rich substances with high surface areas can adsorb mobile P keeping it in a plant-available form. Column, greenhouse, and field tests with three commercial Si fertilizers (Calcium silicate, Pro-Sil, and Zam-Sil) were conducted in Florida in the basin of Okeechobee Lake. Column and greenhouse experiments were conducted with Spodosol and Entisol. Bahiagrass was used as a test plant. Superphosphate and P-bearing solutions of different concentrations were used as source of P. All Si fertilizers tested significantly reduced P leaching in the column and greenhouse trials. Calcium silicate reduced P leaching by 20 to 35%, while Pro-Sil and Zam-Sil reduced it by 60 to 95%. It is important to note that fixed P kept in a plant-available form. The greenhouse test has shown an increase in the plant tissue P, varying from 15 to 25 % and in the plant biomass, varying from 20 to 37 % under Si fertilization. By this means, the Si fertilizers reduced P leaching and kept P as plant-available. The field trial was conducted in the area of about 33 hectares, located about 10 km on the north from Okeechobee Lake. This field was included in the multiyear monitoring by South Florida Water Management District. Automatic sampling of water from nearby creeks was installed 10 years before the experiment with Si fertilizer. Prior to application of the Si fertilizers, the soil P was evaluated. Si fertilizer (Pro-Sil) was applied at various rates depending on micro relief and water accumulation basin. The P was tested in the soil and in the creek waters near by the experimental field. The soil data has demonstrated the benefits from Pro-Sil application in P plant nutrition. The P concentrations in the creeks reduced twice and more as compared with those in previous years.

INTRODUCTION

The transport of phosphorus (P) from agricultural sandy soils to natural waters has been an important environmental concern for more than 50 years. Brayan started the investigation of P leaching from sandy soils on citrus groves in Florida in 1933. Using lysimeters, Neller (1945) demonstrated that 62% to 90% of superphosphates applied to acid sandy soils was lost from the surface horizon due to P leaching. Phosphorus leaching has also been reported to occur in organic soils and coarse-textured mineral soils (Sims et al., 1998). Frequent, heavy rainfall and widespread use of irrigation and drainage can lead to leaching from 20% to 80% of the added nutrients and chemicals from well-drained soils (Campbell et al., 1985; Humphreys and Pritchett, 1971; Sims et al, 1998). Sandy soils usually have low P retention due to (i) the essential lack of aluminosilicates and metal-oxide clay in the albic E horizon (Harris et al., 1996) and (ii) the presence of a seasonal shallow water table promoting lateral P transport within the E horizon (Mansell et al., 1991).

The movement of P through soil is a complex process, controlled by biological, chemical, and physical soil conditions. Plants and microorganisms can absorb P thus contributing in P leaching reduction. Phosphorus reacts with Ca, Al, Fe, or Mn and forms slightly soluble or plant-unavailable P compounds (Lindsay, 1979). So, lime material usually used for reducing P mobility negatively affects P plant nutrition.

Biogeochemically active Si-rich substances (Si fertilizers) usually exhibit very good adsorption capacity (Rochev et al., 1980). Some studies have shown the beneficial role of Si fertilization in reducing the leaching of K and other mobile nutrients from the surface soil horizon (Matichenkov, 1990; Tokunaga, 1991). Solid Si-rich substances, with high surface area adsorb mobile P keeping it in a plant-available form (Matichenkov, 1990; Matichenkov et al, 1997; Olivera et al., 1986). On the other hand, the anion of monosilicic acid can replace the phosphate anion from sparingly soluble Ca, Mg, Al, and Fe phosphates, as a result, the mobility of P increases.

By this means, Si fertilization can initiate two processes: 1) transformation of slightly soluble P into mobile plant-available form and 2) physical adsorption of mobile P on the surface of Si-rich substances, thereby, reduction in P leaching from the soil.

The aim of this investigation was to study the role of Si-rich substances in regulating P behavior in the soil.

MATERIALS AND METHODS

Laboratory experiments

Two types of soils (Spodosol and Entisol) were used in the column test. Entisol (Margate series, sandy, siliceous, hyperthermic Mollic Psammaquents) was collected in Hendry County, native Spodosol (Ancona series, sandy, siliceous, hyperthermic, orstein Arenic Haplaquods) was collected from a pine forest in St. Lucie County near the Indian River Research and Education Center, Ft. Pierce. The soil samples were selected at depths of 0-20 cm., air-dried, and ground to pass through a 1-mm sieve. The selected properties of the soils under investigation are presented in the Table 1.

Table 1. Selected properties of investigated soils.

Soil	Organic matter, %	pH (H_2O)	Water-extractable P, mg kg^{-1}	Acid-extractable P, mg kg^{-1}	Sand, %
Entisol	0.6-0.7	7.4-7.6	0.8-2.4	46-55	95-97
Spodosol	0.6.-0.8	5.0	0.2-0.7	5-12	95-97

Pro-Sil (special product from steel production, PRO-CHEM Chemical Company, FL, USA), lime (chemically pure $CaCO_3$) and Zam-Sil (liquid Si fertilizer, Terra Tech Corp. FL, USA) were used in laboratory and greenhouse experiments. The selected properties of the materials tested are presented in the Table 2.

Table 2 Selected properties of investigated materials.

Material	pH (H_2O)	Ca,%	Fe, %	Al,%	Si, %
Pro-Sil	7.6	27-31	0.08-0.4	0.2-0.3	13-14
Zam-Sil	12	0	0.3-0.4	0.1-0.2	6-8
Lime	8.4	40	0	0	0

The column experiment was designed to evaluate the influence of Pro-Sil, Zam-Sil, and lime on P leaching in different soils. The solid materials at the rate equal to 1 t ha^{-1} were mixed with dry soil samples. Zam-Sil was diluted with water (1:1000) and mixed with soil samples. Then the treated soil samples were dried at 24-30°C. The plastic column had a volume 60 cm^3 and a diameter 2.5 cm. The P-bearing solutions of 2.5 and 10 P mg L^{-1} were added to the column at 6-8 ml h^{-1} using a peristaltic pump. The percolate was collected at 20 mL intervals. After adding a drop of chloroform the solutions were stored in a refrigerator at 4°C. A total of 300 mL solution was applied to each column. Each column was replicated three times and triplicate analyses of each liquid sample were conducted. At the conclusion of the leaching period, the soils were dried at 65^0 C and passed through a 1 mm sieve. Triplicate soil and sand samples were analyzed for water- and acid (0.1 N HCl)-extractable P. The percolate solutions and extracts were analyzed for P colorimetrically (Eaton et al., 1995). All data was subjected to an analysis of variance and standard deviations were calculated. Fisher's coefficients were used for determining LTD_{05}. Excel Microsoft from Office 97 was used for all calculations.

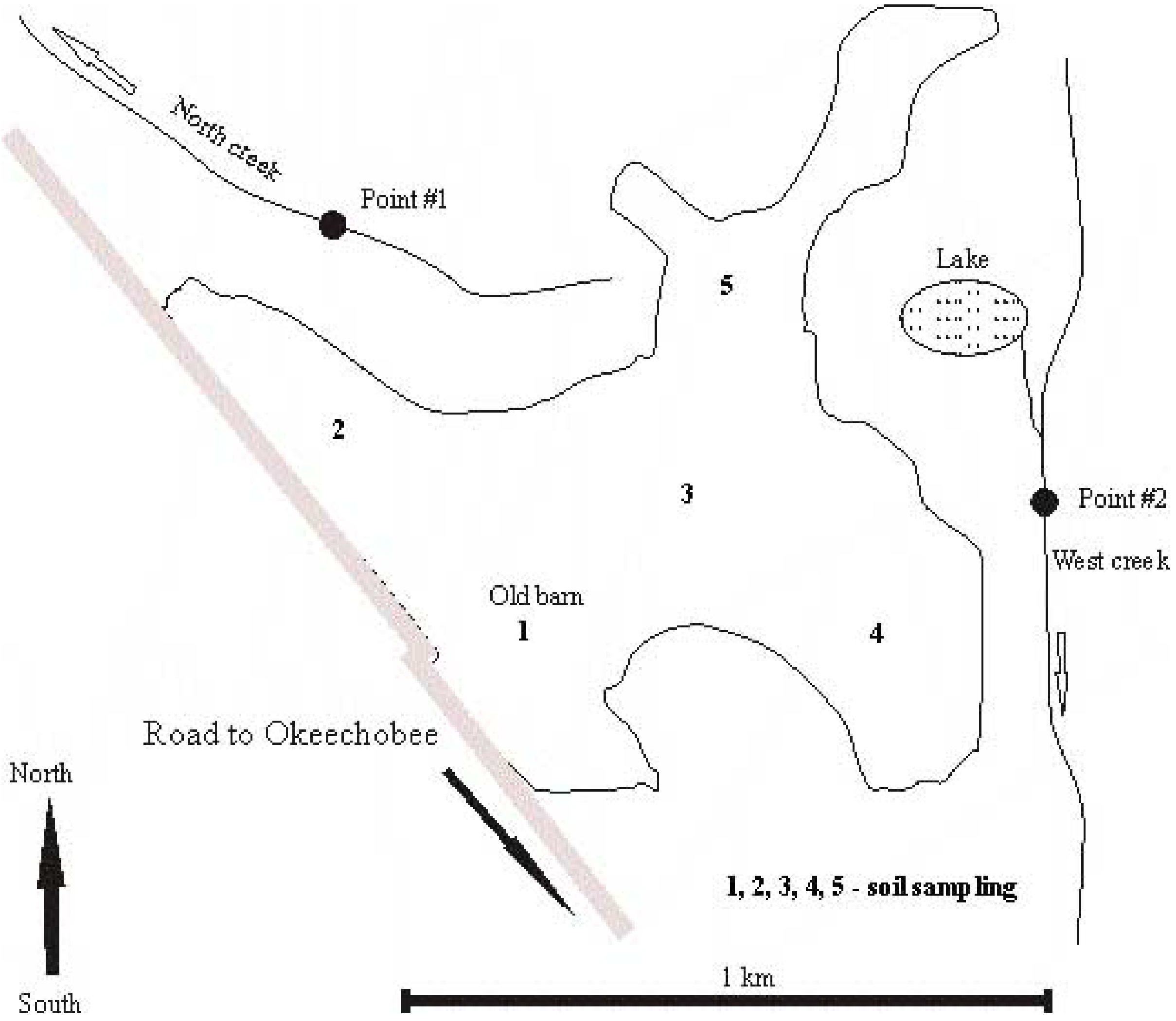
Greenhouse test

Surface horizons of Entisol and Spodosol were used in the greenhouse experiment. Soil samples were treated with Pro-Sil, Zam-Sil (diluted by 1:10) or lime at the rate of 1 g kg^{-1} which is equal to 1 t/ha and put to plastic pots. Bahia grass (*Paspalum Notatum)* was used as a test plant (120 seeds per pot). Each variant had 3 replications. After seeding first percolates were collected from button of pots. Then percolates were sampled at 2-week interval. Phosphorus in the percolate was analyzed by standard method with 3 replications for each pot (Eaton et al., 1995). After 3 months the plants were harvested. One hundred plants from each variant were sampled. The weight of fresh and air-dried (65°C) shoots and roots were measured separately for each 10 plants. Then the dried shoots and roots were ground and the content of total P was determined by standard method. Soil samples from each plot were collected, air-dried, ground, and passed through a 2 mm sieve. Mobile and plant-available P was analyzed in 1-day extracts by distilled water (5g of soil : 30 ml of H_2O) and by 0.1 n HCl (2 g of soil : 20 ml of acid), respectively. The P concentration was determined by standard method. All data were subjected to an analysis of variance and standard deviations were calculated. Fisher's coefficients were used for determining LTD_{05}. Excel Microsoft from Office 97 was used for all calculations.

Field trial

The field trial was performed at the Dry Lake Farm located 10 km on the north from Okeechobee Lake (Figure 1). The total area of the field was 33 hectares. Two points for water sampling were established 5 years before the experiment for monitoring water quality by South Florida Water Management District. Pro-Sil was applied on the whole field by incorporation to the soil using disking at the rate of 4 t/ha. The sorghum was seeded after the Si application. Soil samples were collected before treatment and in 4 months later from the same points at the depth 20-30 cm. Four replications of soil sampling from each point were conducted (Figure 1). The leachable (water-extractable) P and acid-extractable P were analyzed by standard methods. South Florida Water Management District tested soluble P in the both creeks. All data was subjected to an analysis of variance and standard deviations were calculated. Fisher's coefficients were used for determining LTD_{05}. Excel Microsoft from Office 97 was used for all calculations.

Figure 1. Scheme of the field trial.



RESULTS

Laboratory experiments

The figures 2, 3, 4, and 5 show the dynamic of P in the percolated solutions in the column experiments. Pro-Sil was the most effective in reducing P leaching. The effect was observed in the both soils. Lime also reduced P leaching, but usually only in the beginning of the irrigation. With saturating with P, lime impact on P leaching was decreasing. Zam-Sil adsorbed P to a lesser extent than both other chemicals. Under irrigation by the solution of 2.5 ppm of P, Zam-Sil slightly increased P leaching (Figure 2 and 4). Probably, this is explained by the possibility of monosilicic acid to transform plant-unavailable P to plant-available (Matichenkov, 1990; Matichenkov and Ammosova, 1996). This hypothesis is supported by the results of soil P analysis before and after column irrigation by P-bearing solutions (Table 3).

Figure 2. P in percolated solutions from column with Entisol irrigated by solution of 2.5 ppm of P.

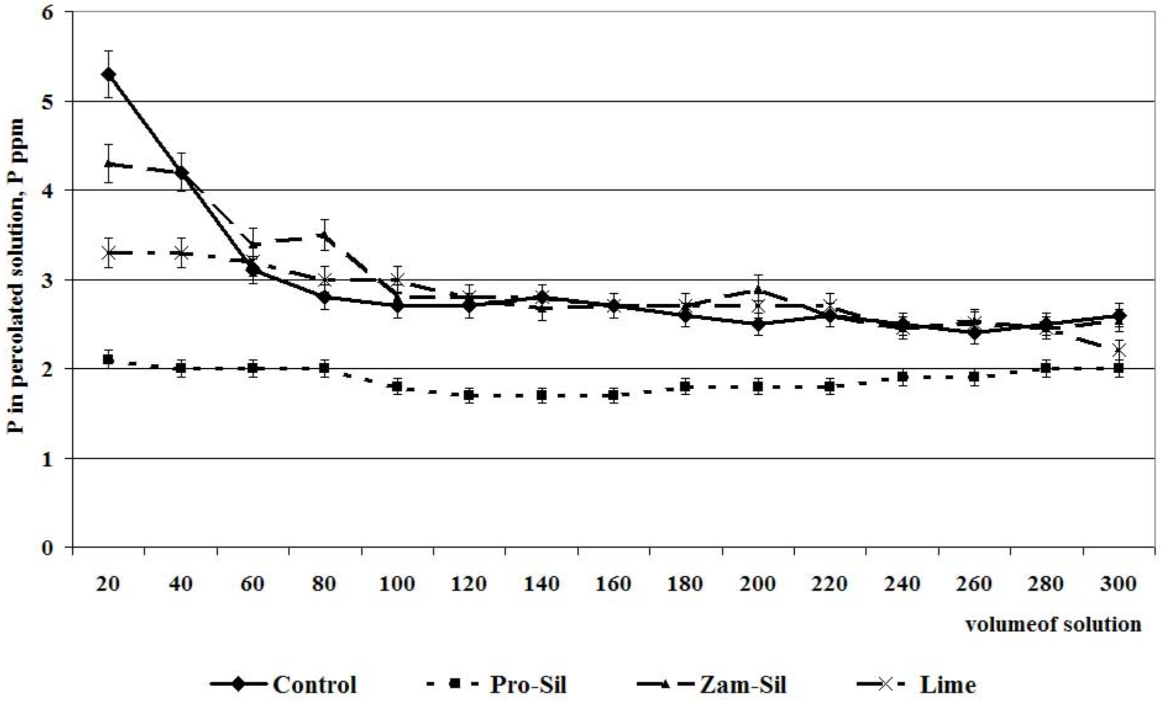


Figure 3. P in percolated solutions from column with Entisol irrigated by solution of 10 ppm of P.

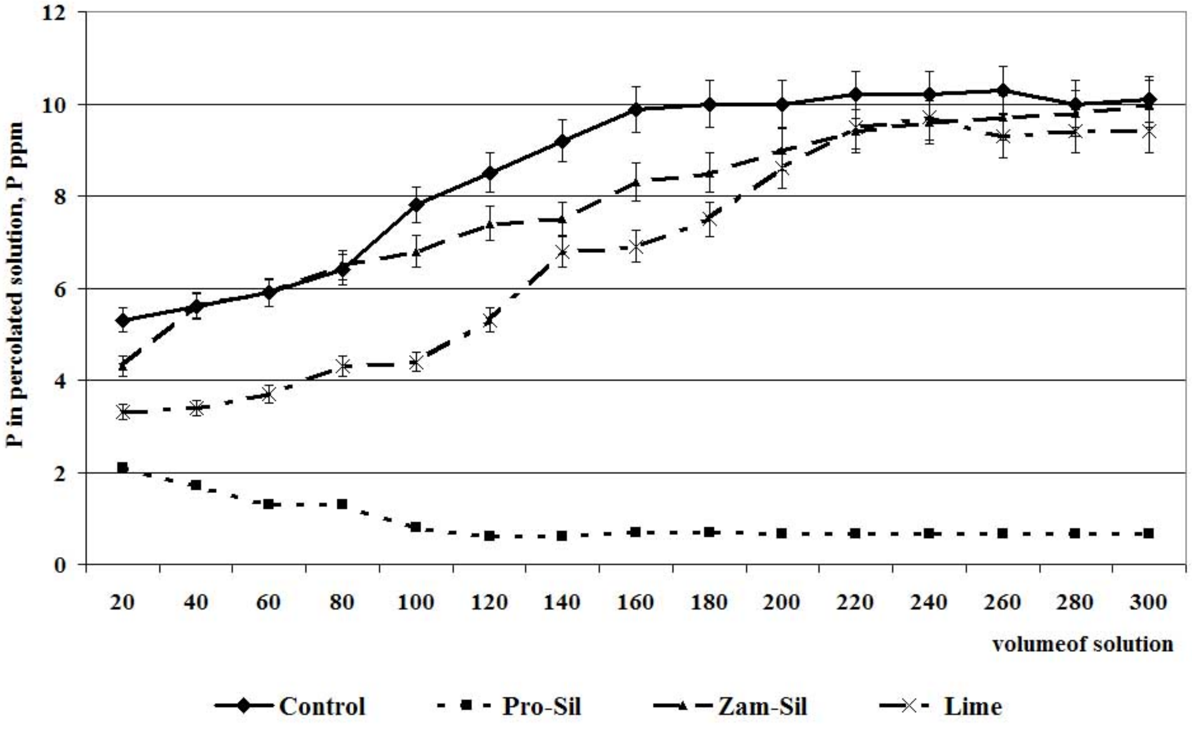


Figure 4. P in percolated solutions from column with Spodosol irrigated by solution of 2.5 ppm of P.

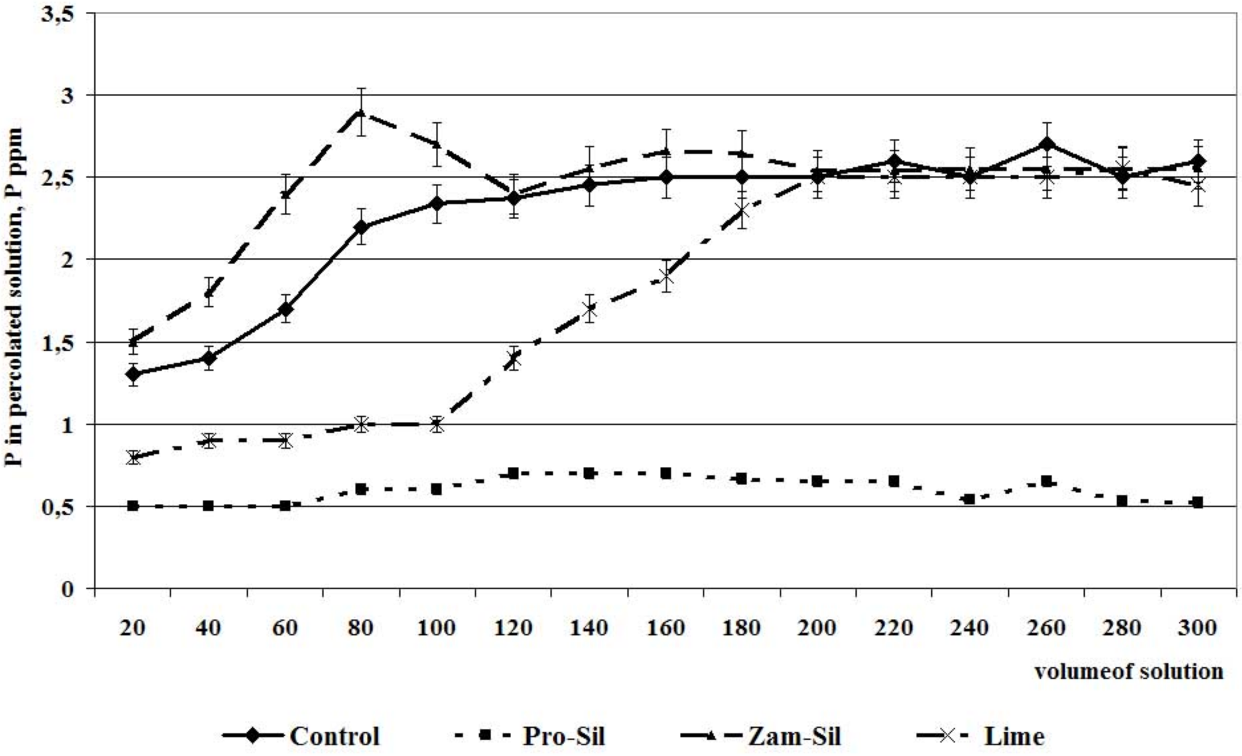
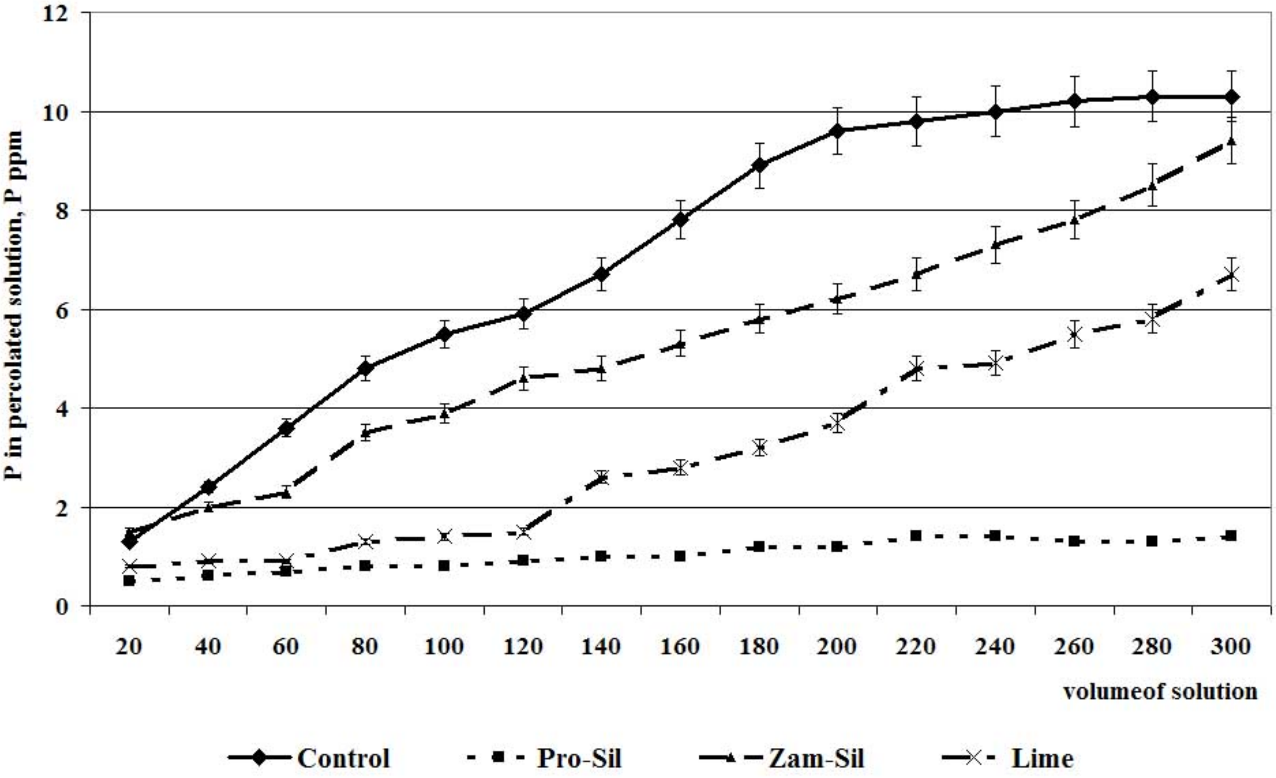


Figure 5. P in percolated solutions from column with Spodosol irrigated by solution of 10 ppm of P.



After irrigation by P-bearing solutions control soil samples contained less water- and acid-extractable P than those treated with Zam-Sil. Pro-Sil showed a similar effect on acid-extractable P. In contrast to Si compounds, lime had no effect on or slightly decreased soluble forms of P in comparison with those in control columns.

Table 3. Water- and acid-extractable P in soil and in column experiment.

Variant	Before irrigation		After irrigation by solution of 2.5 ppm of P		After irrigation by solution of 10 ppm of P	
	P, mg kg^{-1}					
	water - extractable	acid - extractable	water - extractable	acid - extractable	water- extractable	acid - extractable
Entisol						
Control	1.9	51	2.9	25	5.4	102
Pro-Sil	1.5	52	1.4	59	3.0	145
Zam-Sil	2.0	52	4.4	48	6.4	134
Lime	1.4	51	1.6	22	3.1	96
LSD_{05}	1.5	14.8	1.7	8.9	1.7	10.8
Spodosol						
Control	0.3	7	0.7	6	4.6	59
Pro-Sil	0.2	8	0.2	7	2.4	94
Zam-Sil	0.3	8	0.9	6	4.4	74
Lime	0.3	9	0.2	5	3.1	45
LSD_{05}	1.5	5	1.5	5	1.5	5

Greenhouse tests

Figure 6 demonstrates P concentrations in the percolated solutions in the greenhouse experiment. The Pro-Sil application significantly reduced P leaching in both soils. The lime application also reduced P leaching, but not so much. Zam-Sil slightly increased P leaching in both soils.

The Si-rich materials provided enhanced mass of shoots and roots of bahiagrass (Table 4). This effect was observed in the both soils. Lime reduced the plant biomass in the Entisol and had no effect in the Spodosol (Table 4). Plant P was influenced by soil treatments as well (Table 5). P concentrations in bahiagrass reduced under both the Si fertilizer and lime applications. Based on biomass data and plant P concentrations we have calculated total P uptake by plants per pot (Table 6). The results revealed that both Si-rich materials significantly enhanced the amount of P plants have taken up while lime reduced the amount of plant-adsorbed P in the Entisol and slightly increased that in the Spodosol.

Figure 6. P in percolated solutions in greenhouse experiment.

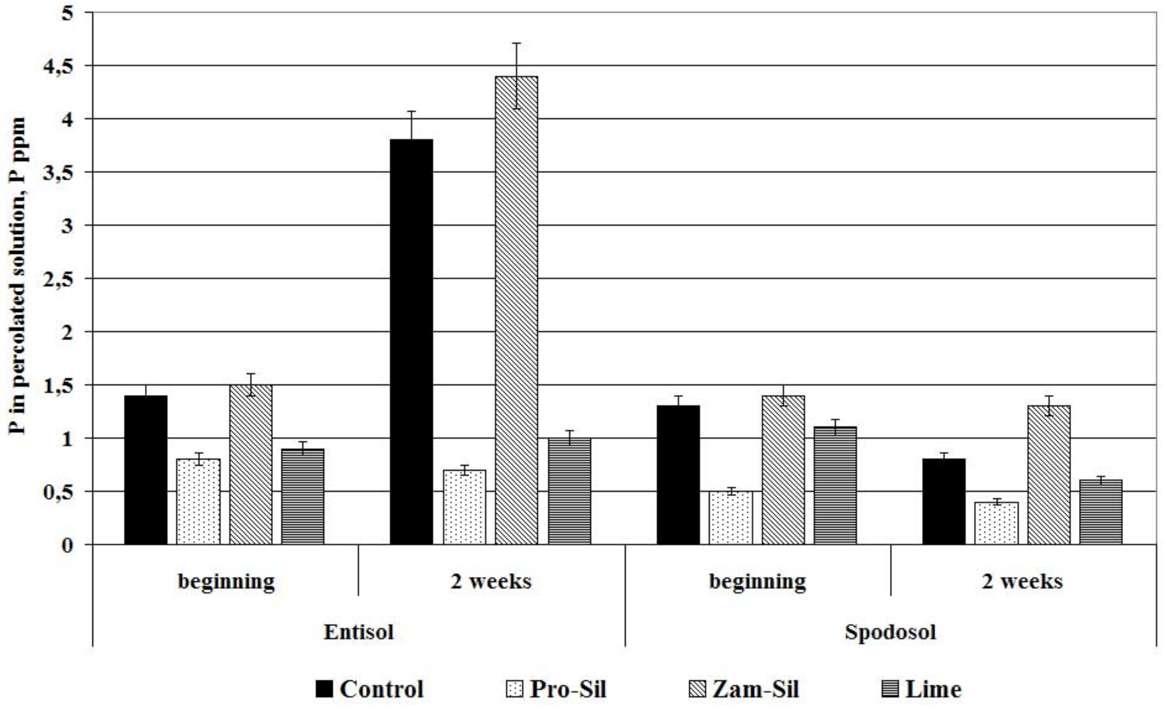


Table 4. Weight of fresh shoots and roots of 3-month old Bahiagrass (average for 10 plants).

Treatment	Entisol		Spodosol	
	Shoots, g	Roots, g	Shoots, g	Roots, g
Control	0.84	0.32	0.54	0.27
Pro-Sil	1.13	1.12	1.12	0.94
Zam-Sil	1.03	0.93	1.18	1.03
Lime	0.59	0.33	0.56	0.23
LSD_{05}	0.10	0.06	0.11	0.05

Table 5. Phosphorus in shoots and roots of 3-month old Bahiagrass.

Treatment	Entisol		Spodosol	
	P, %			
	Shoot	Root	Shoot	Root
Control	0.422	0.306	0.404	0.346
Pro-Sil	0.239	0.211	0.309	0.246
Zam-Sil	0.464	0.353	0.367	0.304
Lime	0.360	0.362	0.418	0.450
LSD_{05}	0.025	0.025	0.025	0.025

Table 6. Phosphorus uptake by Bahiagrass in greenhouse experiment.

Treatment	Entisol			Spodosol		
	P, mg per pot					
	Shoot	Root	Sum	Shoot	Root	Sum
Control	2.48	0.69	3.17	1.53	0.65	2.18
Pro-Sil	1.89	1.65	3.54	2.42	1.62	4.04
Zam-Sil	3.35	2.30	5.65	3.03	2.19	5.22
Lime	1.49	0.84	2.33	1.64	0.72	2.36

Water- and acid-extractable P in the both soils after the greenhouse experiment is present in Table 7. The maximum concentrations of water- and acid-extractable P were observed in the pots with Pro-Sil and Zam-Sil. Minimum water-extractable P was determined in the control pots and minimum acid-extractable P was in the pots treated with lime.

Table 7. Soil water- and acid-extractable P in greenhouse experiment.

Treatment	Entisol		Spodosol	
	P, mg kg^{-1}			
	Water-extractable	Acid-extractable	Water-extractable	Acid-extractable
Control	7.1	95	2.8	63
Pro-Sil	12.9	112	6.8	65
Zam-Sil	12.8	115	7.5	69
Lime	7.8	85	3.6	51
LSD$_{05}$	1.0	10	1.0	10

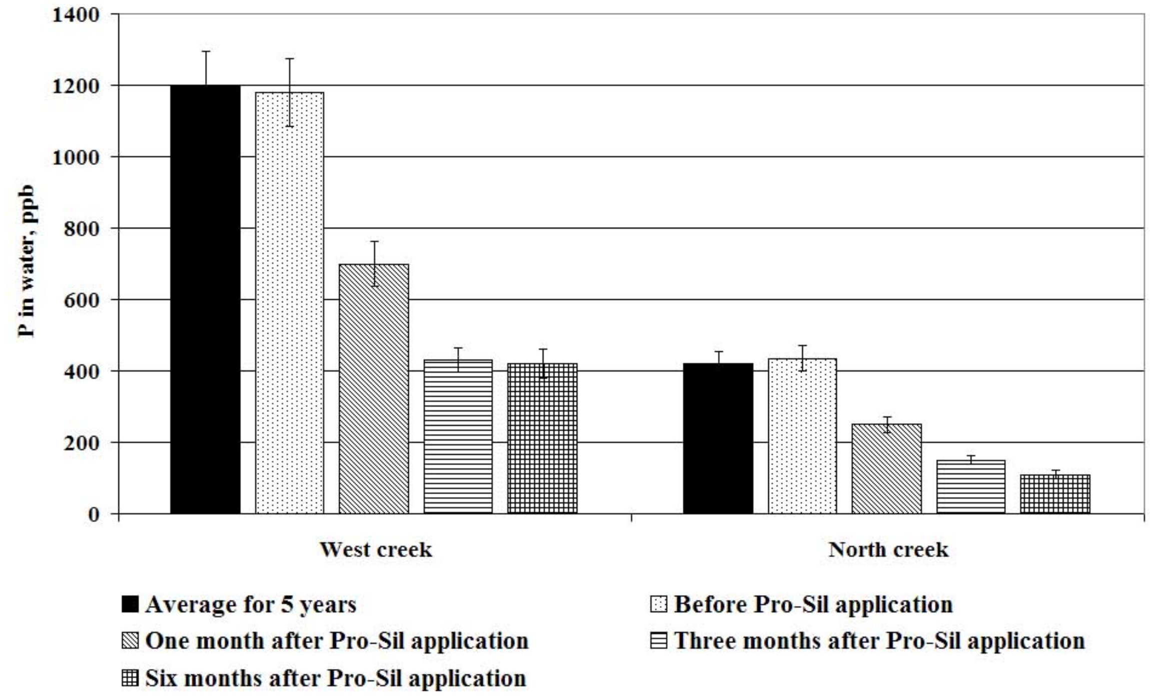
Field trial

Water- and acid-extractable P in the soils is present in Table 8. Under Pro-Sil treatment, the both forms of leachable P were reduced. Over 6 months the P concentrations dropped from 1200 to 400 ppb in the West creek and from 400 to 100 ppb in the North creek (Figure 7).

Table 8. Soil water- and acid-extractable P as effected by Pro-Sil.

	Before Pro-Sil treatment		After Pro-Sil treatment	
	P, mg kg^{-1}			
	Water-extractable	Acid-extractable	Water-extractable	Acid-extractable
Point 1	62,4	411,3	48,3	326,2
Point 2	31,3	147,5	26,8	118,5
Point 3	16,2	34,5	15,4	37,4
Point 4	20,7	168,3	20,2	149,3
Point 5	9,64	20,7	6,05	16,9
LSD_{05}	1.0	10	1.0	10

Figure 7. Dynamic of P in the West and North creeks.



DISCUSSION

The interaction between Si compounds and P was being under investigation since 1906 (Hall and Morrison, 1906). Thermodynamic calculations show that the reaction of displacing the phosphate-anion by the silicate-anion from slightly soluble phosphates with forming the corresponding silicates is possible (Matichenkov and Ammosova, 1996).

Silicon fertilizer applied to the soil produces increasing concentrations of monosilicic acid in the soil solution which is adsorbed on slightly soluble phosphates of calcium, aluminum, iron, and magnesium

(Gladkova, 1982; Matichenkov, 1990). The next phase is the exchange of phosphate-anion by silicate-anion:

$$CaHPO_4 + Si(OH)_4 = CaSiO_3 + H_2O + H_3PO_4$$

$$2Al(H_2PO_4)_3 + 2Si(OH)_4 + 5H^+ = Al_2Si_2O_5 + 5H_3PO_4 + 5H_2O$$

$$2FePO_4 + Si(OH)_4 + 2H^+ = Fe_2SiO_4 + 2H_3PO_4$$

These reactions are followed by the release of the phosphate-anion leading to an increasing concentration of P in the soil solution. A new equilibrium between silicate-anions and phosphate-anions is established. Partly, released P can be adsorbed by new-formed silicates. Our experiments with Si fertilizers support the existence of this model of Si-P interaction (Figures 4, 6, Tables 3 and 7). Pro-Sil and Zam-Sil applied to soil increased solubility of P and consequently its uptake by plants. Besides this effect, it was observed a decrease in P concentrations in percolated solutions especially marked with solid Si fertilizer due to its ability to adsorb P. Increased plant-available P simultaneously with reduced P leaching allow suggesting that P adsorbed by Si compounds remained plant-available. The liquid Si fertilizer had a small influence on P leaching but significantly increased amounts of plant-available P. Lime was effective in reducing P leaching but didn't benefit plant P nutrition. Decreased concentrations of plant-available P under lime application indicate that lime promotes the transformation of mobile P into plant-unavailable.

Thus, Si compounds can regulate the mobility of P in soil, provide a raise in P fertilizer efficiency, thereby, allow reducing application rates of P fertilizer. Beneficial role of Si compounds in decreasing rates of P applied and in reducing P leaching could be exploited to protect rivers against P pollution.

REFERENCE

1. Brayan O.C. 1933. The accumulation and availability of phosphorus in old citrus groves. Soil Sci., 36:245-259.
2. Campbell K.L., J.S. Rogers, and D.R. Hensel 1985. Drainage water quality from potato production. Trans. ASAE, 28:1798-1801.
3. Diakov V.M., V.V. Matichenkov, E.A. Cherepanov, and J. M. Ammosova. 1990. Use of silicon substance in agricultural. Survey information, Moscow..
4. Djodjic,F., L. Bergstrom, B. Ulen and A. Shirmohammadi. 1999. Mode of transport of surface-applied phosphorus-33 through a clay and sandy soils. . J. Environ.Qual., 28:1273-1282.
5. Eaton A.D., Clesceri L. S., Greenberg A.E. (Ed) Standard Methods for Examination of Water and Wastewater, Am. Publ. Health As., 1995.
6. Gladkova K.F., 1982. The role of silicon in phosphate plant nutrition. Agrochemistry, 2:133-144.
7. Hall A.D., and C.G.T. Morrison, 1906. On the function of silica in the nutrition of cereals. Proceed. of the Royal Soc. of London, Ser. B, LXXVII:455-477.
8. Harris W.G., R.D. Rhue, G. Kidder, R.B. Brown, and R. Littell, 1996. Phosphorus retention as related to morphology of sandy coastal plan soil materials. Soil Sci. Soc. Am. J. 60:1513-1521.
9. Humphreys F. R., and W.I. Pritchett, 1971. Phosphorus adsorption and movement in some sandy forest soils. Soil Sci. Soc. Am. Proc., 35:495-500.
10. Lindsay W.L. 1979 Chemical Equilibria in Soil. John Wiley & Sons, New York
11. Mansell R.S., S.A. Bloom, and B. Burgoa, 1991. Phosphorus transport with water floe in an acid, sandy soil. In Jacob B., Corapcioglu M.Y. (ed) Transport process in porous media. Kulwer Acad. Publ.,Dorchester, the Netherlands, p.271-314.
12. Matichenkov V.V. 1990. Amorphous oxide of silicon in soddy podzolic soil and it influence on plants. Authoref. Can. Diss., Moscow State University.
13. Matichenkov V.V., and J.M. Ammosova, 1996. Effect of amorphous silica on soil properties of a sod-podzolic soil. Eurasian Soil Science, 28(10):87-99.
14. Nair,V.D., R.R.Villapando, and D.A.Graetz. 1999. Phosphorus retention capacity of the spodic horizon under varying environmental conditions. J. Environ. Qual., 28:1308-1313.

15. Neller J.R. 1945. Mobility of phosphates in sandy soils. Soil Sci. Soc.Progres. 227-230.
16. Olivera M.G., J.M.Brada, and F.F. Jeles, 1986. Silica and phosphorus reciprocal adsorption and discation in two latosols from the Friangilo Mineiro area Brazil. Revesta Ceres, 33(189):441-448.
17. O'Relly S.E., and J.T. Sims, 1995. Phosphorus adsorption and desorption in a sandy soil amended with high rates of coal fly ash. Com. Soil Sci. and Plant Anal., 26(17-18):2983-2993.
18. Peters, J.M., and N.T.Basta. 1996. Reduction of excessive bioavailable phosphorus in soils using municipal and industrial wastes. J. Environ. Qual. 25:1236-1241.
19. Rochev V.A., R.V. Shveikina, G.A. Barsukoba, and N.N. Popova, 1980. The effect of silica-gel on agrochemical soil properties and crop of agricultural plants. In Plant Nutrition and Programming of Agricultural Plants. Proceed. Sverdlovsky ACI, Perm, 60:61-68.
20. Sims J. T., R.R. Simard, and B.C. Joern, 1998. Phosphorus loss in agricultural drainage: historical perspective and current research. J. Environ. Qual., 27:277-293.
21. Spenser,W.F., 1957. Distribution and availability of phosphates added to a lakeland fine sand. Soil Sci. Society Proceed. p. 141-144.
22. Taylor R.W., W.F.Bleam, and S.I. Tu. 1996. On the langmuir phosphate adsorption maximum. Commun.Soil Sci.Plant Anal., 27(13&14), 2713-2722.
23. Tokunaga Y. 1991. Potassium silicate: A slow release potassium fertilizer. Fert. Res., 30:55-59.