

# Relationships between agronomic and environmental phosphorus analyses of selected soils

MM Nthejane<sup>1</sup>, CC du Preez<sup>1</sup> and CW van Huyssteen<sup>1</sup>

<sup>1</sup>Department of Soil, Crop and Climate Sciences, University of the Free State, PO Box 339, Bloemfontein, 9300, South Africa

Phosphorus (P) is an essential nutrient in crop production and is therefore typically applied as phosphatic fertilisers. This can induce soil P concentrations that may contribute to freshwater eutrophication. Soil P tests developed from a water pollution protection perspective are unlike those developed for agronomic purposes and are also not easily adapted to routine analyses. The aim with this study was therefore to establish whether the values of P extracted from a range of soils by various agronomic and environmental P determination methods are related or not. Topsoil samples were collected from virgin soils in central South Africa and treated with  $\text{KH}_2\text{PO}_4$  to induce different P concentrations and then incubated for 3 months, while subjected to various wetting and drying cycles. The samples were then analysed for P using the extractants of Bray 1, citric acid, ISFEI, Olsen, and Truog, commonly employed to establish the agronomic P status of soils. Environmental P status was determined with calcium chloride ( $\text{CaCl}_2$ ) and ammonium oxalate ( $\text{DPS}_{\text{ox}}$ ) extractants. Generally good relationships were found between  $\text{CaCl}_2$  and ISFEI ( $R^2 = 0.72$ ), between  $\text{DPS}_{\text{ox}}$  and Truog ( $R^2 = 0.79$ ), and between  $\text{DPS}_{\text{ox}}$  and citric acid ( $R^2 = 0.82$ ). Agronomic P soil tests therefore have the potential to be used in regulating application of phosphatic fertilisers to ensure optimum crop yields, while simultaneously limiting freshwater pollution. Further field studies are, however, recommended to determine threshold values from an environmental point of view.

## CORRESPONDENCE

CW van Huyssteen

## EMAIL

[vanhuyssteencw@ufs.ac.za](mailto:vanhuyssteencw@ufs.ac.za)

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## INTRODUCTION

Phosphorus (P) is a key element in crop production. This essential macro-nutrient is therefore an integral part of soil fertility programmes, and is applied to agricultural land as either inorganic or organic fertiliser to meet crop requirements (Havlin et al., 2014). However, the long-term use of phosphatic fertiliser in excessive amounts may increase soil P concentrations to levels beyond crop needs and hence increase the risk of non-point-source pollution (Sharpley and Tunney, 2000). Phosphorus is the principal nutrient associated with eutrophication of recipient water bodies (Haygarth et al., 2013).

Loss of P from agricultural land to surface water bodies has been a concern in South Africa (Harding et al., 2009), with freshwater pollution estimated to be  $0.0047 \text{ mgP}\cdot\text{L}^{-1}$  water. An average P concentration in the natural water resources of the country (as orthophosphate) has been estimated at  $0.07 \text{ mg}\cdot\text{L}^{-1}$ , while an upper threshold value of  $0.1 \text{ mg}\cdot\text{L}^{-1}$  is recommended in Australia, New Zealand, and the United States of America (USEPA, 1986; ANZECC, 2000). The report of De Villiers and Thiart (2007) on the nutrient status of the 20 largest river catchments in South Africa indicated that 60% of the rivers showed significant ( $p < 0.05$ ) upward trends in dissolved orthophosphate content. Harding et al. (2009) state that 35% of the South Africa's total freshwater resources are eutrophic, further indicating P enrichment.

Phosphorus is considered an undesirable element in water bodies because it results in ecological, economic and social problems. This is because P accelerates blue-green algae and various aquatic vegetative growth (Rossouw et al., 2008). The dissolved oxygen levels of water bodies under these eutrophic conditions thus diminish quickly as micro-organisms decompose organic matter. Oxygen depletion impairs the water body and restricts its use for drinking, fishing, industry, and recreation.

Against this backdrop, the South African Water Research Commission initiated investigations into non-point-source pollution of water by agriculture from field to catchment scale, focusing on nitrogen and phosphorus management through modelling (Rossouw and Görgens, 2005; Van der Laan et al., 2012; Van der Laan and Franke, 2019). However, Mardamootoo (2015) emphasised that a more holistic approach is preferable. Such an approach could include soil P testing for quantifying susceptibility of water pollution due to soil P runoff (Horta and Torrent, 2006), modelling of P movement from agricultural land to surface water (Sharpley, 2007), and P indices to establish water pollution risk with P from non-point agricultural sources (Weld and Sharpley, 2007).

The existing environmental soil P testing methods, e.g., calcium chloride ( $\text{CaCl}_2$ ) and ammonium oxalate ( $\text{DPS}_{\text{ox}}$ ), are tedious and time-consuming, which therefore contribute to their unlikely use in routine soil P testing (McDowell and Sharpley, 2001). Unlike the environmental P tests, various routine agronomic soil P test methods, e.g., Bray, citric acid, ISFEI, Olsen, and Truog, have been recommended and used to effectively assess the P-status of soils, and are calibrated for making fertiliser recommendations (Sharpley and Tunney, 2000). It would therefore be prudent if these agronomic methods could also be used in addressing water quality issues, while maintaining the equally important agronomic soil productivity. Moreover, the methods can also be implemented

where limited resources are available, making them appropriate for agronomic and environmental soil P tests. However, agronomic P tests require more evaluation in terms of accuracy in measuring the soil P susceptible to runoff (Magyar et al., 2006).

The aim of this study was therefore to provide information that authenticates the importance of agronomic and environmental soil tests in measuring the P concentration in the surface layer of soils, with the purpose of determining threshold values critical for proper regulatory compliance and management of P sources for both agronomic and environmental purposes.

## MATERIAL AND METHODS

Topsoil samples were collected in natural vegetated veld from the Jacobsdal, Bloemfontein, and Ficksburg districts, all in the Free State Province, South Africa. These districts are located along the 29°S latitude, resulting in different mean annual precipitation (MAP) and mean annual evaporation (MAE) values. Jacobsdal, Bloemfontein, and Ficksburg are classified as arid (200–300 mm MAP and 1 700–1 800 MAE), semi-arid (500–600 mm MAP and 1 600–1 700 MAE), and sub-humid (700–800 mm MAP and 1 300–1 400 MAE), respectively (Midgeley et al., 1994). Their approximate elevation above mean sea level increases from 1 150 m at Jacobsdal, to 1 400 m at Bloemfontein, and 1 850 m at Ficksburg.

The geology is typical of the Karoo Supergroup sequence, with shale of the Ecca Group at Jacobsdal, and sandstone, shale, and mudstone of the Beaufort Group at Bloemfontein. Dolerite intrusions are common in both districts. At Ficksburg, Elliott Formation sandstone and mudstone occurs predominantly, with some inliers of Molteno Formation sandstone, mudstone, and grit, due to narrow dolerite dykes, as well as Clarens Formation sandstone outliers (Geological Survey, 1984).

Soils in Jacobsdal are characterised by shallow to deep, structureless, well-drained, red, eutrophic soils, with yellow soils occurring sub-dominantly (Chromic Luvisols; IUSS Working Group WRB, 2015). The soils in Bloemfontein are structureless, well-drained, red and yellow, eutrophic soils (Chromic Luvisols), with plinthic (Chromic Stagnic Plinthic Luvisols) and duplex (Cutanic Luvisols) soils occurring sub-dominantly. In the Ficksburg area, the soils are structureless, red and yellow, well-drained, dystrophic to eutrophic soils (Chromic Lixisols and Luvisols), with plinthic soils (Chromic Stagnic Plinthic Lixisols and Luvisols) occurring sub-dominantly.

Jacobsdal, with Mixed Nama Karoo vegetation, is situated on the edge of the Nama Karoo Biome. Both Bloemfontein, with Dry Sandy Highveld vegetation, and Ficksburg, with Moist Cool Highveld vegetation, occur in the Grassland Biome (Low and Rebelo, 1996).

Mixed crop and stock farming is practised in all the districts. Stock farming entails grazing of natural vegetation by cattle and/or sheep. Cattle are more dominant in the sub-humid climate of Ficksburg, while sheep farming is more dominant in the arid climate of Jacobsdal. At Jacobsdal, cropping of cotton, lucerne, maize, peanut, potato and wheat is only viable under irrigation. Rainfed maize and wheat are the major crops at Bloemfontein and Ficksburg. Soybean at Ficksburg and sunflower at Bloemfontein are also often planted as alternatives.

Four sites within a radius of 5 km of each other were selected in each district for collection of bulk topsoil samples from vegetated veld with low extractable P content (Table 1), while the other soil properties were very similar to that of cropped soils in the district (Table 2). At each site about 150 kg of soil was collected from the orthic A horizon (approximately 0–300 mm), and all living

**Table 1.** Soil sampling sites, locations, land types (Land Type Survey Staff, 2002), soil forms (Soil Classification Working Group, 1991), and Reference Soil Groups (IUSS Working Group WRB, 2015)

District	Sample No <sup>1</sup>	Latitude	Longitude	Land type	Soil form	Reference Soil Group
Jacobsdal	J1	–29.1751	24.7540	Ae15	Hutton	Chromic Luvisol
	J2	–29.1636	24.6999	Ae15	Hutton	Chromic Luvisol
	J3	–29.1963	24.6280	Ae279	Hutton	Chromic Luvisol
	J4	–29.0527	24.6631	Ag148	Valsrivier	Protocalcic Luvisol (Cutanic)
Bloemfontein	B1	–29.0358	26.1521	Ca8	Bainsvlei	Chromic Stagnic Plinthic Luvisol
	B2	–29.2036	26.1947	Ca22	Hutton	Chromic Luvisol
	B3	–29.2310	26.2027	Ca22	Valsrivier	Protocalcic Luvisol (Cutanic)
	B4	–29.2757	26.1712	Ca8	Valsrivier	Protocalcic Luvisol (Cutanic)
Ficksburg	F1	–28.7989	27.8591	Bd29	Avalon	Stagnic Plinthic Acrisol
	F2	–28.8038	27.8676	Ad4	Clovelly	Haplic Acrisol
	F3	–28.8058	27.8727	Ad4	Clovelly	Haplic Acrisol
	F4	–28.8133	27.8317	Bd29	Avalon	Stagnic Plinthic Acrisol

<sup>1</sup>J = Jacobsdal, B = Bloemfontein, F = Ficksburg

**Table 2.** Selected physical and chemical properties of the studied soils

Sample No. <sup>1</sup>	Particle size distribution (%)			Organic C (%)	pH (H <sub>2</sub> O)	Exchangeable cations (mg·kg <sup>-1</sup> )				CEC (cmol <sub>c</sub> ·kg <sup>-1</sup> )		Extractable oxides (mmol·kg <sup>-1</sup> )	
	Sand	Silt	Clay			Ca	Mg	K	Na	Soil	Clay	Fe	Al
J1	84.4	6.8	6.4	0.66	6.3	518	159	120	14	6.2	96.9	0.87	2.00
J2	78.9	10.6	8.1	0.59	7.1	1 051	376	257	18	11.5	142.2	1.67	3.06
J3	41.0	28.3	27.3	0.90	8.6	5 592	625	519	71	21.1	77.3	2.21	4.08
J4	65.9	14.7	16.4	0.78	7.4	2 413	517	298	23	16.5	100.7	3.97	2.14
B1	84.6	1.0	12.0	0.47	6.2	470	153	144	17	6.3	52.5	0.88	2.24
B2	82.0	2.2	13.0	0.32	6.5	509	170	243	17	6.3	48.5	0.96	2.73
B3	78.6	5.2	12.2	0.76	6.2	583	178	236	15	7.3	59.7	1.76	2.35
B4	62.9	13.6	21.2	0.87	6.1	823	375	285	57	12.3	57.9	6.54	3.61
F1	84.3	10.6	3.3	0.95	5.5	352	80	93	13	5.5	167.9	3.92	2.52
F2	77.0	14.4	4.5	1.41	6.0	513	128	346	21	7.2	160.0	4.29	2.69
F3	72.9	17.5	5.8	1.08	6.0	490	96	113	15	6.0	103.1	1.83	2.94
F4	45.0	36.6	13.7	1.82	6.2	1 138	204	208	15	11.5	84.1	2.20	2.42

<sup>1</sup>J = Jacobsdal, B = Bloemfontein, F = Ficksburg

plants and plant residues were removed. The wet soil was mixed, air dried, crushed, sieved through a 2 mm sieve and mixed again before being stored for treatment and analysis.

Seven different P concentrations (equivalent to 0, 5, 13, 25, 42, 65 and 95 mgP·kg<sup>-1</sup> soil) were applied using KH<sub>2</sub>PO<sub>4</sub> solution to each of the 12 bulk samples, replicated 3 times, giving 252 treatments. For each treatment, 400 g of soil was weighed and spread evenly in a thin layer on a plastic sheet. Sufficient KH<sub>2</sub>PO<sub>4</sub> solution of appropriate concentration was then sprayed onto the soil to wet it to approximately 70% of field water capacity. This was done with a sprayer connected to a burette, to ensure precision application. After spraying, the soil was mixed thoroughly and then placed in a 500 mL plastic container. A perforated lid was put on, which allowed drying at room temperature during incubation. During the three months of incubation, the soil was wetted several times to 70% of field water capacity with distilled water, mixed, and dried again, as described above. After incubation, the treated soil was air dried, sieved and stored for P analyses.

Standard methods (The Non-Affiliated Soil Analysis Working Committee, 1990) were used to analyse the 252 treated samples for particle size distribution (pipette and sieve method), organic carbon (Wakley-Black method), pH (1:2.5 soil water suspension), exchangeable cations and cation exchange capacity (1 mol dm<sup>-3</sup> NH<sub>4</sub>OAc at pH 7). Each of these analyses was done in triplicate.

Soil from the 252 P-treated samples were also analysed in triplicate for extractable P. The agronomic P status of the treated samples was determined using the Bray 1, citric acid, ISFEI, Olsen, and Truog methods (The Non-Affiliated Soil Analysis Working Committee, 1990), while the environmental P status was determined using the CaCl<sub>2</sub> (Kuo 1996) and DPS<sub>ox</sub> (Beck et al., 2004) methods. The DPS<sub>ox</sub> method actually calculates the P saturation from ammonium oxalate extractable P, Fe, and Al. The concentration of P in solution was determined colorimetrically, irrespective of the extraction method used, with the ammonium molybdate method in which ascorbic acid is the reducing agent (Murphy and Riley, 1962).

Linear and non-linear regression models, using Microsoft Excel 2007 in Windows XP were used to establish correlations between P extracted through the different methods. The most suitable

model was selected based on the correlation coefficient ( $R^2$ ), to determine the relationship between and/or among agronomic and environmental P tests for each individual soil's data, when data of all soils from one district were pooled, and when data from all three districts were combined.

## RESULTS

The induced soil P concentrations varied considerably between the studied soils (Table 3), depending on soil properties and extraction method. The smallest differences were observed in the B4 soil, regardless of extraction method used. These differences were, in increasing order: 0.5 mgP·kg<sup>-1</sup> for CaCl<sub>2</sub>, 5.6 mgP·kg<sup>-1</sup> for DPS<sub>ox</sub>, 9.3 mgP·kg<sup>-1</sup> for ISFEI, 10.6 mgP·kg<sup>-1</sup> for citric acid, 20.2 mgP·kg<sup>-1</sup> for Bray 1, 22.3 mgP·kg<sup>-1</sup> for Olsen, and 31.3 mgP·kg<sup>-1</sup> for Truog. On the other hand, the largest differences were observed in the J2 (CaCl<sub>2</sub>), J3 (Olsen, Truog, and DPS<sub>ox</sub>), B1 (citric acid), and F1 (Bray 1) soils. These differences were, in decreasing order: 85.0, 67.7, 61.2, 55.5, 26.0, 24.5, and 10.2 mgP·kg<sup>-1</sup>, for the Truog, Bray 1, Olsen, ISFEI, DPS<sub>ox</sub>, citric acid, and CaCl<sub>2</sub> methods, respectively.

Soil P tests are significantly related to each other per sampling site and when sampling sites were pooled for the Jacobsdal (Table 4), Bloemfontein (Table 5), and Ficksburg (Table 6) districts. The lowest  $R^2$  values were estimated for the Olsen vs. ISFEI at J1 (0.80), Truog vs. Olsen at J2 (0.67), DPS<sub>ox</sub> vs. Olsen at J3 (0.76), and DPS<sub>ox</sub> vs. Truog at J4 (0.82). At B1, B2, B3, and B4 the lowest  $R^2$  values were realised for the CaCl<sub>2</sub> vs. citric acid (0.88), CaCl<sub>2</sub> vs. Olsen (0.89), CaCl<sub>2</sub> vs. citric acid (0.73), and DPS<sub>ox</sub> vs. Bray 1 (0.83), respectively. The  $R^2$ -values of CaCl<sub>2</sub> vs. ISFEI at F1 (0.63), DPS<sub>ox</sub> vs. CaCl<sub>2</sub> at F2 (0.88), DPS<sub>ox</sub> vs. CaCl<sub>2</sub> at F3 (0.87), and DPS<sub>ox</sub> vs. CaCl<sub>2</sub> at F4 (0.91) were the lowest. A large variation between soil P tests was therefore experienced per sampling site.

Lower  $R^2$  values were calculated when the measured soil P concentrations of the sampling sites per district were pooled (Tables 4, 5, and 6). For Jacobsdal, the  $R^2$  values ranged from 0.22 (CaCl<sub>2</sub> vs. Truog) to 0.92 (Truog vs. citric acid). The range of  $R^2$  values for Bloemfontein was from 0.72 (DPS<sub>ox</sub> vs. citric acid) to 0.98 (Truog vs. ISFEI). The  $R^2$  values for Ficksburg varied between 0.23 (DPS<sub>ox</sub> vs. ISFEI) and 0.93 (CaCl<sub>2</sub> vs. citric acid).

**Table 3.** Range of extractable phosphorus contents (mg·kg<sup>-1</sup>) induced to soils used in this study

Sample No. <sup>1</sup>	Agronomic tests					Environmental tests	
	Olsen	Bray 1	Truog	ISFEI	Citric acid	CaCl <sub>2</sub>	DPS <sub>ox</sub>
J1	2.8 – 57.5	2.2 – 62.0	3.8 – 55.0	0.3 – 36.2	0.5 – 13.5	0.3 – 6.3	1.3 – 12.6
J2	16.3 – 49.2	15.7 – 81.5	47.0 – 121.7	5.8 – 48.5	10.3 – 24.3	0.5 – 10.7	9.9 – 24.3
J3	10.5 – 71.7	8.5 – 61.7	150.0 – 235.0	8.0 – 63.5	17.0 – 30.2	0.3 – 5.1	24.7 – 50.7
J4	12.7 – 61.7	8.6 – 71.5	30.7 – 108.3	7.7 – 50.8	4.2 – 20.0	0.3 – 7.5	6.0 – 19.7
B1	1.7 – 43.8	2.8 – 59.7	1.3 – 60.0	0.0 – 22.8	0.5 – 25.0	0.0 – 4.2	1.1 – 13.8
B2	6.0 – 46.3	6.2 – 58.4	4.2 – 64.0	0.3 – 26.2	1.0 – 15.7	0.3 – 5.6	1.7 – 13.8
B3	2.8 – 32.7	2.3 – 43.5	1.3 – 50.7	0.0 – 17.0	0.5 – 11.6	0.0 – 2.5	1.3 – 7.8
B4	3.9 – 26.2	2.4 – 22.6	5.0 – 36.3	1.5 – 10.8	1.0 – 11.6	0.0 – 0.5	3.3 – 8.9
F1	2.7 – 50.1	1.3 – 69.0	2.0 – 62.0	2.3 – 26.6	1.0 – 17.3	0.0 – 2.1	1.7 – 17.3
F2	5.6 – 61.7	2.7 – 61.0	7.5 – 61.3	2.3 – 49.0	4.2 – 20.0	0.3 – 2.5	3.8 – 20.8
F3	3.6 – 30.4	1.3 – 40.8	3.5 – 47.0	0.0 – 19.3	2.0 – 17.1	0.0 – 2.0	4.7 – 27.7
F4	4.8 – 27.5	1.5 – 24.9	25.5 – 70.0	2.3 – 19.5	6.0 – 22.8	0.3 – 4.5	8.4 – 22.1

<sup>1</sup>J = Jacobsdal, B = Bloemfontein, F = Ficksburg

**Table 4.** Coefficients of determination ( $R^2$ ) for the relationships between soil P tests per sampling site and when pooled for the Jacobsdal soils

Site	Method	Method						
		Bray 1	Citric acid	ISFEI	Olsen	Truog	CaCl <sub>2</sub>	DPS <sub>ox</sub>
J1 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.96	1.00					
	ISFEI	0.97	0.95	1.00				
	Olsen	0.92	0.91	0.80	1.00			
	Truog	0.99	0.97	0.96	0.91	1.00		
	CaCl <sub>2</sub>	0.95	0.93	0.97	0.88	0.98	1.00	
	DPS <sub>ox</sub>	0.95	0.93	0.91	0.91	0.96	0.95	1.00
J2 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.96	1.00					
	ISFEI	0.98	0.95	1.00				
	Olsen	0.73	0.65	0.71	1.00			
	Truog	0.99	0.95	0.99	0.67	1.00		
	CaCl <sub>2</sub>	0.98	0.97	0.98	0.73	0.98	1.00	
	DPS <sub>ox</sub>	0.86	0.87	0.81	0.87	0.73	0.85	1.00
J3 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.96	1.00					
	ISFEI	0.98	0.98	1.00				
	Olsen	0.94	0.93	0.93	1.00			
	Truog	0.99	0.96	0.98	0.96	1.00		
	CaCl <sub>2</sub>	0.98	0.92	0.97	0.94	0.96	1.00	
	DPS <sub>ox</sub>	0.85	0.78	0.78	0.76	0.79	0.81	1.00
J4 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.96	1.00					
	ISFEI	0.99	0.96	1.00				
	Olsen	0.97	0.95	0.93	1.00			
	Truog	0.98	0.94	0.96	0.93	1.00		
	CaCl <sub>2</sub>	0.99	0.96	0.99	0.95	0.97	1.00	
	DPS <sub>ox</sub>	0.88	0.90	0.89	0.91	0.82	0.90	1.00
All <i>n</i> = 84	Bray 1	1.00						
	Citric acid	0.58	1.00					
	ISFEI	0.80	0.59	1.00				
	Olsen	0.80	0.57	0.78	1.00			
	Truog	0.42	0.92	0.35	0.44	1.00		
	CaCl <sub>2</sub>	0.98	0.35	0.76	0.80	0.22	1.00	
	DPS <sub>ox</sub>	0.48	0.91	0.40	0.48	0.84	0.32	1.00

**Table 5.** Coefficients of determination ( $R^2$ ) for the relationships between soil P tests per sampling site and when pooled for the Bloemfontein soils

Site	Method	Method						
		Bray 1	Citric acid	ISFEI	Olsen	Truog	CaCl <sub>2</sub>	DPS <sub>ox</sub>
B1 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.96	1.00					
	ISFEI	0.98	0.98	1.00				
	Olsen	0.98	0.96	0.99	1.00			
	Truog	0.99	0.98	0.99	0.99	1.00		
	CaCl <sub>2</sub>	0.89	0.88	0.96	0.94	0.93	1.00	
	DPS <sub>ox</sub>	0.99	0.97	0.98	0.97	0.99	0.97	1.00
B2 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.95	1.00					
	ISFEI	0.97	0.95	1.00				
	Olsen	0.96	0.90	0.95	1.00			
	Truog	0.97	0.98	0.99	0.94	1.00		
	CaCl <sub>2</sub>	0.92	0.95	0.97	0.89	0.96	1.00	
	DPS <sub>ox</sub>	0.97	0.98	0.99	0.95	1.00	0.99	1.00
B3 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.98	1.00					
	ISFEI	0.99	0.96	1.00				
	Olsen	0.98	0.95	0.98	1.00			
	Truog	0.99	0.98	0.99	0.98	1.00		
	CaCl <sub>2</sub>	0.95	0.97	0.95	0.87	0.95	1.00	
	DPS <sub>ox</sub>	0.98	0.95	0.97	0.98	0.98	0.93	1.00
B4 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.91	1.00					
	ISFEI	0.89	0.95	1.00				
	Olsen	0.89	0.93	0.85	1.00			
	Truog	0.93	0.98	0.92	0.95	1.00		
	CaCl <sub>2</sub>	0.63	0.87	0.87	0.80	0.85	1.00	
	DPS <sub>ox</sub>	0.83	0.95	0.89	0.94	0.94	0.97	1.00
All <i>n</i> = 84	Bray 1	1.00						
	Citric acid	0.84	1.00					
	ISFEI	0.94	0.82	1.00				
	Olsen	0.92	0.85	0.95	1.00			
	Truog	0.93	0.92	0.98	0.96	1.00		
	CaCl <sub>2</sub>	0.90	0.73	0.90	0.81	0.85	1.00	
	DPS <sub>ox</sub>	0.87	0.72	0.80	0.76	0.77	0.92	1.00

**Table 6.** Coefficients of determination ( $R^2$ ) for the relationships between soil P tests per sampling site and when pooled for the Ficksburg soils

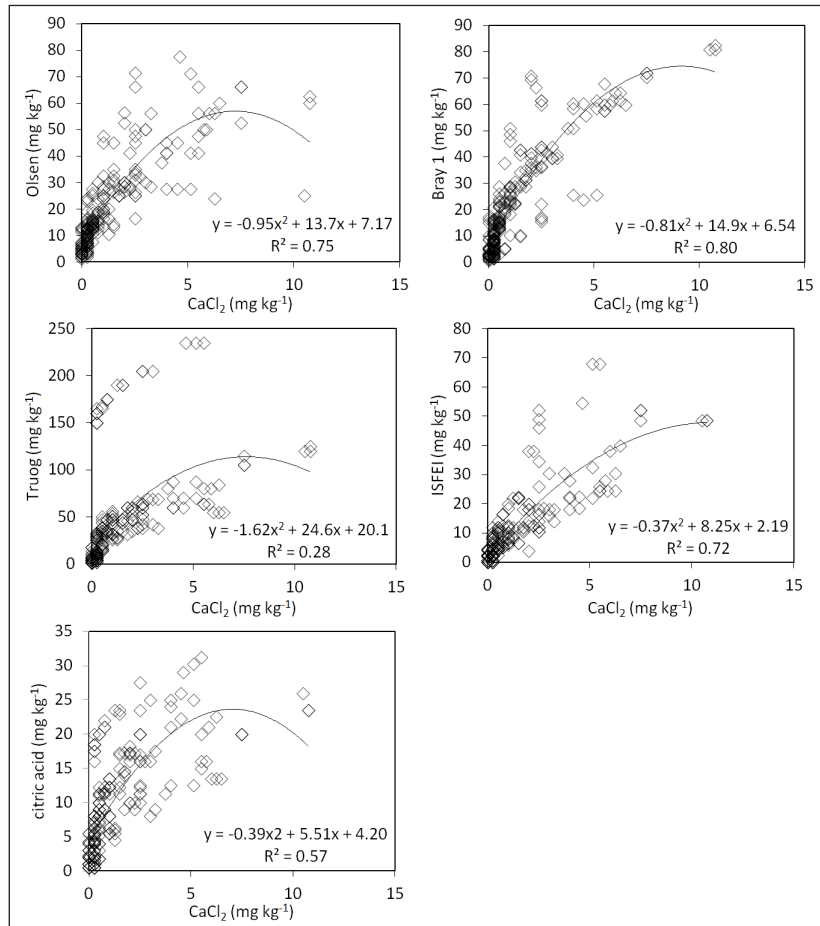
Site	Method	Method						
		Bray 1	Citric acid	ISFEI	Olsen	Truog	CaCl <sub>2</sub>	DPS <sub>ox</sub>
F1 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.98	1.00					
	ISFEI	0.70	0.69	1.00				
	Olsen	0.96	0.94	0.67	1.00			
	Truog	0.99	0.98	0.71	0.96	1.00		
	CaCl <sub>2</sub>	0.94	0.93	0.63	0.85	0.90	1.00	
	DPS <sub>ox</sub>	0.98	0.98	0.69	0.93	0.94	0.98	1.00
F2 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.97	1.00					
	ISFEI	0.97	0.97	1.00				
	Olsen	0.731	0.93	0.91	1.00			
	Truog	0.91	0.98	0.98	0.93	1.00		
	CaCl <sub>2</sub>	0.96	0.95	0.97	0.94	0.97	1.00	
	DPS <sub>ox</sub>	0.90	0.91	0.89	0.92	0.89	0.88	1.00
F3 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.97	1.00					
	ISFEI	0.99	0.99	1.00				
	Olsen	0.98	0.97	0.97	1.00			
	Truog	0.97	0.98	0.99	0.98	1.00		
	CaCl <sub>2</sub>	0.94	0.94	0.99	0.90	0.95	1.00	
	DPS <sub>ox</sub>	0.94	0.94	0.90	0.94	0.93	0.89	1.00
F4 <i>n</i> = 21	Bray 1	1.00						
	Citric acid	0.98	1.00					
	ISFEI	0.98	0.98	1.00				
	Olsen	0.95	0.94	0.94	1.00			
	Truog	0.98	0.96	0.95	0.98	1.00		
	CaCl <sub>2</sub>	0.96	0.98	0.99	0.92	0.95	1.00	
	DPS <sub>ox</sub>	0.98	0.97	0.97	0.91	0.91	0.96	1.00
All <i>n</i> = 84	Bray 1	1.00						
	Citric acid	0.67	1.00					
	ISFEI	0.72	0.75	1.00				
	Olsen	0.89	0.79	0.75	1.00			
	Truog	0.59	0.91	0.55	0.74	1.00		
	CaCl <sub>2</sub>	0.63	0.93	0.59	0.70	0.90	1.00	
	DPS <sub>ox</sub>	0.37	0.71	0.23	0.53	0.73	0.56	1.00

**Table 7.** Coefficients of determination ( $R^2$ ) for the relationships between soil P tests when the Jacobsdal, Bloemfontein, and Ficksburg soils were pooled

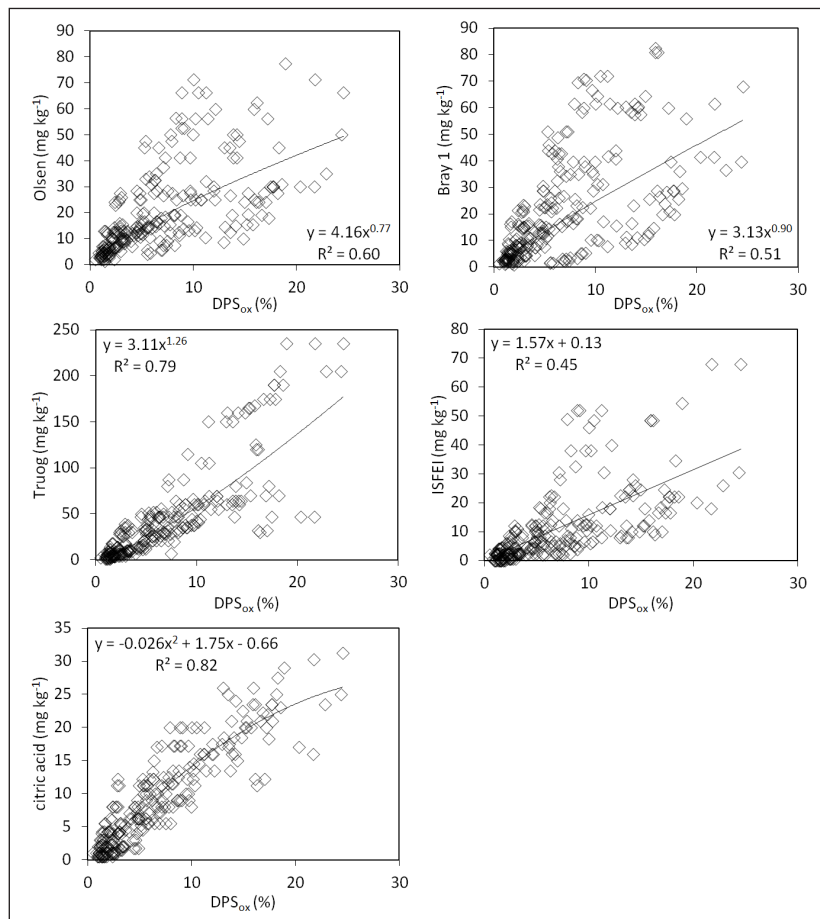
<i>n</i>	Method	Method						
		Bray 1	Citric acid	ISFEI	Olsen	Truog	CaCl <sub>2</sub>	DPS <sub>ox</sub>
252	<b>Bray 1</b>	1.00						
	<b>Citric acid</b>	0.57	1.00					
	<b>ISFEI</b>	0.78	0.71	1.00				
	<b>Olsen</b>	0.86	0.70	0.81	1.00			
	<b>Truog</b>	0.58	0.87	0.52	0.70	1.00		
	<b>CaCl<sub>2</sub></b>	0.80	0.57	0.72	0.75	0.28	1.00	
	<b>DPS<sub>ox</sub></b>	0.51	0.82	0.45	0.60	0.79	0.40	1.00

The pooling of soil P concentrations from all three districts gave  $R^2$  values (Table 7) of 0.40 (DPS<sub>ox</sub> vs. CaCl<sub>2</sub>) to 0.87 (Truog vs. citric acid). Soil P extracted with CaCl<sub>2</sub> correlated well with ISFEI ( $R^2 = 0.72$ ), Olsen ( $R^2 = 0.75$ ), and Bray 1 ( $R^2 = 0.80$ ), indicating that these agronomic soil P tests can probably be used for the

determination of environmental soil P (Fig. 1). Conversely, soil P extracted with DPS<sub>ox</sub> correlated well with those soils extracted with Truog ( $R^2 = 0.79$ ), and citric acid ( $R^2 = 0.82$ ), suggesting that these two agronomic soil P tests can also be considered to measure environmental soil P (Fig. 2).



**Figure 1.** Relationships between P extracted with  $\text{CaCl}_2$  and the different agronomic tests for all soils ( $n = 252$ ) from the three districts



**Figure 2.** Relationships between  $\text{DPS}_{\text{ox}}$  and the different agronomic tests for all soils ( $n = 252$ ) from the three districts

## DISCUSSION

The results presented here proved that a generally good relationship exists between the environmental and agronomic soil P tests. The strength of these observed relationships depends on the extractant used, because they differ in their abilities to extract P from different soils (Kuo, 1996). The closeness of a relationship also depends on the group of soils included since the correlation was stronger when individual soils were correlated separately rather than when all the soils from a district were grouped. As expected, a weaker correlation manifested when all soils' extractable P data were regressed. This reflects the conclusions of other studies (Lookman et al., 1996; Pote et al., 1996; Sims et al., 1998), which stated that the correlation is usually strong when the studied soils are fairly homogeneous in clay content and pH, but weaker if soils with a wide range in these properties are considered. However, White et al. (2020) report strong correlations ( $r > 0.85$ ) between some agronomic soil P tests for 48 South African pristine and cultivated soils with large pH (4–8) and clay content (6–45%) ranges. They emphasise that each agronomic soil P test was developed for a specific set of soil conditions and that inconsistencies in soil P analyses can be expected. No environmental soil P tests were, however, included in their study.

Some threshold values for the  $\text{CaCl}_2$  extractable P and for  $\text{DPS}_{\text{ox}}$  extractable P are given in Tables 8 and 9, respectively. The values were  $1.49 \text{ mgP}\cdot\text{kg}^{-1}$  for  $\text{CaCl}_2$  extractable P and 21.1% for  $\text{DPS}_{\text{ox}}$  extractable P. These averages were subsequently used to calculate agronomic P threshold values for each of the three districts and when the districts' data were grouped (Table 10).

Based on the average  $\text{CaCl}_2$  extractable P threshold value, the estimated P threshold values of the agronomic soil P tests for each district and over the three districts were lower than the optimum extractable P values used locally for P fertiliser recommendations (Table 11), except for the Olsen P test (Table 10). The implication is that when the extractable P status of cropped soils are maintained at optimum levels, as measured with Bray 1, citric acid, ISFEI, and Truog, the fertilised soil may be a threat in terms of causing water P pollution.

**Table 8.** Threshold values for  $\text{CaCl}_2$  extractable P used in evaluating soil's threat to water pollution

Region	Threshold P value ( $\text{mg}\cdot\text{kg}^{-1}$ )	Reference
Italy	2.7	Indiati and Rossi (1999)
Delaware (USA)	0.9	Kleinman et al. (2000)
China	0.75	Zhao et al. (2007)
USA	1.59	Maguire and Sims (2002)
Average	1.49	

**Table 9.** Threshold values for  $\text{DPS}_{\text{ox}}$  used in evaluating soil's threat of water pollution

Region	Threshold P value (%)	Reference
Delaware (USA)	>25	Sims et al. (1998)
Netherlands	25	Breeuwisma et al. (1995)
Belgium	30	De Smet et al. (1996)
Germany	30	Leinweber et al. (1997)
Indiana (USA)	23	Provin (1996)
Florida (USA)	20	Nair et al. (2004)
Delaware (USA)	>30	Pautler and Sims (2000)
Average	26	

**Table 10.** Threshold values for agronomic soil P tests, estimated from the average of  $\text{CaCl}_2$  and  $\text{DPS}_{\text{ox}}$  extractable P values given in Table 8 and 9, respectively

Soil test	Jacobsdal	Bloemfontein	Ficksburg	All soils
Estimated from $\text{CaCl}_2$ average threshold value ( $\text{mg}\cdot\text{kg}^{-1}$ )				
Olsen	26	24	32	27
Bray 1	26	31	36	25
Truog	62	34	48	14
ISFEI	15	11	18	21
citric acid	11	11	14	12
Estimated from $\text{DPS}_{\text{ox}}$ average threshold value ( $\text{mg}\cdot\text{kg}^{-1}$ )				
Olsen	51	65	42	58
Bray 1	60	80	40	52
Truog	284	86	104	41
ISFEI	47	53	11	191
citric acid	30	35	15	63

**Table 11.** Optimum extractable phosphorus values ( $\text{mg}\cdot\text{kg}^{-1}$ ) for cropped soils in South Africa

Agronomic test	Optimum P values	Reference
Olsen	12	Eloff (1971)
Bray 1	35	FSSA (2003)
Truog	31	Botha and Meyer (2004)
ISFEI	30	FSSA (2003)
citric acid	35	Lambrechts (2012)

When the threshold values of the agronomic soil P tests for each district and over the three districts were estimated with the average  $\text{DPS}_{\text{ox}}$  extractable P threshold value, they were much higher (Table 10) than the optimum extractable P values used in South Africa for fertiliser recommendations (Table 11). Thus, the maintenance of the cropped soil P status at optimum levels should not result in a threat of water P pollution from these soils. This was converse to the threshold values estimated for the  $\text{CaCl}_2$  extractable P.

In general, the results presented here indicated that the estimated threshold values depend on the extractant used and on the variation in soil properties. This therefore implies that grouping of soils that would respond similarly to P extraction is essential in areas where soils exhibit substantial variation in chemical and mineralogical properties, if these agronomic P tests are to be used for effective management of surface water P pollution.

Generally, it seemed feasible that agronomic soil P tests, used in routine soil analyses for fertiliser recommendations, can also be appropriate in managing the risk of surface water P pollution from cropped soils. Of the five agronomic soil P tests evaluated in this study, it was only the Olsen test that showed the potential to develop a simple threshold for all soils. Further studies are however warranted to establish reliable threshold P values before agronomic soil P tests could be considered for this purpose. It is believed that reliable threshold values can be only established through field studies, by relating the P in runoff to the extracted P from cropped soil.

## CONCLUSIONS

The results presented here indicated that P threshold values for the agronomic P soil tests, which were established from the average P threshold values for the environmental P soil tests,

vary depending on the test used and also on the soil properties. Some of the values were below and others were above the optimum extractable P values used in South Africa for crop P fertiliser recommendations. Thus, the use of agronomic soil P tests for the environmental assessment of soil P would require further investigation into the grouping of soils for an appropriate extraction method for selecting threshold values from an environmental point of view. However, the general observation made from the data reported in this study was that agronomic soil P tests could be used in regulating application rates of P fertiliser to decrease the risk of excessive P accumulation and its subsequent loss to the environment, while still ensuring optimum agricultural production.

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