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Phosphorus status of some Malawi soils

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Investigations conducted on Malawi soils ranging from highly weathered to less weathered soils show that P build-up due to fertilisation is much higher in soils managed by commercial estates than in soils managed by smallholder farmers. This suggests a need to monitor potential environmental impacts of the P build-up in the soils. The P build-up may be monitored using soil P tests used as a basis for P fertilisation. The present investigations have shown that the efficacy of selected soil tests in predicting P uptake was in the following increasing order: Olsen P > Nelson P > Bray P1=Resin P > Mehlich 3 > $(0.5pCa + pH_2PO_4)_{eq}$. However, when potentially mineralisable soil organic P was included in the regressions of P uptake on each of the soil P tests, the accuracy of the soil tests was in the following increasing order: Bray P1 > Olsen P > Mehlich 3 > Nelson P > Resin P > $(0.5pCa + pH_2PO_4)_{eq}$. The effectiveness of Bray P1 extraction method may be attributed to the acidic nature of the extractant (pH 2.6), which increases the activity of phosphate ions in soil solutions following dissolution of Ca-, Al-, and Fe-bound P forms and both the complexation of Al and Fe by humic substances and the precipitation of Ca (CaF_2) by the fluoride (F^-) component of the extractant. Mehlich 3 is used in Malawi as a basis for P fertilisation. It could also be used for monitoring potential environmental impacts of P build-up in Malawi soils.

Key words: Phosphorus status, extractants, ferruginous soils, ferralitic soils, alluvial soils, potentially mineralisable soil organic P.

INTRODUCTION

The overall development policy objectives of Malawi government include self-sufficiency in staple food, food security at both national and household levels, increased export production, and improved nutrition for Malawians. The main staple crop in Malawi is maize, which is grown by smallholder farmers whose landholding size averages 0.3 ha. Per capita consumption of maize is 133 kg, and it accounts for 54% of the caloric intake of households in Malawi. The national need for maize is 2 million tonnes per year and yet there have been years when annual yields produced have fallen far short of this quantity. Malawi has the germplasm to increase significantly the maize yields to over 10 tonnes per hectare (t/ha) and yet yields obtained using the high-yielding varieties under

recommended fertilizer management practices on farmers' fields average only about 33% of the established yield potentials. The decline in soil fertility is what explains the observed disparity. One of the limiting nutrients is observed to be soil phosphorus (P).

In the growth of plants P has a unique, irreplaceable role in biochemical and physiological processes, and it is the third major element required for plant growth. The mean total P contents of soils on smallholdings of resource-poor farmers in Malawi vary from 180 to 500 mg/ha. Total P, however, does not reflect P bioavailability. P exists in soils in organic and inorganic forms. Inorganic P usually accounts for 35 to 70% of total soil P. The sources of inorganic P include primary P

minerals such as apatites, strengite, and variscite and secondary minerals such as calcium (Ca), iron (Fe), and aluminium (Al) phosphates.

The primary P minerals are very stable, and the release of bioavailable P from these minerals through weathering is generally too slow to meet the demand of most annual crops such as maize. The P bioavailability from the secondary minerals is dependent on the dissolution rates of the minerals, which is a function of mineral particle size and soil reaction (Pierzynski et al., 2005; Oelkers and Valsami-Jones, 2008). The solubility of Fe and Al phosphates increases with increasing soil pH, while the solubility of Ca phosphate increases with decreasing pH.

Soil organic P exists mainly in stabilised forms such as inositol phosphates and phosphonates, and in active forms as orthophosphate diesters, labile orthophosphate monoesters, and organic polyphosphates (Turner et al., 2002; Condrón et al., 2005). The P from the organic form can be mineralised by processes mediated by soil organisms and plant roots in association with phosphatase secretion.

The processes are influenced mainly by soil pH, soil redox potential (Eh), soil surface physical-chemical properties, soil moisture, and soil temperature. Information currently available shows that organic P can provide a significant amount of bioavailable P. This has generated increasing interest in better incorporating organic P dynamics into nutrient management recommendations (Blair and Boland, 1978; White and Ayoub, 1983; Tate, 1984; Stewart and Tiessen, 1987; McLaughlin et al., 1988; Sharpley and Smith, 1989; Sharpley, 1992; Oehl et al., 2001). In highly weathered mineral soils, which are generally acidic in their reactions, P is dominantly sorbed on reactive surfaces of low activity clay (kaolinite) minerals and amorphous oxyhydroxides of Al such as gibbsite [γ -Al(OH)₃], and of Fe such as haematite (α -Fe₂O₃) (Parfitt, 1989). The adsorption of P on these surfaces involves formation of various complexes.

The non-protonated and protonated bidentate surface complexes may coexist at pH ranging from 4 to 9, with protonated bidentate inner-sphere complex predominating under acidic soil conditions (Luengo et al., 2006; Arai and Sparks, 2007), with P sorption increasing with an increase in ionic strength.

Increasing reactions on the large specific surface areas of the 1:1 clay minerals and the amorphous oxyhydroxides of Al and Fe, results in P becoming occluded in nanopores that frequently occur in Fe/Al oxides, and as a result become unavailable to plants (Arai and Sparks, 2007). Given the low solubility and nonlabile nature of inorganic P in such soils due to sorption and precipitation reactions, mineralisation of organic P is of agronomic importance. Net P mineralisation has been observed to be greater in unfertilised than in fertilised soils, that most mineralised P comes from a moderately labile pool of organic P

that is NaHCO₃-extractable P (Sharpley, 1985), and that P mineralisation is highly correlated with soil phosphatase activity.

In neutral-to-calcareous soils, P retention is dominated by precipitation reactions (Lindsay et al., 1989). P can also be adsorbed in such soils on the surface of Ca carbonate (Larsen, 1967) and clay minerals (Devau et al., 2010). The reaction between phosphate and Ca results in the precipitation of dicalcium phosphate (DCP) that is bioavailable but, with time, the DCP ultimately becomes transformed into more stable forms such as octocalcium phosphate (OCP) and hydroxyapatite (HAP), both of which are less available to plants at alkaline pH (Arai and Sparks, 2007).

This shows that P forms in soils exist in complex equilibria with each other, varying from nonlabile to labile P and solution P, indicating that bioavailability of soil P is extremely complex and highly associated with P dynamics and transformation among various P sinks, and that it is a function of the kinetics of the transfer of P from soil to soil solution and the capacity of soils to buffer soil solution P. For efficient soil P management, therefore, it is important to identify the different pools of soil P, quantify their contribution to plant nutrition (Yerokun, 2008) and understand the relationships and interactions among the various forms of P in soils as well as the numerous factors that influence soil P bioavailability.

Chemical extraction methods have been developed to determine the fraction of soil P that is bioavailable. In developing the extraction methods, the chemistry of soils is taken into account. For acid soils in which the P supplying ability is related to aluminium and iron phosphates, two extractants have been developed (Bray and Kurtz, 1945).

The extractants developed are ammonium fluoride-hydrochloric acid (NH₄F-HCl) mixtures having the same strength (0.03 M) of ammonium fluoride but one in 0.025 M HCl at pH 2.5 to 3.5, and another in 0.1 M HCl at pH 1.5 to 1.6. The extractant consisting of 0.03 M NH₄F in 0.025 M HCl is sometimes known as the Bray and Kurtz P1 but is commonly referred to as the Bray P1 method while the other extractant consisting of 0.03 M NH₄F in 0.1 M HCl is commonly known as the Bray P2 method. The Bray P1 test is the extractant that has been used in Malawi for routine evaluation of available soil P during the 1950 to the early 1980 period as a basis for fertilizer P recommendations to farmers. Bray P1 has now replaced with the Mehlich 3 extractant as a routine soil P test for soil P management in crop production. No information is, however, available to indicate the basis for the decision to start using Mehlich 3 extractant as a routine soil P test. The main objectives of the present investigations were therefore to determine the interrelationships among indices of soil P availability using some Malawi soils, and the efficacy of the predictive value of the soil P tests in evaluating effects of soil P management practices on P status of the selected

Table 1. Malawi soils selected for present investigations.

Soil No.	Classification system		Soil taxonomy	Fertility management	Site sampled
	Malawian	FAO/UNESCO			
1(a)	Ferruginous	Luvisols	Alfisols	Inadequate P fertiliser use	Lilongwe
1(b)	Ferruginous	Luvisols	Alfisols	P fertiliser adequately used	Lilongwe
2(a)	Ferruginous	Luvisols	Alfisols	Inadequate P fertiliser use	Namwera
2(b)	Ferruginous	Luvisols	Alfisols	P fertiliser adequately used	Namwera
3(a)	Ferralitic	Ferralsols	Oxisols	Inadequate P fertiliser use	Mchinji
3(b)	Ferralitic	Ferralsols	Oxisols	P fertiliser adequately used	Mchinji
4(a)	Ferralitic	Ferralsols	Oxisols	Inadequate P fertiliser use	Thyolo
4(b)	Ferralitic	Ferralsols	Oxisols	P fertiliser adequately used	Thyolo
5(a)	Alluvial	Fluvisols	Fluvents	Inadequate P fertiliser use	Mangochi
5(b)	Alluvial	Fluvisols	Fluvents	P fertiliser adequately used	Mangochi

Malawi soils.

MATERIALS AND METHODS

Soil samples each representing a composite of twenty randomly collected surface (0-23 cm) cores of equal volume, were collected from five sites in Malawi to represent ferruginous, ferralitic, and alluvial soils as described by Young and Brown (1962) and cropped under different practices (Table 1). The soil samples were air-dried and ground to pass a 2 mm screen. The sieved samples were and stored at ambient laboratory temperature before analysis. The soils were analyzed for pH on a saturated soil paste using a glass electrode. Textural analysis was by hydrometer method (Day, 1965). Organic carbon was determined by Walkley and Black procedure (Nelson and Somers, 1996) while organic matter was estimated as organic carbon multiplied by 1.724. Total nitrogen was determined by the micro Kjeldhal method (Bremner, 1965). Total inorganic and organic P were determined by the ignition method (Saunders and Williams, 1955). Samples of ignited (550°C, 2 h) and unignited soils were extracted for 2 h with 1 M H₂SO₄. Organic P was calculated as the difference between inorganic P in the ignited and unignited samples. The phosphate retention capacity was determined as described by Friend and Birch (1960) and "available mineralised" P (P_{am}) was expressed as follows (Friend and Birch, 1960):

$$P_{am} = K \left[\sum P_o - \left(\sum P_o * \frac{P_{ret}}{100} \right) \right]$$

where $\sum P_o$ denotes total organic P, P_{ret} denotes P retention and K is the organic P fraction mineralised. Available phosphorus was extracted by Bray P1 (Bray and Kurtz, 1945), Olsen P (Olsen et al., 1954), the CI form of the strongly basic anion exchange "Amberlite" resin IRA-410 (Maida, 1973), Nelson soil P test (Nelson, 1953), and Mehlich P test (1984) methods. All extractions were performed in duplicate. Extracts were filtered through Whatman No. 42 paper, and P was determined by an ascorbic acid-ammonium molybdate colorimetric method based on the Murphy and Riley (1962) method.

The determination of phosphate potential and buffering capacity entailed adding 0, 15, 30, 45, 60 and 75 cm³ of 0.01M KH₂PO₄ to 5 g air-dry soil (< 2 mm) weighed into 250 cm³ polythene bottles to give, respectively, 0, 30, 60, 90, 120 and 150 μmol P g⁻¹. Microbial activity was suppressed by treating the suspensions with three drops of chloroform which does not interfere with the measurement

shaken on a reciprocating shaker for 23 h at room temperature that of phosphate (Jensen, 1970). The bottles were stoppered and ranged from 21 to 23°C. After the pH was measured on an aliquot of each suspension, the remainder was centrifuged at 2500 revolution per minute (980 g) for 30 min. 5 cm of the extract were diluted to 100 cm and Ca was determined by atomic absorption spectrophotometry.

The phosphate potential ($\frac{1}{2}Ca + pH_2PO_4$) was computed from the pH values and concentrations of calcium and phosphorus (Aslyng, 1954). The differential phosphate buffering capacity (DPBC), defined as "the amount of phosphate to be added or removed per gram of soil in order to obtain a certain alteration of the phosphate potential" (Jensen, 1970), was determined from the equation:

$$DPBC = - \left(\frac{\Delta Q}{\Delta I} \right)_l$$

where I_0 is an equilibrium value of phosphate potential ($\frac{1}{2}Ca + pH_2PO_4$)_{eq} at which P is neither lost nor gained (Beckett and White, 1964). The limits of $\Delta Q = 0$ and $\Delta Q = 5$ and the corresponding values of ΔI were used.

The extent to which the accuracy of the P availability index determined by each of the soil P tests could be improved by including the portion of organic P mineralised under room conditions was also assessed in the present investigations. To obtain mineralised P, the soils were incubated. The incubation entailed placing pots containing the soils in a dish after adjusting soil water content to 75% of field capacity, weighing each of the pots containing soils plus dishes, and compensating water losses exceeding 10% of the initial values. The incubation was carried out at room temperature for 30 days. The incubated soil samples were taken to greenhouse. Six seeds of the test crop were planted per each pot and later thinned to three plants per pot.

The effects of soil P management on the P status of the Malawi soils was evaluated on the basis of observed decreases or increases ($\pm\Delta\%$) in extractable P values using selected soil P tests conventionally used for evaluating soil P availability. The $\pm\Delta\%$ was computed using the following equation:

$$\pm \Delta = \frac{(P_{shf} - P_{wm})}{P_{shf}}$$

where P_{shf} denotes soil P test values obtained from analyses of representative soil samples collected from fields of smallholder farmers and P_{wm} denotes soil P test values obtained from analyses

Table 2. Some chemical and physical properties of the soils.

Soil		pH	Clay	Silt	Organic matter	Total N	K	Mg	Ca	P _o	ΣP	P _{ret}
No	Group											
		% (w/w)			cmol kg ⁻¹			(mg kg ⁻¹)		(mg/100 g soil)		
1(a)	Ferruginous	5.1	30.5	4.3	5.4	0.19	0.28	1.23	5.56	220	363	21
1(b)	Ferruginous	4.6	38.1	4.0	6.1	0.21	0.26	1.00	8.40	244	476	27
2(a)	Ferruginous	5.3	23.6	4.0	2.9	0.12	0.25	0.30	4.00	155	280	11
2(b)	Ferruginous	5.6	15.0	8.3	2.5	0.10	0.36	0.62	2.56	154	426	19
3(a)	Ferralitic	5.4	10.7	5.0	4.3	0.11	0.21	0.49	2.08	178	273	25
3(b)	Ferralitic	4.1	19.8	7.0	2.7	0.09	0.13	0.22	1.90	246	451	21
4(a)	Ferralitic	5.6	13.5	7.7	2.5	0.08	0.18	0.47	3.00	79	176	18
4(b)	Ferralitic	5.8	15.0	7.7	2.3	0.08	0.19	0.52	2.00	101	196	9
5(a)	Alluvial	4.4	31.6	9.1	5.8	0.19	0.54	3.00	5.24	133	381	8
5(b)	Alluvial	6.1	24.2	6.6	7.9	0.30	0.71	2.70	3.27	159	457	9

P_o, organic P; ΣP, total P; P_{ret}, P retention capacity.

of representative soil samples collected from relatively well fertilized fields.

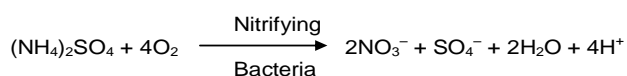
RESULTS AND DISCUSSION

Soil physical and chemical characteristics

Representative soil samples collected for the present investigations are given in Table 1. Sampled were the soils that are predominantly used for agricultural production in Malawi. Some physical and chemical characteristics of the soils are given in Table 2 and the analytical data for P values are summarised in Table 3.

Soil reaction

The soils used for the present investigations are acidic (pH < 5.4) in their reaction (Table 2). Highly weathered soils such as the Oxisols (Soil Survey Staff, 1999) are usually acidic in their reaction. However, effects of nutrient management on the observed low soil pH values cannot be ruled out. Prior to the first half of the 1970s, smallholder farmers in Malawi were advised to apply 20:20:0 granular compound fertilizer as a basal dressing and ammonium sulphate as topdressing for maize production. As the following reaction shows, the oxidation of ammonium sulphate results in increasing the hydrogen ion concentration in the soil solution:



After it was observed that the soils became increasingly acidic with continued use of ammonium fertilizer, calcium ammonium nitrate was recommended for topdressing on the soils whose laboratory tests showed them to be acidic. The Oxisols are acidic and highly weathered soils

dominated by low activity clays and oxides, oxyhydroxides, and hydroxides of Al and Fe.

As stated previously, in such soils, the orthophosphate anion such as H₂PO₄⁻ can exchange with a functional group either OH⁻ or OH₂ on the colloidal surface of low activity clays (e.g., kaolinite), resulting in monodentate or bidentate forms of P adsorption. The bidentate form of P adsorption is irreversible and therefore, in short term, not bioavailable. The latter is explained by declines of crop production that is increasingly attributed to, *inter alia*, declines in soil P bioavailability.

Soil P tests

The Bray P1 test is generally recommended for evaluation of bioavailable P on acid soils such as those used in the present investigations, and on neutral soils. It is not suitable (Bray and Kurtz, 1945) for (a) clay soils with a moderately high degree of base saturation, (b) silty clay loam or finer-textured soils that are calcareous or have a high pH value (pH > 6.8) or have a high degree of base saturation, (c) soils with a calcium carbonate equivalent > 7% of the base saturation, or (d) soils with large amounts of lime (> 2% CaCO₃). On calcareous soils, it tends to underestimate bioavailable P. It is, however, reliable on acid or neutral soils (Bray and Kurtz, 1945). In the present investigations, it has been observed that the extractable P values obtained from each of the soils varied with the type of extractant used and the nutrient management practices to which the soils used in the study have been subjected to (Table 3). The quantity of P extracted from all soils except soil No 2 (Table 3) by the Mehlich 3 was higher than that of any of the other soil P test values. The Bray P1 method was second to the Mehlich 3 extraction method in extracting large quantities of P (Table 3). The mean Bray P1 extractable P value of over 30 mg P kg⁻¹ in the topsoil (15 cm) is regarded in

Table 3. Extractable P and other P values.

Soil No.	Group	mg kg ⁻¹					$\frac{1}{2}pCa+pH$ _{2PO₄}	DPBC	P _m	P (uptake mg/100 g soil)
		Bray-P	Olsen P	Nelson P	Mehlich P	Resin P				
1(a)	Ferruginous	7	5	4	9	1	7.5	32	172	1.94
1(b)	Ferruginous	59	26	25	56	17	6.9	102	176	2.66
	±Δ%	783	420	525	522	1700	-0.8	219	2	37
2(a)	Ferruginous	8	4	3	11	1	7.4	55	67	1.79
2(b)	Ferruginous	11	6	7	12	1	7.3	30	95	1.92
	±Δ%	50	50	133	19	0	-1	-45	42	-7
3(a)	Ferralitic	34	11	15	32	7	6.6	28	140	2.16
3(b)	Ferralitic	119	52	47	143	23	6.2	129	126	2.40
	±Δ%	250	373	207	347	229	-6	361	-10	11
4(a)	Ferralitic	55	21	19	60	3	6.8	34	123	2.24
4(b)	Ferralitic	68	27	32	72	17	6.5	34	146	2.66
	±Δ%	24	29	68	20	467	-4	26	19	19
5(a)	Alluvial	3	4	3	6	1	7.6	71	133	1.83
5(b)	Alluvial	11	19	19	24	12	6.7	45	194	2.33
	±Δ%	267	375	533	300	1100	--12	-37	46	27

Malawi as the national average and yet on smallholdings of resource-poor farmers the mean Bray P1-extractable P in the topsoil used to be generally less than 10 mg P kg⁻¹ and in the subsoil it was about 4 mg P kg⁻¹. In the present investigations, it has been observed that the two samples representing ferruginous soils (the Alfisols, Soil Taxonomy) under the nutrient management practices by smallholder farmers have Mehlich 3- and Bray P1-extractable P values far less than the minimum required national average P value (Table 3).

The large quantities extracted by the Bray P1 and the Mehlich 3 soil P tests can be explained by the compositions and ionic strength of the two extractants. The Bray P1 extraction method consists of ammonium fluoride-hydrochloric acid (NH₄F-HCl) mixture containing 0.03 M ammonium fluoride in 0.025 M HCl at pH 2.5 to 3.5 while the Mehlich 3 extraction method contains 0.2 M CH₃COOH + 0.25 M NH₄NO₃ + 0.15 M NH₄F + 0.013 M HNO₃ + 0.001 M EDTA (Mehlich, 1984). The effectiveness of the Mehlich 3 and Bray P1 extraction methods may be attributed to the fluoride (F⁻) component of the extractants that can react with soluble Ca²⁺ in the soil to yield CaF₂. The acidic nature of Bray P1 extractant (pH 2.6) also contributes to dissolution of available P from Al, Ca, and Fe-bound forms in most soils.

Among the Malawi soils used for the present investigations are highly weathered acid soils containing inorganic P that is largely adsorbed on hydroxy-Al polymers on kaolinitic clay surfaces or held in reserve on discrete sesquioxide particles (e.g., amorphous Al and Fe oxides) after orthophosphate anions have exchanged with ligand on the particles. The F⁻ ions supplied by the

two extractants can react with the dissolved Al ions to form aluminium-fluoride complexes, AlF₆³⁻, that are precipitated, and suppress the re-adsorption of solubilised P by soil colloids, thus rendering the thermodynamic (effective) concentration, and therefore bioavailability, of orthophosphate ions to increase. When compared to the P values extracted by the Bray P1 extractant from the Malawi soils, the P values extracted by the Mehlich 3 extractant are generally higher (Table 3). This may be attributed to the fact that unlike the Bray P1 extractant, the Mehlich 3 method is a triple action extractant in that it removes elements by the processes of desorption (by the NH₄F and NH₄NO₃), dissolution (by acids), and chelation (by the EDTA).

The P values extracted by the Olsen soil P test (Table 3) suggest that this P soil test came third after Bray P1 and Mehlich 3 methods in evaluating the extractable P status of the Malawi soils. The Olsen P extractant consists of 0.5 M NaHCO₃ adjusted to pH 8.5 with 50% (w/v) sodium hydroxide, and is designed to reduce the activity of calcium through its precipitation as calcium carbonate. The high pH of the resultant solution is not conducive to the dissolution of the calcium carbonate (CaCO₃). The CaCO₃ therefore precipitates, thus increasing the effective concentration and bioavailability of the orthophosphate (HPO₄²⁻) ion. It has been observed that although Olsen P method was developed for calcareous soils, it can also be used for evaluation of available P in acid soils, particularly those containing Al- and Fe-bound P (Rajan et al., 1974; Hartikainen, 1981). Because the Olsen soil P test is buffered at pH 8, it can promote the activity of orthophosphoric ions in solution

Table 4. Matrix of correlation coefficients

Soil variable	Nelson P	Bray P1	Mehlich P	Olsen P	Resin P	$\frac{1}{2}\text{pCa+pH}_2\text{PO}_4$
Bray-P1	0.950***					
Mehlich	0.960***	0.987***				
Olsen P	0.983***	0.952***	0.975***			
Resin P	0.940***	0.834**	0.840**	0.913***		
$\frac{1}{2}\text{pCa+pH}_2\text{PO}_4$	-0.905***	-0.819**	-0.830**	-0.854**	-0.833**	
P uptake	0.916***	0.897***	0.877***	0.927***	.0.923***	-0.753*

** $P < 0.01$; *** $P < 0.001$. Number of observations (n) = 10.

due to P being desorbed by the increased concentration of hydroxyl ions (Rajan et al., 1974; Hartikainen, 1981; Hartikainen and Yli-Halla, 1996).

The soil P status of the Malawi soils is higher on soils that received relatively adequate P fertilization than on fields of smallholder farmers (Table 3), indicating that there has been a build-up of P in the soils that received P fertilisation. Phosphorus build-up can be beneficial in cases when soil fertility is the only concern. A build-up that leads to soil P values well above those needed for crop production is, however, conducive to losses of P to water bodies. Traditionally, a soil solution P concentration of 0.2 mg dm^{-3} ($6.45 \times 10^{-5} \text{ mol dm}^{-3}$) is often used as a sufficiency level required to correct P deficiency (Sanchez and Uehara, 1980). To prevent the accumulation of P in soils to values that enhance the risk of nonpoint pollution of surface and groundwaters, a soil solution concentration of 1.0 mg dm^{-3} ($3.2 \times 10^{-5} \text{ mol dm}^{-3}$) is occasionally used as a benchmark. The Mehlich 3- and Bray P1-extractable P values of greater than 30 mg kg^{-1} obtained from the Oxisols (Table 3) under the nutrient management practices by smallholder farmers suggest that in some areas such as the one in Lilongwe, soils are benefiting from smallholder farmers' applications of subsidised P fertilizers to the soils.

Interrelationships between the P values

To determine the interrelationships between the P values in the Malawi soils, correlations between soil P tests were computed and statistical tests of the correlation coefficients are given in Table 4. In these acid soils, the Bray P1 values were highly correlated with each of the other P values (Table 3). This is consistent with other findings that have shown that Mehlich 3, Olsen, and Bray P1 are often well correlated in acid to neutral soils (Beegle and Oravec, 1990; Tran et al., 1990; Mallarino, 1997; Lucero et al., 1998; Mallarino, 2003). Because of the chemistry of these acid soils, it is not surprising to observe that the amounts of P extracted by Mehlich 3 and Bray were the best correlated (Table 4) and were almost of similar magnitude in these acids soils (Table 3). The similarity in the amounts of P extracted by these two

extractants is consistent with observations made by other workers (Beegle and Oravec, 1990; Mallarino, 1997). It has, however, been observed that in soils with high pH or high carbonate contents Bray P1 does not perform as well as does Mehlich 3 (Hooker et al., 1980; Mallarino, 2003; Herman et al., 2004; Mallarino and Atia, 2005). Bray P1 has also been observed not to correlate well with other soil P tests in soils with soil inorganic carbon contents ranging from 2.2 to 4.8 g kg^{-1} (Hooker et al., 1980; Mallarino, 1997; Mallarino and Atia, 2005).

In the present investigations, the P uptake was highly related to all soil P tests except the equilibrium phosphate potential at the 0.1% probability level (Table 4). The relationship between P uptake and the equilibrium phosphate potential [$(\frac{1}{2}\text{pCa+pH}_2\text{PO}_4)_{\text{eq}}$] was significant at the 5% probability level ($r = 0.753$). It has been observed that the most important variable that contributes to the total variation in the regression of $(\frac{1}{2}\text{pCa+pH}_2\text{PO}_4)_{\text{eq}}$, Bray P 1, Olsen P and resin-extractable P was the Al-bound P (Maida, 1978).

Stepwise regressions of P uptake on Soil P tests and mineralisable P

The extent to which soil organic P pool is taken into account by the extractants that are used to determine soil P availability has been investigated (Bowman and Cole, 1978; Hayes et al., 2000). Eid et al. (1951) have suggested that the accuracy of chemical soil tests for P availability would be improved by taking into account the appropriate organic P fraction. In the present investigations, P_m values obtained from the selected Malawi soils ranged from 67 to 194 (Table 3) and the effect of P_m on the predictive value of each of the soil P tests was determined using stepwise regressions of P uptake on each of the soil P tests and the P_m .

Bray P1 soil test

When P uptake was regressed on Bray P1, the following first-order (straight line) model was obtained:

$$P_{\text{uptake}} = 2.54 + 0.0318\text{Bray P1} \quad R^2 = 0.8042 \quad (1)$$

The statistical significance of the standard error (± 0.0056) of the regression coefficient associated with the predictor variable, Bray P1, was determined, using the *t*-test, and it was found to be significant at the 0.1% probability level ($t = 5.68$). The square of the multiple correlation coefficient (R^2) was calculated as the ratio of the sum of squares due to regression to the corrected total sum of squares ratio, that is,

$$R^2 = \frac{\Sigma(\hat{Y} - \bar{Y})^2}{\Sigma(Y - \bar{Y})^2}$$

The R^2 therefore measures the proportion of the total variation about the mean explained by the regression (Draper and Smith, 1966). Equation (1) shows that about 80% of the total variation in P uptake were accounted for by soil P evaluated by Bray P1 soil test.

When P_m was included in Equation (1), the following relationship was obtained:

$$P_{\text{uptake}} = 1.11 + 0.0318\text{Bray P1} + 0.0084P_m \quad R^2 = 0.9295 \quad (2)$$

The standard error (± 0.0036) of the regression coefficient associated with Bray P1 remained statistically significant ($t = 8.83$) at 0.1% probability level while the standard error (± 0.0024) of the regression coefficient associated with P_m was significant ($t = 3.50$) at 1% probability level. The fact that inclusion of P_m in Equation (1) after the effects of Bray P1 were allowed for did not change the regression coefficient of Bray P1 suggests that the regression coefficient was stable.

The statistical significance of the regression coefficients of Bray P1 and P suggests that Bray P1 and P_m were good predictors of P uptake on the selected Malawi soils. About 93% of the total variation in P uptake was accounted for by both P_m and the soil P evaluated by Bray P1 (Equation 2), and the increase in R^2 ($\Delta R^2 = 0.1253$) after inclusion of P_m as a predictor variable second to Bray P1 was statistically significant at the 1% probability level.

Mehlich-3

When P uptake was regressed on Mehlich-3, the following equation was obtained:

$$P_{\text{uptake}} = 2.55 + 0.0415\text{Mehlich-3} \quad R^2 = 0.7692 \quad (3)$$

The standard error (± 0.0080) of the regression coefficient associated with Mehlich-3 was significant at the 0.1% probability level ($t = 5.19$) and about 77% of the total variation in P uptake was accounted for by the soil P evaluated by the Mehlich 3 soil P test. Inclusion of P_m as a second predictor variable in Equation (3) yielded the following relationship:

$$P_{\text{uptake}} = 1.12 + 0.0414\text{Mehlich-3} + 0.0085P_m \quad R^2 = 0.8930 \quad (4)$$

The standard error (± 0.0058) of the regression coefficient associated with Mehlich-3 was still statistically significant ($t = 8.83$) at the 0.1% probability level but the standard error (± 0.0029) of the regression coefficient associated with P_m regression was significant ($t = 2.90$) at the 5% probability level. Equation 4 shows that the coefficient of Mehlich, like that of Bray P-1, was stable and that both P_m and Mehlich 3 were good predictors of P uptake, accounting for about 89% of the total variation in P uptake was accounted for by the soil P evaluated by the Mehlich 3 soil P test and P_m .

Olsen P

The regression of P uptake on Olsen P yielded the following model:

$$P_{\text{uptake}} = 2.30 + 0.819 \text{Olsen P} \quad R^2 = 0.8595 \quad (5)$$

The standard error (± 0.0117) of the regression coefficient associated with Olsen P was statistically significant at the 0.1% probability level ($t = 7.00$) and about 86% of the total variation in P uptake was accounted for by the soil P evaluated by Olsen P method. Inclusion of P_m as a second predictor variable in Equation (5) yielded the following relationship:

$$P_{\text{uptake}} = 1.52 + 0.0788 \text{Olsen P} + 0.0048P_m \quad R^2 = 0.9001 \quad (6)$$

The standard error (± 0.0107) of the regression coefficient associated with Olsen P remained statistically significant ($t = 7.36$) at the 0.1% probability level while the standard error (± 0.0029) of the regression coefficient associated with P_m was not statistically significant ($t = 1.66$). The fact that inclusion of P_m in Equation (1) after the effects of Olsen P were allowed for did not change the regression coefficient of Olsen P suggests that the regression coefficient was stable, but the fact that the regression coefficient associated with P_m was not statistically significant suggests that taking into account effects of P_m did not improve the accuracy of Olsen P in predicting P uptake on these acid soils.

Nelson P

When P uptake was regressed on Nelson P, the following relationship was obtained

$$P_{\text{uptake}} = 2.25 + 0.0854 \text{Nelson P} \quad R^2 = 0.8393 \quad (7)$$

The standard error (± 0.0132) of the regression coefficient associated with Nelson P was statistically significant at the 0.1% probability level ($t = 6.47$) and about 84% of the total variation in P uptake was accounted for by the soil P evaluated by Nelson P method. Inclusion of P_m as a second predictor variable in

Equation (7) yielded the following relationship:

$$P_{\text{uptake}} = 1.44 + 0.0822 \text{ Nelson P} + 0.0051 P_m \quad R^2 = 0.8838 \quad (8)$$

The standard error (± 0.0122) of the regression coefficient associated with Nelson P remained statistically significant ($t = 6.75$) at the 0.1% probability level while the standard error (± 0.0031) of the regression coefficient associated with P_m was not statistically significant ($t = 1.65$). The fact that inclusion of P_m in Equation (7) after the effects of Nelson P were allowed for did not change the regression coefficient of Nelson P suggests that the regression coefficient was stable, but the regression coefficient associated with P_m was not statistically significant. This suggests that taking into account effects of P_m did not improve the accuracy of Nelson P in predicting P uptake on these acid soils.

Anion exchange resins

Unlike chemical extractants, anion exchange resins act as sinks for P and therefore mimic plant uptake. In the present investigations, regressing P uptake on resin-P yielded the following relationship:

$$P_{\text{uptake}} = 2.50 + 0.1476 \text{ Resin-P} \quad R^2 = 0.8042 \quad (9)$$

The standard error (± 0.0218) of the regression coefficient associated with Resin-P was statistically significant at the 0.1% probability level ($t = 6.77$) and about 85% of the total variation in P uptake was accounted for by the soil P evaluated by Resin-P method. Inclusion of P_m as a second predictor variable in Equation (9) yielded the following relationship:

$$P_{\text{uptake}} = 2.42 + 0.1461 \text{ Resin-P} + 0.0006 P_m \quad R^2 = 0.8525 \quad (10)$$

The standard error (± 0.0249) of the regression coefficient associated with resin-P remained statistically significant ($t = 5.87$) at the 0.1% probability level while the standard error (± 0.0037) of the regression coefficient associated with P_m was not statistically significant ($t = 1.16$) and this suggests that taking into account effects of P_m did not improve the accuracy of Nelson P in predicting P uptake on these acid soils.

Equilibrium phosphate potential

When P uptake was regressed on $(\frac{1}{2}p\text{Ca}+p\text{H}_2\text{PO}_4)_{\text{eq}}$, the following relationship was obtained:

$$P_{\text{uptake}} = 18.19 - 2.0795 (\frac{1}{2}p\text{Ca}+p\text{H}_2\text{PO}_4)_{\text{eq}} \quad R^2 = 0.5669 \quad (11)$$

The standard error (± 0.6426) of the regression coefficient associated with $(\frac{1}{2}p\text{Ca}+p\text{H}_2\text{PO}_4)_{\text{eq}}$ was statistically significant at the 5% probability level ($t = 3.24$)

and about 57% of the total variation in P uptake was accounted for by $(\frac{1}{2}p\text{Ca}+p\text{H}_2\text{PO}_4)_{\text{eq}}$. Inclusion of P_m as a second predictor variable in Equation (11) yielded the following relationship:

$$P_{\text{uptake}} = 16.45 + - 1.9848 (\frac{1}{2}p\text{Ca}+p\text{H}_2\text{PO}_4)_{\text{eq}} + 0.0063 P_m \quad R^2 = 0.6361 \quad (12)$$

The standard error (± 0.6350) of the regression coefficient associated with $(\frac{1}{2}p\text{Ca}+p\text{H}_2\text{PO}_4)_{\text{eq}}$ remained statistically significant ($t = 3.13$) at the 5% probability level while the standard error (± 0.0054) of the regression coefficient associated with P_m was not statistically significant ($t = 1.17$). The fact that inclusion of P_m in Equation (11) after the effects of $(\frac{1}{2}p\text{Ca}+p\text{H}_2\text{PO}_4)_{\text{eq}}$ were allowed for did not change the regression coefficient of $(\frac{1}{2}p\text{Ca}+p\text{H}_2\text{PO}_4)_{\text{eq}}$ suggests that the regression coefficient was stable, but the regression coefficient associated with P_m was not statistically significant. This suggests that taking into account effects of P_m did not improve the accuracy of $(\frac{1}{2}p\text{Ca}+p\text{H}_2\text{PO}_4)_{\text{eq}}$ in predicting P uptake on these acid soils.

The present findings show that when P_{am} was not included in the regressions of P uptake on each of the soil P tests, the accuracy of the soils tests predicting the pool of P that is available for P uptake is in the following increasing order:

Olsen P > Nelson P > Bray P1 = Resin P > Mehlich 3 > $(0.5p\text{Ca} + p\text{H}_2\text{PO}_4)_{\text{eq}}$

However, when P_{am} was included in the regressions of P uptake on each of the soil P tests, the accuracy of the soils tests predicting the pool of P that is available for P uptake is in the following increasing order:

Bray P1 > Olsen P > Mehlich 3 > Nelson P > Resin P 3 > $(0.5p\text{Ca} + p\text{H}_2\text{PO}_4)_{\text{eq}}$

Conclusions

The build-up of P in some of the Malawi soils that received P fertilisations suggests the need for monitoring P budget for agricultural systems in Malawi particularly those that are managed by commercial estates where P fertilisation is significantly much higher than the one received by soils on fields managed by smallholders. The estates do have their soils tested to identify the need for fertilisation of P and other essential elements. The present findings suggest the need for monitoring also the potential environmental impacts of P build-up in the soils using soil P availability indices whose predictive value should be updated constantly through research and field-scale validation.

Some of the mixtures of reagents routinely used as agronomic soil P tests have been demonstrated in the present investigations to be highly interrelated and the

effectiveness of each of them to be statistically significant at the 0.1 probability level. Their efficacy in accounting for the total variation in P uptake, however, has been shown to be markedly variable, with Olsen P accounting for the highest (86%) total variation in P uptake. This suggests that the increased hydroxyl (OH⁻) ions in the soil solution, supplied by the Olsen P extractant that was buffered at pH 8, were able to exchange with the orthophosphate sorbed on the surfaces of non-silicate minerals and oxides and hydroxides of Al and Fe that are dominant in these heavily weathered acid soils, which was well related to the high total variation in P uptake. Bray P1 and Mehlich 3 were the extractants whose accuracy in evaluating soil P availability in the selected Malawi soils was improved after taking into account P_m. The observation that inclusions of P_m in the models of P uptake regressed on, respectively, Bray P1 and Mehlich 3 resulted in the standard error (SE) of the regression associated with P_m to be more statistically significant in the regression of P uptake on Bray P1 suggests that the predictive value of Bray P1 is better improved than that of Mehlich 3. However, because of its use for the evaluation of other essential elements such as K and Mg in addition to P, the use of Mehlich 3 as a basis for agronomic soil P testing is more attractive. The use of Mehlich 3 for routine work, however, must be based on detailed correlation and calibration work using crop yield data obtained from field experiments.

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