

Critical Evaluation of Methods for Determining Total Organic Phosphorus in Tropical Soils

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ABSTRACT

The determination of total organic phosphorus (TOP) in soils presents several methodological problems, particularly on strongly weathered and tropical soils. We reviewed the application of several methods for TOP determination to soils from different zones of the globe and evaluated the applicability of one ignition and two extraction methods to tropical soils from Brazil and Ghana. Reproducibility (coefficients of variation) was within 6% for the ignition method, and 13% for the extraction methods, due to the simplicity of the former. The two extraction methods produced results similar to each other, while the ignition method generally gave higher TOP contents. Unusually low C to organic P ratios indicate that the ignition method overestimated TOP in several soils. The Bowman extraction method, developed on weakly weathered soils, appeared also suitable for a variety of tropical soils.

NUMEROUS STUDIES have shown that organic P plays an important role in P cycling and plant P nutrition in temperate (Chater and Mattingly, 1980; Harrison, 1982; Sharpley, 1985; Stewart and Tiessen, 1987) and tropical (Acquaye, 1963; Adepetu and Corey, 1976) soils. A more detailed evaluation of the transformations of organic P in strongly weathered soils, which would be required for a prediction of its role in plant nutrition, is hampered by problems associated with the determination of TOP in such soils (Anderson, 1975, 1980; Tiessen, 1989).

The objectives of this study were to (i) present an updated review of methods for determining TOP, particularly for strongly weathered soils, and (ii) evaluate on tropical soils a new rapid extraction-digestion method for determining TOP that has recently been developed by Bowman (1989). The initial evaluations carried out by Bowman (1989) were mainly confined to weakly weathered soils (Mollisols), and indicated that this particular method compared favorably with long-established sequential-extraction techniques and was superior to the ignition method.

LITERATURE REVIEW

The main purpose of this review is to outline the different techniques that have been developed to determine TOP, and to assess their suitability for use on selected soils from different areas of the world.

Methods developed for the determination of TOP in soil can be divided into two distinct categories, extraction and ignition methods.

Extraction methods

These methods are based on the extraction of organic P from the soil by sequential treatment with a selection of acid and alkali solvents of varying strengths. The primary function of the acid extraction is to remove binding metal cations

such as Ca, while subsequent treatment with alkali is designed to extract the organic components (including P) from the soil. Numerous studies have found that several treatments with acid and alkali are required to effect quantitative extraction of organic P from soil (Anderson, 1975). Sequential-extraction schemes developed over the past 50 yr include combinations of mineral acids (e.g., HCl, H₂SO₄), organic acids (e.g., HOAc), strong alkali (e.g., NaOH, KOH), weak alkali (e.g., NaHCO₃) and chelating agents (e.g., EDTA, oxine, acetylacetone) (Anderson, 1975).

The main shortcomings of the extraction techniques include incomplete extraction and hydrolysis of organic P during extraction, particularly when strong mineral acids such as 12 M HCl are used (Anderson, 1975; Olsen and Sommers, 1982). The latter has been minimized to a large extent by the adaptation of extraction techniques to include extraction with alkali prior to treatment with strong mineral acid (Anderson, 1960). However, Bowman (1989) showed that treatment with concentrated (18 M) H₂SO₄ caused minimal hydrolysis (<10%) of organic P esters (glycerol phosphate, inositol hexaphosphate, nitrophenyl phosphate) added to soil. The technique developed by Mehta et al. (1954) and the adapted version proposed by Anderson (1960) are generally considered the reference or standard extraction methods for TOP.

In view of the time taken in performing the various sequential extractions and in determining organic P in the resulting extracts as total P minus inorganic P, the extraction techniques have mainly been used in research studies and have not been widely employed in either soil survey or routine soil testing programs. Attempts have been made to reduce the time involved in extraction techniques by using ultrasonic dispersion in conjunction with strong alkali. While some studies have reported good recoveries of organic P compared with traditional extraction methods (Stewart and Oades, 1972; Soltanpour et al., 1987), others have found that, frequently, less than half of the total soil organic P was recovered using rapid ultrasonic extraction techniques (Tate and Newman, 1982; Hawkes et al., 1984).

Ignition Methods

These methods are based on determining the organic-P content from the difference in acid-extractable inorganic P in unignited and ignited samples of soil. Many different ignition techniques have been developed based on differences in ignition temperature (200–600 °C) and mineral acid type (HCl or H₂SO₄) and strength (0.1–12 M) (Anderson, 1975; Olsen and Sommers, 1982). Nonetheless, the method originally developed by Saunders and Williams (1955) and later adapted by Walker and Adams (1958) is widely regarded as the standard or reference ignition technique for determining TOP.

Compared with the extraction techniques, the ignition method is faster and easier to perform. The ignition method is, consequently, well suited for use with large numbers of soil samples, and it has been widely used in soil surveys and research. While the ignition procedure may be easier to perform, however, several potential sources of error are known to be associated with it, i.e., incomplete oxidation of organic P during ignition, loss of P by volatilization during ignition and, most importantly, changes in the acid solubility of soil inorganic P as a result of ignition (Dormaer and Webster, 1964; Williams et al., 1970; Anderson, 1975). According to the latter, soil minerals containing inorganic P may become soluble in acid following ignition, and irreversible adsorption

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of released inorganic P may occur during extraction of ignited soil. These potential errors are more pronounced in strongly weathered soils than in weakly weathered soils (Williams and Walker, 1967; Williams et al., 1970; Oniani et al., 1973). Furthermore, Williams et al. (1970) found that, in a range of soil and rock materials in New Zealand, the proportion of inorganic P extracted from unignited soil by 0.5 M H₂SO₄ decreased with increasing degree of weathering and concluded that the nonextracted portion of the inorganic P was rendered acid soluble by ignition and thereby resulted in inflated values for TOP in strongly weathered soils.

The remainder of this review deals specifically with selected studies in which the standard ignition (i.e., Saunders and Williams) and extraction (i.e., Mehta or Anderson) techniques for determining TOP have been compared.

In several studies, close agreement has been found between ignition and extraction values for TOP in soils from Great Britain (Hance and Anderson, 1962), Nigeria (Omotoso and Wild, 1970; Omotoso, 1971; Ipinmindun, 1973) and North America (Dormaer, 1964; Soltanpour et al., 1987; Bowman, 1989). In most of the reported comparative studies, however, ignition values tended to be greater than those obtained by extraction (Anderson, 1960; Enwezor and Moore, 1966; Williams and Walker, 1967; Williams et al., 1970; Oniani et al., 1973). On the other hand, results from humid tropical soils from Costa Rica (Bornemisza and Igue, 1967) and Sri Lanka (Oniani et al., 1973) showed that values obtained for TOP by extraction were markedly greater than those obtained by ignition. Results from tropical soils in Hawaii and Costa Rica showed that the differences between ignition and extraction data for TOP were greater in subsoils than in the corresponding topsoils (Bornemisza and Igue, 1967; Soltanpour et al., 1987).

From the studies cited above, some broad conclusions can be drawn on the relationship between soil characteristics and TOP values obtained with the different methods. In general, the closest agreement between ignition and extraction methods has been found in weakly weathered soils, and in acid soils in which a large proportion of the soil inorganic P is

soluble in mineral acid. Ignition values tend to be markedly different from extraction values in more strongly weathered soils (Anderson, 1960; Hance and Anderson, 1962; Williams and Walker, 1967; Williams et al., 1970; Oniani et al., 1973; Bowman, 1989). For example, Williams et al. (1970) found that, in five weakly weathered New Zealand soils, the average TOP determined by ignition (675 mg kg⁻¹) and extraction (636 mg kg⁻¹) were similar, whereas corresponding data from strongly weathered soils showed large differences between TOP determined by ignition (284 mg kg⁻¹) and extraction (38 mg kg⁻¹).

Oniani et al. (1973) suggested an influence of dithionite-extractable Fe (Fe_d) content on the determination of TOP in soils by ignition and extraction. In selected soils from the USSR and Great Britain containing between 12 and 32 g kg⁻¹ of Fe_d, values for TOP determined by ignition were consistently greater than those determined by extraction, whereas, in acid tea soils from Sri Lanka that contained greater quantities of Fe_d (54–58 g kg⁻¹), the extraction values were greater than the ignition values.

In this study, we have assessed the performance of one ignition and two extraction methods on several tropical soils.

MATERIALS AND METHODS

Soils

The 23 soils selected for this study were taken from northeastern Brazil (20) and Ghana, West Africa (3) and comprised soils from humid and semiarid regions. Samples included examples of the major soil types found in the tropics, i.e., Alfisols, Ultisols, Oxisols, and Vertisols, and covered a wide range of total-P and organic-P contents.

Most of the soil samples were from the A horizon, although one complete profile (Noncalcic Brown A1, A3, B2, and C) and separated concretionary material from a subsoil horizon were included. The soils and their major chemical characteristics by horizon are shown in Table 1. All soils were air dried and finely ground (<150 μm) prior to analysis.

Table 1. Major chemical characteristics of selected soils from northeastern Brazil (Pernambuco) and Ghana.

Soil no.	Horizon	Soil type	Taxonomic suborder	pH (H ₂ O)	Organic C	Total N	Total P	Exchangeable cations		Oxalate		Citrate-dithionite	
								Al	Ca + Mg + K	Al	Fe	Al	Fe
					g kg ⁻¹	mg kg ⁻¹		cmol _c kg ⁻¹		g kg ⁻¹			
1	A	RY† Podzolic	Udult	5.7	8.2	496	40	0.9	13	0.42	0.32	0.28	0.3
2	Bc‡	RY Podzolic	Udult	4.9	9.7	206	88	10.8	1	7.09	0.31	4.12	0.8
3	A	RY Podzolic (eutrophic)	Udult	6.6	17.1	1184	638	0.1	89	0.98	1.74	2.02	25.0
4	A	RY Latosol (humic)	Humox	5.2	16.3	756	131	9.5	26	1.44	0.91	1.76	8.1
5	A	Terra Roxa (eutrophic)	Udult	5.3	22.9	1169	1588	3.2	50	1.78	5.11	6.40	77.5
6	A	Vertisol	Torrert	7.6	17.8	1690	420	0.3	447	1.94	4.09	1.24	13.6
7	A1	Noncalcic brown	Xeralf	7.2	5.8	570	632	0.1	80	0.69	1.68	1.01	16.3
8	A3	Noncalcic brown	Xeralf	6.7	4.2	573	464	0.2	96	0.18	1.85	1.18	19.9
9	B2	Noncalcic brown	Xeralf	7.2	3.7	466	296	0.0	185	1.05	1.81	1.99	29.8
10	C	Noncalcic brown	Xeralf	7.9	1.2	164	1374	0.0	246	0.78	1.12	1.07	13.3
11	A	Vertisol	Xerert	7.5	10.0	923	789	0.1	497	1.87	1.78	0.94	5.1
12	A	RY Latosol	Ustox	5.1	15.3	1017	139	5.5	14	1.02	2.39	1.55	10.6
13	A	RY Latosol	Ustox	5.3	8.7	493	84	2.9	10	1.07	2.37	1.44	10.7
14	A	Savannah Ochrosol §	Ustalf	6.6	7.0	896	166	0.1	57	0.32	0.59	0.85	1.1
15	Ac‡	Savannah Ochrosol §	Ustalf	6.7	4.0	408	843	0.1	40	0.64	1.58	10.2	199
16	A	Savannah Gleisol §	Aquept	5.5	3.8	306	68	4.0	12	0.28	0.70	0.18	0.9
17	A	RY Latosol (distrophic)	Orthox	5.5	21.1	1800	211	1.0	64	—	—	—	—
18	A	RY Podzolic	Udult	4.1	15.6	1300	154	7.0	15	—	—	—	—
19	A	Terra Roxa (distrophic)	Udult	4.9	21.6	1000	1466	3.0	5	—	—	—	—
20	A	Noncalcic brown	Xeralf	4.8	11.5	1044	509	2.7	78	1.01	4.96	1.43	14.0
21	A	Brunizem	Ustalf	5.7	17.7	2316	190	0.2	128	1.42	1.97	1.46	11.2
22	A	Terra Roxa (distrophic)	Udalf	5.9	18.8	1590	456	0.1	71	1.34	2.29	2.96	36.3
23	A	RY Podzolic	Udult	6.1	8.7	1120	337	0.5	63	1.10	2.85	1.24	11.3

† RY = Red-yellow.

‡ Concretionary material.

§ Soils from the Savannah zone of Ghana, all others from Brazil.

Total soil P was determined by carbonate fusion (Lim and Jackson, 1982).

Methods for Determining Total Soil Organic Phosphorus

Amounts of TOP in the selected soils were determined using three different methods:

1. Saunders-Williams ignition method (Saunders and Williams, 1955; Walker and Adams, 1958) (550 °C, 1 M H₂SO₄).
2. Anderson-Mehta extraction method, slightly modified from that described by Anderson (1960). A sample of 0.5 g of soil was shaken with 30 mL of 0.3 M NaOH for 16 h. The soil suspension was centrifuged (relative centrifugal force 12 500g, 10 min) and the supernatant decanted into a 100-mL volumetric flask. The soil residue was then heated with 10 mL of concentrated (11.3 M) HCl in a water bath at 82 °C for 10 min. A further 5 mL of concentrated HCl was added and allowed to stand for 1 h at room temperature with regular vortex shaking. The soil suspension was centrifuged and the supernatant decanted and made to volume (50 mL) with deionized water. The soil residue was next shaken with 20 mL of 0.5 M NaOH and allowed to stand for 1 h at room temperature with regular vortex shaking. The soil suspension was centrifuged and the supernatant added to previous alkali extract. The soil residue was again shaken with 30 mL of 0.5 M NaOH, covered and heated at 82 °C in an oven for 8 h and allowed to cool. The soil suspension was centrifuged and the supernatant added to the two previous alkali extracts and made to volume (100 mL) with deionized water. Inorganic, total, and organic P in the acid and alkali extracts were determined according to the methods outlined by Tiessen et al. (1983). Total soil organic P was determined as the sum of the organic P in the acid and alkali extracts.
3. Bowman extraction method, slightly modified from that described by Bowman (1989). A 2-g soil sample was placed into a 250-mL plastic centrifuge tube and 3 mL of concentrated (18 M) H₂SO₄ was added via a long-stemmed funnel while mixing gently. Four separate 1-mL aliquots of deionized water were added with shaking between each addition, followed by a further 41 mL of deionized water (total volume 48 mL). The soil suspension was cooled and centrifuged, and the supernatant Millipore filtered (Millipore Corp., Bedford, MA) at 45 µm. The soil was washed with deionized water and centrifuged, and the supernatant discarded. The soil residue (including the millipore filter from the acid extract) was then shaken with 98 mL of 0.5 M NaOH for 2 h at room temperature. The soil suspension was centrifuged and the supernatant millipore filtered. Inorganic, total, and organic P in the acid and alkali extracts were determined and total soil organic P was calculated as the sum of organic P in the acid and alkali extracts.

To enable statistical analysis of the reproducibility of values obtained for TOP by the different methods, four replicate samples of each soil were used for each method under investigation.

RESULTS AND DISCUSSION

The soils selected for this study were predominantly acidic (pH <6) and contained small amounts of organic C (1–23 g kg⁻¹) and total N (0.2–2.3 g kg⁻¹) (Table 1). Total P ranged from 40 to 1588 mg kg⁻¹, with an overall average of 482 mg kg⁻¹ (Table 1). The greatest amounts of total P were found in the eutrophic Terra

Table 2. Amounts of total P extracted from soils by the Saunders-Williams (SW), Anderson-Mehta (AM), and Bowman (BOW) methods.

Soil no.†	SW		AM		BOW	
	mg kg ⁻¹	% of total‡	mg kg ⁻¹	% of total‡	mg kg ⁻¹	% of total‡
1	34	85	35	87	28	71
2	58	66	43	49	26	30
3	375	59	607	95	616	97
4	102	78	126	96	102	78
5	1492	94	1202	76	843	53
6	404	96	387	92	412	98
7	522	83	622	98	587	93
8	356	77	445	96	390	84
9	197	67	285	96	162	55
10	1395	102	1497	109	1476	107
11	766	97	849	108	829	105
12	90	68	140	101	97	70
13	70	84	85	101	63	75
14	151	91	167	101	170	102
15	461	55	847	100	266	32
16	44	65	58	85	39	57
17	169	80	179	85	159	76
18	134	87	154	100	114	74
19	1180	81	1021	70	784	54
20	446	88	495	97	507	100
21	171	90	191	101	183	97
22	356	78	440	97	391	86
23	267	79	299	89	283	84
Arithmetic means	402	83	442	92	371	77

† See Table 1 for descriptions.

‡ Percentage of total soil P, as determined by fusion.

Roxa (no. 5, 1588 mg kg⁻¹), Noncalcic Brown C (no. 10, 1374 mg kg⁻¹) and the dystrophic Terra Roxa (no. 19, 1466 mg kg⁻¹) soils. The concretory material in the Savannah Ochrosol (no. 15) contained markedly more total P (843 mg kg⁻¹) than the corresponding nonconcretory material (no. 14, 166 mg kg⁻¹) (Table 1).

Amounts of total P extracted by the methods under investigation are shown in Table 2. In general, these results show that a greater proportion of the total soil P was extracted using the Anderson-Mehta method (mean 91.7%) than by either the Saunders-Williams (mean 83.4%) or Bowman (mean 76.9%) methods. These data cannot be directly compared with the data of Bowman (1989), since no total soil P or extracted total P data was included, although they are consistent with the findings of Bornemisza and Igue (1967) for the Mehta and Saunders-Williams methods in soils from Costa Rica. The lowest overall recovery of total P by the three methods occurred in the concretory material (no. 2, 29.9–66.4%).

Amounts of TOP determined by the Saunders-Williams ignition method (range 23–1253 mg kg⁻¹, mean 209 mg kg⁻¹) were substantially greater than the corresponding amounts determined by the Anderson-Mehta (range 13–206 mg kg⁻¹, mean 78 mg kg⁻¹) and the Bowman (range 9–248 mg kg⁻¹, mean 88 mg kg⁻¹) extraction methods (Table 3). Total organic P determined by the Saunders-Williams, Anderson-Mehta, and Bowman methods, therefore, represented an average of 43, 16, and 18% of the total soil P, respectively (Tables 1 and 3).

Differences between the Saunders-Williams and An-

Table 3. Amounts of organic P extracted from soils by the Saunders-Williams (SW), Anderson-Mehta (AM) and Bowman (BOW) methods.

Soil no.†	Organic P extracted						LSD‡
	SW		AM		BOW		
	mg kg ⁻¹	CV%‡	mg kg ⁻¹	CV%‡	mg kg ⁻¹	CV%‡	
1	23.6	5.5	13.0	4.0	9.2	1.7	5.2
2	50.6	9.5	13.2	2.4	12.0	1.3	5.5
3	180	2.9	101	1.3	125	1.0	17.2
4	75.1	1.3	49.1	2.0	43.8	7.8	9.6
5	1253	2.2	188	1.3	193	3.7	42.2
6	221	2.1	110	3.6	178	4.1	8.8
7	161	14	78.2	6.6	109	14	25.2
8	156	5.3	67.4	7.0	90.4	14	12.4
9	117	3.1	40.2	2.0	43.4	10	9.0
10	58.3	20	16.3	2.9	63.8	21	17.0
11	72.6	22	91.8	4.1	81.6	14	NS
12	57.4	12	44.3	2.1	34.0	22	12.9
13	47.0	5.3	25.8	2.0	22.7	12	5.8
14	111	1.2	71.6	3.6	79.8	3.9	3.9
15	341	3.5	26.2	3.4	24.8	21	14.5
16	34.6	11	32.8	3.0	22.0	11	NS
17	117	3.8	81.8	1.0	68.2	6.7	9.8
18	99.8	2.0	54.1	1.5	38.1	9.2	8.3
19	952	2.0	206	3.3	248	16	40.5
20	172	4.8	134	1.1	166	9.8	21.1
21	131	4.4	102	5.8	104	4.6	8.8
22	223	2.3	145	4.8	159	6.5	12.5
23	149	5.5	106	1.2	108	8.1	15.8
Arithmetic means	208	6.4	78	1.5	88	1.1	—

† See Table 1 for descriptions.

‡ Coefficient of variation on mean of four extractions.

§ Fisher's protected least significant difference at $P \leq 0.05$ (horizontal comparison only).

derson-Mehta/Bowman methods were statistically significant ($P < 0.05$) in 21 of the 23 soils examined (except in the Vertisol [no. 11] and Savannah Gleisol [no. 16] soils) (Table 3). The differences observed between the three methods in the Noncalcic Brown C horizon (no. 10) (Table 3) were probably erroneous due to the small amount of TOP relative to acid-extractable inorganic P (Ca-bound P) (> 1300 mg kg⁻¹) in this subsoil (Table 4). Similar quantities of TOP were determined by the Anderson-Mehta and Bowman methods in 10 soils. In seven other soils, significant differences were found between the Anderson-Mehta and Bowman methods, although corresponding differences from TOP determined by the Saunders-Williams method (Table 3) were much greater. Nonetheless, large differences in TOP were observed between the Anderson-Mehta and Bowman methods in the Vertisol (no. 6) and Noncalcic Brown (no. 20) soils (Table 3).

The greater values for TOP determined by ignition than by extraction in these strongly weathered soils are consistent with several other studies on similar soil types (Enwezor and Moore, 1966; Williams et al., 1970). To test the role of dithionite-extractable Fe suggested by Oniani et al. (1973), we correlated Al and Fe contents (Table 1) with the ratio of ignition to extractable (Bowman) TOP, and obtained correlation coefficients (r^2) of 0.89 and 0.82 with dithionite-extractable Al and Fe, respectively. This indicates that the ignition method measures higher apparent TOP values in soils with high dithionite-extractable Al and Fe contents, a result opposite to the one obtained by Oniani et al. (1973) in their comparison between temperate and tropical soils. The high correlation, though,

Table 4. Relative proportions of total organic P extracted by component acid and alkali reagents in Anderson-Mehta (AM) and Bowman (BOW) methods.

Soil no.†	AM‡			BOW§	
	NaOH I	HCl	NaOH II	H ₂ SO ₄	NaOH
	%				
1	75	10	15	70	30
2	75	2	23	88	12
3	55	30	15	88	12
4	71	6	23	84	16
5	59	12	39	86	14
6	19	47	34	80	20
7	39	19	42	91	9
8	45	17	38	90	10
9	27	17	56	79	21
10	72	0	28	86	14
11	17	38	45	62	38
12	62	9	29	80	20
13	64	14	22	89	11
14	53	23	24	86	14
15	96	0	4	91	9
16	60	5	35	85	15
17	74	7	19	83	17
18	57	8	35	85	15
19	83	6	11	86	14
20	58	17	25	87	13
21	71	14	15	72	28
22	63	19	18	86	14
23	68	14	18	83	17
Arithmetic means	59	14	27	83	17

† See Table 1 for descriptions.

‡ NaOH I (0.3 M NaOH); HCl (12 M HCl); NaOH II (0.5 M NaOH, 90 °C).

§ H₂SO₄ (18 M H₂SO₄); NaOH (0.5 M NaOH).

is almost entirely dependent on Samples 2, 5, and 15, greatly reducing the significance of this result.

The reproducibility of the different methods can be assessed from the respective coefficients of variation (CV%) associated with the determination of TOP in four replicate samples of each soil. These data (Table 3) demonstrate that greater variability occurred with the multiple-extraction Anderson-Mehta (mean CV 15%) and Bowman (mean CV 11%) methods than with the Saunders-Williams ignition method (mean CV 6.4%). This may be at least partly attributed to the relative simplicity of the Saunders-Williams technique, which involved only one extraction of unignited and ignited soil with 1 M H₂SO₄, while the Bowman and Anderson-Mehta methods involved two and four separate sequential extraction steps, respectively. Increased analytical error may, therefore, be associated with the dispensing and separation of different soil extractants and the determination of inorganic and total P in the component acid and alkali extracts of the Anderson-Mehta and Bowman methods. Bowman (1989) also found that the variability associated with both extraction methods was slightly greater than with the Saunders-Williams method.

The respective proportions of total soil organic P extracted by the component acid and alkali extractants in the Anderson-Mehta and Bowman methods are shown in Table 4. In the Bowman method, most (62–91%, mean 83%) of the TOP was extracted by the initial treatment with concentrated H₂SO₄. A similar finding was reported by Bowman (1989) for a range of North American soils. In the Anderson-Mehta method, 17 to 96% (mean 59%) of the TOP was ex-

Table 5. Ratios of organic C to total N (C/N) and organic C to organic P (C/P_o) as determined by the Saunders-Williams (SW), Anderson-Mehta (AM), and Bowman (BOW) methods.

Soil no.†	C/N	C/P _o		
		SW	AM	BOW
1	16.5	347	631	891
2	47.1	192	735	808
3	14.4	95	170	137
4	21.6	217	332	372
5	19.6	18	122	118
6	10.5	81	161	100
7	10.2	36	74	53
8	7.3	27	62	47
9	7.9	32	92	85
10	7.3	21	74	19
11	10.8	138	109	123
12	15.0	267	345	450
13	17.6	185	337	383
14	7.8	63	98	88
15	9.8	12	153	161
16	12.4	103	116	173
17	11.7	181	258	309
18	12.0	156	288	409
19	21.6	23	105	87
20	11.0	67	86	69
21	7.6	135	173	170
22	11.8	84	130	118
23	7.8	59	82	81
Means‡	12.9	115	196	219

† See Table 1 for descriptions.

‡ A horizon soils only (i.e., excluding soils no. 2, 9, and 10).

tracted by the first alkali extract (0.3 M NaOH). It is noteworthy that the smallest proportions of TOP extracted by 0.3 M NaOH in the Anderson-Mehta method occurred in the two Vertisols (no. 6 and 11; 19% and 17%). This was compensated by greater proportions of TOP extracted by the subsequent concentrated-HCl step (38–47%).

The ratios of organic C to total N (C/N) and organic C to organic P (C/P_o) as determined by the three methods under investigation are shown in Table 5. The C/N ratio varied from 7.3 to 47.1 with a mean of 12.9, which is consistent with values reported for most soils of 10 to 12 (Stevenson, 1982). As expected, the C/P_o ratios were markedly greater when the organic P was determined by the Anderson-Mehta (62–631, mean 196) and Bowman (19–891, mean 219) methods, compared with the Saunders-Williams method (12–347, mean 115). Ratios of C/P_o reported for microbes range from 15 to 45, while those of temperate soils are usually above 50 (Stewart and Tiessen, 1987). Simple correlation coefficients between C/N and C/P_o ratios were 0.37, 0.75, and 0.66 when P_o was determined by the Saunders-Williams, Anderson-Mehta, and Bowman methods, respectively. The rather low C/P_o values and low correlation with C/N ratios obtained by the Saunders-Williams method would suggest that this method overestimates P_o. The Bowman method gives a low C/P_o in only one soil, the Anderson-Mehta method in none.

These results clearly show that the apparent C/P_o ratio in strongly weathered soils will be determined, to a large extent, by the method used to determine organic P. It is, therefore, very difficult to compare data from different studies. For example, Neptune et al. (1975) reported that, in four subtropical agricultural soils from São Paulo state in Brazil, the C/P_o ratio

ranged from 45 to 247, using an ignition method to determine total soil organic P.

CONCLUSIONS

Results of this study demonstrate that the high-temperature ignition (Saunders-Williams) method for determining total organic P in strongly weathered tropical soils substantially overestimates soil organic-P content, compared with values obtained by combined acid-alkali extraction techniques (Anderson-Mehta and Bowman methods).

In general, there was little difference between the amounts of organic P determined by the Anderson-Mehta and Bowman methods. Since the Bowman method is faster and involves fewer technical manipulations than the Anderson-Mehta method, it may be the preferred method for use in soil nutrient surveys and where available technical and manpower resources are limited. However, the proportion of total soil P recovered by extraction was greater with the Anderson-Mehta method than with the Bowman method. This may account for the slightly greater amounts of organic P determined by Anderson-Mehta, compared with Bowman, in many of the soils studied. This, in turn, implies that a fraction of the organic P in these strongly weathered soils may only be extracted from the soil with hot alkali (0.5 M NaOH). Accordingly, in strongly weathered tropical soils, the alkali extraction step of the Bowman method could be carried out at 80 to 90 °C. A similar adaptation was suggested by Bowman (1989) for strongly acid soils.

A very high proportion of the total soil organic P determined by the Bowman method was extracted during the initial treatment with concentrated H₂SO₄ (62–91% overall, 79–91% for 20 of the 23 soils) (Table 4). It may, therefore, be possible to use this acid-extractable organic-P fraction as a rapid single-step method of determining organic P in short-term studies of soil P transformations under different management systems in the tropics.

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