A Study on Distribution of Forms of Phosphorus in Calcareous Soils of Western Australia

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ABSTRACT

The forms, amounts and distribution of phosphorus (P) were determined in 28 calcareous soils from South-Western Australia to evaluate soil P status and their contribution to soil P tests. The soils under study exhibited wide ranges in content of total P (TP), organic P (org.-P), inorganic P (P_i) fractions and of P extracted by soil tests for plant available P. The values of TP ranged from 33 to 392 mg/kg with a mean of 176 mg P/kg soil. Org.-P constituted a considerable portion of TP (mean 35%). The mean ratio of organic C/ org.-P was 287. In general, the distribution of P_i fraction was Ca_2-P, 15; Ca_8-P, 27; Al-P, 26; Fe-P, 14; occluded-P (O-P), 20, Ca_{10}-P, 16 mg P/kg soil, accounting respectively for 13%, 23%, 22%, 12%, 17%, and 13% of total P_i. The pattern of distribution of the Pi fractions, however, differed between virgin and cultivated soils. For virgin soils, the average relative abundance of P_i in the secondary Ca-P [(Ca_2-P)+(Ca_8-P)], nonoccluded Fe- and Al-P [(Al-P)+(Fe-P)] and acid extractable P (primary Ca phosphate (Ca_{10}-P)) was 2.5:2:1 and in cultivated soils was 2:2.5:1, respectively. Statistical analysis indicates that the Ca_2-P, Al-P, Fe-P and Ca_{10}-P fractions made significant contributions to available P as estimated by the Olsen and Colwell methods. Stepwise regression showed that most of variation in Olsen-P (90%) and Colwell-P (82%) was accounted for by Ca_2-P. Scanning electron microscopy (SEM) showed that P was uniformly distributed in the soil matrix to the limit of the spatial resolution and sensitivity of this technique. There were no local concentrations of P or spatial associations of other elements with P.

Keywords: Available P, Inorganic P fractions, P in calcareous soils.

INTRODUCTION

Knowledge of the amounts, forms and distribution of P in soils can assist considerably in understanding pedogenic processes and serve as a useful measure of soil development. Two major processes involved in transformation and translocation of phosphorus in the soil are geochemical and biological processes (Cross and Schlesinger, 1995). Geochemical processes apparently determine the long-term distribution of P in soils, but in the short-term, biological processes influence the movement and distribution of labile forms of P due to considerable available P being derived from organic matter (Smeck, 1985; Stewart and Tiessen,

1987). In the very early stages of soil formation, phosphorus is a constituent of primary minerals, predominantly apatite (Williams and Walker, 1969; Smeck, 1973). Primary apatite gradually undergoes hydrolysis and inorganic phosphate becomes labile. The soluble phosphate is then utilized by plants, leached from the system, adsorbed or precipitated as calcium, aluminium, or iron phosphate. Once the primary mineral apatite has weathered in the soil, the P concentration in soil solution is governed by the solubility of Ca, Al and Fe phosphates which exist as discrete compounds or surface complexes. Studies on acidic soils have shown that with increasing soil age, nonoccluded Al and Fe-bound P (phosphate ions sorbed at

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the surfaces of iron and aluminium oxides and hydroxides), secondary Ca-bound P and P occluded in the Fe oxides increase (Walker and Syers, 1976). In the later stages of soil development, nonoccluded P forms decrease while occluded forms increase. The relative proportion of different P_i fractions is determined by the activities of calcium, iron and aluminium in the soil which, in turn, are greatly influenced by weathering processes. In general, as pedogenic weathering progresses, the pH decreases, resulting in the conversion of Ca phosphate minerals to Fe and Al phosphates. Parent material and climate are fundamental factors to determine the overall weathering rate, and these factors influence the balance between phosphorus loss and retention (Gardner, 1990).

Various sequential P fractionation procedures have been used to identify the forms of P and to determine the distribution of P fractions in soils (Chang and Jackson, 1957, Williams *et al.*, 1967; Hedley *et al.*, 1982), but are not particularly sensitive to the various P compounds that may exist in calcareous soils. Recently, a new sequential fractionation scheme has been suggested for calcareous soils by which three types of Ca-phosphates i.e. dicalcium phosphate, octacalcium phosphate, and apatite could be identified (Jiang and Gu, 1989). These types of Ca-phosphates were described as Ca_2-P ($NaHCO_3$-extractable P), Ca_8-P (NH_4Ac-extractable P) and Ca_{10}-P (apatite type), respectively. However, the chemical fractionation analyses provide no direct information about the precise forms of inorganic P in a soil. Some of the existing uncertainties in fractionation methods may be clarified when these methods are combined with electron microscopy (SEM) and energy-dispersive x-ray microanalysis (EDXA) to directly identify P compounds (Tiessen, 1995).

Assessments of the amount of phosphorus that a soil can supply to a crop during the growing season are commonly made by means of empirical chemical extractions rather than being based on a direct estimation of the availability of P compounds to plants. P fractionation studies have been fre-quently used for the purpose of assessing the forms of P that contribute to P availability as estimated by soil P tests (Al-Abbas and Barber, 1964) and plant growth but this approach has not been widely used for calcareous soils.

The aims of this study were to investigate the nature of soil P and to determine the distribution of various forms of soil P. it also aimed to establish the interrelationships of P forms with available P as measured by soil P tests and with soil properties for virgin and fertilized calcareous soils in South-Western Australia.

MATERIALS AND METHODS

Twenty eight surface soil samples used for the laboratory studies were collected from the top 10 cm of soil profiles located in valley floors in the Kellerberrin, Beacon, Kondinin, Jerramungup, Salmon Gums areas and the Swan Coastal Plain of South-Western Australia. The soil notation Kell 9, SCP 7, Bea 1, Kon 1, Kon 5, Jer 3, and SG 2 follows that of McArthur (1991). The characteristics and, physicochemical properties of the soil samples and the procedure for determination of soil P forms have been described elsewhere (Samadi and Gilkes, 1998). Table 1 shows some of the properties of the soils. The identification of clay and carbonate minerals was carried out by x-ray diffraction (XRD) using random powder and oriented clay on ceramic plate procedures. The XRD pattern and d-spacings were derived and interpreted with the computer program XPAS (Singh and Gilkes, 1992). Scanning electron microscopy (SEM) coupled with energy-dispersive x-ray analysis (EDXA) was used to examine the distribution of P and its association with the elements Al, Fe, Ca, and Si in the soil.

A Mediterranean climate exists in the region with mean annual rainfall ranging from 300 to 350 mm/year and mean minimum and maximum temperatures from 6 to 16 ^{o}C in July (winter) and 17 to 34 ^{o}C (summer) in January (McArthur 1991) except for the

Swan Coastal Plain area, which has a rainfall of about 900 mm .

RESULTS AND DISCUSSION

Properties of the Soils

Although a Mediterranean-type climate exists in the areas of South-Western Australia where calcareous soils are found, the chemical and physical properties and in particular the P status of these soils differ from those reported for soils in Mediterranean regions in the northern hemisphere. These differences reflect the much more complex and ancient nature of the land surface in South western Australia.

The total $CaCO_3$ (CCE) content of the 25 fine-textured soils studied ranged from 12 to 398 g/kg. Active $CaCO_3$ (ACCE) ranged from 0 to 70 g/kg and was highly correlated with the total $CaCO_3$ (r = 0.73, p<0.0001). X-ray diffraction (XRD) analysis showed that Mg-calcite $[Mg_xCa_{1-x}(CO_3)]$ is the most common carbonate in the soils with a low degree of Mg substitution (average 4.6 mole %). Figure 1 shows scanning electron images of calcite grains found in Kell9 calcareous soil. Possible sources of calcium carbonate in this soil might be deposition of $CaCO_3$ in aeolian dust from playa lakes or rainfall (McArthur, 1991).

The amount of oxalate-extractable Fe (Fe_o) ranged from 0.11 to 1.89 g/kg which was much less than the dithionite extractable Fe

Table 1. Physical and chemical properties of the surface soil samples.

Soil	pH (CaCl$_2$)	Clay	CCE	ACCE	OC	CEC [cmole (+)/kg]	Al$_d$	Al$_o$	Fe$_d$	Fe$_o$
			(g/kg)					(g/kg)		
1 Kell 9	8.0	158	51	34	18	20.0	0.81	1.37	4.3	0.61
2 Kell 9	8.0	267	94	70	13	21.0	0.74	1.99	6.0	0.69
3 Kell 9	8.0	395	71	63	14	19.2	0.83	1.99	6.4	1.11
4 Kell 9	8.1	182	53	32	12	17.2	0.66	1.52	4.2	0.72
5 Kell 9	8.2	190	69	42	15	16.4	0.78	2.51	3.8	0.81
6 Kell 9	8.1	184	62	41	15	19.8	0.83	2.19	3.8	0.74
7 Kell 9	7.7	190	30	5	9	9.7	0.69	1.09	7.3	0.67
8 Kell 9	8.0	421	40	14	8	18.4	0.95	1.19	7.0	0.72
9 SCP 7	8.8	19	398	38	8	1.8	0.07	0.021	0.9	0.11
10 SCP 7	8.5	23	392	44	4	1.5	0.15	0.12	1.3	0.11
11 SCP 7	8.8	9	220	22	4	1.3	0.072	0.022	0.8	0.11
12 Bea 1	7.4	318	12	8	13	28.8	1.1	1.27	13.8	1.32
13 Bea 1	7.9	353	54	52	13	17.2	0.87	1.22	11.3	0.82
14 Bea 1	7.9	281	27	22	10	19.0	0.98	1.37	14.4	0.8
15 Bea 1	8.0	254	46	30	10	16.2	0.95	1.27	13.2	0.97
16 Bea 1	6.8	280	17	3	12	12.3	1.21	1.22	8.2	0.92
17 Kon 5	7.6	486	47	0	17	24.8	1.31	1.24	23.0	1.89
18 Kon 5	6.8	479	25	11	13	32.2	1.29	1.56	32.8	1.87
19 Kon 1	7.8	373	40	10	16	21.2	1.6	2.78	15.6	1.4
20 Kon 1	7.5	390	54	10	15	22.4	1.4	2.12	14.3	1.22
21 Kon 1	8.1	247	62	42	13	15.4	0.67	0.94	7.3	0.71
22 Jer 3	5.7	84	24	0	9	14.7	2.12	0.89	9.9	0.52
23 SG 1	7.9	429	68	30	14	23.0	0.81	1.24	4.0	0.71
24 SG 1	8.4	394	140	70	12	18.6	0.48	1.5	0.9	0.57
25 SG 1	8.1	342	47	11	12	26.0	1	1.35	5.7	0.63
26 SG 2	8.7	196	74	12	14	13.8	0.54	1.61	1.5	0.5
27 SG 2	8.6	310	144	48	17	19.0	0.45	2.33	1.5	0.78
28 SG 2	8.0	274	54	7	12	28.5	0.93	1.5	3.6	0.57
Average	7.9	269	86	28	12	17.8	0.87	1.41	8.1	0.81

ACCE, active $CaCO_3$; CCE, total $CaCO_3$ equivalent; Al$_d$ and Fe$_d$, citrate-dithionite-bicarbonate Al and Fe; Al$_o$ and Fe$_o$, oxalate-extractable Al and Fe; OC, organic carbone

(Fe$_d$) (Table 1). This suggests that only a small proportion of the total free Fe oxide is in paracrystalline form. The values of dithionite extracted Al (Al$_d$) are closely related to Fe$_d$ (p<0.001; r = 0.641), suggesting that much of the Al dissolved by CDB was Al substituting for Fe in iron oxides. The strong relationships between clay content and Fe$_d$ (p<0.01; r = 0.574) and Fe$_o$ (p<0.001; r = 0.769) suggests that iron (hydr) oxides are concentrated in the clay fraction.

While a Mediterranean climate exists in the region, the clay mineralogy of the soils is different from soils of most Mediterranean regions where illite is an abundant clay mineral (Matar *et al.*, 1992). X-ray diffraction patterns of the clay fraction show that kaolnite and minor smectite and illite plus mixed layer minerals are the dominant clay minerals in the soils (Samadi, 1999).

Forms of P

The soils exhibited wide ranges of total P (TP), organic P (OP), inorganic P (P$_i$) fractions and of P extracted by soil tests (Table 2). The values of TP ranged from 33 to 392 mg/kg with a mean of 176 mg P/kg soil. These values were, however, much lower than those reported for agricultural soils of dryland regions in the western United States and Lebanon (Ryan, 1983) and also for many other Australian soils (Norrish and Rosser, 1988). These differences are again a consequence of the great age and stability of the S.W. Australian land surface (McArthur, 1991). In comparison with soils of other Mediterranean regions and other semiarid areas, organic P constituted a larger proportion of total P (35%). Positive relationships exist between organic P and both extractable Fe (Fe$_o$) and organic matter. The mean ratio of organic C/ organic P was 287.

This type of statement is suitable for introduction. In general, the average abundance of inorganic P fraction (P$_i$) was Ca$_2$-P (Na-HCO$_3$-extractable P), 15; Ca$_8$-P (NH$_4$Ac-extractabe P), 27; Al-P (NH$_4$F-extractabe P), 26; Fe-P (NaOH and Na$_2$CO$_3$-extractable P), 14; occluded-P (O-P), 20; Ca$_{10}$-P (H$_2$SO$_4$-extractable P), 16 mg P/kg soil, accounting respectively for 13%, 23%, 22%, 12%, 17%
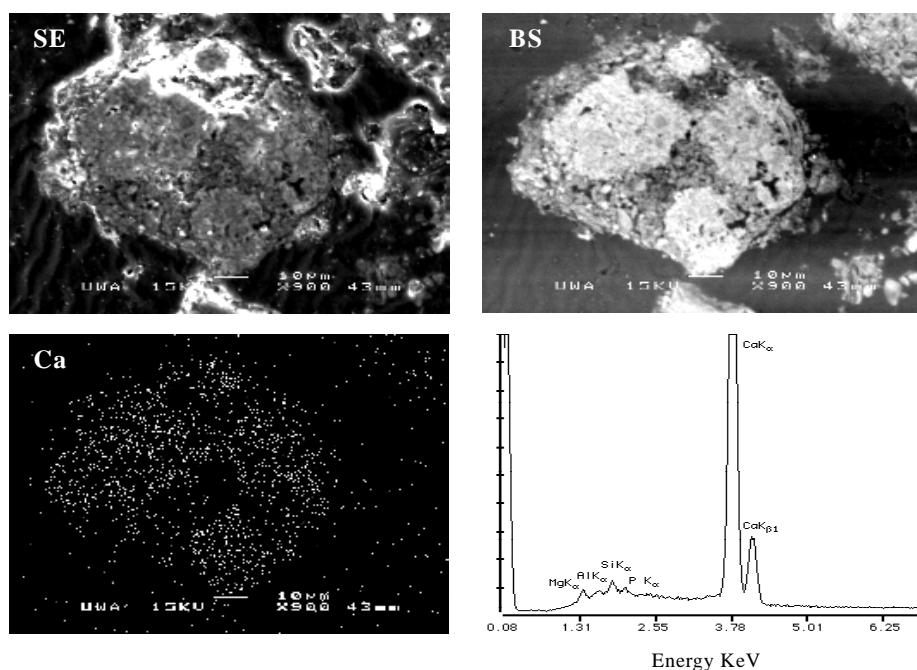

Figure 1. SEM data for the polished surface of 1 Kell 9 calcareous soil showing secondary electron (SE) and backscattered electron (BS) images, X-ray image of Ca distribution, and X-ray spectrum for Ca-rich material.

and 13% of total P_i. The pattern of distribution of the P_i fractions, however, differed between virgin and cultivated soils (Figure 2). For virgin soils, the average relative abundance of P_i forms. as secondary Ca-bound P $[(Ca_2\text{-}P)+(Ca_8\text{-}P)]$, nonoccluded Fe- and Al-bound P $[(Al\text{-}P)+(Fe\text{-}P)]$ and acid extractable P as a measure of primary Ca phosphate ($Ca_{10}\text{-}P$) was 2.5:2:1 and in culti-

vated soils was 2:2.5:1, respectively. The high percentage of secondary Al and Fe phosphates and the low percentage of acid extractable P ($Ca_{10}\text{-}P$) in the soil samples suggests that, as weathering proceeds, the Ca-P fraction is progressively transformed to nonoccluded and finally to occluded Fe and Al forms. It is noticeable that the pattern of distribution of P forms in calcareous soils of

Table 2. Soil P fractions (mg/ kg) and soil available P (mg/ kg) as measured by soil P tests (Olsen et al., 1954; Colwell, 1963). O-P = occluded P (mg/ kg); TP_i = total inorganic P (mg/ kg); TP = total P (mg/ kg); OP = organic P (mg/ kg); OC = organic carbon (g/kg).

| Soil	$Ca_2\text{-}P$	$Ca_8\text{-}P$	Al-P	Fe-P	O-P	$Ca_{10}\text{-}P$	TP_i	TP	OP	OC/OP	Olsen-P	Colwell-P
1 Kell 9	14	8	21	14	15	8	80	158	71	254	6.0	8.0
2 Kell 9	5	6	27	16	16	8	76	165	70	186	3.2	4.0
3 Kell 9	34	68	61	32	30	38	262	358	78	180	15.6	22.0
4 Kell 9	46	69	78	23	23	28	266	300	53	226	18.0	20.0
5 Kell 9	14	5	35	11	13	7	84	150	53	283	5.6	6.0
6 Kell 9	76	69	103	23	17	23	310	392	112	134	28.0	32.0
7 Kell 9	42	20	27	27	32	13	159	217	137	66	13.2	14.0
8 Kell 9	21	23	54	37	19	32	185	258	178	45	8.8	14.0
Mean	**31**	**33**	**50**	**23**	**21**	**19**	**178**	**250**	**94**	**138**	**12.3**	**15.0**
9 SCP 7	3	118	7	6	35	48	216	283	30	267	6.4	8.0
10 SCP 7	2	98	10	2	21	17	149	192	12	333	2.4	4.0
11 SCP 7	10	117	11	7	14	25	183	183	3	1333	4.8	8.0
Mean	**5**	**111**	**9**	**5**	**23**	**30**	**183**	**219**	**15**	**356**	**4.5**	**6.7**
12 Bea 1	4	5	6	12	70	11	106	133	43	302	4.0	12.0
13 Bea 1	25	60	68	35	30	41	259	292	39	333	17.6	22.0
14 Bea 1	5	3	12	8	37	8	72	100	20	500	1.6	4.0
15 Bea 1	21	11	36	18	26	17	126	167	40	250	5.6	10.0
16 Bea 1	5	3	9	7	16	7	46	108	68	177	1.6	4.0
Mean	**12**	**16**	**26**	**16**	**36**	**17**	**122**	**160**	**42**	**276**	**6.1**	**10.4**
17 Kon 5	3	5	5	6	20	14	53	117	80	213	4.4	6.0
18 Kon 5	18	11	20	30	30	29	138	225	150	87	8.0	14.0
Mean	**11**	**8**	**13**	**18**	**25**	**22**	**96**	**171**	**115**	**130**	**6.2**	**10.0**
19 Kon 1	11	3	14	9	20	7	63	125	95	168	4.0	8.0
20 Kon 1	18	8	41	26	30	17	138	242	162	93	8.0	14.0
21 Kon 1	28	17	28	4	26	14	115	217	160	81	11.2	16.0
Mean	19	9	27	13	25	13	105	195	139	106	7.7	12.7
22 Jer 3	0	0	4	6	6	4	20	33	21	429	0.0	0.0
Mean	**0**	**0**	**4**	**6**	**6**	**4**	**20**	**33**	**21**	**429**	**0.0**	**0.0**
23 SG 1	4	5	3	5	4	9	29	58	43	326	0.8	4.0
24 SG 1	0	2	5	4	4	3	17	58	43	279	0.8	4.0
25 SG 1	3	2	14	12	5	8	42	100	65	185	2.0	4.0
Mean	**2**	**3**	**7**	**7**	**4**	**7**	**30**	**72**	**50**	**252**	**1.2**	**4.0**
26 SG 2	5	5	7	3	10	2	32	83	58	241	2.4	4.0
27 SG 2	9	16	20	7	0	13	64	142	97	175	6.8	8.0
28 SG 2	2	2	7	8	1	4	23	67	52	231	2.0	4.0
Mean	**5**	**8**	**11**	**6**	**4**	**6**	**39**	**97**	**69**	**208**	**3.7**	**5.3**
Total mean	**15**	**27**	**26**	**14**	**20**	**16**	**118**	**176**	**73**	**287**	**6.9**	**9.9**
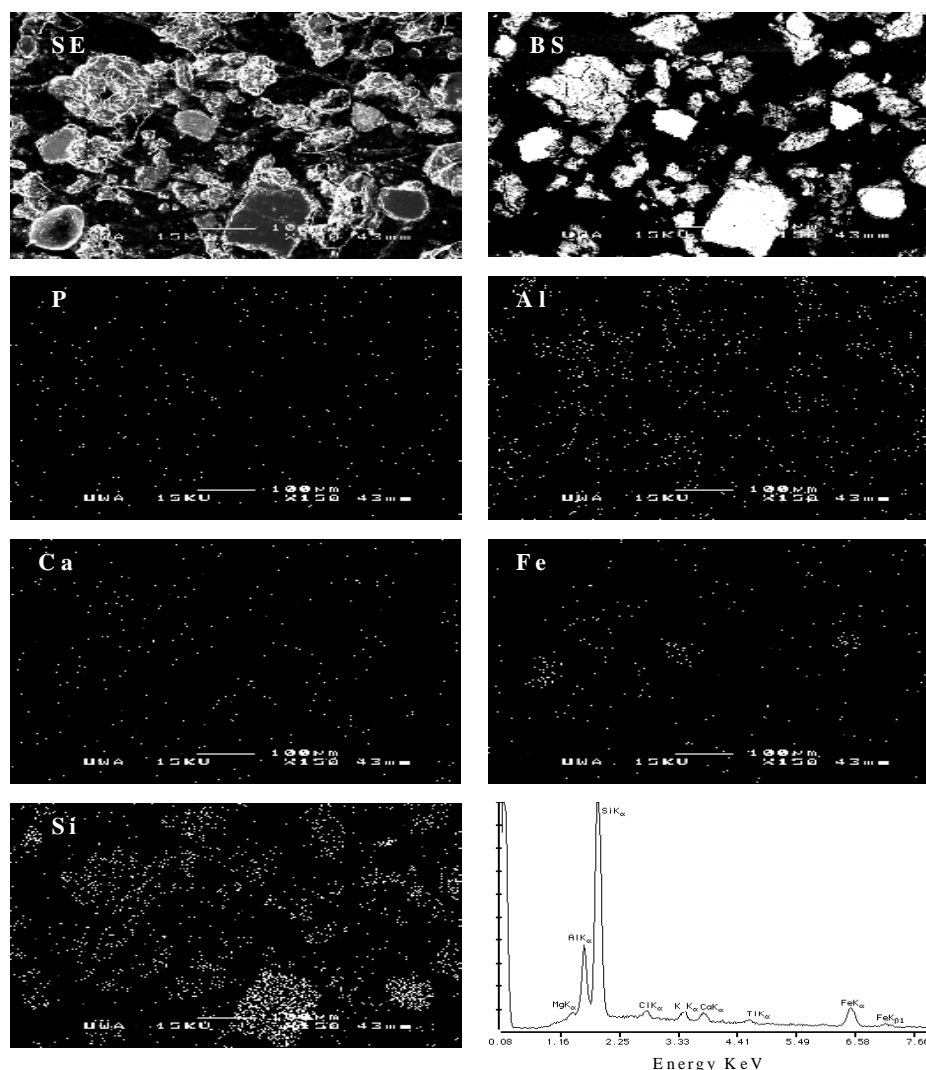
Figure 2. SEM data for the polished surface of Kon 5 slightly calcareous soil. Secondary electron (SE) and backscattered electron (BS) images, element distribution maps for P, Al, Ca, Fe, and Si, and x-ray spectrum for a whole field of view. No local concentrations of P are evident**.**

western Australia does not follow that of P forms in calcareous soils of some other Mediterranean regions where Fe- and Al-P forms are usually less abundant than secondary Ca-forms (Ryan and Zghard, 1980; Matar *et al.*, 1992).

Scanning electron microscopy analysis (SEM)

A SEM study showed that P was uniformly distributed in the soil matrix to the limit of the spatial resolution of this technique

(Figure 3). There were no local concentrations of P or spatial associations of other elements with P. This may be attributed to the high degree of dispersion of P in the clay matrix of the soil. If this dispersed form of P is associated with particular minerals (e.g. Fe oxide) dispersed through the soil matrix then their particle size of these constituents is too small (<1 μm) to be analyzed as a distinct grains with the microprobe so such associations can not be demonstrated (Norrish and Rosser, 1983).

44

Table 3. Stepwise multiple regression equations relating available P as measured by soil P tests to different inorganic P fractions. (r = 0.66 for *P*<.0001, 0.59 for *P*<0.001, and 0.38 for *P*<0.05).

Olsen-P	r^{2a}	Δr^2
$Y = 1.50 + 0.35\ Ca_2\text{-}P$	0.897***	
$Y = 0.94 + 0.24\ Ca_2\text{-}P + 0.093\ Al\text{-}P$	0.925***	0.028
$Y = -0.11 + 0.26\ Ca_2\text{-}P + 0.053\ Al\text{-}P + 0.11\ Ca_{10}\text{-}P$	0.956***	0.031
$Y = 0.61 + 0.25\ Ca_2\text{-}P + 0.065\ Al\text{-}P + 0.12\ Ca_{10}\text{-}P - 0.043\ Fe\text{-}P$	0.958***	0.002
$Y = 0.075 + 0.26\ Ca_2\text{-}P + 0.068\ Al\text{-}P + 0.16\ Ca_{10}\text{-}P - 0.073\ Fe\text{-}P - 0.013\ Ca_8\text{-}P$	0.960***	0.002
Colwell-P	r^{2a}	
$Y = 4.1 + 0.38\ Ca_2\text{-}P$	0.817***	
$Y = 3.4 + 0.23\ Ca_2\text{-}P + 0.12\ Al\text{-}P$	0.852***	0.035
$Y = 1.9 + 0.26\ Ca_2\text{-}P + 0.058\ Al\text{-}P + 0.16\ Ca_{10}\text{-}P$	0.905***	0.088
$Y = 1.7 + 0.26\ Ca_2\text{-}P + 0.044\ Al\text{-}P + 0.15\ Ca_{10}\text{-}P - 0.051\ Fe\text{-}P$	0.907***	0.002
$Y = 1.7 + 0.28\ Ca_2\text{-}P + 0.051\ Al\text{-}P + 0.26\ Ca_{10}\text{-}P - 0.036\ Fe\text{-}P - 0.037\ Ca_8\text{-}P$	0.915***	0.008

[a]Significant at <0.001 (***).

Contributions and relationships of the P_i fractions to P availability

Figures 4 and 5 show bivariate plots and simple linear regression equations for Olsen- and Colwell-P versus P_i fractions, organic P (OP) and TP. Values of Olsen- and Colwell-P were closely correlated with values of Ca_2-, Al-, Fe-, Ca_{10}-P, TP_i and TP. The similarity
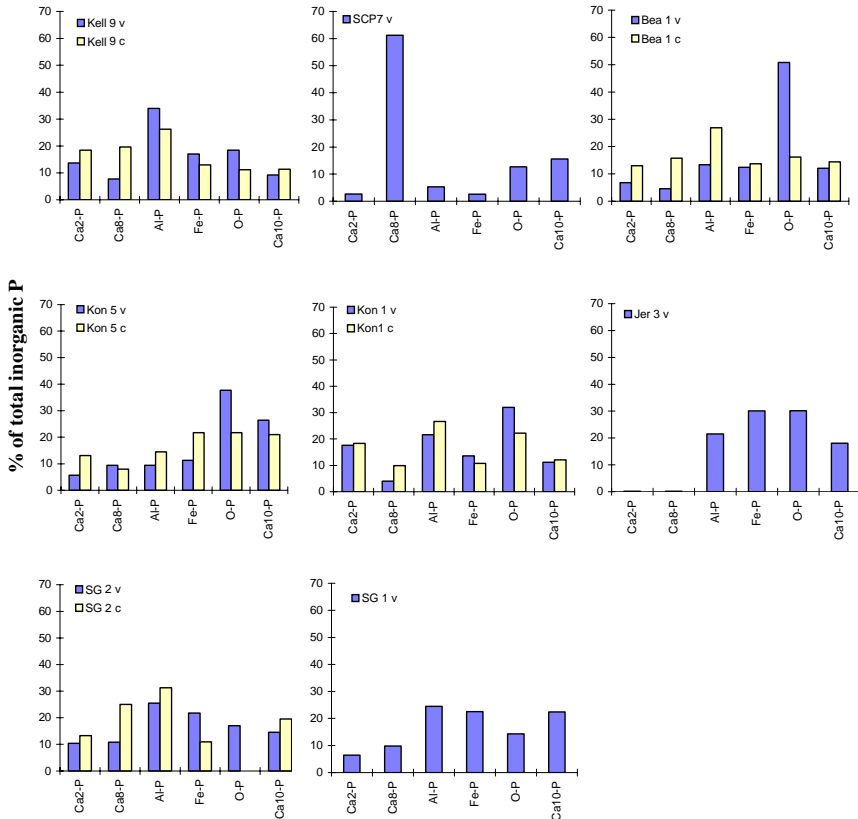

Figure 3. Distribution of inorganic P fractions expressed as % of total inorganic P (P_i) in calcareous (Kell 9; Bea 1; SCP 7; Kon5; Kon 1; SG1; SG2) and non-calcareous soils (Jer 3) in virgin (v) and cultivated (c) states.
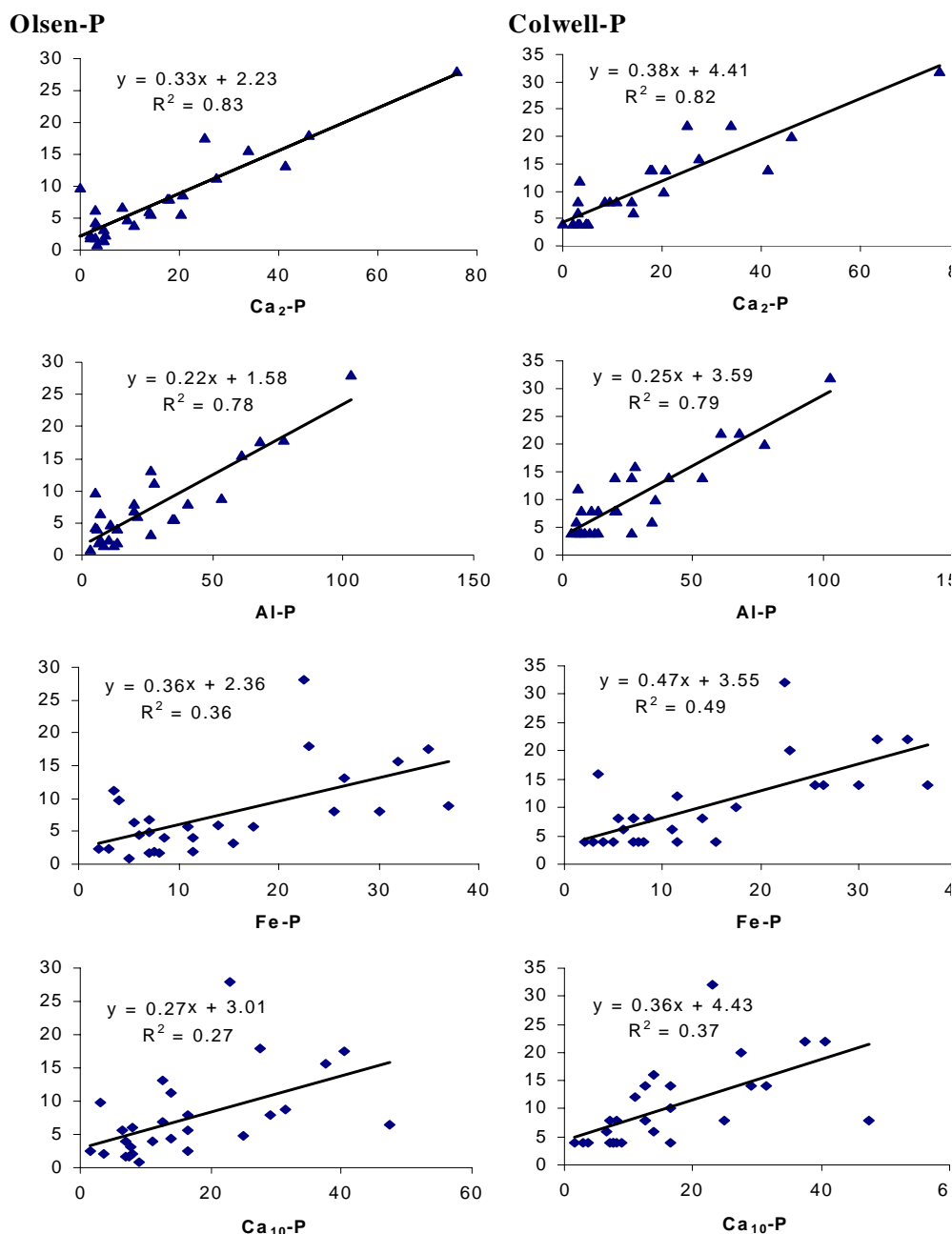
Figure 4. Relationships of Olsen and Colwell values (mg P/kg) of available P with various inorganic P fractions (mg P/kg).

in slope of the pairs of regression lines relating Olsen- and Colwell-P to Ca_2-, Al-, Fe- and Ca_{10}-P fractions suggests that the two soil tests extract about the same proportions of each of those forms of P. Statistical analysis indicates that the Ca_2-P, Al-P, Fe-P and Ca_{10}-P fractions made significant contributions to available P as estimated by Olsen and Colwell methods (Table 3). Stepwise regression showed that most of the variation in Olsen-P (90%) and Colwell-P (82%) was accounted for by Ca_2-P.
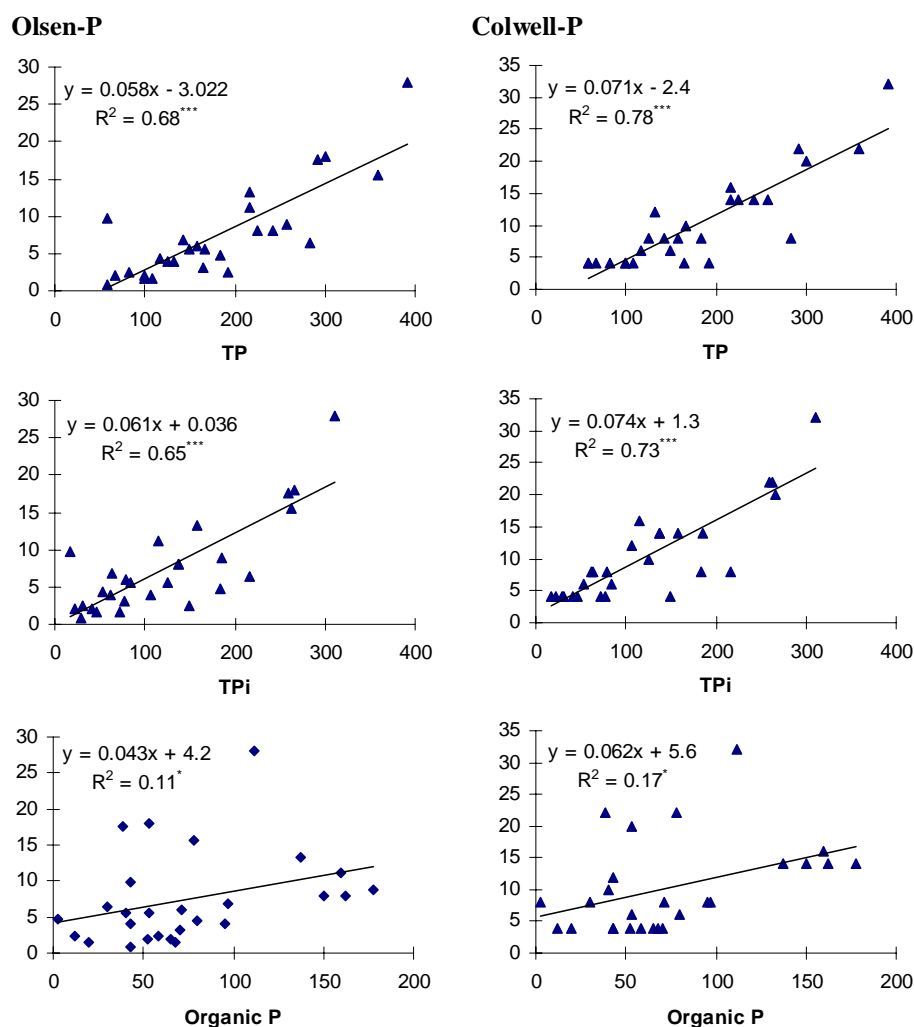
Olsen-P   **Colwell-P**

Figure 5. Relationships of Olsen and Colwell values of available P (mg P/kg) with total P (TP), total inorganic P (TP_i) and organic P (mg P/kg).

CONCLUSION

The soils under study exhibited wide ranges of total P (TP), organic P (OP), inorganic P (P_i) fractions and of P extracted by soil tests. In comparison with Mediterranean regions and other semiarid area, organic P constituted a considerable portion of total P (35%). Positive relationships exist between organic P and both extractable Fe (Fe_o) and organic matter. The pattern of distribution of the P_i fractions, differed between virgin and cultivated soils. For virgin soils, the average relative abundance of P_i in the secondary Ca-bound P [$(Ca_2\text{-}P)+(Ca_8\text{-}P)$], nonoccluded Fe- and Al-bound P [$(Al\text{-}P)+(Fe\text{-}P)$] and acid extractable P as a measure of primary Ca phosphate ($Ca_{10}\text{-}P$) was 2.5:2:1 and in cultivated soils was 2:2.5:1, respectively. The $Ca_2\text{-}P$, Al-P, Fe-P and $Ca_{10}\text{-}P$ fractions made significant contributions to available P as estimated by the Olsen and Colwell methods. Stepwise regression showed that most of variation in Olsen-P (90%) and Colwell-P (82%) was accounted for by Ca_2-

P. Scanning electron microscopy (SEM) showed that P was uniformly distributed in the soil matrix. There were no local concentrations of P or spatial associations of other elements with P.

ACKNOWLEDGEMENTS

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مطالعه توزيع شكلهاي فسفر در خاكهاي آهكي ايالت استراليای غربي

ع. صمدی

چکیده

به منظور ارزيابي وضعيت فسفر (P) خاك و سهم شكلهاي فسفر معدني (P_i) در آزمونهاي اندازه‌گيري فسفر خاك، مقادير، توزيع و شكلهاي P در ۲۸ خاك آهكي ايالت استراليای غربي تعيين شدند. مقادير فسفر كل (TP) ، فسفر آلي (Org-P) ، فسفر معدني (P_i) و فسفر قابل استفاده گياه در خاكهاي تحت مطالعه (عمق ۰ -۱۰سانتيمتر) در گستره وسيعي قرار داشتند. مقدار TP بين ۳۹۲-۳۳ ميلي گرم در كيلوگرم (متوسط ۱۷٦ ميلي گرم در كيلوگرم) ، Org-P حدود ۳۵٪ از TP را تشكيل داده و نسبت كربن آلي به فسفر آلي ۲۸۷ بود. بطور كلي توزيع اجزا فسفر معدني به قرار زير بود: ۱۵= Ca_2-P , ۱۷= Ca_8-P ، ۲٦ = Al-P ، ۱٤ = Fe-P ، ۲۰ = O-P (فسفر محبوس شده در اكسيدهاي آهن و آلومينيوم) و ۱٦ = Ca_{10}-P ميلي‌گرم در كيلوگرم خاك كه به ترتيب ۱۳٪، ۲۳٪، ۲۲٪، ۱۲٪ ، ۱۷٪ و ۱۲٪ از كل P_i خاك را تشكيل مي داد. الگوي توزيع اجزا P_i بين خاكهاي زراعي و بكر تفاوت داشت. در خاكهاي بكر، متوسط فراواني نسبي P_i در فسفات‌هاي كلسيمي ثانويه [(Ca_2-P)+(Ca_8-P)]، فسفات‌هاي Fe و Al محبوس نشده [(Al-P)+(Fe-P)] و فسفر قابل عصاره‌گيري با اسيد (فسفات‌هاي كلسيمي اوليه) (Ca_{10}-P) به ترتيب ۲/۵ : ۲ : ۱ و در خاكهاي زراعي ۲ : ۲/۵ : ۱ بود. تجزيه هاي آماري نشان داد كه اجزا Al-P، Ca_2-P، Fe-P و Ca_{10}-P سهم قابل ملاحظه‌اي در فسفر قابل استفاده گياه (قابل عصاره‌گيري با روشهاي اولسن و كلول) داشتند. تجزيه رگرسيون چند متغيره نشان داد كه عمده تغييرات در اولسن-P (۹۱٪) و كلول-P (۸۲٪) از جزء Ca_2-P ناشي مي‌شد. مطالعه ميكروسكوپ الكتروني (SEM) نشان داد كه P بطور يكنواخت در حد قدرت تفكيك (resolution) دستگاه در زمينة خاك توزيع شده و علائم ناشي از تجمع موضعي فسفر يا ارتباط مكاني فسفر با ساير عناصر مشاهده نگرديد.