Phosphate sorption of European volcanic soils

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Introduction

Due to the presence of active and amorphous Al- and Fe-compounds (allophane/imogolite, ferrihydrite), Al- and Fe- organic matter complexes and high variable charge in the soil colloidal system, a high ability to adsorb P is one of the characteristics of volcanic soils (Mizota and Reeuwijk 1989, Shoji et al. 1993). Therefore, the phosphate retention percentage is one of the requirements of andic soil properties in Soil Taxonomy (SSS 2003) and of the diagnostic andic horizon of WRB (Driessen et al. 2001). However, this parameter corresponds to a single determination that reflects P-adsorption kinetics rather than capacity and that does not adequately reflect differences between Andisols with regard to P availability and the risk of P losses. Wide differences of P-sorption in volcanic soils were recently reported by Van Ranst et al. (2004) from a sequence of Andisols from the island of Java (Indonesia). These authors characterized the reactivity of these soils by the P-sorption maximum and by P-bonding energy, calculated from the fitted Langmuir adsorption isotherm, considering that the simple Langmuir equation is more suitable and able to fit the P-sorption data than the formerly used Freundlich equation. They found a close relationship between the P-sorption maximum and allophane content, oxalate soluble Al (Al_o) and Al_o+½Fe_o contents (R^2=0.82, 0.92, and 0.95, respectively). Similar strong correlations were observed between the bonding energy (k value) and the allophane, Al_o, and Al_o+½Fe_o contents. Furthermore, Balkovic and Slivkova (2002) observed that P-sorption in andic horizons was also positively influenced by soil pH, and that the measured P-sorption maximum may reach 10 g kg^{-1}. These authors also studied the effect of different Al_o, Al_p and Fe_o concentrations on P-retention at pH 4.65, and concluded that phosphate was immobilized both on non-crystalline Al/Fe colloids and on Al/Fe humic complexes. Espino-Mesa et al. (1993) reported that active Al_o is positively correlated with cation exchange capacity determined by 1 M ammonium acetate at pH 7.

In volcanic soils, phosphorus is often a growth-limiting nutrient for crops, given the ability of these soils to strongly bind phosphate. On the other hand, because of the risk of eutrophication of water bodies, the loss of adsorbed P from intensively managed volcanic soils, through surface runoff and infiltration, is an environmental concern (Pinheiro et al. this book). Evaluation of soil behavior with respect to P availability to crops, and to P desorption is therefore of utmost importance. At a given P content, extractable P is influenced by soil constituents, but also highly dependent on the extraction method (Kuo 1996, Monteiro 2005). Hence, more information regarding the ability of different methods to extract P from volcanic soils is needed.

Within this context, a study was carried out on twenty pedons of European volcanic soils to assess: (i) the P retention percentage; (ii) the phosphate sorption isotherms and the influence of soil characteristics which determine the maximum phosphate sorption capacity; and, (iii) the amounts of extracted P by several methods and the relationships between these amounts and soil properties.

Materials and methods

P-retention values were determined in all samples of twenty European volcanic soil profiles, as described in *The physico-chemical data base* (this book). In addition to these soils, samples from other Hungarian volcanic soils were used to assess the phosphate sorption isotherms, bringing the total number of samples to 114. To determine the adsorption isotherm and the P adsorption maximum, samples were equilibrated for 24 hours with 10 cm^3 of 0, 50, 100, 500, 1000, 3000, 5000 and 10000 mg kg^{-1} P solutions. The Langmuir equation (Füleky and Tolner 1990), used to fit the data, was;

$$Pads = \frac{P_{\max} kc}{1 + kc},$$

where P_{max} is the maximum amount of phosphate which could be adsorbed (and used as a soil characteristics in further statistical analysis), k is a constant related to the adsorption energy, and c the P concentration in the solution. All data of the EUR soils are in *The physico-chemical data base* (this book) and they are also compiled in *phosphate data.xls* attached to this chapter.

Extractable P was obtained for each sample in four replicates. Extraction of P by distilled water and 0.01 M $CaCl_2$ extractions involved shaking the sample for 1 h and 2 h, respectively, at a 2:20 soil: solution ratio (Self-Davis et al. 2000). Extractable P by the Bray 2 method (BR) was obtained by shaking 2 g soil with 20 ml 0.03 N NH_4F + 0.1 N HCl solution at pH 2.6 for 40 sec (Bray and Kurtz 1945). Phosphorus by the Mehlich 3 method (ME) was extracted using a soil:solution (0.013 M HNO_3 + 0.02 M CH_3OOH + 0.015 M NH_4F + 0.025 M NH_4NO_3 + 0.001 M EDTA) ratio of 2:20 at pH 2.5, and shaking for 30 min (Mehlich 1984). Extractable P determined by the Egnér-Riehm method (ER) was obtained by shaking 1 g of soil with 20 ml of $K(SbO)C_4H_4O_6,½H_2O$ solution at pH 3.7 to 3.8 for 2 h (Riehm 1958). A 2:20 soil to solution (0.5 M $NaHCO_3$) ratio at pH 8.5 and 30 min shaking was used to extract P by the Olsen (OL) method (Olsen et al. 1954). Phosphorus was determined in filtered extracts by the molybdate blue coloring method (Murphy and Riley 1962), using a spectrophotometer (adsorbance at 882 nm).

Correlation coefficients were obtained for single and multiple correlations between variables, using Statistica 6.0.

Results and discussion

Phosphate retention

As expected, samples corresponding to non-Andisols (EUR01–02, EUR13–15, EUR18–20) showed lower P-retention values throughout the soil profile (2.0–42.6%, Figure 1), than the threshold percentages of 85% and 70% used by Soil Taxonomy (SSS 2003) or WRB (Driessen et al. 2001), respectively, to recognize andic soil properties or the diagnostic andic horizon (Figure 1). This is in agreement with the low content of Al in the forms of Al-humus complexes and allophane in these soils. Nevertheless, P-retention values were strongly correlated with Al_o (r=0.838; p<0.01) and Al_o+½Fe_o (r=0.916; p<0.01) contents.

Relationships between P-retention values and Al_o+½Fe_o or Al_o contents are shown in Figure 1. Pedons classified as Andisols mostly showed P-retention values higher than 85% for Al_o+½Fe_o or Al_o contents higher than 2.0%. Above this content, P-retention was always higher than 70%. Some exceptions should be taken into account, as horizons with Al_o and Al_o+½Fe_o contents >2% may show P-retention values lower than 85%, and P-retention values of 85% or more were observed in horizons with low contents of Al_o and Al_o+½Fe_o. For example, pedon EUR03 with high contents of Al_o (2.49–3.33%), allophane (7.1–11.8%) and Al_o+½Fe_o (2.52–3.61%) showed P-retentions ranging from 80.5 to 84.5%. This pedon also had a much lower anion exchange capacity than the other studied soils (Madeira et al. this book). This characteristic may contribute to a lower the phosphate adsorption potential. Conversely, pedon EUR12 with low contents of Al_o (1.21%) and Al_o+½Fe_o, (1.55%) and no allophane, showed a P-retention of 86%. This is in line with data reported by Madeira et al.

(1994) for non-allophanic soils from Madeira Island, which in spite of their low Al_o content (1.2–1.4%, mostly as Al-humus complexes) showed a high P-retention (96–98%). Retention values higher than 85% were also reported by Shoji et al. (1985) for Andisols with Al_o>1%. Finally, very low P retention values were found in some horizons of pedon EUR11. This may be due to the extremely high extractable P, by water and other extractants, which is much higher than in other studied pedons (see section P extraction).

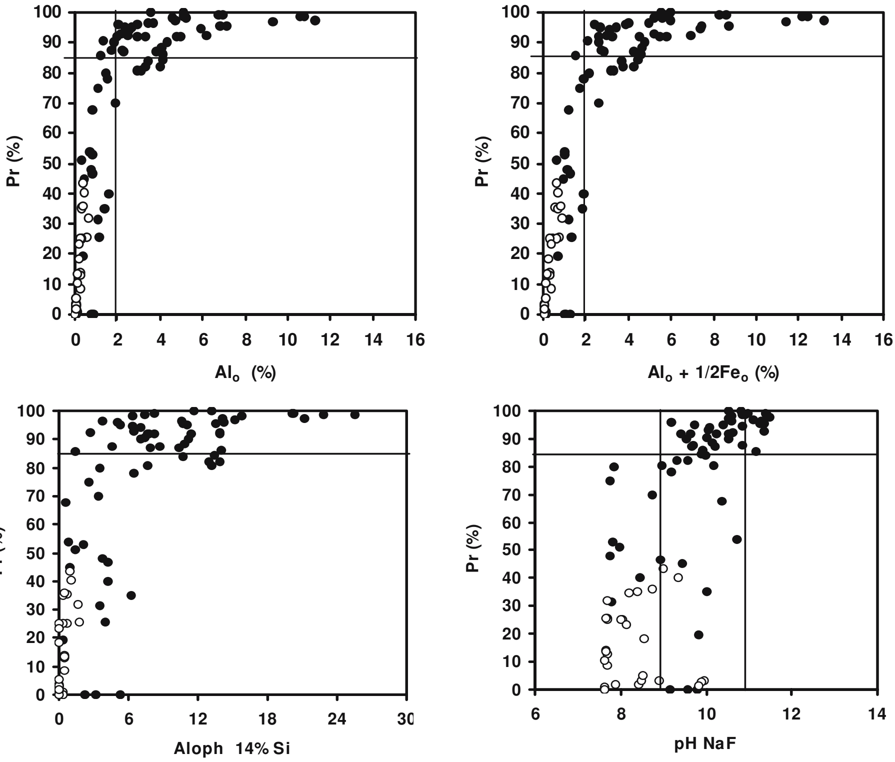

Figure 1. P-retention in studied volcanic soils in relation to Al_o, Al_o+½Fe_o and allophane contents, and to pH-NaF values. Black and open dots correspond, respectively, to Andisols and to non-Andisols.

P-retention increased with the calculated allophane content (Figure 1), but the relationship was much less clear than that observed for the Al_o and Al_o+½Fe_o contents. Values higher than either 70 or 85% were obtained for a wide range of allophane contents (1.4–24.2%), which indicates that constituents other than allophane (e.g., Al-humus complexes) also adsorb P. Values of pH-NaF did not adequately discriminate andic horizons from non-andic ones (Figure 1), and are not well-correlated with P-retention in Andisols. Although all horizons with a P-retention higher than 85% showed a pH-NaF between 9 and 12, some other horizons with similar high pH values (9–11) had lower P-retention.

Maximum P-sorption

The studied soils showed a wide range of P-sorption values (see *The physico-chemical data base*, this book and *phosphate data.xls*). In horizons without andic properties (non-Andisols) the values were lower than 2000 mg kg^{-1}, while in the A and B horizons of Andisols values ranged from 2215 to 10.200 mg kg^{-1}. This range is within that reported by Van Ranst et al. (2004) for Andisols from Java, and by Auxtero et al. (2005) for Andisols from the Azores.

The P_{ret} value does not indicate a maximum adsorbed amount but a value relative to the offered amount. Soils with high phosphate fixing capacity can adsorb much more phosphate than 5000 mg kg^{-1}, the concentration for P_{ret} determination. At the same time, the k-value, which is correlated with the bonding energy, could explain differences in the steepness of curves at lower concentrations of soils with similar P_{max} (Figure 2).

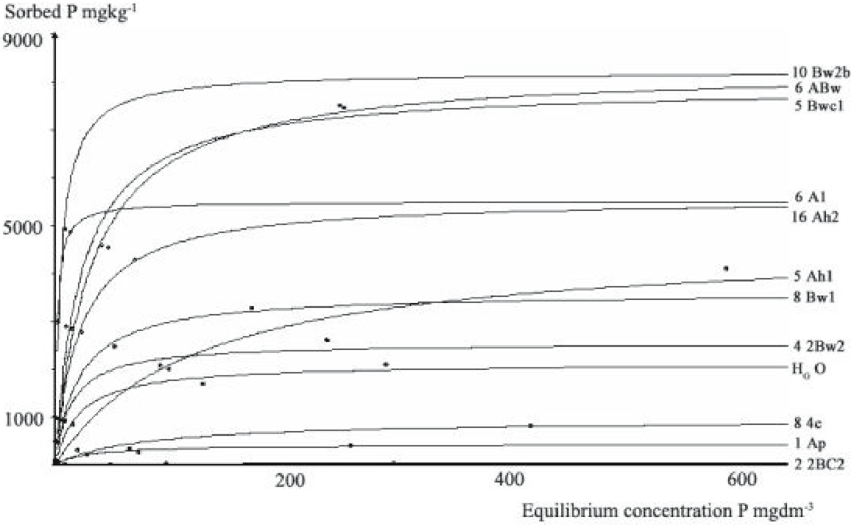

Figure 2. Phosphate sorption isotherms of selected horizons. The number before the horizon code indicates the EUR profile.

The maximum amounts of phosphate (P_{max}) sorbed by the European volcanic soils, as calculated from the Langmuir adsorption isotherms, are shown in *phosphate data.xls* (on CD). The calculated phosphate sorption maxima ranged from 0 to 10000 mg P kg^{-1} soil. At low concentrations, some of the volcanic soils sorbed a large fraction of the added phosphate, some of them somewhat less. This difference in phosphate binding kinetics causes the differences observed in the shape of Langmuir adsorption isotherms (Figure 2).

Soil characteristics that determine the rate of phosphate sorption are shown in Table 1. In some cases, there are inner correlations between the soil characteristics, such as Fe_o and Al_o, Al_d and Al_o.

Table 1. Linear correlation between some soil characteristics and the phosphate sorption maximum, n=114.

Soil characteristic	R^2	Soil characteristic	R^2	Soil characteristic	R^2
Al_o%+½Fe_o	0.753	P-retention %	0.555	Base sat.% (n=64)	0.609
Al_o%	0.734	Allophane (Parfitt)	0.514	CEC-NH_4OAc	0.256
Al_o%-Al_p%	0.574	Fe_o%	0.514	Sum of Bases	0.202
Al_d%	0.711	Fe_d%	0.478	Organic C%	0.139
Al_p%	0.443				

The most significant positive correlation was obtained between the maximum phosphate sorption (P_{max}) and Al_o+½Fe_o% (Figure 3). 75% of phosphate sorption ability of soils is explained by the Al_o+½Fe_o content, and 73% by the Al_o content alone. The correlation between P_{max} and Al_o%-Al_p% was closer (0.574) than that for Al_p (0.443). Both relationships demonstrate the predominance of non-crystalline Al oxi-hydroxides (Al_o) in phosphate fixation compared with that of humus-bound Al. For the subset of andic horizons, the correlation between phosphate sorption ability and Al_o (R^2=0.57) and Al_o+½Fe_o (R^2=0.59) contents was weaker than for the whole data set, which was also observed by Auxtero et al. (2005) for Andisols from the Azores Islands. The base saturation, excluding soils above 100% saturation (most of the non-Andisols), showed a close negative correlation with the phosphate sorption (R^2=0.609) (Figure 4). This is probably an indirect relation. In fact, base saturation in studied Andisols showed a significant negative correlation with the contents of allophane and Al-humus complexes (Madeira et al. this book).

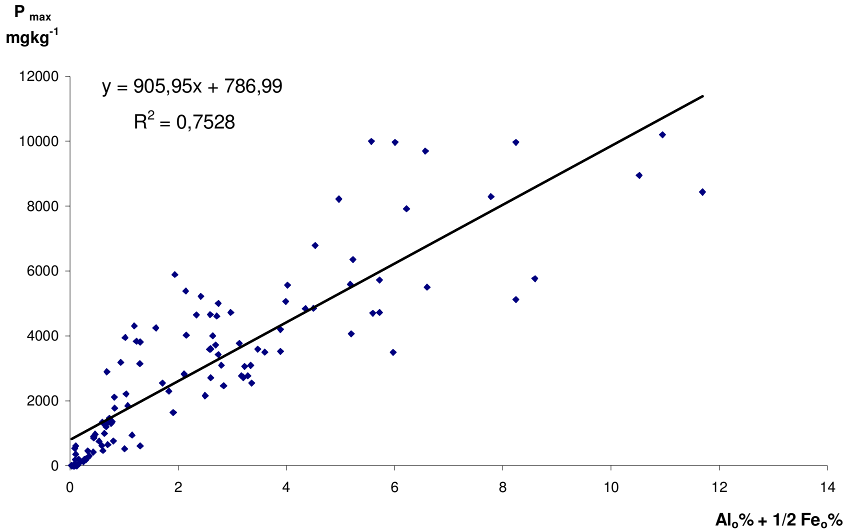

Figure 3. Linear relationship between Al_o+½Fe_o content and phosphate sorption maximum, n=114.

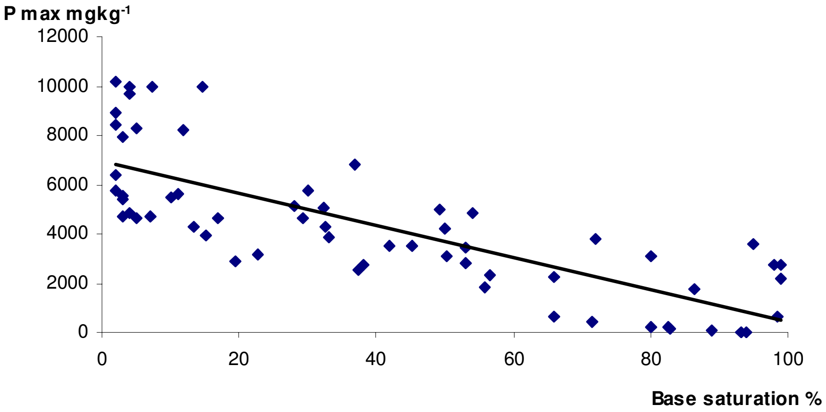

Figure 4. Linear relationship between phosphate sorption maximum (P_{max}) and base saturation (n=64) .

Extractable P

P extracted by H_2O and $CaCl_2$ were determined because they correspond to a measurement of P in solution that correlates well with the concentration of dissolved reactive P in runoff (Self-Davis et al. 2000), corresponding then to a measurement of P in solution, and are independent of soil type (Monteiro 2005). Methods estimating the amount of sorbed P were also used. The Bray (BR), Mehlich (ME), and Egnér-Riehm (ER) methods are commonly used in acid soils, while the Olsen (OL) method, which is mostly used in neutral and alkaline soils but also in acid soils, is less dependent on soil type than the other methods.

Extractable P in non-Andisols varied considerably between soils and methods, and it may reflect differences in land use. Amounts extracted by the BR method were greater (24.6–291.6 mg kg^{-1}) than those determined by the other methods (0–197.6 mg kg^{-1}), and amounts extracted by the ER and ME methods were about double those obtained by the OL method (Figure 5). The large quantities of P extracted from pedons EUR01 and EUR19 by Bray (259–292 mg kg^{-1}) and by Olsen (97–109 mg kg^{-1}) methods are noteworthy. These high values are also associated with large amounts of P extracted by H_2O (5.8–24.7 mg kg^{-1}) and by $CaCl_2$ (4.0–24.2 mg kg^{-1}), suggesting that high amounts of P could be released to the soil solution. This may be related to anthropic influence, as pedon EUR19 is in the site of a Bronze Age settlement found at the profile description, and pedon EUR01 is located in a man-made terrace (with pot shards) used for apple tree orchards (see Profile descriptions, this book). We may emphasize that the Olsen-P values in those pedons are far beyond the limit (21 and 57 mg kg^{-1}) found for soils with similar amounts of oxalate-extractable Fe and Al, in which P losses increase from soil to drainage water, and from soil to runoff (Monteiro 2005).

In Andisols, the amounts of extracted P varied widely with soil type and method. As observed in *The physico chemical data base*, the extracted P was generally lower than in non-Andisols (Figure 5), especially in the subsurface horizons. As observed for the non-Andisols, P extracted by the BR method was usually higher than that extracted by the other methods, and it was usually higher in the topsoils (Ah, O) than in the subsurface horizons. This decrease with soil depth was more pronounced in P-fractions obtained by the ER and ME methods. Pedon EUR11 showed very high P values by the BR (460.2 mg kg^{-1}), ER (172.6 mg kg^{-1}) and OL (67.6 mg kg^{-1}) methods, which coincides with high amounts extracted by H_2O and $CaCl_2$ (5.9 and 5.5 mg kg^{-1}, respectively). As this pedon is under forest, apparently there is not a relation between high P values and anthropic influence; instead, these high P values might be related to natural conditions as the parent material corresponds to superposed basaltic scoria and layers of basaltic lapilli (see Soil descriptions, this book). High P values in H_2O were also measured in the topsoil of pedons EUR03 (4.3 mg kg^{-1}), EUR04 (4.0 mg kg^{-1}) and EUR07 (13.6 mg kg^{-1}), which may be associated with the high amounts of partly decomposed organic matter observed in these layers.

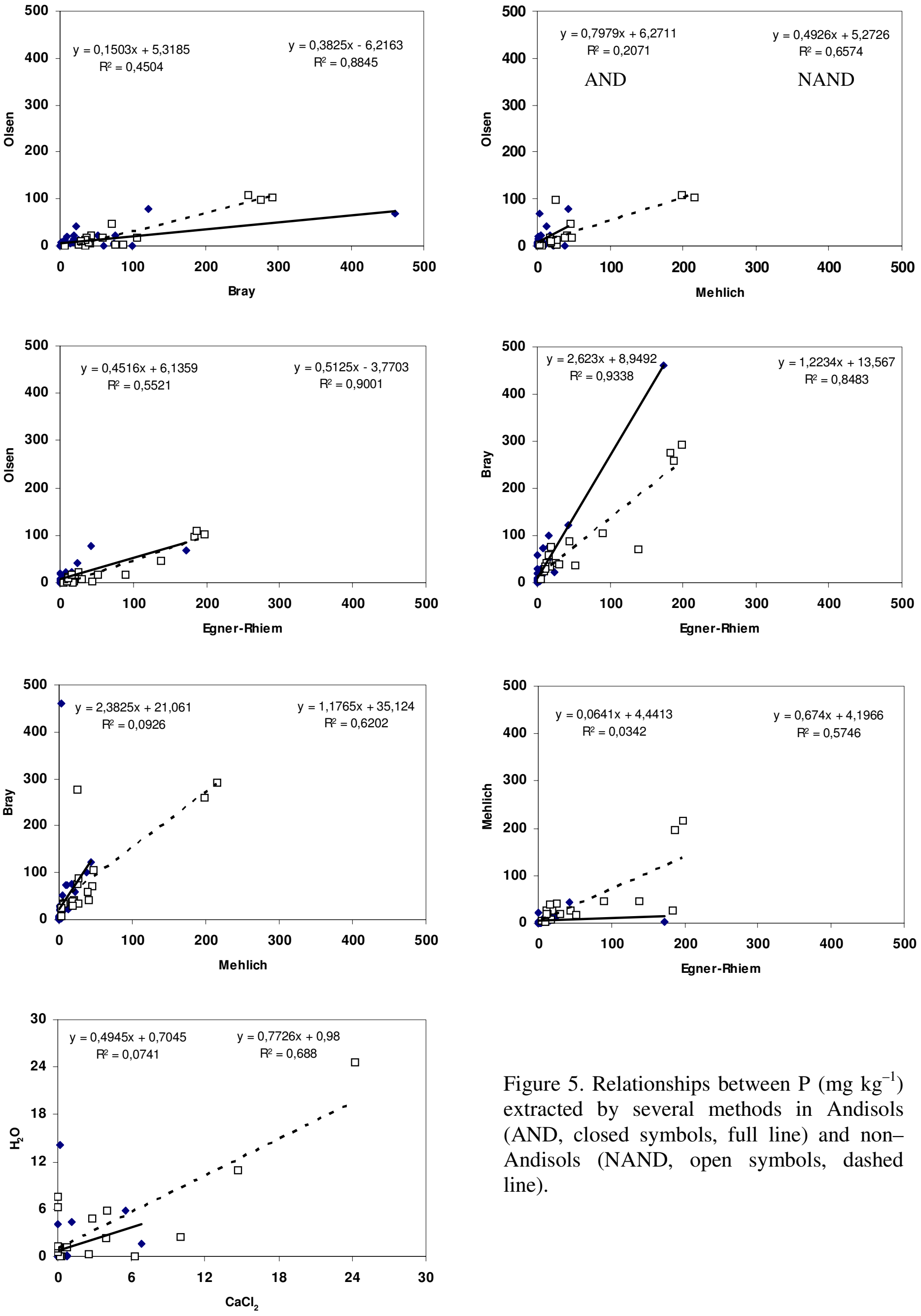

Figure 5. Relationships between P (mg kg^{-1}) extracted by several methods in Andisols (AND, closed symbols, full line) and non–Andisols (NAND, open symbols, dashed line).

Extractable P and soil characteristics

The amounts of P obtained by the various methods showed different relationships with soil type and constituents (Table 2). In the whole set of studied soils, P extracted by the different methods showed a weak negative correlation with P_{max}, and the correlation coefficient (r; $p<0.05$) varied between –0.33 and –0.44. However, in Andisols the amounts of P extracted by the different methods were not correlated with values of P_{max}. The lack of this relationship may be explained by the fact that soils are not P-saturated and the extracted fraction is therefore an accidental part of the total adsorption capacity. On the other hand, the extractable P was negatively correlated with P-retention (PR) values, with correlation coefficients (r) of –0.70, –0.65, –0.57, –0.53, –0.43 and –0.39, respectively, for the BR, EG, OL, ME, WT and CA extractions. This correlation was expected, because P-retention is decreased by the part of the binding sites that is already occupied by phosphate, which is in agreement with the fact that the best correlation was with the strongest extractant (BR method). P extracted by the Olsen method was negatively correlated with Al_o (–0.34), Si_o (–0.34), allophane (–0.34) and $Al_o+½Fe_o$ (–0.34) contents, and positively with organic C content (0.53). The latter correlation corroborates the fact that P adsorbed on metal-organic matter complexes is one of the P Olsen sources (Monteiro 2005). A similar pattern was observed for P extracted by the ME method. Conversely, amounts obtained by the BR and EG methods were not correlated with the above mentioned soil constituents. As also observed for the Olsen extraction, amounts of P extracted by H_2O were weakly and negatively correlated with Al_o (–0.33) and $Al_o+½Fe_o$ (–0.32), and positively with organic C (0.43) contents, while the fraction extracted by $CaCl_2$ was not significantly correlated to measured soil properties. The similar behaviour observed for both H_2O and OL methods is in line with findings of Kuo et al. (1988), who reported that P extracted by the OL is a function of the fraction of P coverage on the surfaces of soil particles, reflecting P in soil solution rather than sorbed P.

Contrarily to Andisols, P extracted by the different methods from non-Andisols was not correlated with P-retention. This pattern may be related to the low sorption capacity shown by these soils, being the extracted P mostly dependent on the amount of P retained by soil. It is noteworthy that P extracted by the OL and ME methods was positively correlated ($p<0.05$) with both organic C (r=0.56, 0.63) and Fe_o (r=0.60, 0.67) contents. Extractable P by the ER method was positively correlated (0.50) with Fe_o content alone, while that extracted by the BR method did not show any correlation with soil constituents. P extracted by H_2O and $CaCl_2$, as observed for the OL and ME methods, was positively correlated ($p<0.05$) with organic C (0.56) content, and that extracted by $CaCl_2$ was also correlated with Fe_o (0.56) content. The positive correlation between extractable P and Fe_o contents, as well as the lack of a negative effect of Al_o and allophane on P extraction, do not follow the general pattern observed for Andisols in this study, suggesting that these constituents (in low amounts) in non-Andisols are of great importance to soil P availability.

Table 2. Coefficients (R) of correlations between P-fractions extracted by various methods and some soil properties. Numbers in bold are significant at $p<0.05$.

Extraction method	P_{max}	P_{ret}	Al_o	Fe_o	$Al_o+½Fe_o$	Allophane	Org. C
Andisols (n=41)							
H_2O	**–0.332**	**–0.435**	**–0.333**	–0.153	**–0.319**	–0.298	**0.434**
$CaCl_2$	–0.180	**–0.392**	–0.241	–0.09	–0.229	–0.260	0.176
Olsen	–0.259	**–0.572**	**–0.340**	–0.186	**–0.337**	**–0.339**	**0.532**
Mehlich 3	–0.052	**–0.534**	–0.283	–0.252	–0.302	**–0.322**	**0.583**
Egner-Riehm	–0.216	**–0.647**	0.255	–0.173	–0,259	–0.268	0.199
Bray 2	–0.161	**–0.700**	–0.258	–0.234	–0.277	–0.288	0.166
Non-Andisols (n=17)							
H_2O	–0.135	0.077	0.032	0.397	0.188	–0.164	**0.556**
$CaCl_2$	0.090	0.293	0.179	**0.559**	0.348	0.007	**0.540**
Olsen	0.046	0.393	0.335	**0.595**	0.462	0.109	**0.560**
Mehlich 3	0.043	0.306	0.242	**0.671**	0.436	–0.004	**0.630**
Egner-Riehm	–0.062	0.272	0.207	**0.504**	0.344	0.006	0.427
Bray 2	–0.046	0.253	0.227	0.479	0.345	0.043	0.372

Relationships between methods

In non-Andisols, P extracted by H_2O (Table 3 and Figure 5) was positively correlated ($p<0.05$) with that extracted by $CaCl_2$ (r=0.87), and also with that extracted by the ME, OL, BR and EG methods (r=0.81, 0.75, 0.72 and 0.68, respectively). Correlations with P extracted by $CaCl_2$ and the other methods were stronger than for H_2O (r=0.81, 0.84, 0.75 and 0.77, respectively). This proportionality between desorbed P by those methods and by H_2O or dilute $CaCl_2$ suggests that P losses from the soil to water might be estimated from any of these values. Amounts of P extracted by the ME, OL, BR and EG methods were positively correlated (Figure 5). The amount of P extracted by the OL method was strongly correlated with that obtained by the BR (r =0.94) and the ER (0.95) methods; P by the BR and ER methods were also strongly correlated (0.92). Correlations between these methods have been found among soils, especially when they are of the same type (Kuo 1996, Monteiro 2005).

Table 3. Coefficients (R) of correlation between P-fractions extracted by various methods. Numbers in bold are significant at $p<0.05$.

Extraction method	**H_2O**	$CaCl_2$	Mehlich 3	Olsen	Bray 2	Egner-Riehm
All EUR soils (n=58)						
H_2O		**0.75**	**0.58**	**0.72**	**0.57**	**0.67**
$CaCl_2$	**0.75**		**0.64**	**0.71**	**0.57**	**0.72**
Mehlich 3	**0.58**	**0.64**		**0.56**	**0.49**	**0.56**
Olsen	**0.72**	**0.71**	**0.56**		**0.80**	**0.89**
Bray 2	**0.57**	**0.57**	**0.49**	**0.80**		**0.88**
Egner-Riehm	**0.67**	**0.72**	**0.56**	**0.89**	**0.88**	
Non-Andisols (n=17)						
H_2O		**0.87**	**0.61**	**0.75**	**0.72**	**0.68**
$CaCl_2$	**0.87**		**0.90**	**0.84**	**0.75**	**0.77**
Mehlich 3	**0.81**	**0.90**		**0.81**	**0.78**	**0.75**
Olsen	**0.75**	**0.84**	**0.81**		**0.94**	**0.95**
Bray 2	**0.72**	**0.75**	**0.78**	**0.94**		**0.92**
Egner-Riehm	**0.68**	**0.77**	**0.75**	**0.95**	**0.92**	
Andisols (n=41)						
H_2O		0.26	0.04	**0.56**	**0.35**	**0.45**
$CaCl_2$	0.26		–0.04	**0.44**	**0.55**	**0.61**
Mehlich 3	0.04	–0.04		0.03	0.13	0.00
Olsen	**0.56**	**0.44**	0.03		**0.67**	**0.74**
Bray 2	**0.35**	**0.55**	0.13	**0.67**		**0.96**
Egner-Riehm	**0.45**	**0.61**	0.00	**0.74**	**0.96**	

In Andisols, in contrast to the previous, P extracted by H_2O was not correlated with that extracted by $CaCl_2$. (Table 3, Figure 5) The former was correlated with P extracted by the OL (0.56) and ER (0.45) methods, whereas the latter showed stronger correlations with P extracted by the ER (0.61) and BR (0.55) methods. This means that in Andisols the value of such data for estimating P losses from soil to water is smaller than in non-Andisols. Correlations between the OL, ME, ER and BR methods were less significant than in soils without andic soil properties. For example, extractable P by the ME method was not correlated with that determined by the other methods, but a correlation was observed between the OL and BR (0.67) and the OL and ER (0.74) methods. In addition, P extracted by the BR method showed a strong correlation with that obtained by ER method

(0.96) (Figure 5). Correlations between methods were less significant in Andisols (ME and OL methods were not correlated) than for non-Andisols, which may result from the larger heterogeneity of soil constituents in the former than in the latter.

Ass commonly reported, the BR extracted more P than the ME, ER OL methods in both Andisols and non-Andisols (Kuo 1996, Monteiro 2005). OL extracted less P than ME and ER, but differences were more pronounced in non-Andisols than in Andisols (Figure 5). The combination of its strong acidity with the effect of fluoride on the formation of Al complexes may explain why the BR method extracted more P than the other methods (Jackson 1958). The effectiveness of ME and ER extractions in comparison to OL may also be based on the high acidity of the extractant and on the role of acetate fluoride and lactate anions in solubilizing or complexing cations (Ca, Al, Fe) and in desorbing P from active surfaces.

Conclusions

1. The P-retention percentage discriminates Andisols from non-Andisols. However, the lower limit of 85% does not correspond exactly to the threshold values of Al_o+½Fe_o 2.0%.
2. The Langmuir isotherm properly describes the phosphate sorption in volcanic soils of Europe at 0–600 mg dm^{-3} P concentration interval.
3. Because P_{ret} does not assess the total capacity of the soil to bind phosphate, the estimated phosphate adsorption maximum (P_{max}) is a better property for the characterization of the surface activity of soils developed on volcanic parent material.
4. Oxalate-soluble Al is the main factor explaining the observed variations (73%) of P_{max}.
5. Soils showed a wide variation of extractable P for each of the extractors. In non-Andisols, amounts of P extracted by H_2O, $CaCl_2$ and other methods were correlated, whereas in Andisols correlations were weaker. As Andisols are not P-saturated and the extractable fraction is an accidental part of the total adsorption capacity, extracted P was not correlated with P_{max} values. It was, however, negatively correlated with P-retention values.
6. In Andisols, P extracted by the Olsen and Mehlich methods was positively affected by soil organic constituents, and negatively by mineral constituents (Al_o, allophane). Contrarily to Andisols, low amounts of Fe_o in non-Andisols may increase the amount of extractable P.

7. The BR method extracted more P than the other methods, which may be explained by the combination of strong acidity and by the effect of fluoride on the formation of Al complexes.

Acknowledgements

E. Auxtero gratefully acknowledges the award of a post-doctoral research fellowship by the Fundação para a Ciência e a Tecnologia. The authors express their appreciation to Isabel Meireles and Ana Batista for technical assistance in the laboratory, to Paulo Marques for preparation of the manuscript, and to Prof. Ana Carla Madeira for improving the language.

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Appendix materials on CD-Rom

phosphate data.xls