Soil properties that affect Olsen P critical values in different soil types and impact on P fertiliser recommendations

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Description of statistical methodology

For the soil characteristics measured prior to P addition to the soil, Pearson product-moment correlation coefficients were calculated for all pairs of characteristics across the 10 soils included in the experimental study, and these correlations tested for differences from zero (two-sided test). The linearity of the relationships was assessed through pairwise scatter plots. Results were considered significant at $p < 0.05$.

The relationship between soil PBI and each of the individual soil characteristics was assessed using simple linear regression. Soil PBI values were $\log_{10}$ transformed prior to modelling, to satisfy the assumption of homogeneity of variance, and soil characteristics were also $\log_{10}$ transformed when necessary (with the addition of a small constant (1) to cope with the transformation of observed values of zero) to reduce the influence of extreme values. Having ranked the importance of the individual soil characteristics based on the adjusted R^2 statistics from the simple linear regressions, the five highest ranked soil characteristics were included in a stepwise multiple linear regression (MLR) analysis to select the best combination of soil characteristics to explain the variability in soil PBI values. The most parsimonious and best-fitting model was identified by considering both the Akaike Information Criteria (AIC) and adjusted R^2 values for each model considered. Significance of each soil characteristic was analysed using the t-test.

The relationship between initial Olsen-P and added P was assessed for each soil using polynomial regression, comparing between linear and quadratic models. After identifying that quadratic models were required for each soil, a combined analysis across soils allowed the assessment of whether common fitted parameters could be considered, or if separate parameters were needed for each soil. Inverting the fitted quadratic model to express added

P as a function of Olsen-P allows the estimation of the amount of P (fertilizer) to be added to increase the Olsen-P value from a starting level (Olsen-P_1) to a target level (Olsen-P_2):

$$Added\ P = \frac{1}{2q}\left[\sqrt{l^2 - 4q(c - OlsenP_1)} - \sqrt{l^2 - 4q(c - OlsenP_2)}\right] \qquad (2)$$

where *c*, *l* and *q* are the fitted intercept, linear and quadratic parameters, respectively, of the Olsen-P quadratic models. The relationship between the fitted quadratic equation parameters for these Olsen-P models and each of the individual soil characteristics was assessed using simple linear regression, with the fits for each quadratic parameter (*c*, *l*, *q*) against each soil characteristic ranked based on the adjusted R^2 statistic. Individual (hydr)oxides as well as combinations of amorphous iron and aluminium (hydr)oxides and crystalline iron and aluminium were tested. This was carried out as amorphous (hydr)oxides have much greater reactive surface areas than crystalline (hydr)oxides and different (hydr)oxides (Al, Fe, Mn) will have points of zero charge at different pHs and therefore their surface charge will be affected differently by pH. Also, as all the elements for the amorphous (hydr)oxides and all for the crystalline (hydr)oxides were extracted with the same extractant solution pseudo-correlation may be a possibility. Variable selection using stepwise MLR was applied to the five highest ranked soil characteristics, and the most parsimonious and best-fitting model for each of the Olsen-P quadratic parameters was identified by considering both the AIC and adjusted R^2 statistic. Soil characteristics were $\log_{10}$ transformed as required as described above.

Table S1 Soil location and description

Soil Name	**Latitude Longitude**	**Land Use**	**Soil Texture**[†]	**Soil Series**[†]
Barnfield	51.806888 -0.359524	Improved grassland	Silty Clay Loam	Profundic Chromic Endostagnic Luvisol
Halstead	51.958701 0.677979	Arable	Silty clay loam	Clayic Stagnic Luvisol
Knowstone	50.984892 -3.660713	Unimproved grassland	Silty clay loam	Clayic Dystric Histic Stagnosol
Peldon	51.807683 0.882917	Arable	Silty Clay Loam	Eutric Vertic Stagnosol
Rough	50.829539 -3.168825	Unimproved grassland	Sandy Clay Loam	Eutric Endoskeletic Cambisol
Sleaford	51.894365 0.738108	Arable	Silty clay loam	Clayic Fluvic Calcaric Gleysol
Stowford	50.923021 -4.289364	Unimproved grassland	Loam	Clayic Eutric Stagnosol
Tadham	51.205056 -2.823009	Improved grassland	Clay	Drainic Rheic Fibric Histosol
Thornby	52.371567 -1.008050	Arable	Clay Loam	Clayic Stagnic Luvisol
Woodah	50.667666 -3.630628	Unimproved grassland	Clay Loam	Eutric Endoceptic Cambisol

[†]FAO (2015) World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. FAO, Rome, Italy

Table S2. Experimental Treatments

P Treatment mg kg^{-1}	Experiment 1	Experiment 2
0	X	X
2.5	X	
5	X	
10	X	
15	X	X
20	X	
25	X	
27.5	X	
30	X	X
32.5	X	
35	X	
37.5	X	
40	X	
45	X	
50	X	X
75	X	X
100	X	X
125	X	
150	X	X
200	X	X
300		X
400		X
600		X

Table S3. Correlation matrix of soil parameters

% Clay	-													
% OC	0.7555*	-												
CAlox	-0.0372	-0.2896	-											
CFeox	-0.1555	-0.5575	0.6926*	-										
CAlFeox	-0.1512	-0.5514	0.7223*	0.9991***	-									
CMnox	0.4326	0.3126	0.1712	-0.2178	-0.1988	-								
AAlox	0.0624	0.3342	-0.0207	0.0966	0.0915	-0.0056	-							
AFeox	0.2183	0.5225	0.0522	-0.0638	-0.0582	0.0418	0.7153*	-						
AAlFeox	0.1852	0.4990	0.0336	-0.0196	-0.0169	0.0302	0.8461**	0.9777***	-					
AMnox	-0.0437	-0.0101	0.0140	0.4220	0.4054	-0.2617	0.7901**	0.3128	0.4760	-				
PBI	0.2339	0.3640	0.1990	-0.2453	-0.2236	0.5996	0.4354	0.6656*	0.6385*	-0.0534	-			
pH	0.1888	-0.3170	-0.1525	0.1772	0.1610	0.0715	-0.6695*	0.7823**	0.7979**	-0.2958	-0.5971			
TP	0.6521*	0.6460*	-0.1498	0.0370	0.0267	0.1954	0.4985	0.4592	0.5001	0.4979	0.0929	-0.0616	-	
CV90	0.4263	0.4596	-0.4399	-0.2910	-0.3046	-0.1016	-0.1301	0.0971	0.0349	-0.1114	-0.2304	0.1431	0.2251	-
	% Clay	% OC	CAlox	CFeox	CAlFeox	CMnox	AAlox	AFeox	AAlFeox	AMnox	PBI	pH	TP	CV90

% OC = organic carbon, CAlox = crystalline aluminium oxides, CFeox = crystalline iron oxides, CAlFeox = crystalline aluminium and iron oxides, CMnox = crystalline manganese oxides, AAlox = amorphous aluminium oxides, AFeox = amorphous iron oxides, AAlFeox = aluminium and iron oxides, AMnox = amorphous manganese oxides, PBI = phosphorus buffering index, TP = total P in soil before dosing with P, CV90 = Critical Olsen P values at 90% of maximum yield. * significant correlation $p < 0.05$, ** significant correlation $p < 0.01$, *** significant correlation $p < 0.001$

Table S4. Initial soil Olsen-P concentrations 1 week after P addition

Added P mg kg^{-1}	Soil									
	Barnfield	Halstead	Knowstone	Peldon	Rough	Sleaford	Stowford	Tadham	Thornby	Woodah
	Initial Olsen-P mg kg^{-1}									
0	2.91	6.26	2.06	5.49	6.38	3.49	3.51	9.83	10.0	3.71
2.5	2.93	6.16	3.50		5.62	5.02	3.45			
5	2.61	7.52	2.84		6.28	4.55	4.25			
10	3.14	8.08	3.52		7.80	5.55	4.89			
15	3.33	9.24	4.20	7.45	7.48	6.13	5.53	3.51	14.1	4.39
20	3.98	9.72	4.09		8.43	7.51	6.31			
25	4.47	10.6	5.03		12.6	9.09	7.34			
27.5	4.31	10.6	4.44		9.98	8.99	7.62			
30	4.53	11.5	9.30	9.35	11.2	10.6	7.19	5.93	14.5	6.57
32.5	4.48	12.1	3.99		12.2	11.5	8.11			
35	4.86	13.0	5.96		12.8	11.4	8.90			
37.5	5.20	12.5	4.87		13.6	11.9	8.84			
40	5.43	14.4	4.72		14.4	13.3	9.31			
45	5.46	7.00	5.33		14.7	14.0	9.59			
50	6.37	16.8	6.34	16.1	15.76	16.1	10.3	7.41	18.9	8.21
75	8.67	24.5	7.67	27.9	21.4	24.4	14.7	9.77	24.3	10.9
100	11.2	29.7	9.45	40.6	23.9	31.0	20.5	11.7	30.7	14.9
125	14.4	37.7	11.9		34.6	37.2	26.6			
150	18.8	42.4	19.7	58.1	39.2	48.6	33.2	17.1	44.0	21.1
200	26.5	63.9	31.5	73.8	48.0	76.4	44.3	22.7	110	30.0
300				123				49.7	72.8	43.9
400				131				65.7	116	59.3
600				189				98.8	201	92.8

Table S5. Final soil Olsen P concentrations

Added P mg kg^{-1}	Soil									
	Barnfield	Halstead	Knowstone	Peldon	Rough	Sleaford	Stowford	Tadham	Thornby	Woodah
	Final Olsen-P mg kg^{-1}									
0	5.03	5.39	3.10	7.76	6.66	0	6.30	10.98	9.08	1.94
2.5	4.21	5.85	3.84		4.23	0	0.14			
5	4.45	6.31	4.36		8.35	0	0.00			
10	4.55	6.19	3.62		5.03	0	0.00			
15	5.19	6.79	3.92	9.92	4.63	0	0.00	13.84	4.84	2.68
20	5.17	7.71	3.84		0.02	0	5.30			
25	5.37	8.51	5.28		7.23	0.90	4.40			
27.5	5.53	6.07	5.88		7.72	0.45	2.27			
30	5.51	7.39	5.40	8.86	7.54	0.16	0.95	9.84	6.66	2.26
32.5	5.45	7.85	5.14		6.24	0.84	2.60			
35	5.75	7.71	4.94		3.55	0.69	0.38			
37.5	6.13	7.55	5.66			0.96	4.98			
40	5.85	6.93	5.26		4.26	0.79	2.01			
45	2.07	8.31	5.76		4.05	2.06	6.33			
50	5.47	8.61	6.54	13.0	1.03	2.23	3.48	11.24	6.10	5.96
75	7.45	11.3	7.34	12.1	10.3	5.66	1.71	12.60	7.90	5.08
100	8.61	13.2	9.22	12.2	8.65	6.41	2.94	12.42	9.26	3.46
125	11.6	16.5	11.6		10.2	11.5	14.1			
150	15.1	20.3	14.6	15.7	15.5	20.5	12.3	10.8	11.2	5.48
200	18.1	28.9	20.6	22.5	18.6	21.0	17.3	18.0	11. 8	6.22
300				21.1				16.0	14.5	9.16
400				41.0				11.0	28.3	14.3
600				102				0.62	48.8	18.7

Table S6. Total P removed by the grass during the experimental time (P concentration in grass * biomass) mg P per pot

Added P mg kg^{-1}	Soil									
	Barnfield	Halstead	Knowstone	Peldon	Rough	Sleaford	Stowford	Tadham	Thornby	Woodah
0	0.921	1.54	1.22	0.659	3.55	0.851	1.23	2.75	1.95	5.41
2.5	1.01	2.01	1.05		3.80	1.23	2.17			
5	1.03	2.04	0.843		4.51	1.59	2.50			
10	1.40	2.20	0.901		4.63	1.50	2.523			
15	1.61	2.58	1.04	0.985	4.56	2.27	2.69	3.25	5.40	6.34
20	1.76	4.95	1.31		5.37	2.82	2.87			
25	2.02	2.55	1.76		6.30	2.54	3.73			
27.5	2.22	3.96	1.71		6.94	2.82	3.72			
30	2.62	3.56	1.87	2.43	6.61	3.62	2.41	3.84	5.37	7.29
32.5	2.68	3.82	1.61		7.76	3.67	3.87			
35	2.54	3.53	1.61		6.66	3.51	4.39			
37.5	2.61		1.90		6.87	4.21	3.61			
40	3.61	4.96	2.13		7.68	4.97	4.07			
45	3.36	3.79	2.81			4.57	5.05			
50	3.42	5.30	2.55	1.20	7.71	3.88		4.78	9.71	9.84
75		5.32	3.31	5.42	10.7	7.23	7.68	5.50	10.3	12.9
100	6.74		3.30	8.39	11.1	8.79		7.74	16.9	13.1
125	8.32	9.70	4.36		12.0	9.59	9.33			
150	7.56	10.9	3.99	14.9	15.4		15.2	11.3	22.8	18.6
200	9.99	15.0		19.0	17.3	17.6	15.7	14.8	29.5	25.5
300				25.9				24.1	34.8	41.6
400				31.2				31.4	47.6	37.1
600				40.0				40.7	64.7	69.0

Table S7. Weight per volume of soil conversion (<2 mm)

Soil	kg per L
Barnfield	1.166
Halsted	1.225
Knowstone	0.789
Peldon	1.241
Rough	1.069
Sleaford	1.299
Stowford	0.953
Tadham	0.903
Thornby	1.077
Woodah	0.892