

Report

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INSTITUTE OF TERRESTRIAL ECOLOGY
(NATURAL ENVIRONMENT RESEARCH COUNCIL)

ITE PROJECT T01014A5

REPORT TO THE WATER RESEARCH CENTRE

UK SOILS: THEIR PHOSPHORUS SORPTION CAPACITY
AND POTENTIAL FOR P REMOVAL FROM SEWAGE
EFFLUENTS IN EMERGENT HYDROPHYTE TREATMENT
SYSTEMS.

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SUMMARY

The removal of phosphorus (P) from sewage effluents by Emergent hydrophyte Treatment Systems (EHTS - e.g. reedbeds) is, at present, not very efficient; concentrations of P in effluents from such systems can range from 0.03 to 15 mg P litre⁻¹ as ortho-phosphate (the total P may be considerably greater) and can sometimes exceed those in the sewage flowing into the reedbeds. The choice of soil for use in the construction of reedbeds is considered to be a critical factor, and those soils with high P sorption capacity should clearly be preferred.

To assist in the selection of soils, an analysis has been carried out of : i) the range of P sorption capacity and ii) the association between P sorption capacity and various soil chemical and physical properties, in soils of 8 different types (acid brown earth, basic brown earth, brown podzolic, podzol, peaty podzol, peat, peaty gley and gley) in the UK.

Using the Bache & Williams (1971) single concentration method, values for 104 UK soils varied from 0 to 1590 mg P kg⁻¹, with some of the highest values being for brown podzolic, peaty podzol and peaty gley soils. Regression analysis showed that P sorption capacity of soils was significantly related to iron, aluminium, calcium, clay, silt, sand and organic matter contents, and to pH. Different relationships were found for different soil types. Between 54 and 95% of the variation (depending on soil type) in P sorption capacity was explained by the above soil properties. Results of the analyses are fully presented, together with graphs showing the relationships between observed and predicted P sorption capacities for each soil type.

The results are discussed in relation to the choice of soils for EHT Systems. Factors additional to P sorption capacity, which are likely to influence P removal from sewage effluents are also discussed. These include additions of lime, aerobic/ anaerobic conditions, associated ions in effluent, effluent flowrate and direction, P chemistry and biological cycling.

1. INTRODUCTION

In the last five years, there has been much interest throughout Europe in the use of Emergent Hydrophyte Treatment Systems (EHTS - e.g. reedbeds, Figure 1) for the purification of sewage and effluents. Several experimental reedbeds have recently been established in Britain (Cooper *et al* 1988), but whilst they have already achieved good treatment of BOD and suspended solids, their effectiveness in removal of P has been highly variable and often disappointing (Table 1). These average removal efficiencies conceal the facts that there are i) considerable temporal variations in P concentrations in effluents and ii) peak P concentrations in effluents that can exceed those in the concomitant sewage inflows.

TABLE 1 Removal of P from Effluents in Artificial Reedbeds

LOCATION	MEDIA	IN	OUT	%REMOVAL	REF.
ORTHO-PO ₄ -P (mg l ⁻¹)					
Gravesend bed 1	2.5mm gravel	14.0	7.0	50	Cooper <i>et al</i> (1988)
" bed 2	" "	14.0	7.0	50	
" bed 3	" "	14.0	4.2	70	
Holtby	soil	7.7	7.1	8	
Middleton	sandy	12.7	9.1	28	
Bluther Burn	fine PFA	11.2	3.6	68	
" "	coarse PFA	11.2	1.8	84	
" "	uneven gravel	11.2	0.9	92	
" "	graded gravel	11.2	3.3	70	
TOTAL P (mg l ⁻¹)					
Moesgard	fine loamy sand	6.3	4.2	27	Brix & Schierup (1986)
Hjordkaer	washed gravel	13.3	11.5	11	
Ingstrup	coarse sandy loam	48	4.2	83	% removal calculate on basis of flows
Rugballebard	rich fine loam	18.9	3.0	83	
Lunderskov	peaty clay silt	4.1	2.5	38	
Knudby	coarse loamy sand	10.9	6.2	37	
Borup humous	coarse loamy sand	10.7	8.8	17	
Kalo	humous clay	8.9	8.3	8	
Egeskov	sand / loam	5.0	1.8	60	
Bredballebard	rich loamy sand	7.2	1.9	63	
Fousing	humous/ coarse loamy sand	12.3	11.1	18	
Ostjyden	coarse sandy	1.8	0.8	9	
Mannersdorf bed 1		7.3	3.9	47	Haberl & Janauer (1986)
" bed 2		7.6	3.4	55	
" bed 3		6.0	2.7	55	
" bed 4		5.8	4.1	29	

Phosphate removal has not been a primary concern in the design of artificial reedbeds constructed in this country, but it is likely to become more important in the future as stricter EEC regulations are introduced. Expensive technology can provide nearly complete removal of P in effluents, but EHT has the potential to provide a cost-effective alternative. ITE has therefore been commissioned by the Water Research Centre to assist in the identification of those soils and soil characteristics which would maximise the sorption of P by reedbeds. The

core of this report is based on an analysis of data from previous ITE studies examining the range of fertility of UK soils (Harrison & Hornung 1983). Equations for the prediction of P sorption capacity from soil chemical and physical characteristics have been produced for 8 broad soil groups.

2. SOILS AND SOIL CLASSIFICATION

One hundred and four soils were collected from various parts of the UK, and were classified into eight groups (acid brown earth, base-rich brown earth, brown podzolic, podzol, peaty podzolic, peat, peaty gley and gley) broadly in line with the classification of Avery (1980). The locations of the sites and the land use are presented (Appendix I; Figure 2). After removing recent litter materials, the top 20cm layer (generally the main rooting zone of the site vegetation) was sampled at each site irrespective of the pedological horizons (descriptions are however, available on the horizons and their constitution). 200-250 kg of the fresh soil was collected and the whole sample sieved through 12mm sieve mesh using a modified cement mixer (Benham & Harrison, 1980). After thorough mixing, a subsample about 2kg of the soil was taken for various analyses. The bulk of the soil sample was used for plant growth studies (Harrison & Hornung, 1983). Roughly half of the subsample was air-dried and sieved through a 2mm screen, the >2mm fraction being retained for mass measurements. The <2mm air-dried fraction was used for all the measurements discussed in this report.

3. ANALYTICAL METHODS

3.1 P sorption capacity

The single P concentration method of Bache & Williams (1971) was used to obtain an index of P sorption capacity of all the soils. 2 g air dried soil was shaken in 100ml of 0.02M KCl containing 3 mg P as KH_2PO_4 (with addition of 2 drops of chloroform to reduce microbial activity) on a reciprocal shaker/waterbath at 20°C for 18hrs. Suspensions were then filtered through Whatman No 44 papers and the filtrates centrifuged at 3500 rpm for 30 mins. Inorganic P remaining in the supernatant solution was determined, after suitable dilution, by the method of John (1970). P sorption capacity of the soils has been calculated as the amount of P taken out of solution and expressed as mg P kg^{-1} soil; moisture content of the air-dried soil was determined by drying soil at 105°C for 24 hrs. Determinations were carried out in duplicate, with good agreement between the replicates.

3.2 Total Aluminium, Iron and Calcium contents

Total Al, Fe and Ca contents were determined, after dissolution of the soil material by perchloric-hydrofluoric acid digestion, using inductively-coupled plasma analysis according to the methods of Walsh & Howie (1980).

3.3 Extractable Calcium content

Extractable Ca content was determined by extraction in ammonium acetate solution at pH 7 using atomic absorption method (Allen et al, 1974).

3.4 Particle size analysis

Clay, silt and sand contents of the soils were determined by the sedimentation method using a Bouyoucos hydrometer (Allen et al, 1974). For soils with organic matter contents greater than 20%, appropriate amounts of air-dried soil were digested with H_2O_2 to provide about 50 g mineral material for analysis. The clay, silt and sand contents were then calculated allowing for the organic matter content.

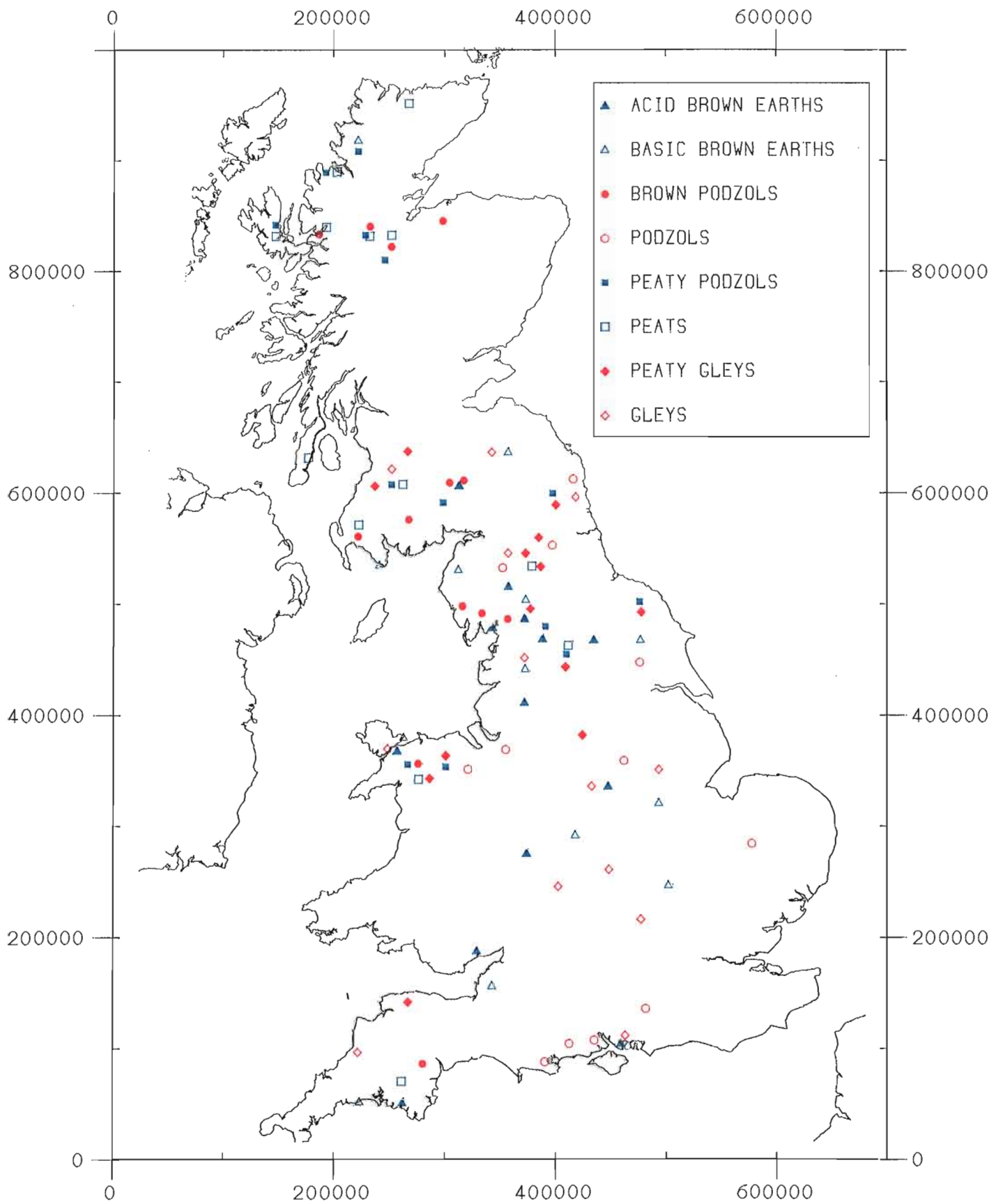


FIGURE 2. DISTRIBUTION OF SITES FROM WHICH SOILS WERE SAMPLED

3.5 Organic matter

Organic matter was determined by loss-on-ignition of oven-dried soil at 550°C for 2 hr (Allen *et al*, 1974).

3.6 Soil pH

Soil pH was determined on fresh soil by bringing the soil to saturation point by addition of distilled water, mixing thoroughly and allowing to stand for 30 mins. A dual glass electrode was employed.

4.0 ANALYTICAL RESULTS

4.1 Ranges of Soil Properties

The minimums, means and maximums of the above soil properties have been summarized in Table 2. The capacity of the soils to fix inorganic phosphate, based on the mean value (mg P kg⁻¹ soil) for each group was in the order brown podzolic soils > peaty gleys > peaty podzols > acidic brown earths > gleys > peats > basic brown earths and podzols. There was considerable variation (coefficients of variation % ranging from 17.3 to 133.7) in the P sorption capacity of soils within a single group. The significance of the differences in P sorption capacity between soil types are presented in Table 3.

The soil types also showed a fairly wide range in the other physico-chemical properties, which will be important in conditioning the P sorption capacity of the individual soils, and indeed the suitability of the soil for use in the EHT System. These properties include organic matter, particle size fractions, aluminium, iron, and calcium contents and soil pH.

Table 2. Soil properties of the eight soil types sampled.

<u>All Soils</u>	Min.	Mean	Max.	CV%
P sorption capacity (mg kg ⁻¹)	0	661	1590	67.3
pH	3.0	4.6	7.7	24.8
Clay (g kg ⁻¹)	0	93	541	93.6
Silt (g kg ⁻¹)	2	149	496	68.2
Sand (g kg ⁻¹)	24	480	926	52.0
Organic matter (g kg ⁻¹)	26	274	970	110.9
Ext. Ca (mg kg ⁻¹)	40	1544	12000	143.7
Total Al (g kg ⁻¹)	1.3	38	111	66.4
Total Fe (g kg ⁻¹)	0.24	21.6	63.4	70.8
Total Ca (g kg ⁻¹)	0.14	5.0	57.0	165.9

Table 2 cont.

<u>Acid brown earths</u>	Min.	Mean	Max.	CV%
P sorption capacity (mg kg ⁻¹)	130	670	1250	39.8
pH	3.4	4.6	6.5	19.3
Clay (g kg ⁻¹)	27	115	193	46.9
Silt (g kg ⁻¹)	127	211	370	38.1
Sand (g kg ⁻¹)	367	589	754	18.5
Organic matter (g kg ⁻¹)	45	85	150	33.9
Ext. Ca (mg kg ⁻¹)	40	813	2700	97.9
Total Al (g kg ⁻¹)	23	48	68	29.1
Total Fe (g kg ⁻¹)	18.9	30.6	49.1	26.3
Total Ca (g kg ⁻¹)	0.52	2.2	6.8	81.6
<u>Basic brown earths</u>	Min.	Mean	Max.	CV%
P sorption capacity (mg kg ⁻¹)	160	352	740	52.8
pH	4.9	6.4	7.7	13.0
Clay (g kg ⁻¹)	28	112	219	41.8
Silt (g kg ⁻¹)	87	213	496	47.6
Sand (g kg ⁻¹)	412	599	796	19.4
Organic matter (g kg ⁻¹)	30	76	160	45.5
Ext. Ca (mg kg ⁻¹)	760	2958	11000	88.0
Total Al (g kg ⁻¹)	21	46	77	35.7
Total Fe (g kg ⁻¹)	12.2	29.3	46.3	34.7
Total Ca (g kg ⁻¹)	1.4	8.6	57.0	172.2
<u>Brown podzolics</u>	Min.	Mean	Max.	CV%
P sorption capacity (mg kg ⁻¹)	730	1140	1400	17.3
pH	3.9	4.4	4.9	6.7
Clay (g kg ⁻¹)	33	71	131	46.0
Silt (g kg ⁻¹)	111	206	348	33.5
Sand (g kg ⁻¹)	391	592	768	17.7
Organic matter (g kg ⁻¹)	75	131	180	27.7
Ext. Ca (mg kg ⁻¹)	60	517	2200	129.7
Total Al (g kg ⁻¹)	45	59	82	17.7
Total Fe (g kg ⁻¹)	11.9	29.5	44.2	34.0
Total Ca (g kg ⁻¹)	0.67	5.1	21.9	118.3

Table 2 cont.

<u>Podzols</u>	Min.	Mean	Max.	CV%
P sorption capacity (mg kg ⁻¹)	0	188	870	133.7
pH	3.1	3.8	6.2	24.0
Clay (g kg ⁻¹)	9	38	129	80.6
Silt (g kg ⁻¹)	18	60	90	37.4
Sand (g kg ⁻¹)	547	808	926	12.4
Organic matter (g kg ⁻¹)	26	93	240	63.4
Ext. Ca (mg kg ⁻¹)	70	502	3200	171.9
Total Al (g kg ⁻¹)	1.3	10	40	99.8
Total Fe (g kg ⁻¹)	0.4	6.4	27.0	142.7
Total Ca (g kg ⁻¹)	0.14	1.0	6.7	168.8
<u>Peaty podzols</u>	Min.	Mean	Max.	CV%
P sorption capacity (mg kg ⁻¹)	130	768	1590	67.3
pH	3.0	3.8	4.8	15.1
Clay (g kg ⁻¹)	0	75	207	93.9
Silt (g kg ⁻¹)	4	111	338	90.0
Sand (g kg ⁻¹)	24	279	647	73.5
Organic matter (g kg ⁻¹)	160	503	970	59.2
Ext. Ca (mg kg ⁻¹)	65	457	1100	84.7
Total Al (g kg ⁻¹)	2.5	29	68	77.9
Total Fe (g kg ⁻¹)	3.6	17.4	63.4	108.1
Total Ca (g kg ⁻¹)	0.38	6.3	30.6	148.5
<u>Peats</u>	Min.	Mean	Max.	CV%
P sorption capacity (mg kg ⁻¹)	0	573	1570	97.4
pH	3.2	4.2	5.1	15.2
Clay (g kg ⁻¹)	1	19	83	163.8
Silt (g kg ⁻¹)	2	28	130	164.4
Sand (g kg ⁻¹)	25	95	377	101.0
Organic matter (g kg ⁻¹)	410	858	970	19.6
Ext. Ca (mg kg ⁻¹)	400	1954	5600	95.2
Total Al (g kg ⁻¹)	1.5	10.0	35.5	109.7
Total Fe (g kg ⁻¹)	0.24	6.98	15.17	69.6
Total Ca (g kg ⁻¹)	1.4	7.3	42.5	155.3

Table 2 cont.

<u>Peaty gleys</u>	Min.	Mean	Max.	CV%
P sorption capacity (mg kg ⁻¹)	550	1005	1580	34.2
pH	3.0	4.0	4.9	14.1
Clay (g kg ⁻¹)	1	97	205	70.0
Silt (g kg ⁻¹)	11	126	293	61.6
Sand (g kg ⁻¹)	88	439	768	50.6
Organic matter (g kg ⁻¹)	86	338	900	76.6
Ext. Ca (mg kg ⁻¹)	110	895	3600	116.7
Total Al (g kg ⁻¹)	7.1	38.3	111	68.9
Total Fe (g kg ⁻¹)	3.6	15.6	37.6	68.7
Total Ca (g kg ⁻¹)	0.46	1.6	5.6	89.6
 <u>Gleys</u>	 Min.	 Mean	 Max.	 CV%
P sorption capacity (mg kg ⁻¹)	300	589	900	34.1
pH	4.3	5.8	7.4	17.3
Clay (g kg ⁻¹)	63	219	541	63.9
Silt (g kg ⁻¹)	176	236	317	17.7
Sand (g kg ⁻¹)	135	439	680	34.4
Organic matter (g kg ⁻¹)	53	105	160	26.1
Ext. Ca (mg kg ⁻¹)	300	4259	12000	87.8
Total Al (g kg ⁻¹)	43.4	67.6	90.5	21.8
Total Fe (g kg ⁻¹)	16.7	37.0	54.1	32.8
Total Ca (g kg ⁻¹)	0.66	7.70	25.25	82.4

Table 3. Differences between the mean P sorption capacities of the eight soil types.

Soil type							
Brown podzolic (BP)							
Peaty gley (PG)	135						
Peaty podzol (PP)	372	237					
Acid brown earth (ABE)	470 [*]	335	98				
Gley (G)	551 ^{**}	416	179	81			
Peat (P)	567 ^{**}	432 [*]	195	97	16		
Basic brown earth (BBE)	788 [#]	653 [#]	416	318	237	221	
Podzol (PD)	952 [#]	817 [#]	580 ^{**}	482 [*]	401	385	164
	BP	PG	PP	ABE	G	P	BBE

* = P<0.05, ** = P<0.01, # = P<0.001

4.2 Relationships between P sorption capacity and soil properties.

4.2.1 Simple relationships with individual soil properties

Relationships between soil P sorption capacity and the measured soil properties were found to be complex, for when all the 104 soils were examined as a single group no strong correlations were found (Table 4). Yet when soil types were examined separately, significant and strong relationships between P sorption capacity and some of the soil properties were found (Table 4).

4.2.2 Relationships with all soil properties

Similarly when all soils were treated as a single group, a total of only 51% of the variation in P sorption capacity could be explained by all 9 variables. Examination of soil types separately also enabled higher proportions of the variation in P sorption capacity to be explained by soil properties. This indicated that the sorption of P was related differently to soil properties in the various soil types.

Multiple regression equations have therefore been developed for each of the soil types. These have been structured on two different bases i) a common format whereby the same soil properties (clay, organic matter, total aluminium and total iron contents and soil pH) have been included and ii) using the best five properties for each individual soil type. The proportions of the variation in P sorption capacity accounted for by soil properties have been presented in Table 5 and the equations relating the properties have been listed in Tables 6 and 7.

The match of the predictions of P sorption capacity to observed values are presented in graphical form in the Appendix 2. Good fits are found for most soil types. Error terms cannot easily be attached to the regressions as the error varies across the range of values.

Table 4. Linear relationships (r) between P sorption capacity and soil properties for each of the different soil types.

Soil Type	Clay	Silt	Sand	OM	pH	Al	Fe	Ca	Ext.Ca
All soils	.15	.29	-.13	-.03	-.06	.50	.42	.22	-.03
Acid b/earth	-.23	-.03	-.05	.72	-.44	.40	.58	-.28	-.40
Basic b/earth	.31	.40	-.72	.46	.39	.54	.43	.53	.56
Brown podzolic	-.06	.16	-.37	.84	-.18	-.27	.32	-.23	.10
Podzol	.14	.54	-.37	.35	.22	.92	.67	.20	.17
Peaty podzol	.67	.58	.48	-.60	.73	.94	.86	.70	-.61
Peat	.74	.71	.60	-.68	.77	.83	.79	.46	.74
Peaty gley	.03	.33	-.23	.09	.11	.59	.87	.00	.09
Gley	.20	-.29	-.14	.21	-.52	.16	-.21	.10	-.04

Number of soils in each group was 13; values $>.55$ or $<-.55$ significant at $P<0.05$.

Table 5 The proportions of the variation in P sorption capacity of soils for each soil group explained by soil properties.

Soil Type	Proportion Explained (R^2) by	
	a) Clay, OM, Al, Fe & pH	b) The best 5 properties
Acid brown earth	.55	.84
Basic brown earth	.22	.85
Brown Podzolic	.68	.81
Podzol	.90	.90
Peaty Podzol	.89	.95
Peat	.89	.91
Peaty Gley	.68	.84
Gley	.21	.55

R^2 adjusted for the number of parameters in the model.

Table 6 Multiple Regression Equations* relating P sorption capacity of soil types to clay, organic matter, aluminium and iron contents and soil pH.

Soil type	Regression coefficients for Properties					Constant
	Clay	OM	Al	Fe	pH	
Acid brown earth	.48	4.88	-4.0	18.7	-95.9	260
Basic br. earth	1.07	0.68	7.4	-5.2	100.1	-644
Brown podzolic	.16	3.43	-9.0	9.4	-42.0	1118
Podzols	-1.54	0.92	17.9	7.5	71.1	-338
Peaty podzol	-0.22	0.29	19.5	7.8	15.0	-122
Peat	-17.0	0.87	81.7	61.0	52.0	-1323
Peaty gley	1.08	0.38	-1.1	30.2	62.6	89
Gley	0.74	2.27	-.14	-3.2	-126.3	1049

* The equations take the form of:

P sorption capacity = c(clay) + c(OM) + c(Al) + c(Fe) + c(pH) + constant
where c is the coefficient listed in the table.

Table 7 Multiple Regression Equations* relating P sorption capacity of soil types to the best five soil properties.

Soil type	Soil properties in regression					Constant
	Clay	Sand	OM	Ca	ext. Ca	
Acid brown earth	-2.99	-1.45	5.26	198.9	-0.58	1458
Basic brown earth	Sand	Silt	Clay	Fe	Al	Constant
	-5.07	-3.72	-4.04	8.4	-9.4	4812
Brown podzolic	Clay	OM	Fe	Al	Ca	Constant
	-2.38	2.07	17.8	-10.1	-16.1	1191
Podzol	Clay	OM	Fe	Al	pH	Constant
	-1.54	0.92	7.5	17.9	71.1	-338
Peaty podzol	Sand	OM	Fe	Al	Ca	Constant
	1.76	1.68	-19.7	34.5	33.1	-1439
Peat	Fe	Al	Ca	Ext.Ca	pH	Constant
	71.1	43.7	-22.3	-.06	111.9	-551
Peaty gley	OM	Fe	Al	Ca	pH	Constant
	1.58	10.6	9.0	-249.8	633	-2191
Gley	Clay	Sand	OM	Ext.Ca	Ca	Constant
	3.81	2.74	9.9	-0.12	40.4	-2279

* The equations take the form of:

P sorption capacity = c(1) + c(2) + c(3) + c(4) + c(5) + constant
 where c is the coefficient listed in the table.

5. DISCUSSION

5.1 Prediction of P sorption capacity in soils

The capacity of soils to react with and sorb anions, such as inorganic phosphate, is largely related to the amount of iron, aluminium, calcium, clay and organic matter; and to the surface area and the charge (mainly affected by soil pH) of soil particles. The complex physico-chemical reactions and surface chemistry, including the adsorption-desorption processes, are reviewed elsewhere (e.g. Barrow, 1985). However, despite the complexity of these processes, good predictions of P sorption capacity in the 8 soil types have been derived using multiple regression equations generated from simple measurements of a number of soil parameters.

The results from these studies concur with the observations of other researchers (Table 8). Note that the values presented in this report have been kept 'quantitative' and are expressed as amounts of P sorbed by soils (mg P kg^{-1} soil), rather than as P sorption indices. Soils of different types clearly have different capacities to sorb P, but there is also considerable variation within each soil type: so it is clear that P sorption capacity cannot simply be assumed from a soil classification.

TABLE 8 Comparison of P sorption capacities with those of other studies.

Soil description	Range of P sorption index	Reference
8 UK Soil types	0 - 80.2	Present study
42 British soils	5 - 64	Bache and Williams (1971)
Peats	0.8 - 39.9	Cuttle (1983)
Soils of South England & Wales	1.5 - 77.9	Lopez-Hernandez and Burnham (1974a)
Basaltic forest	32.8 - 44.8	James et al (1978)
Naturally precipitated hydrated ferric oxide 'iron floc'	453	Burnham & Lopez-Hernandez (1982)
Aged 'iron floc' 'bog limonite'	111	Burnham & Lopez-Hernandez (1982)

'P sorption index' is $(x/\log C)$, where x_1 is the sorption in $\text{mg P } 100\text{g}^{-1}$ soil and C is $\text{micro-mol P litre}^{-1}$.

5.2 Comparison of P sorption Capacity in Natural Soils with P removal in Emergent Hydrophyte Treatment Beds.

Many of the upland soils, particularly the brown podzolics and peaty gleys, have a higher capacity for P sorption than the agricultural soils, like gleys and basic brown earths which have commonly been used in EHT systems. However EHT beds at both Acle (Anglian Water - Reeve 1986, but note 100-fold typing error) and Holtby (Yorkshire Water - Loveland pers.comm.) had an initial sorption

capacity of 1300-1400 mg P kg⁻¹ soil. These P sorption capacities are similar to those in brown podzolic soils, the soil group with the best P retention capacity measured in this report (averaging 1140 mg P kg⁻¹ soil). It ought to be pointed out that our results relate to the 0-20cm of soil profiles; B-horizons with higher iron contents may be able to absorb significantly more P than those we have studied.

The method for measuring the P sorption capacity of the soils in both the Acle and Holtby Reed Bed Systems was the same as that used in this study (Loveland, pers. comm.), so the results are directly comparable. However, Acle is not yet receiving effluent, and Holtby has a gravel underdrain which appears to divert most of the flow away from the soil (see section 5.3.1). Thus it is still unknown whether the high inherent P sorption capacity of these soils will be reflected in effective P removal across the beds.

We have provided a number of highly significant regression equations relating laboratory-measured P sorption to a number of soil parameters. From these equations, the P sorption capacity of other soils can be predicted. Similarly, Richardson (1985) found that 92% of the variation in P sorption from 20 soils in the US was explained simply by the soil-extractable aluminium content. However, when Brix and Schierup (1986) attempted to explain the variation in P removal shown by 12 Danish EHT schemes using multiple correlations with loss on ignition, clay, calcium, iron and aluminium, none of the correlation coefficients were found to be statistically significant. This emphasises that even in soils with a high potential P sorption capacity, several other factors can intervene to prevent efficient P removal in the bed as a whole.

EHT systems may use gravel, soil, or a variety of industrial and mining wastes. Course gravels will not provide long term reduction of phosphates in effluent, and soil media have therefore been employed in beds where this is required. Nevertheless, initial results from British EHT systems have shown better P removal on gravels than in soils (Table 1). However the sorption surface on gravels is much smaller than in soils, and will rather quickly be saturated. Successful P removal has been achieved using reeds growing in pulverised fuel ash (PFA) media in Scotland (Cooper et al, 1988) and South Africa (Alexander & Wood 1986), and this confirms that mining or industrial wastes may be more effective filters for phosphate than soils (Table 8). P removal in EHT beds using red mud wastes from alumina processing is currently being investigated in Australia (Wrigley pers.comm.)

5.3 Possible Reasons for Poor P removal in EHT systems.

5.3.1 The path of effluent flow through the Reed Beds

Danish, German and Austrian experience with P removal has not been encouraging except in over-size beds with high retention times (e.g. Ingestrup and Rugballegard - Table 1). Clearly, little P removal should be expected if overland flow and surface channeling carry most of the effluent through the bed without coming in contact with the soil. However, the 55% P removal achieved from Mannersdorf (Table 1) suggests that some treatment is possible, even when most of the flow does run across the surface. Mannersdorf was planted in spring 1983, and the reeds are now well established (90% cover, 3-3.5m tall) relative to beds in this country. It has a particularly well established 'f-layer' of surface humic material, composed of actively decomposing reed leaves, and this layer seems to be responsible for significant biological uptake, and adsorption onto organic components.

5.3.2 Changes in the physical and chemical conditions within the soil

Lime has been added to the soil in many British EHT beds, following the

recommendations of Professor Kickuth. There are several possible reasons:

a) to enhance the stability and hydraulic conductivity of the soil (Reading Agricultural Consultants, 1985), b) to achieve a pH close to the optimum for the growth of emergent hydrophytes, c) to increase the sink which draws air into the rooting space by precipitating the respiratory CO_2 as calcium carbonate (Raskin & Kende 1985). d) to increase the rates of both nitrification and denitrification.

We are unable to comment on the issue of soil structure, but nutrient rich wetlands tend towards a circumneutral pH, and it is doubtful that initial additions of lime will hold soil pH high for long. Reeds grow prolifically in domestic sewage effluent and do not require additions of lime. Point c) is still entirely speculative.

One disadvantage to the addition of lime to high P sorbing soils is the reduced adsorption of P caused by the increasingly negative charges on soil particles (however interactions between iron, aluminium, pH, organic matter and phosphate are very complicated - see Syers *et al.*, 1973; Rowell, 1981; Barrow, 1985; Haynes & Swift 1985). P can also be precipitated in alkaline soils as tricalcium phosphate or apatite, but flooding will quickly release much of the P (Ponnamperuma, 1972). Increasing the pH of several English soils from pH 4 to pH 8 was found by Lopez-Hernandez and Burnham (1974b) to reduce P sorption by 60%. Liming will also affect the behaviour of organically bound P (see below).

A number of other factors will modify the P removal capacities of EHT systems as a whole. These can be summarized as a) variations in temperature, b) time for adsorption onto soil particles and c) the concentrations of other ions present in the effluents (Barrow, 1985). Furthermore, increasingly anaerobic conditions will increase the solubility of iron and aluminium, and reduce the sorption of P by soil materials (Syers *et al.*, 1973; Rowell, 1981).

5.3.3 The chemistry of the P entering and leaving the Reed Bed.

Williams *et al.* (1971) has described 6 forms in which P can exist in flooded soils:

- i) "Nonoccluded P" is inorganic P present as orthophosphate ions sorbed on the surfaces of P-retaining components such as clays.
- ii) "Occluded P" is inorganic P present as orthophosphate ions within the matrices of P-retaining components.
- iii) "Discrete P" is orthophosphate P present in discrete phosphate minerals such as variscite (AlPO_4), strengite (FePO_4), vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) and apatite ($\text{Ca}_{10}(\text{PO}_4)_6\text{X}_2$).
- iv) "Pore water P" which is soluble P in the soil pore water
- v) "Inorganic polyphosphates" can be a significant fraction where soil pollution by detergents occurs.
- vi) "Organic P" consists of organic esters of phosphoric acid.

The relative proportions of these P fractions in wetland soils are dependent on a variety of factors. If measurements of P behaviour in and removal from effluents within EHT systems is confined to soluble and sorbed P (i & iv), significant proportions of the total P burden in sewage may not be being considered in the P budgets of these systems. It is important, therefore, that

the effectiveness of EHT P removal should be assessed using measurements of both total and soluble P.

In sewage effluents, a significant proportion of the P may be organically bound. In faecal material up to 70% of P may be in organic forms (Harrison, 1987), which are likely to be sorbed by the same basic mechanisms onto iron, aluminium and clays as inorganic P (Jackman and Black, 1951; Anderson and Arlidge, 1962; Greaves and Wilson, 1969). Organic P compounds are more stable and strongly sorbed under low pH conditions, but are readily mineralised i.e. converted to inorganic P, at pHs of 5.5-7.5 and particularly after addition of lime (Harrison, 1987). This mineralisation may take place within the EHT system, in which case the inorganic P released will behave as normal inorganic P, but the P loading on the bed will have been underestimated. Similarly, if any organic P is discharged from EHT systems in the effluent waters, it may not be measured as P in a conventional ortho-phosphate determination.

5.3.4 Biological uptake and cycling

EHT Systems are essentially mini-ecosystems and as such, particularly when fully established, will have P undergoing processes of biological cycling (see Harrison, 1985, included as Appendix IV).

Natural wetlands have long demonstrated the ability to remove significant amounts of phosphate from effluents. However, much of the evidence is contradictory and has generated considerable debate. One theory, for example, holds that emergent hydrophytes (e.g. reeds) cause a net flow of nutrients from sediment to the surface water; another theory is that such plant communities are sinks for nutrients. The differences in observed treatment efficiencies (Appendix III) can be largely explained by factors such as the season of measurement, the loading of the reedbed in relation to its size, and the previous history of effluent loading.

EHT systems with standing water and a thin cover of emergent hydrophytes may undergo rapid growth of algal communities, and significant uptake of P (Kairesalo & Uusi-rauva, 1983). Ripl (1983) found that the algae associated with the base of reed stems could contain almost as much P as the reeds themselves. However this storage is largely temporary, and will be released as the algae decompose in autumn and winter.

Emergent hydrophytes supplied with sewage normally show increased growth, and may have increased tissue nutrient concentrations. Above-ground yields of 2 kg m⁻² dry matter from reedbeds are possible in the British climate, with a P concentration of 0.1-0.15% in the green leaves. This represents a maximum of 30 g P m⁻².

Unfortunately, summer harvesting of these species (particularly reed) will considerably diminish regrowth in following seasons. It will also decrease root and rhizome growth, which is a more permanent sink for P than above ground production. For example, Dolan et al. (1981) found that, whilst the soil was responsible for 69% of the observed P removal, roots and rhizomes retained 23% (8.8 g m⁻²) and leaf-litter 5% (2.0 g m⁻²). Harvesting later in the year will sustain regrowth, but will remove less than 10% of the P contained in green leaves. For these reasons harvesting has not been recommended as a management technique. It will also impair the functioning of EHT systems by removing the carbon source necessary for nitrification, and reducing the insulation provided to the bed during winter.

Furthermore, the presence of dead leaves on the soil surface may sequester some P from effluents by adsorption and microbial immobilization (van der Valk, 1978). Dead leaves have a high C/P ratio, and a large uptake of P is necessary

to balance the carbon and nitrogen used in bacterial growth. In sediments from productive lakes this can be more important than inorganic exchange (Hesse 1973). Patric & Mahapatra (1968) found that 87% of the total P in swamp mud was in organic combination, and some authors felt that humus can have a considerable P sorbing capacity (Sinha 1971). Brix (1986) feels that the high P sorption capacity in two EHT beds was due the relatively high soil organic matter content and adsorption onto fulvic and humic substances. Other authors disagree however, and have measured low P sorption capacities in organic soils (Fox & Kamprath, 1971; Twinch & Breen 1982). The results presented in this report suggest that P sorption in organic soils can vary considerably depending on the degree of decomposition and contents of Fe Al and Ca.

6. CONCLUSIONS

1. P sorption capacities of soils can be predicted from a number of soil chemical and physical characteristics, as shown in this report.
2. Soils, or other media, with a high P sorption capacity should be used wherever possible. However, by itself, P sorption capacity will be an incomplete predictor of P removal efficiency from effluents by EHT Systems.
3. Other factors affecting P removal are: alteration in pH caused by lime additions, temperature, effluent flow rate, concentrations of accompanying ions, aerobic/anaerobic conditions, mineralisation rates of organically bound P and biological cycling. These factors may both
 - i) modify the estimated capacity of soil within the EHT System to retain P, and
 - ii) account for the very significant seasonal and day-to-day variations in P removal efficiency which have been noted for many EHT systems.
 - iii) in mature reed-beds, biological immobilisation processes e.g. accumulation of organic matter, may be more important than the physico-chemical reactions with iron, clay etc. discussed earlier.
4. More research is needed to assess the complex interactions between these factors and P removal in operational EHT Systems.

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APPENDIX I

Locations of the UK sites from which soils were sampled.

No.	SOIL TYPE	SITE NAME	KME	KMN	LANDUSE
1	Acid Brown Earth	Dent	372.2	487.2	Rough Grazing
2	Acid Brown Earth	Moffat	312.9	607.3	Softwood Forestry
3	Acid Brown Earth	Wyre Forest	374.5	276.9	Hardwood Forestry /coppice
4	Acid Brown Earth	Modbury	262.2	052.4	Permanent Grass
5	Acid Brown Earth	Portsmouth	459.1	105.5	Improved Grazing
6	Acid Brown Earth	Shap	357.3	517.3	Short Ley
7	Acid Brown Earth	Ilkeston	447.3	337.4	Rough Grazing
8	Acid Brown Earth	Bolton	372.1	412.9	Recreation
9	Acid Brown Earth	Malham	388.4	469.4	Improved Grazing
10	Acid Brown Earth	Bangor	257.4	368.3	Semi-Natural Woodland
11	Acid Brown Earth	Meathop	343.6	479.6	Coppice with Standards
12	Acid Brown Earth	Newport	328.9	188.3	Improved Grazing
13	Acid Brown Earth	Ripon	434.5	468.3	Semi-Natural Woodland
14	Basic Brown Earth	Cockermouth	312.3	532.4	Permanent Grass
15	Basic Brown Earth	Whithorn	241.8	536.6	Cereals
16	Basic Brown Earth	Grantham	492.55	322.65	Cereals
17	Basic Brown Earth	Bedford	502.5	248.55	Green Crops
18	Basic Brown Earth	Clitheroe	372.9	442.1	Permanent Grass
19	Basic Brown Earth	Sutton Coldfield	417.8	292.8	Rough Grazing
20	Basic Brown Earth	Melrose	357.1	637.3	Permanent Grass
21	Basic Brown Earth	Penmon	262.3	380.8	Permanent Grass
22	Basic Brown Earth	Winscombe	342.3	157.9	Improved Grazing
23	Basic Brown Earth	Malton	476.2	468	Improved Grazing
24	Basic Brown Earth	Kirkby Stephen	373.4	504.8	Improved Grazing
25	Basic Brown Earth	Polperro	222.8	052.3	Rough Grazing
26	Basic Brown Earth	Elphin	221.9	909.6	Rough Grazing
27	Brown Podzolic	Stromeferry	186.4	834.4	Softwood Forestry
28	Brown Podzolic	Glenluce	222.3	562.3	Rough Grazing
29	Brown Podzolic	Cannich	232.5	831.8	Forestry
30	Brown Podzolic	Ferness	297.7	846.9	Softwood Forestry
31	Brown Podzolic	Kendal	357	487	Cult Land/Fallow
32	Brown Podzolic	Eskdale	315.7	499.2	Rough Grazing
33	Brown Podzolic	Grizedale	333.8	492.9	High Forest
34	Brown Podzolic	Glen Mor	251.8	823.2	Softwood Forestry
35	Brown Podzolic	New Galloway	267.7	577.8	Rough Grazing
36	Brown Podzolic	Gwydyr Forest	276	357.3	Softwood Forestry
37	Brown Podzolic	Moretonhampstead	280.3	087.1	Rough Grazing
38	Brown Podzolic	Moffat	317	612.8	Rough Grazing
39	Brown Podzolic	Greskine Forest	304.4	610	Softwood Forestry
40	Podzol	Penrith	352.2	534.8	Unimproved Grazing
41	Podzol	Wareham Forest	390.7	089.5	Softwood Forestry
42	Podzol	Alice Holt	481.6	137.5	Forestry
43	Podzol	Lyndhurst	435.4	108.4	Softwood Forestry
44	Podzol	Ringwood	412.9	105.5	Softwood Forestry
45	Podzol	Penrith	352.3	534.8	Improved Grazing
46	Podzol	Pocklington	475.6	448.1	Softwood Forestry
47	Podzol	Mansfield	461.6	360.8	Softwood Forestry
48	Podzol	Delamere Forest	355.5	370.9	Hardwood Forestry /recreation
49	Podzol	Brandon	577.1	285.2	Softwood Forestry
50	Podzol	Wrexham	320.9	352.7	Unimproved Grazing
51	Podzol	Alnwick	415.7	613.5	Unimproved Grazing
52	Podzol	Slaley Forest	397	554.8	Softwood Forestry
53	Peaty Podzol	Elphin	221.9	909.6	Rough Grazing

54	Peaty Podzol	Cannich	228.5	833.4	Rough Grazing
55	Peaty Podzol	Skye	147.5	832.3	Softwood Forestry
56	Peaty Podzol	Arncliffe	390.9	470.5	Unimproved Grazing
57	Peaty Podzol	Forest of Ae	298.7	592.8	Softwood Forestry
58	Peaty Podzol	Gruinard Bay	192.7	890.3	Unimproved Grazing
59	Peaty Podzol	Dalmellington	252.4	608.5	Softwood Forestry
60	Peaty Podzol	Cropton Forest	475.5	492.3	Softwood Forestry
61	Peaty Podzol	Ilkley	410.1	445.4	Unimproved Grazing
62	Peaty Podzol	Hardwood Forest	397.4	590.4	Softwood Forestry
63	Peaty Podzol	Capel Curig	266.8	356.2	Unimproved Grazing
64	Peaty Podzol	Fort Augustus	245.9	811.5	Softwood Forestry
65	Peaty Podzol	Clocaenog Forest	300.8	354.8	Softwood Forestry
66	Peat	Gruinard Bay	192.7	890.3	Unimproved Grazing
67	Peat	Dalmellington	252.4	608.4	Softwood Forestry
68	Peat	Glenluce	222.9	562.3	Unimproved Grazing
69	Peat	Borgie Forest	267.1	952.1	Softwood Forestry
70	Peat	Saddell Forest	176.7	632.7	Softwood Forestry
71	Peat	Dartmoor	261.4	071.3	Rough Grazing
72	Peat	Upper Teesdale	378.2	535.2	Unimproved Grazing
73	Peat	Glen Mor	252.0	823.4	Unimproved Grazing
74	Peat	Dornie	193.1	830.8	Unimproved Grazing
75	Peat	Skye	147.1	832.9	Unimproved Grazing
76	Peat	Pateley Bridge	411.3	463.6	Unimproved Grazing
77	Peat	Cannich	232.3	832.1	Unimproved Grazing
78	Peat	Migneint	276.3	343.7	Unimproved Grazing
79	Peaty Gley	Alston	372.8	547.4	Rough Grazing
80	Peaty Gley	Haydon Bridge	384.6	561.3	Unimproved Grazing
81	Peaty Gley	Cropton Forest	477.0	493.0	Softwood Forestry
82	Peaty Gley	Ilkey	409.3	444.8	Unimproved Grazing
83	Peaty Gley	Hardwood Forest	400.2	590.0	Softwood Forestry
84	Peaty Gley	Hathersage	424.4	383.0	Rough Grazing
85	Peaty Gley	Migneint	276.5	344.9	Unimproved Grazing
86	Peaty Gley	St. John's Chapel	386.4	535.4	Rough Grazing
87	Peaty Gley	Maybole	237.7	607.7	Unimproved Grazing
88	Peaty Gley	Darvel	267.0	638.0	Grouse Moor/rough Grazing
89	Peaty Gley	Clocaenog Forest	300.8	354.8	Softwood Forestry
90	Peaty Gley	Exmoor	267.3	142.4	Improved Grazing
91	Peaty Gley	Kirkby Stephen	377.5	496.7	Unimproved Grazing
92	Gley	Evesham	402.7	247.8	Cereals
93	Gley	Lincoln	492.7	352.2	Fallow
94	Gley	Southam	447.9	262.4	Cereals
95	Gley	Hambleton	462.9	112.4	Fallow
96	Gley	Derby	432.7	337.8	Improved Grazing
97	Gley	Week St. Mary	222.7	097.8	Semi-Natural Woodland
98	Gley	Cumnock	252.7	622.2	Improved Grazing
99	Gley	Aylesbury	477.3	217.5	Improved Grazing
100	Gley	Croglin	357.2	547.8	Root Crops
101	Gley	Galashiels	342.4	637.3	Improved Grazing
102	Gley	Clitheroe	372.2	442.4	Permanent Grass
103	Gley	Menai Bridge	249.1	370.5	Improved Grazing
104	Gley	Morpeth	417.9	597.4	Improved Grazing

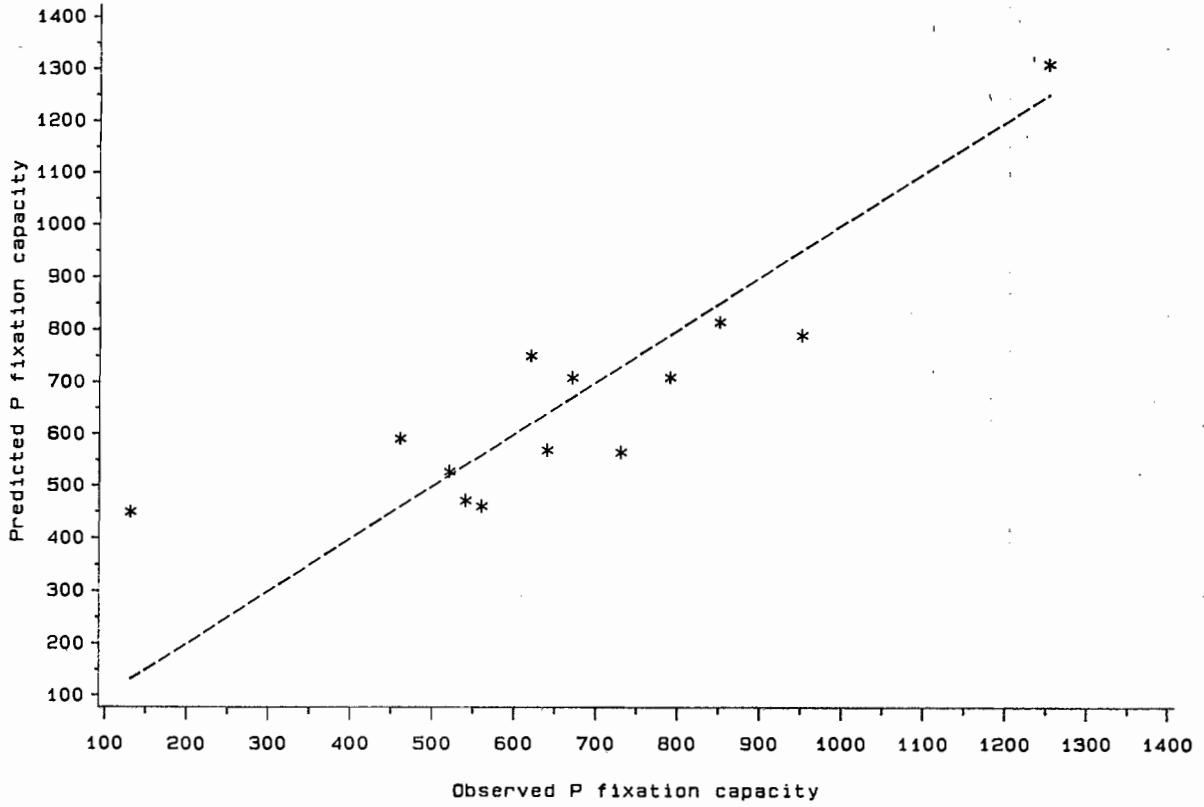
APPENDIX II

Graphical presentations of the predicted* and observed values of P sorption by soils of the 8 soil types studied.

* from the multiple regressions presented in Tables 6 & 7.

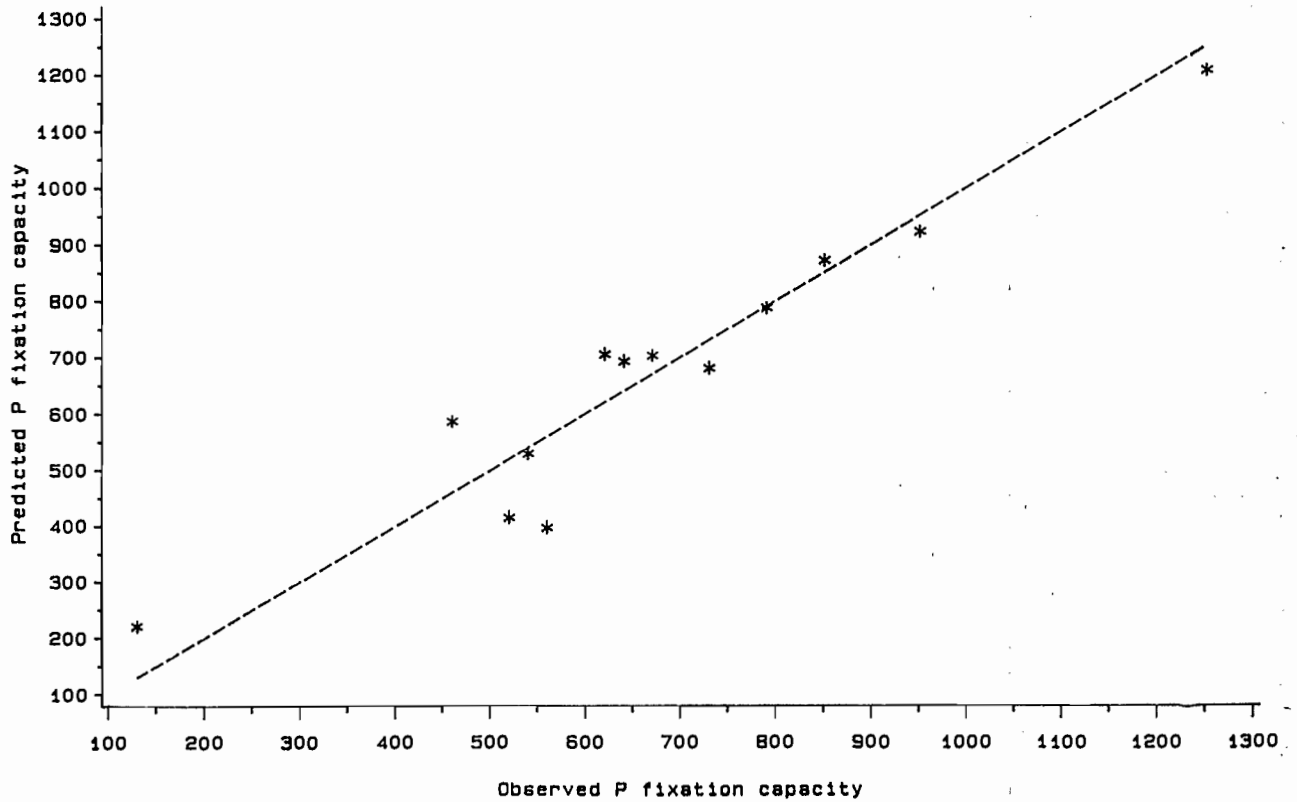
Acid Brown Earths

P fixation capacity=f (Clay, OM, Fe, Al, pH)



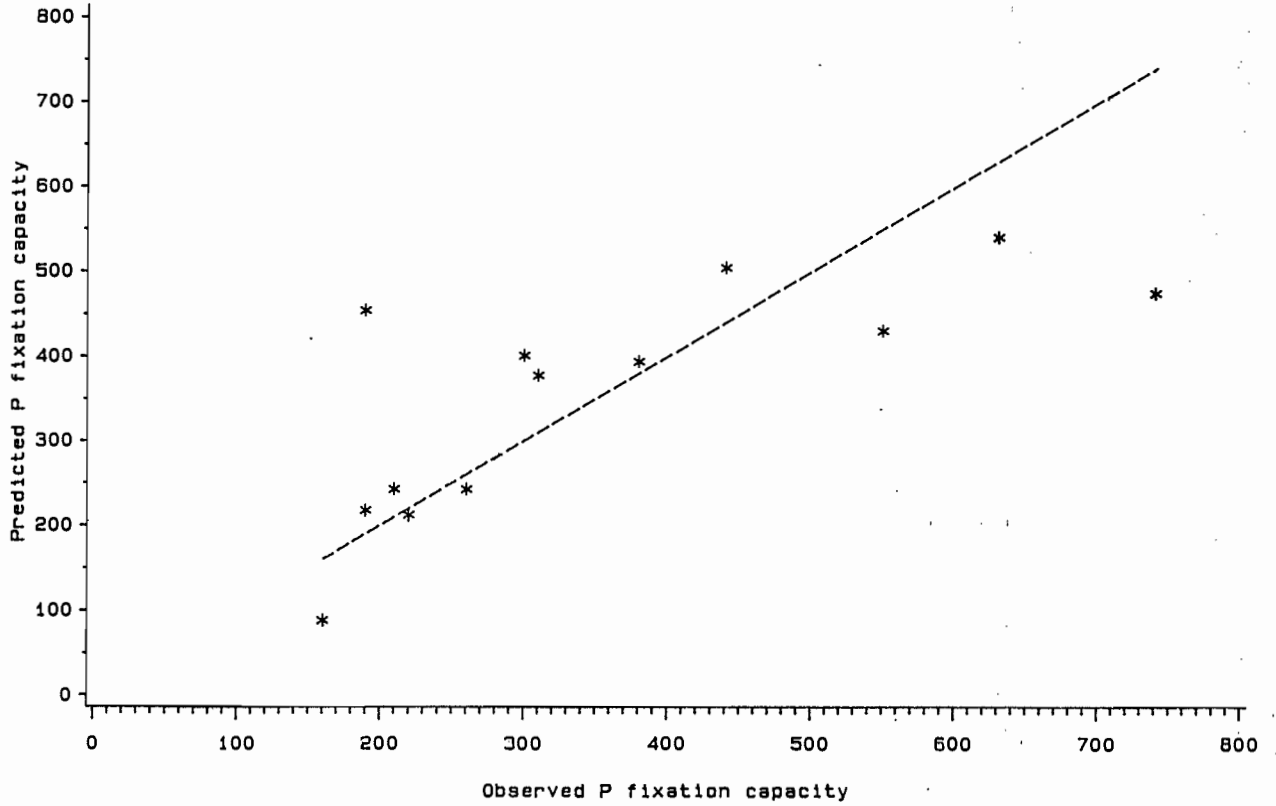
Acid Brown Earths

P fixation capacity=f (Clay, Sand, OM, Ca, Extractable Ca)



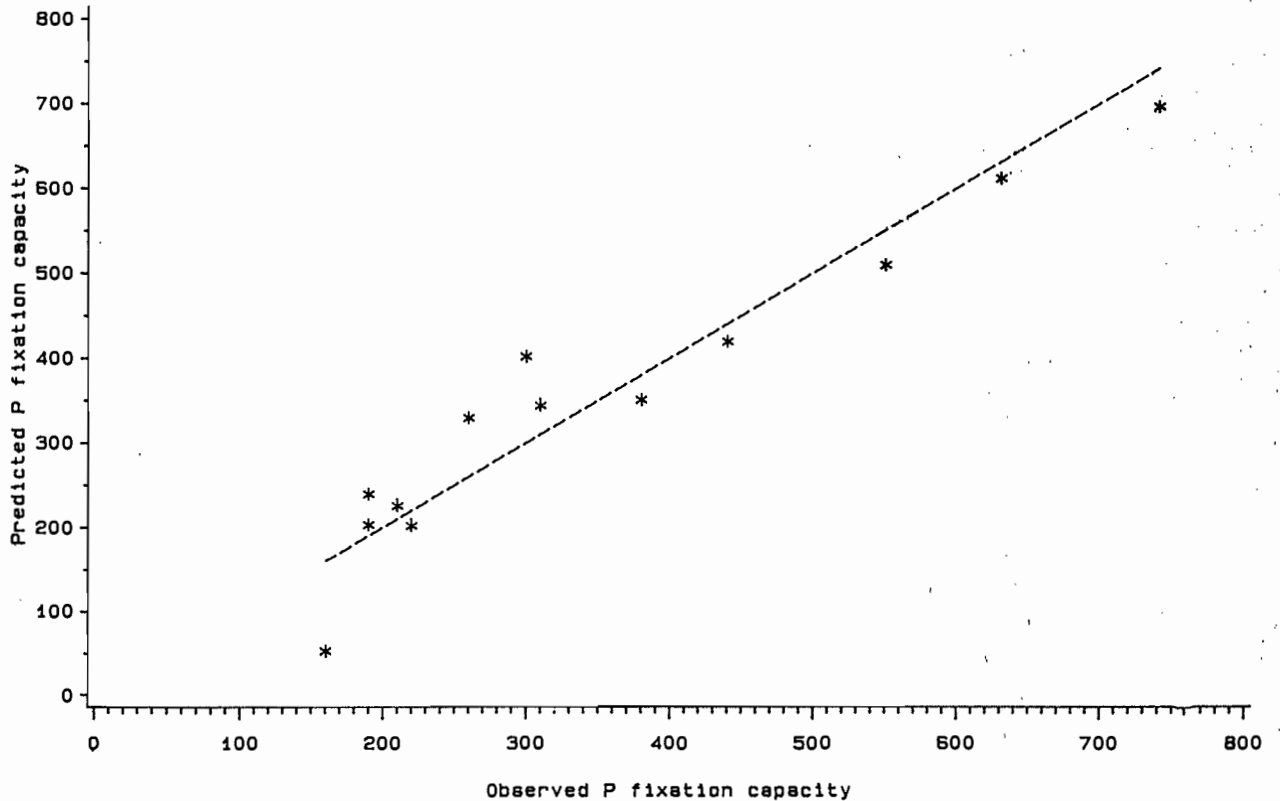
Basic Brown Earths

P fixation capacity=f (Clay, OM, Fe, Al, pH)



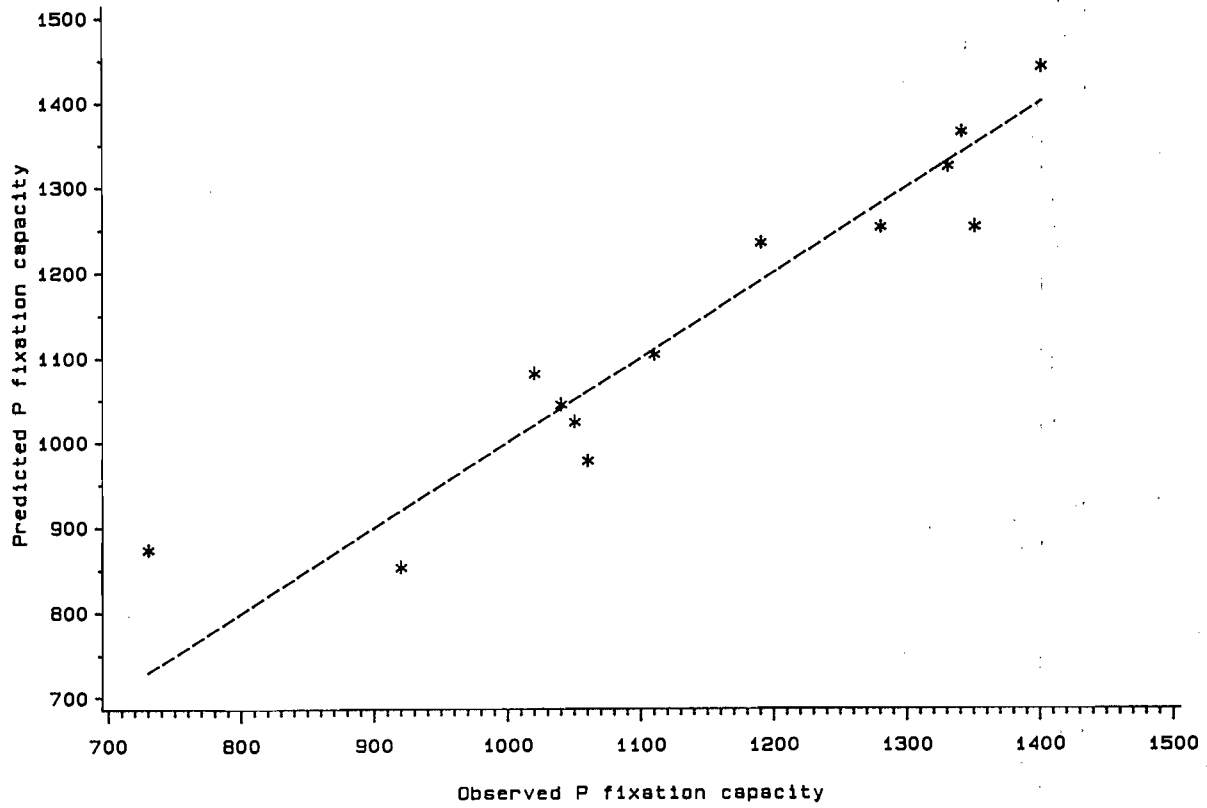
Basic Brown Earths

P fixation capacity=f (Sand, Silt, Clay, Fe, Al)



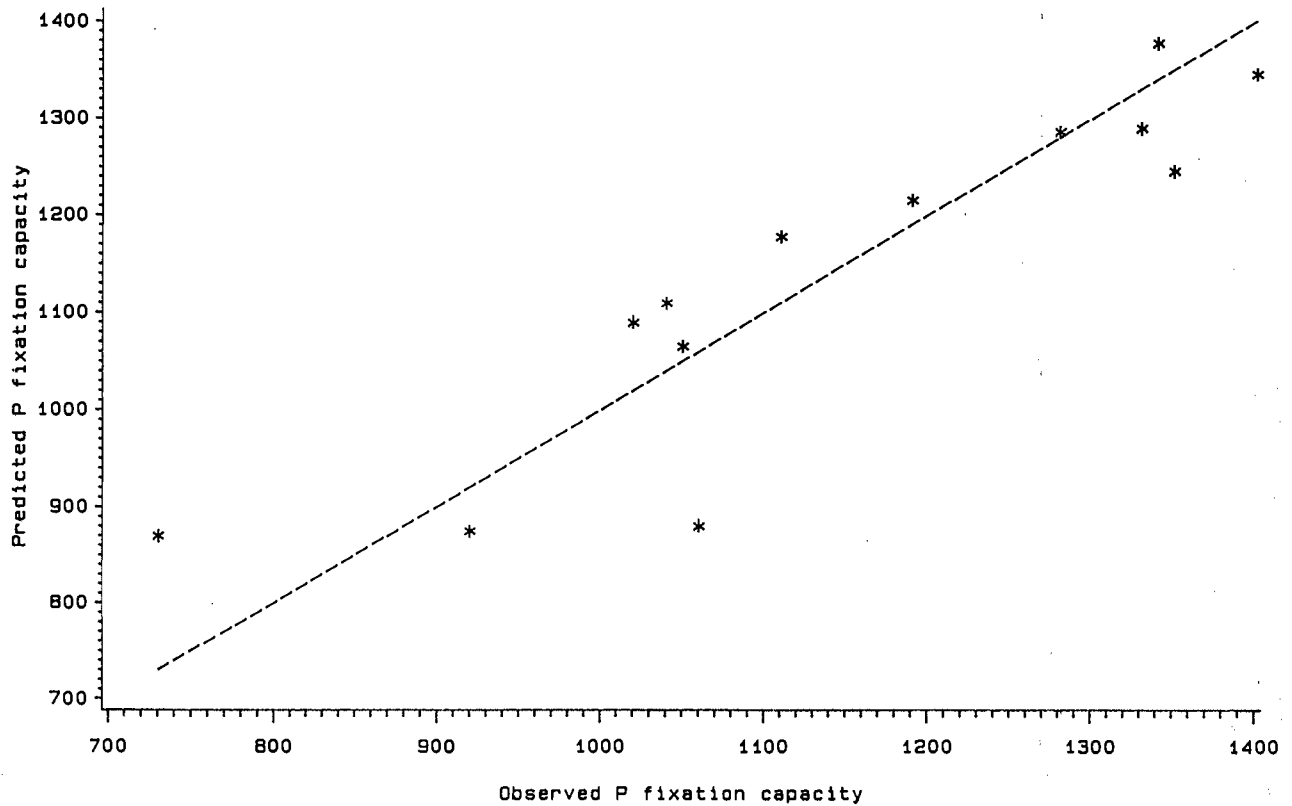
Brown Podzolic

P fixation capacity=f (Clay, OM, Fe, Al, Ca)



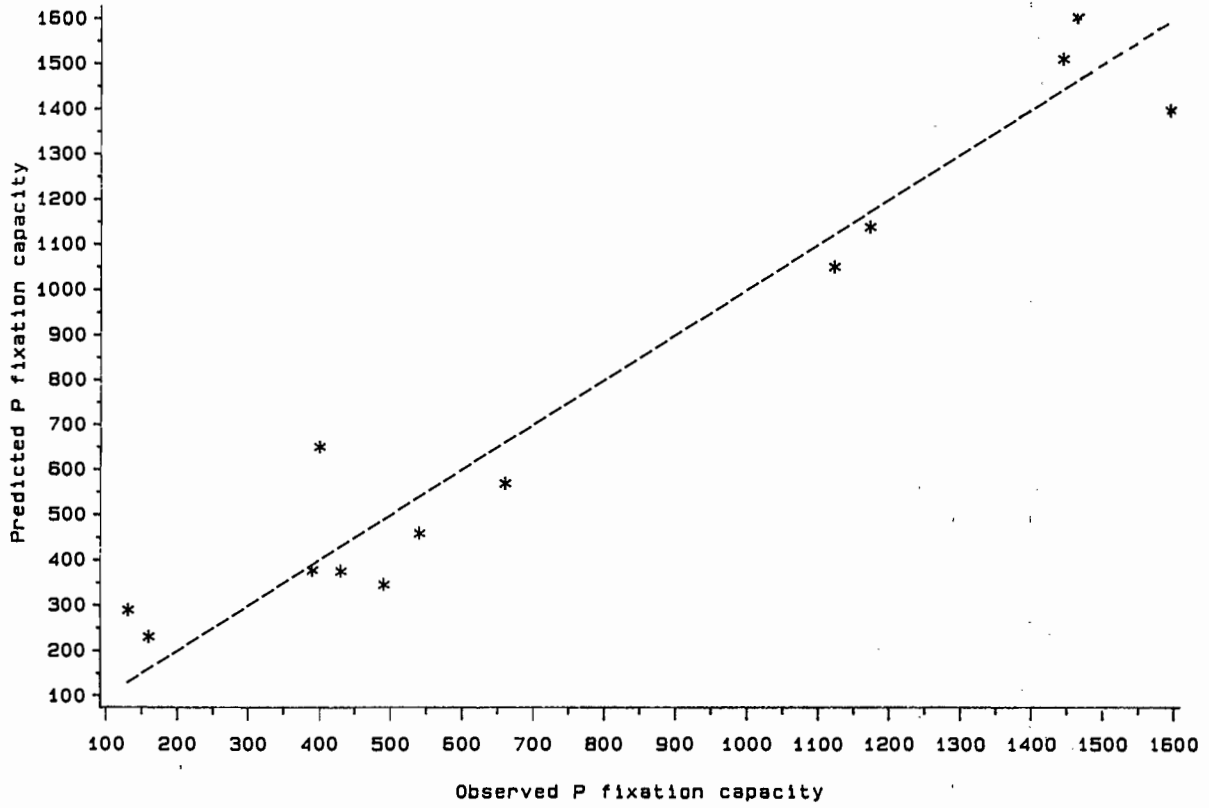
Brown Podzolic

P fixation capacity=f (Clay, OM, Fe, Al, pH)



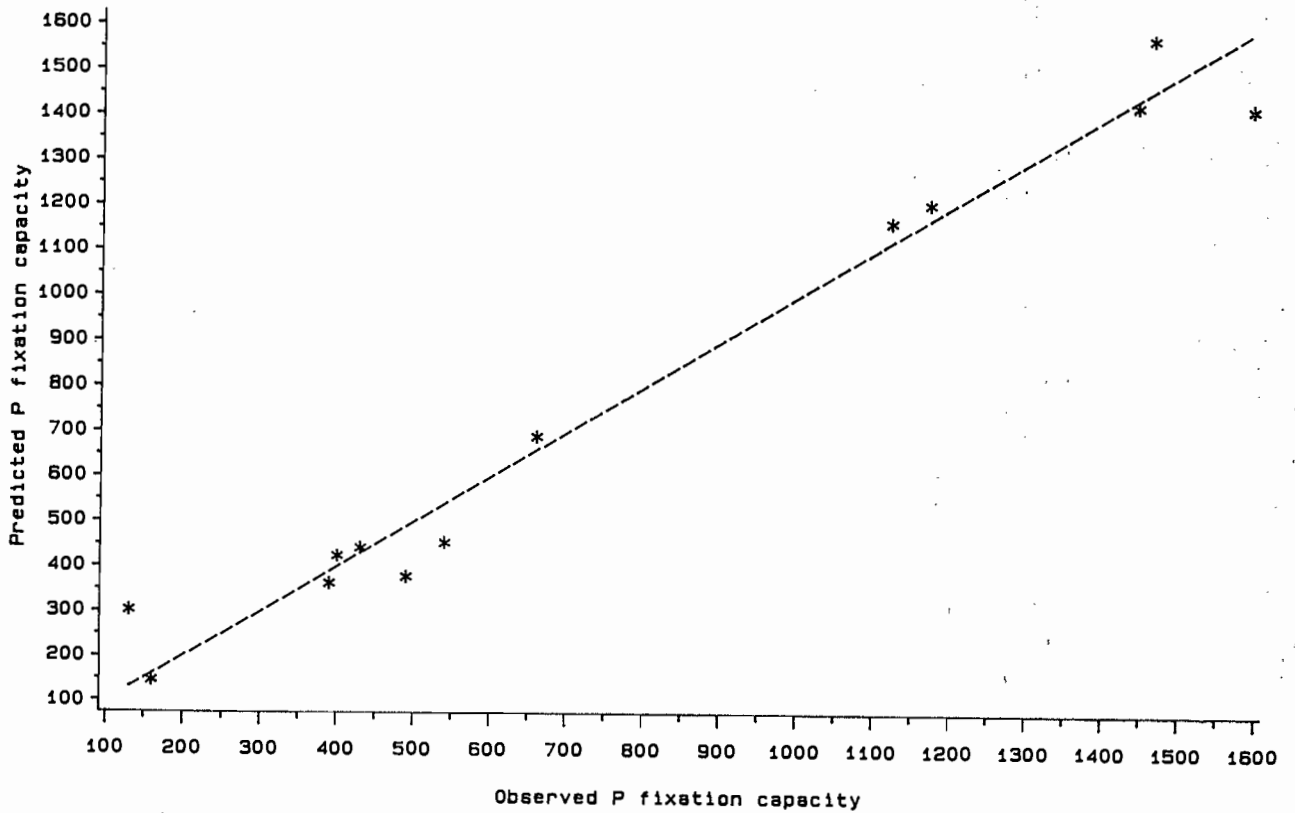
Peaty Podzol

P fixation capacity=f (Clay, OM, Fe, Al, pH)



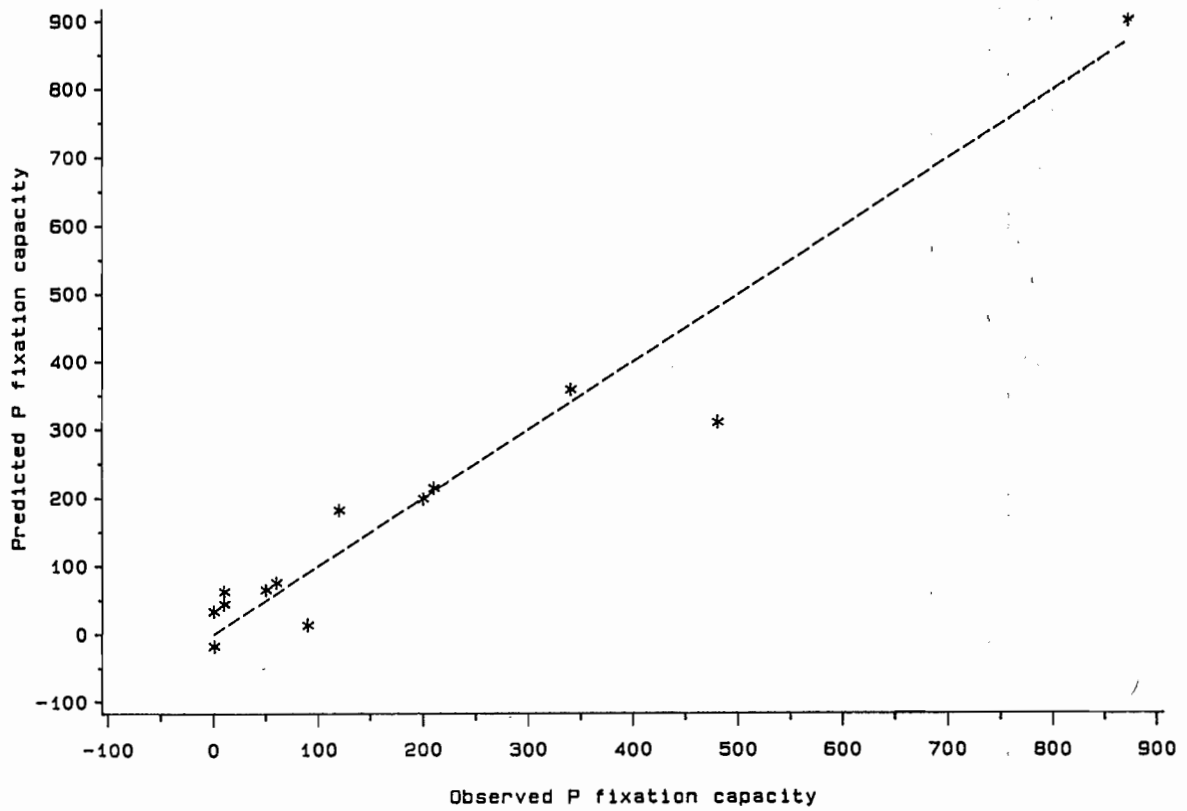
Peaty Podzol

P fixation capacity=f (Sand, OM, Fe, Al, Ca)



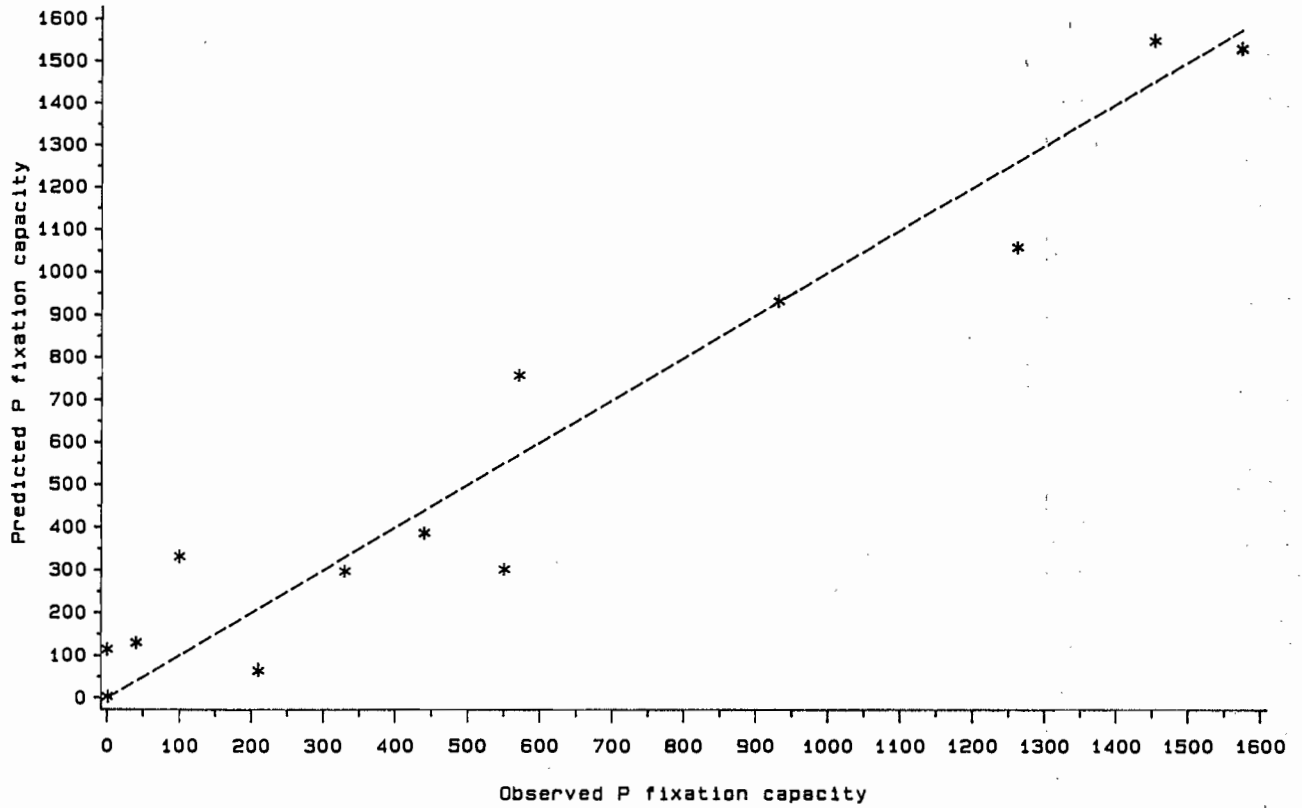
Podzol

P fixation capacity=f (Clay, OM, Fe, Al, pH)



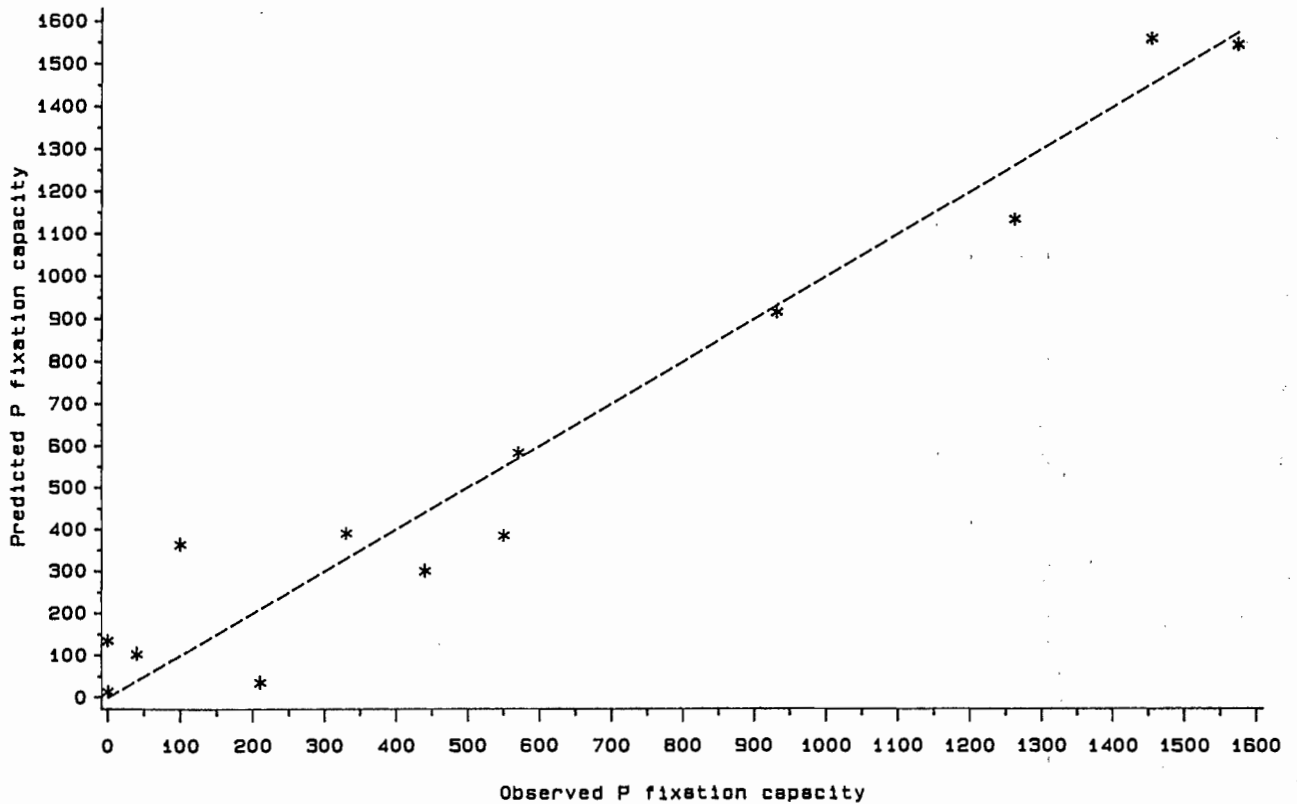
Hill Peat

P fixation capacity=f (Clay, OM, Fe, Al, pH)



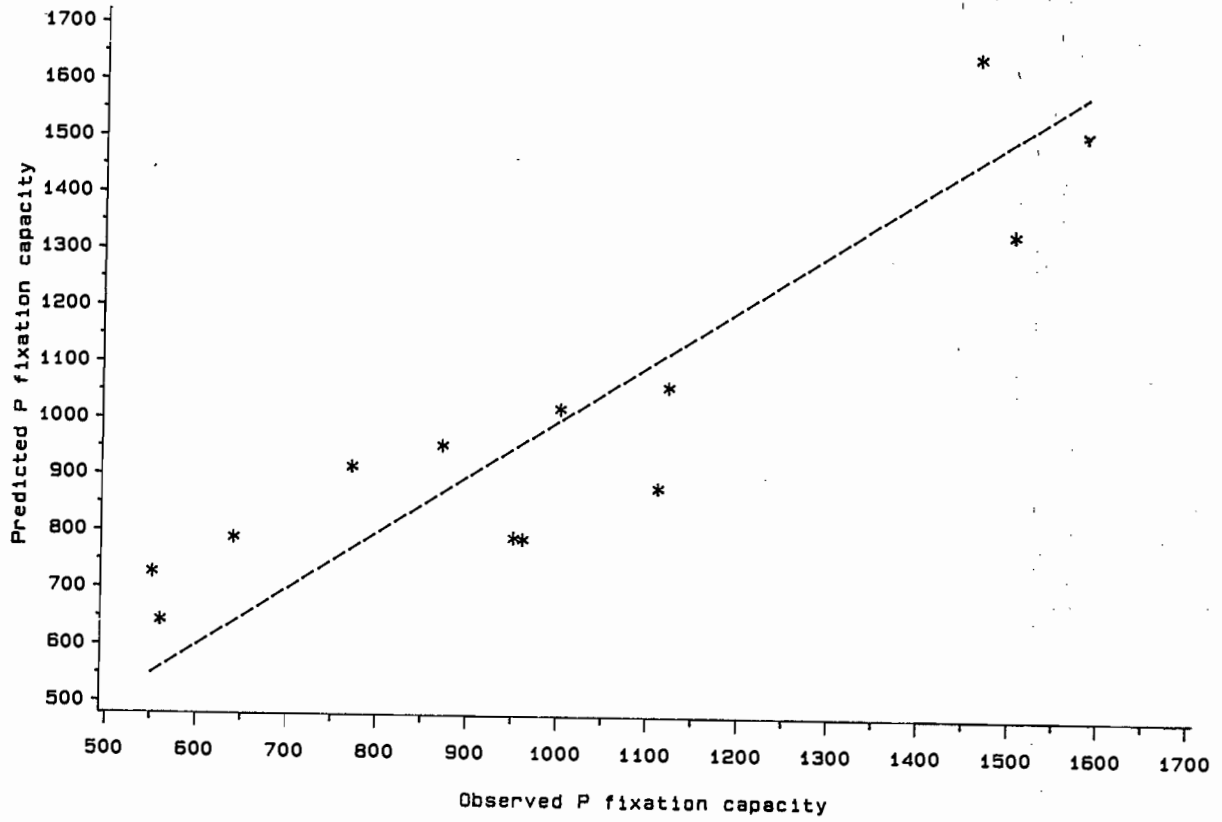
Hill Peat

P fixation capacity=f (Fe, Al, Ca, Extractable Ca, pH)



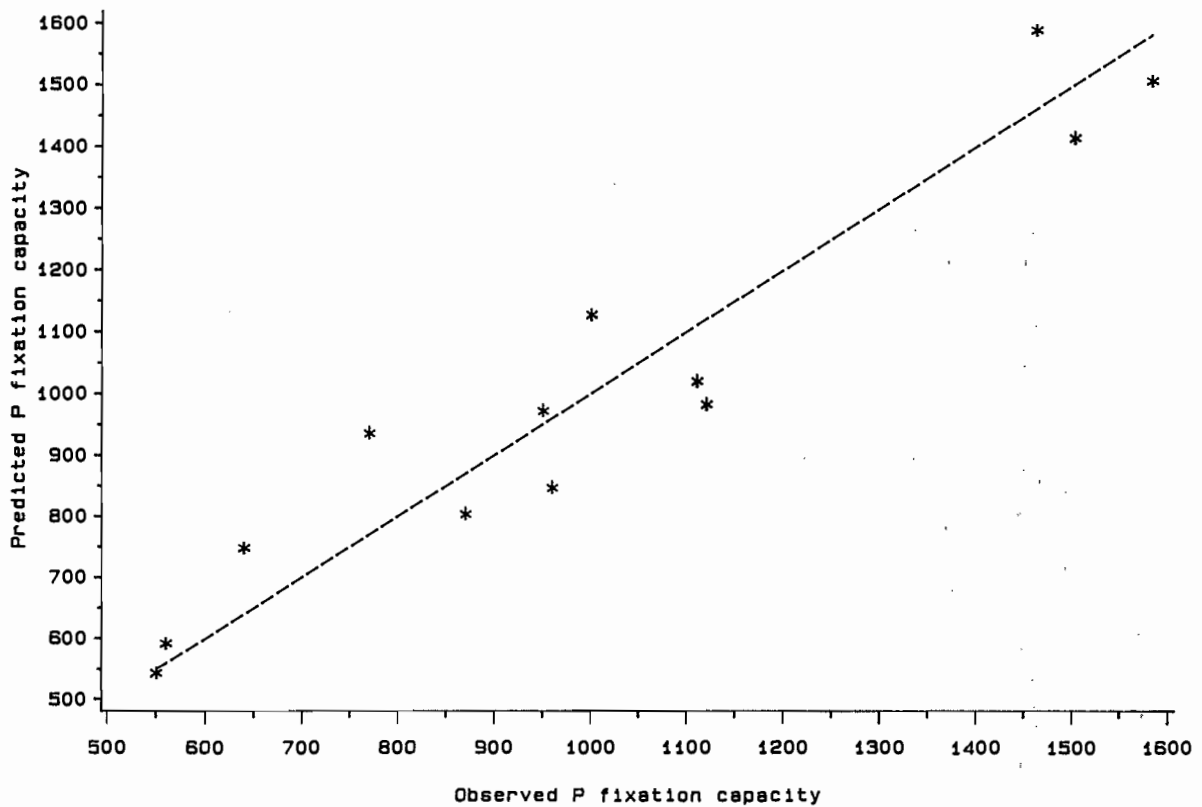
Peaty Gley

P fixation capacity=f (Clay, DM, Fe, Al, pH)



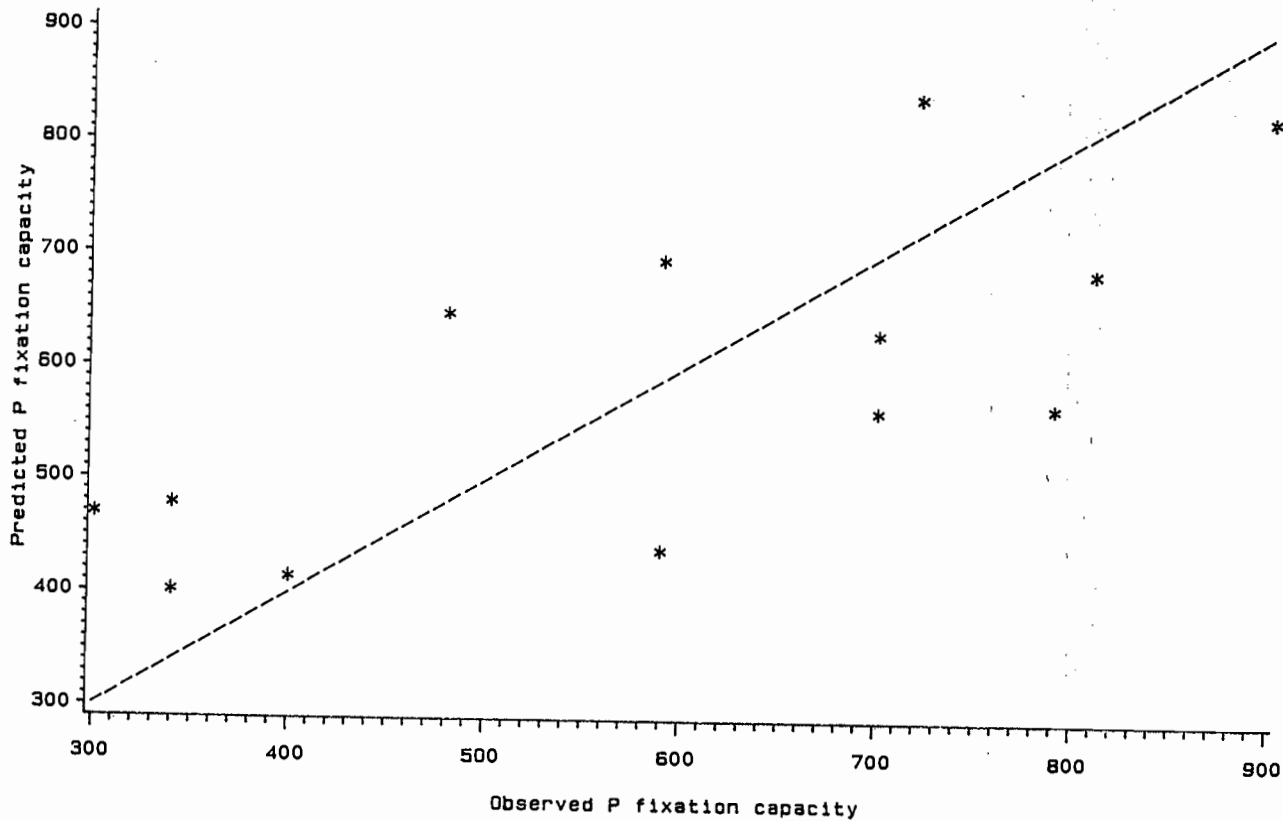
Peaty Gley

P fixation capacity=f (DM, Fe, Al, Ca, pH)



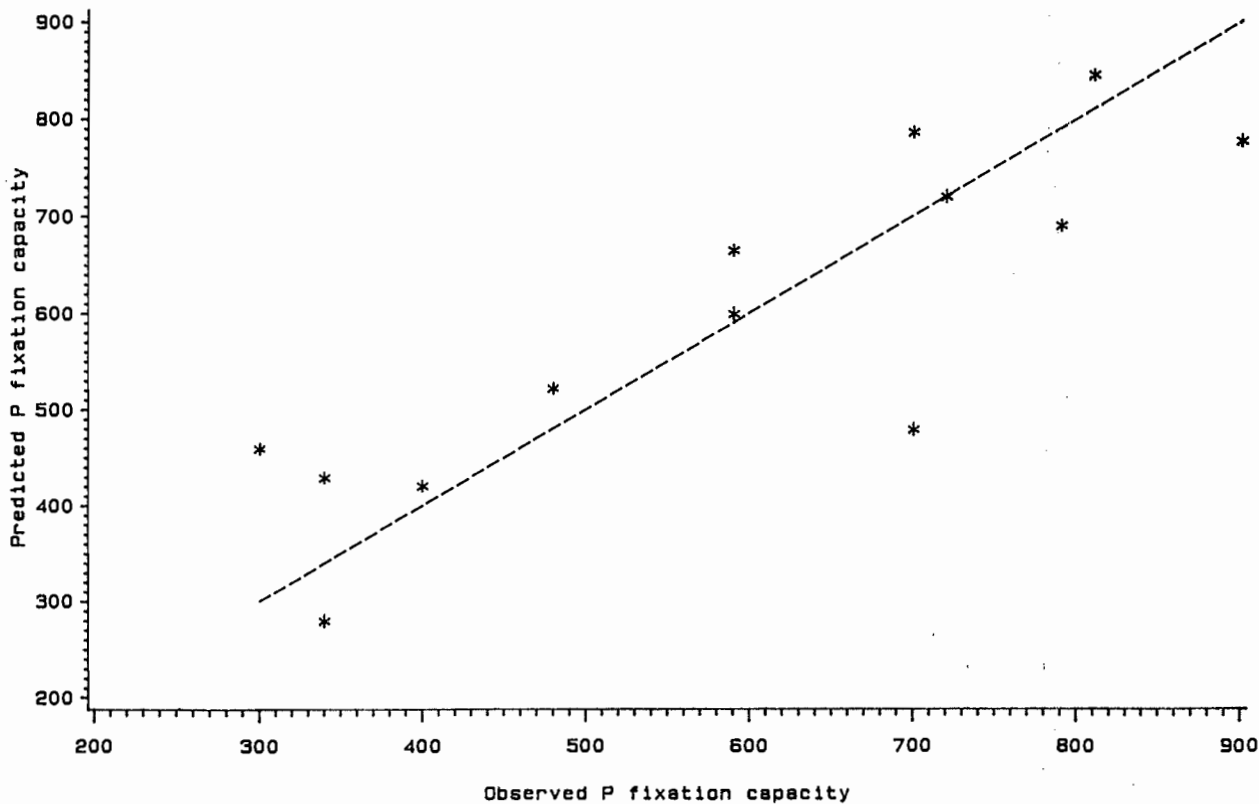
Gley

P fixation capacity=f (Clay, OM, Fe, Al, pH)



Gley

P fixation capacity=f (Clay, Sand, OM, Extractable Ca, Ca)



APPENDIX III

Removal of P from Water in Natural Wetlands

LOCATION	TYPE	INPUT (mg/l)	OUTPUT (mg/l)	% REMOVAL	REF.
Natural Carex peatland Michigan	TDP	16.8 [#]	0.9 [#]	95	Kadlec & Tilton (1979)
White Cedar swamp, Michigan	TDP	3.48	0.11	97	Kadlec & Tilton (1979)
Deep cattail marsh, Wisconsin	TP	3.43	2.97	13	Fetter <u>et al.</u> (1978)
Natural forested swamps, Central Florida	TP	6.40	0.12	98	Boyt <u>et al.</u> (1977)
Deep water marsh, Massachusetts	P04-P	2.2	0.7	68	Kadlec & Tilton (1979)
Natural carex wetland, Michigan	TDP	1.57	0.07	96	Tilton & Kadlec (1979)
Natural marsh, Florida	TP	8.88	0.20	98	Dolan <u>et al.</u> (1981)
Forested peatland, Michigan	P04-P	262 [*]	85 [*]	68	Richardson <u>et al.</u> (1978)
Deep cattail marsh, Wisconsin	P04-P	3.75	1.21	68	Spangler <u>et al.</u> (1976)
Natural marshes, Wisconsin	TP			0	Lee <u>et al.</u> (1975)
Sedge meadow, NW Territory, Canada	TP	4.73	0.4	93	Hartland-Rowe & Wright (197)
Reed swamp, Hungary	TP	4.5	0.08	98	Toth (1972)
Rush pond, Holland	TP			93	de Jong (1976)
Salt marsh, Massachusetts	TP			91	Valiela <u>et al.</u> (1976)

= kg ; * = kg ha⁻¹

TDP = Total dissolved phosphorus; TP = Total phosphorus;
P04-P = Ortho-phosphate phosphorus