Report

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INSTITUTE OF TERRESTRIAL ECOLOGY

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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.

A F HARRISON, D M HOWARD & G J LAWSON

Merlewood Research Station,
Grange-over-sands,
Cumbria, LA11 6JU.

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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-PO4-P (mg $l^{-1}$) | | | |
| Gravesend bed 1 | 2.5mm gravel | 14.0 | 7.0 | 50 | Cooper et al (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) % removal calculate on basis of flows |
| Hjordkaer | washed gravel | 13.3 | 11.5 | 11 | |
| Ingstrup | coarse sandy loam | 48 | 4.2 | 83 | |
| Rugballegard | 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 | |
| Bredballegard | 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 predition 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 $20^0C$ 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 $105^0C$ 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.

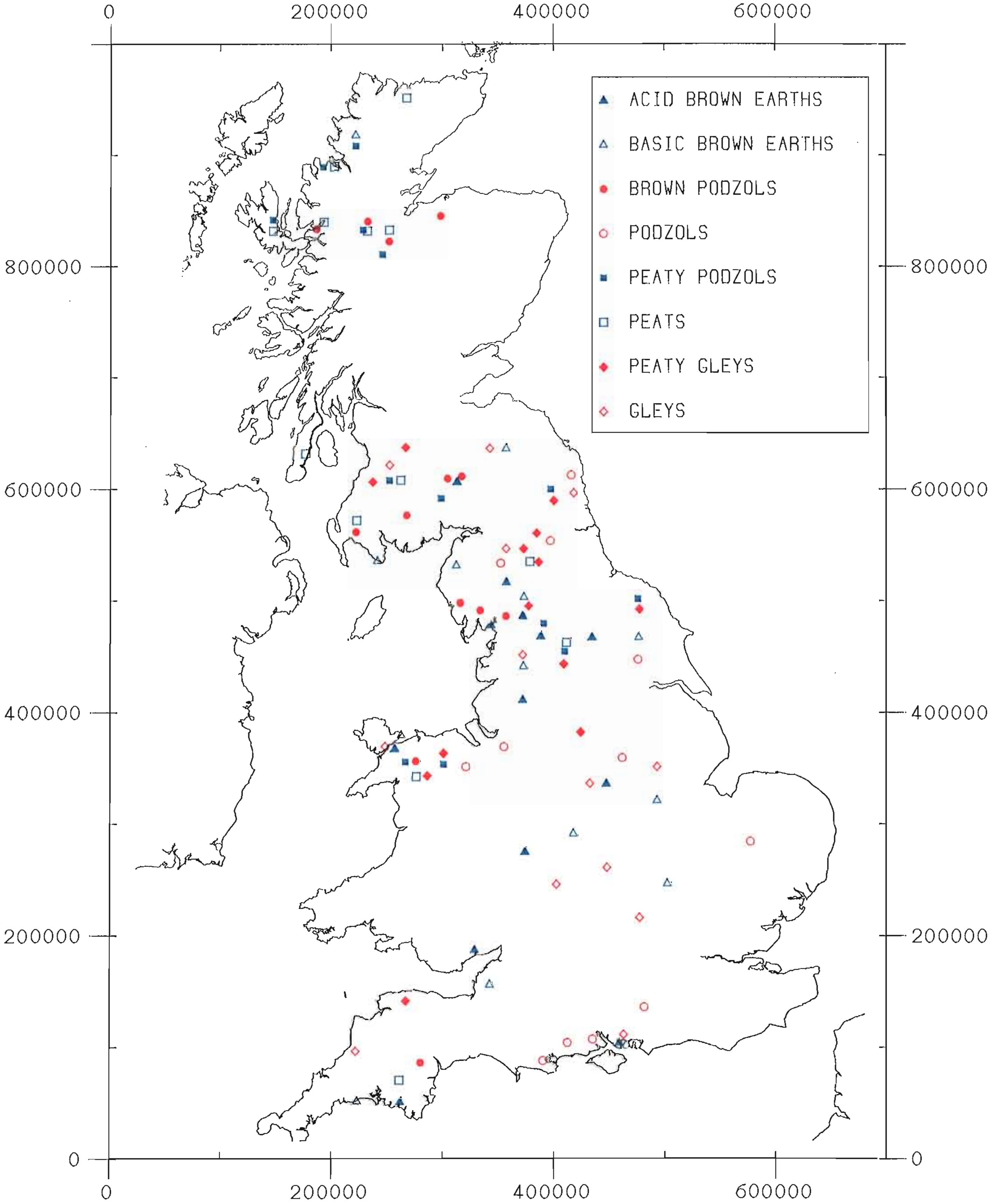

FIGURE 2. DISTRIBUTION OF SITES FROM WHICH SOILS WERE SAMPLED

### 3.5 Organic matter

Organic matter was determined by loss-on-ignition of oven-dried soil at 550°C for 2 hr (Allen <u>et al</u>, 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.

| Acid brown earths | 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 |

| Basic brown earths | 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 |

| Brown podzolics | 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.

| Podzols | 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 |

| Peaty podzols | 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 |

| Peats | 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.

| Peaty gleys | 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 |

| Gleys | 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 properies 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<br>a) Clay, OM, Al, Fe & pH | <br>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<br>Clay | <br>OM | <br>Al | <br>Fe | <br>pH | Constant |
|---|---|---|---|---|---|---|
| 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 | | | | | |
|---|---|---|---|---|---|---|
| Acid brown earth | Clay | Sand | OM | Ca | ext. Ca | Constant |
| | -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 the 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 mg P $100g^{-1}$ soil and C is 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 <u>et al</u>, 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 (AlPO4), strengite (FePO4), vivianite (Fe3(PO4)2.8H2O) and apatite (Ca10(PO4)6X2).

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 fell 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 effciency 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.

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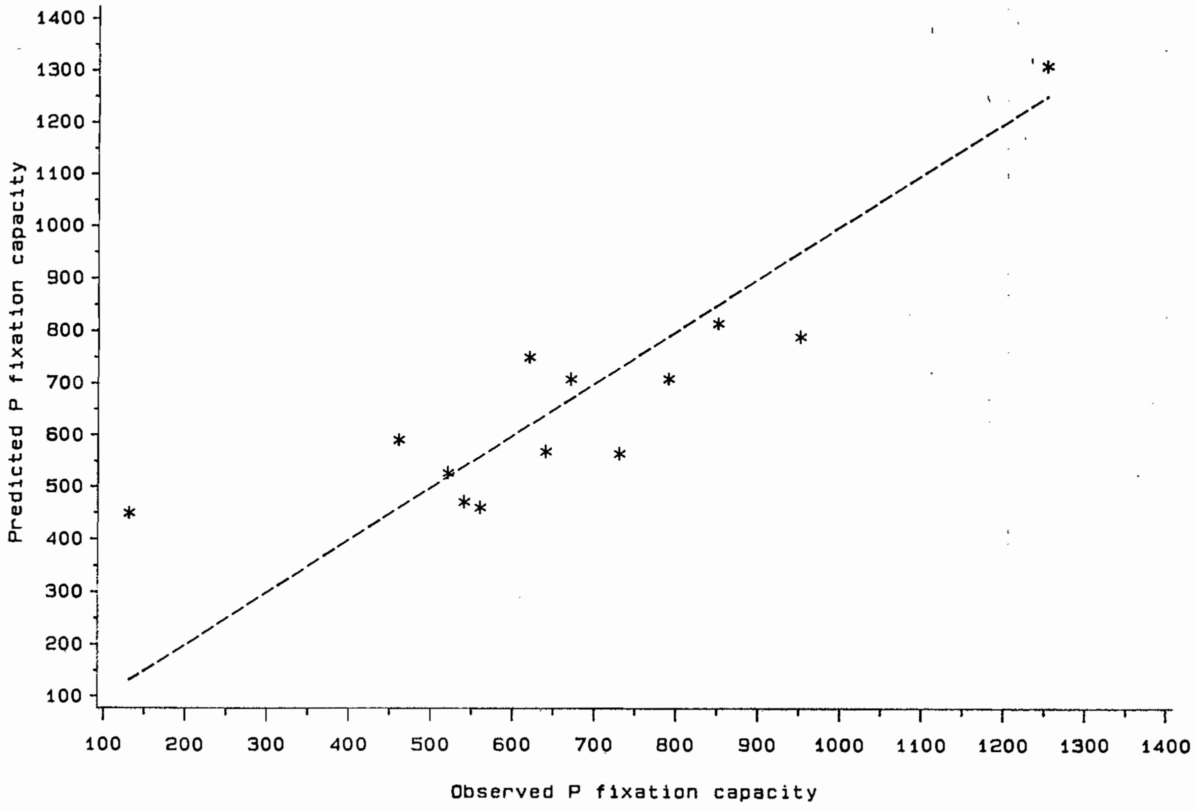
* from the multiple regressions presented in Tables 6 & 7.

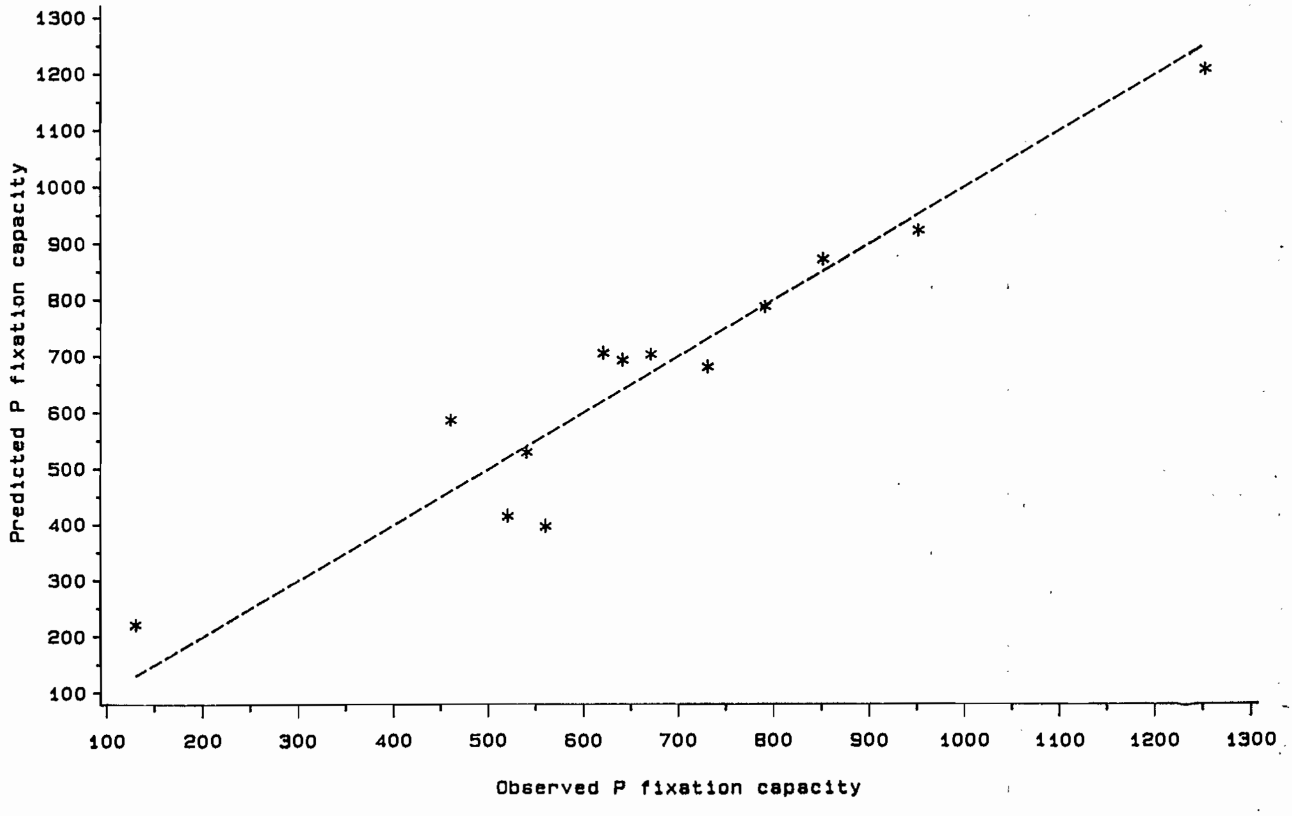
## Acid Brown Earths

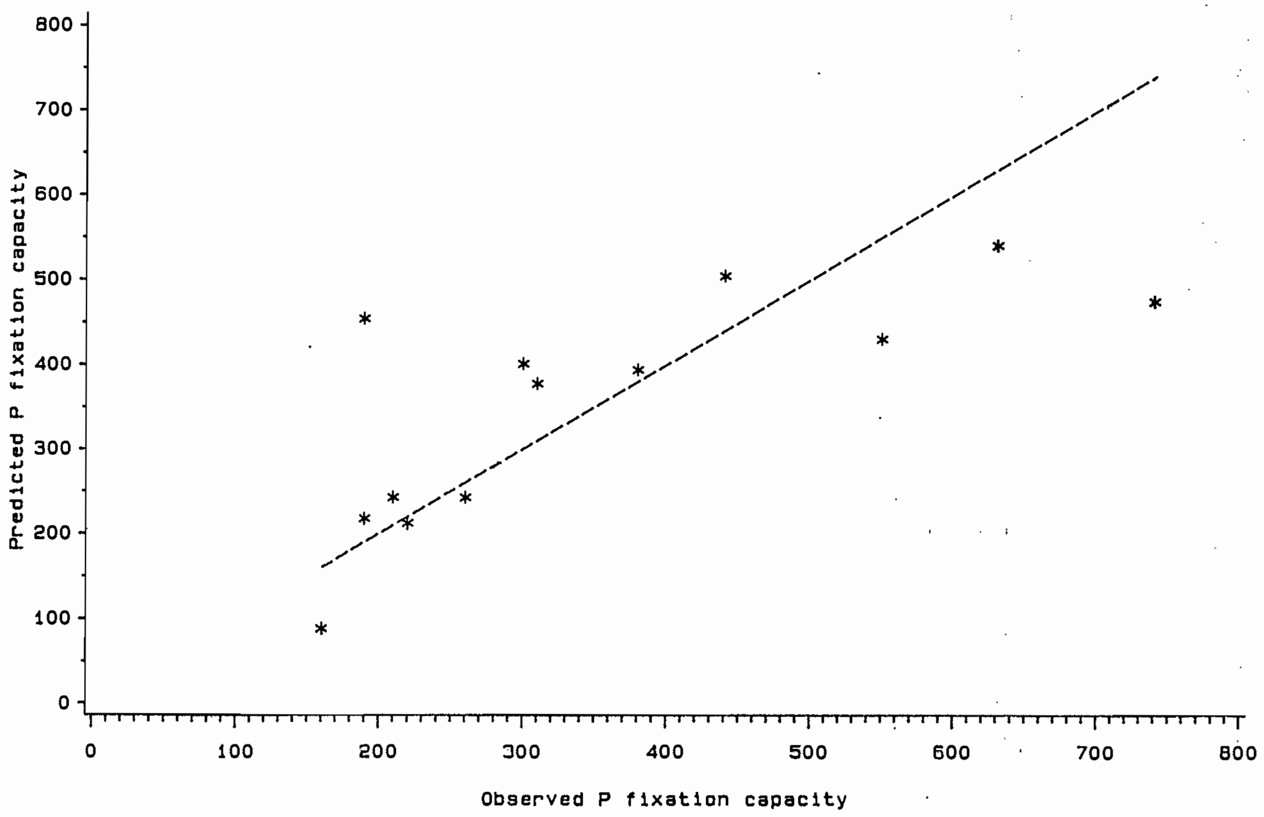
P fixation capacity=f (Clay, OM, Fe, Al, pH)



## Acid Brown Earths

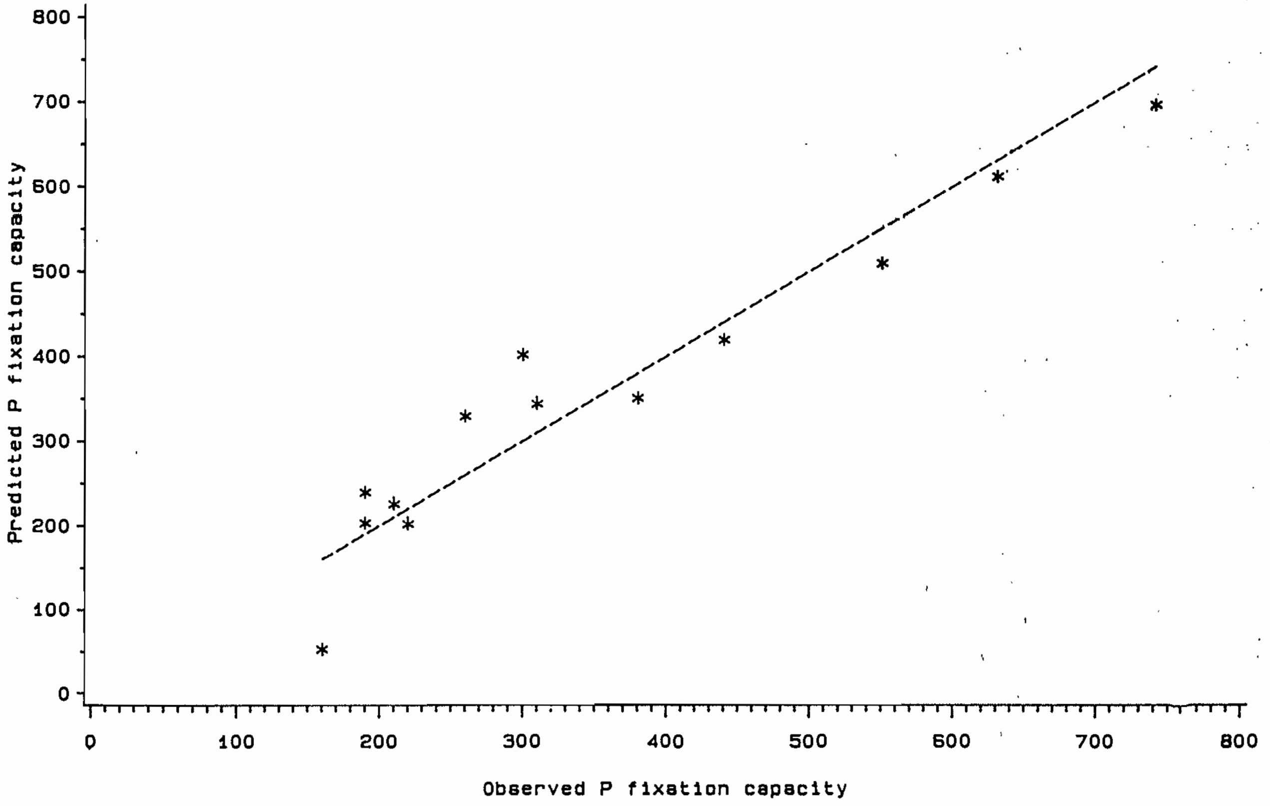
P fixation capacity=f (Clay, Sand, OM, Ca, Extractable Ca )





Basic Brown Earths

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

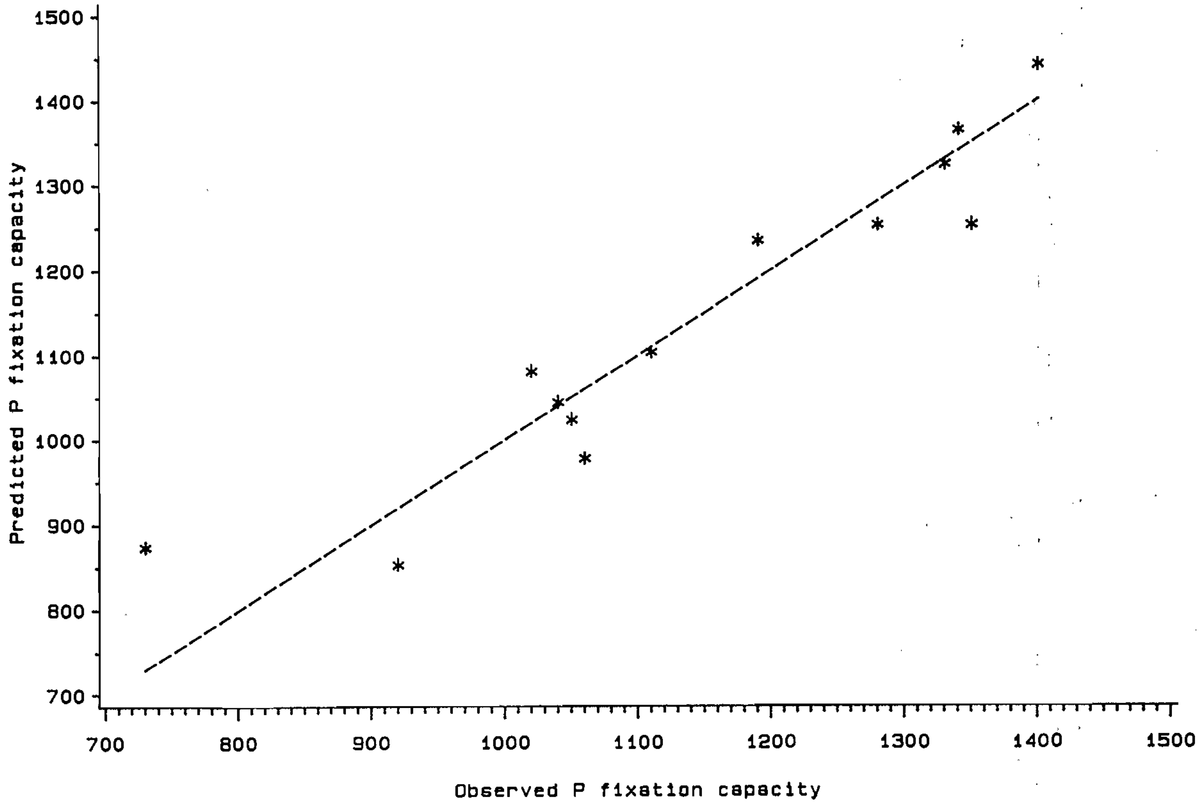


Basic Brown Earths

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

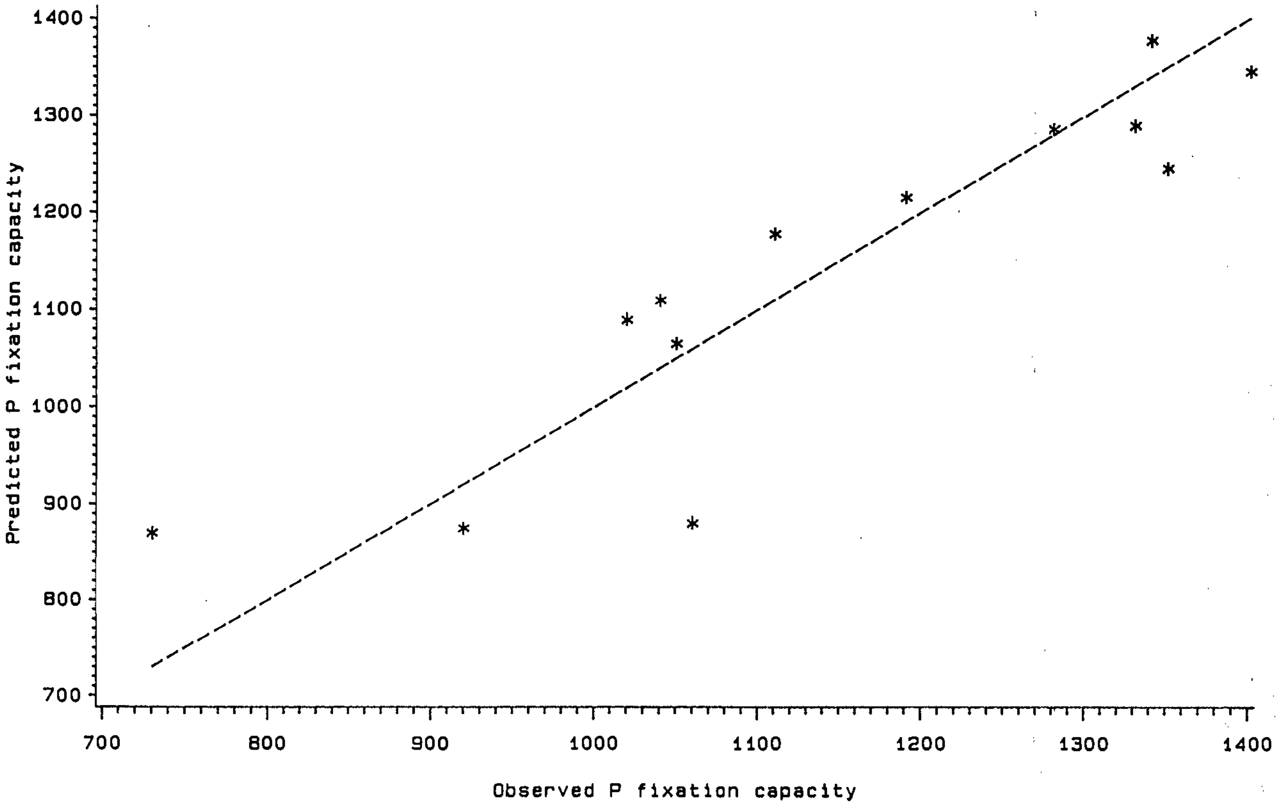
## Brown Podzolic

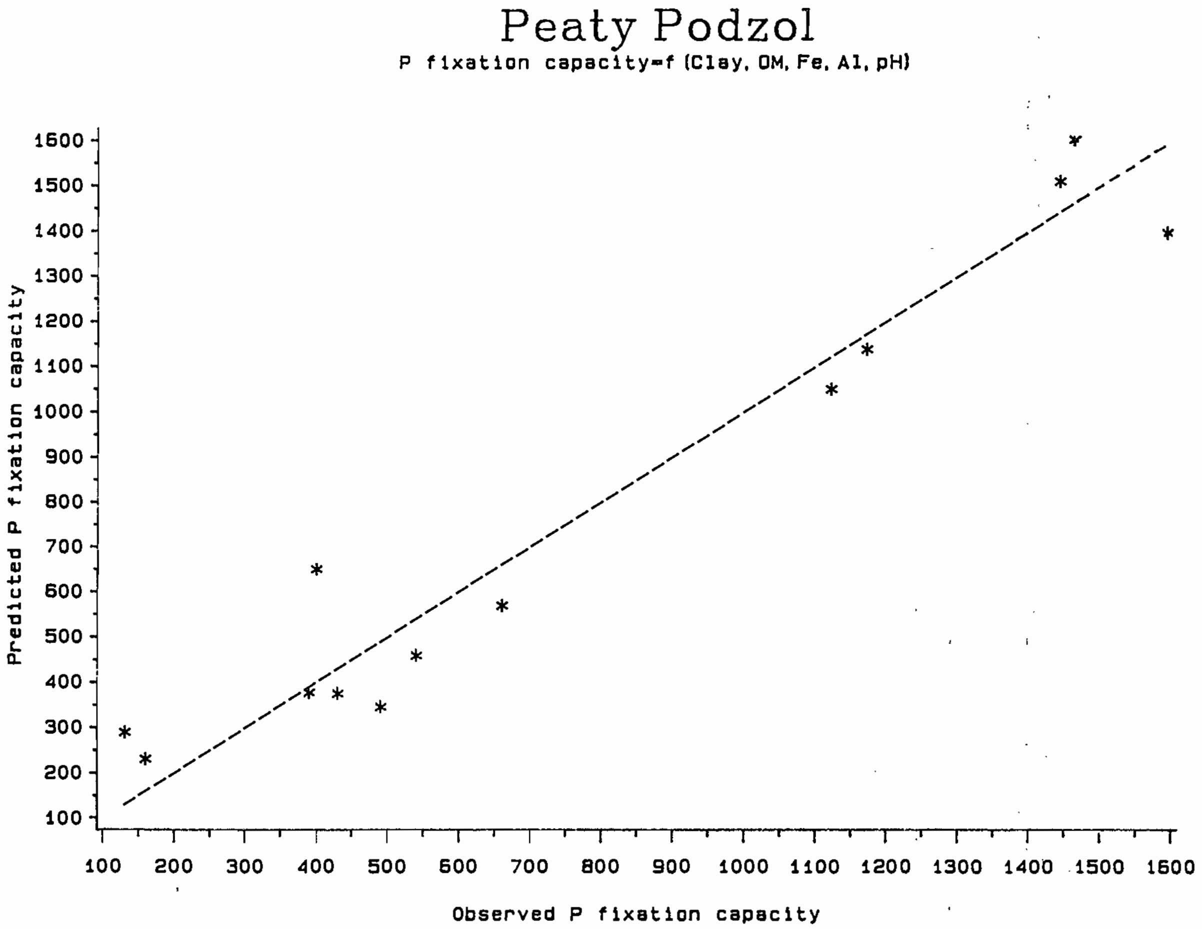
P fixation capacity=f (Clay, OM, Fe, Al, Ca)



## Brown Podzolic

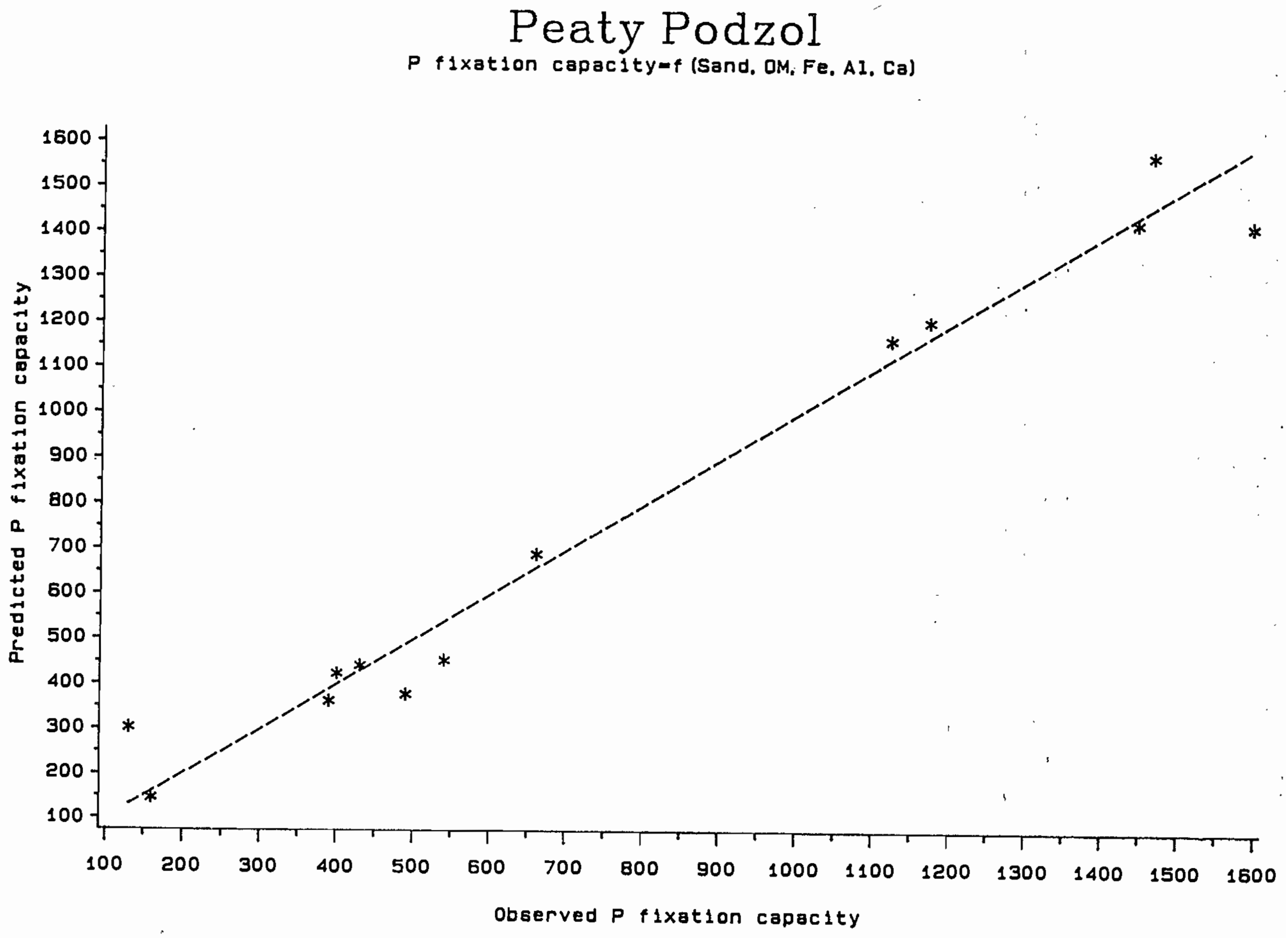
P fixation capacity=f (Clay, OM, Fe, Al, pH)





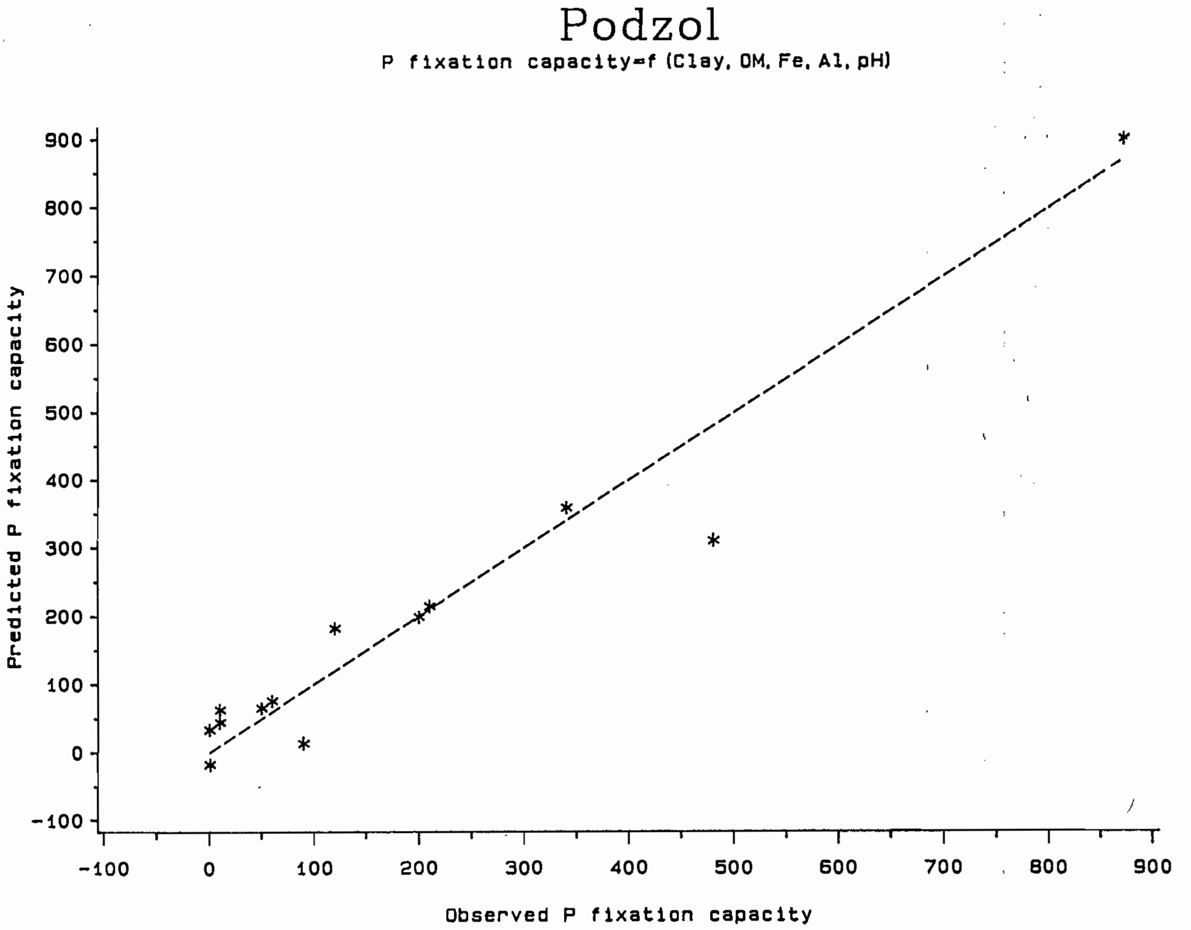
Peaty Podzol

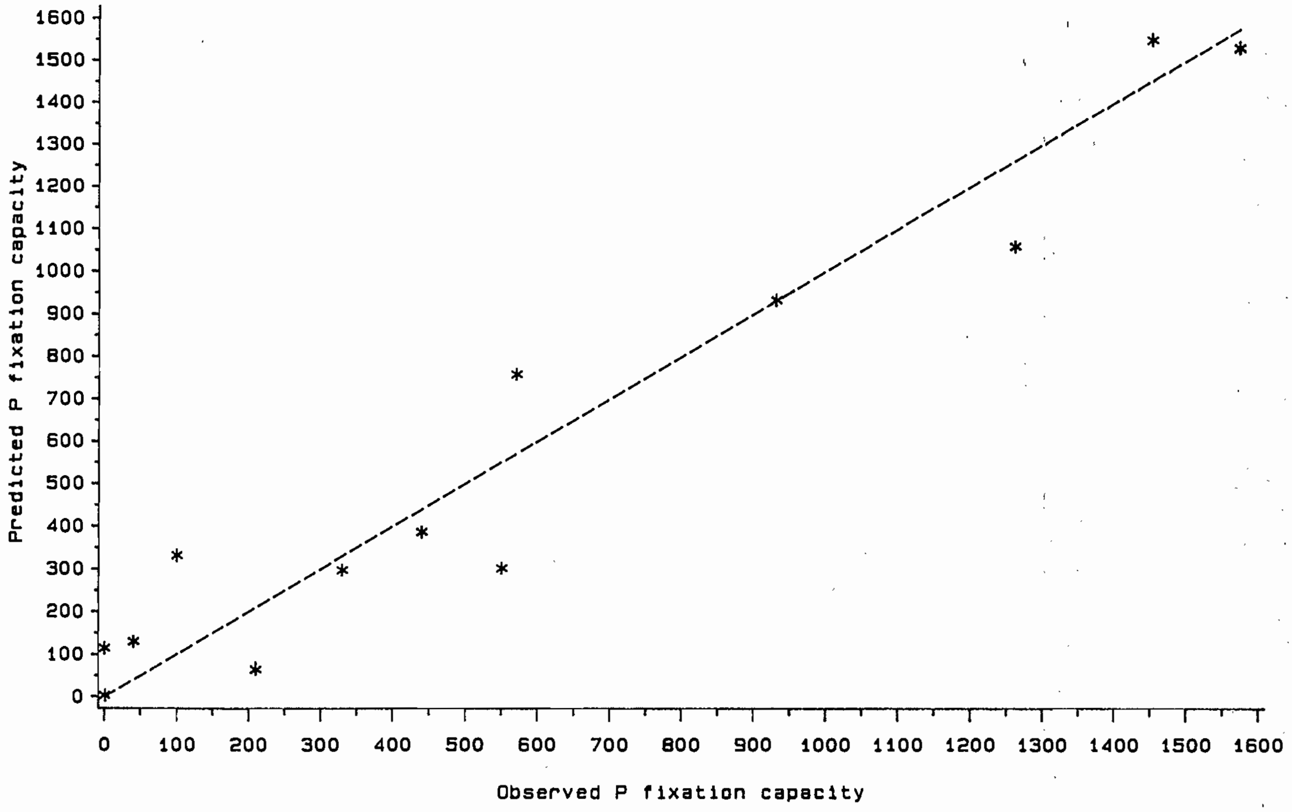
P fixation capacity=f (Clay, OM, Fe, Al, pH)



Peaty Podzol

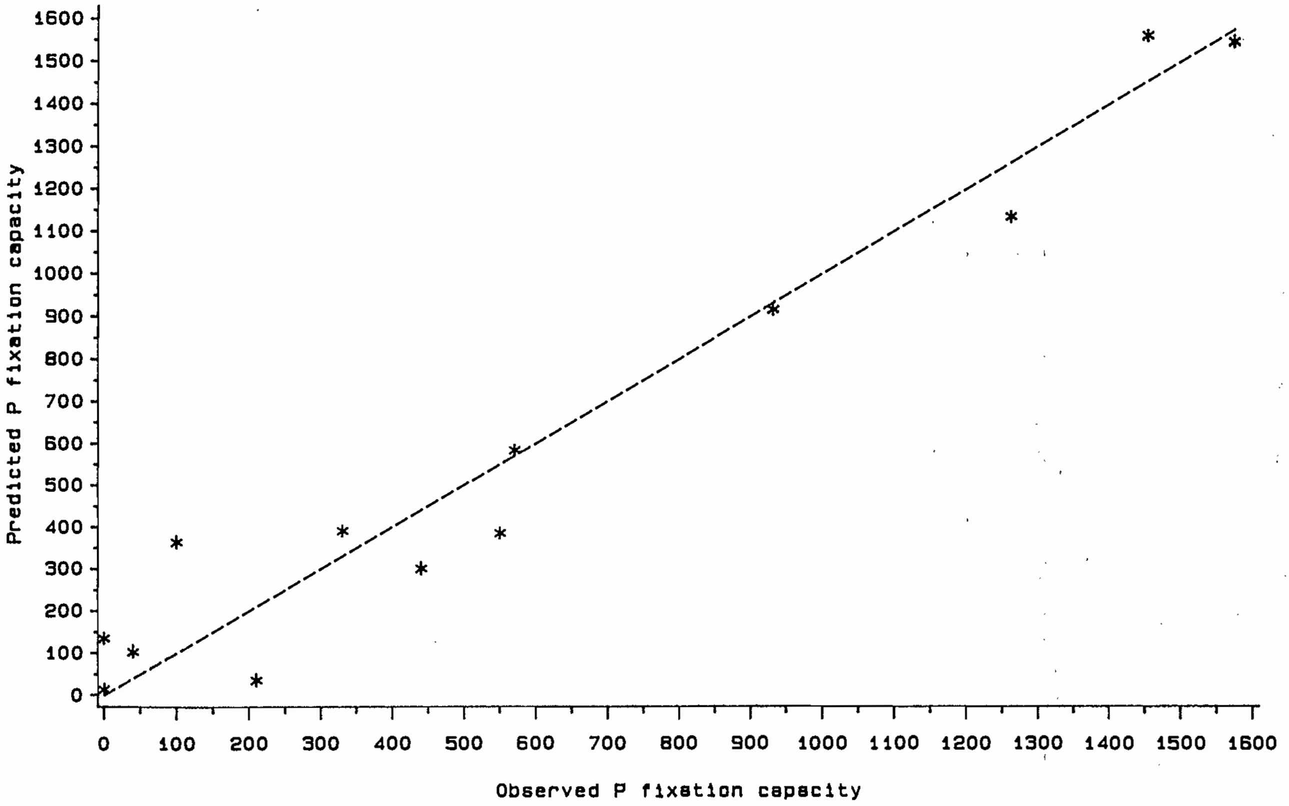
P fixation capacity=f (Sand, OM, Fe, Al, Ca)


Podzol
P fixation capacity=f (Clay, OM, Fe, Al, pH)
Predicted P fixation capacity
900
800
700
600
500
400
300
200
100
0
-100
-100
0
100
200
300
400
500
600
700
800
900
Observed P fixation capacity



Hill Peat

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

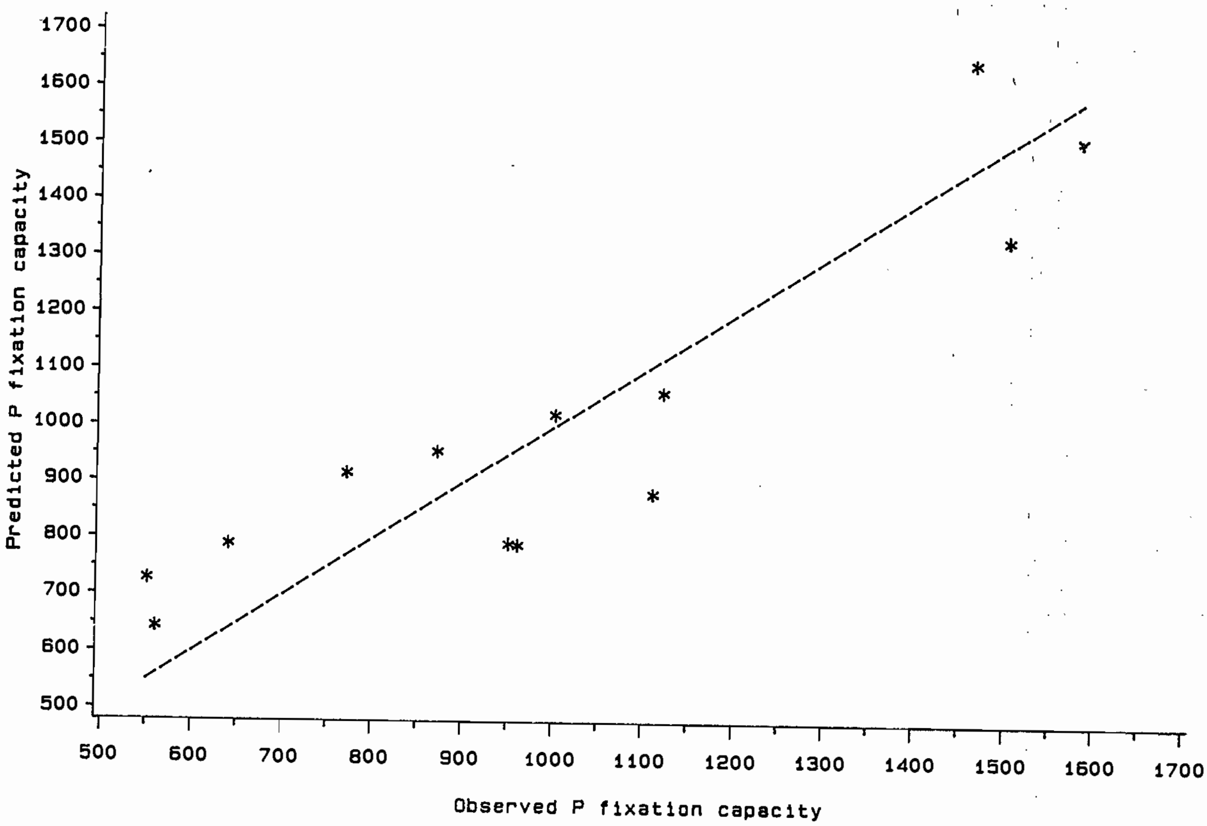


Hill Peat

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

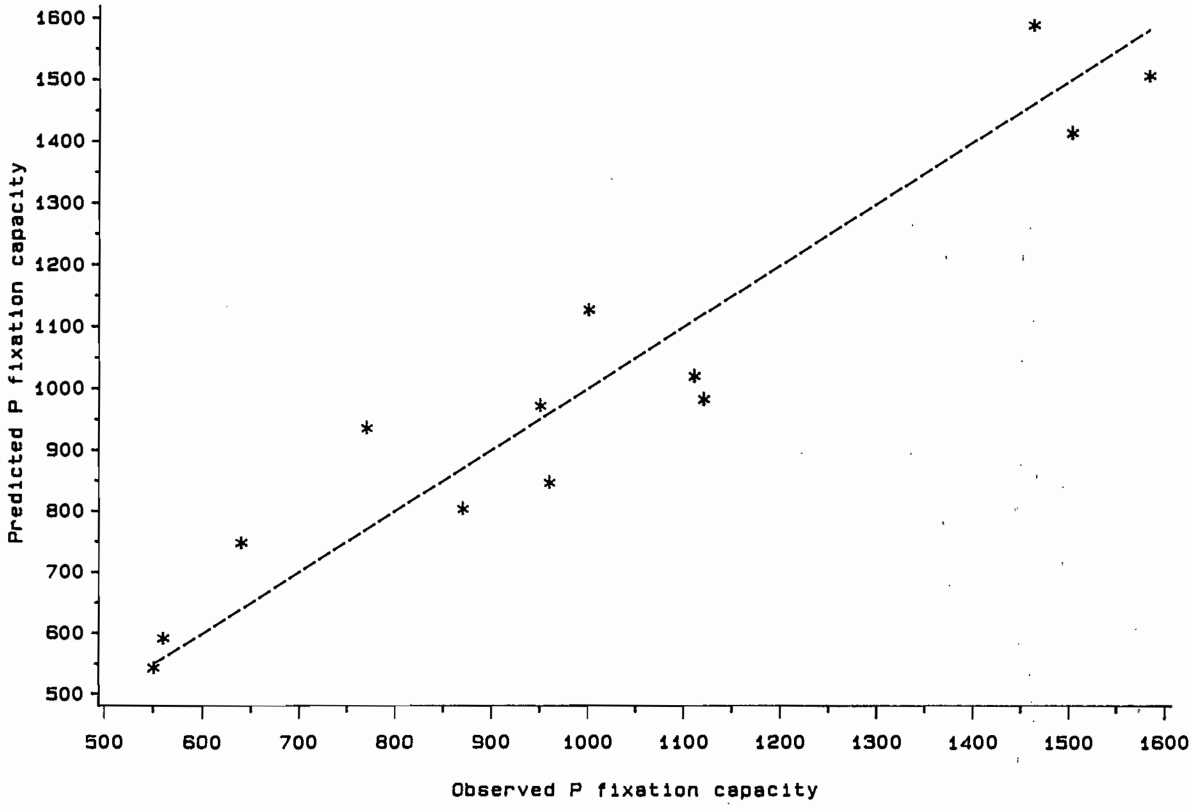
## Peaty Gley

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



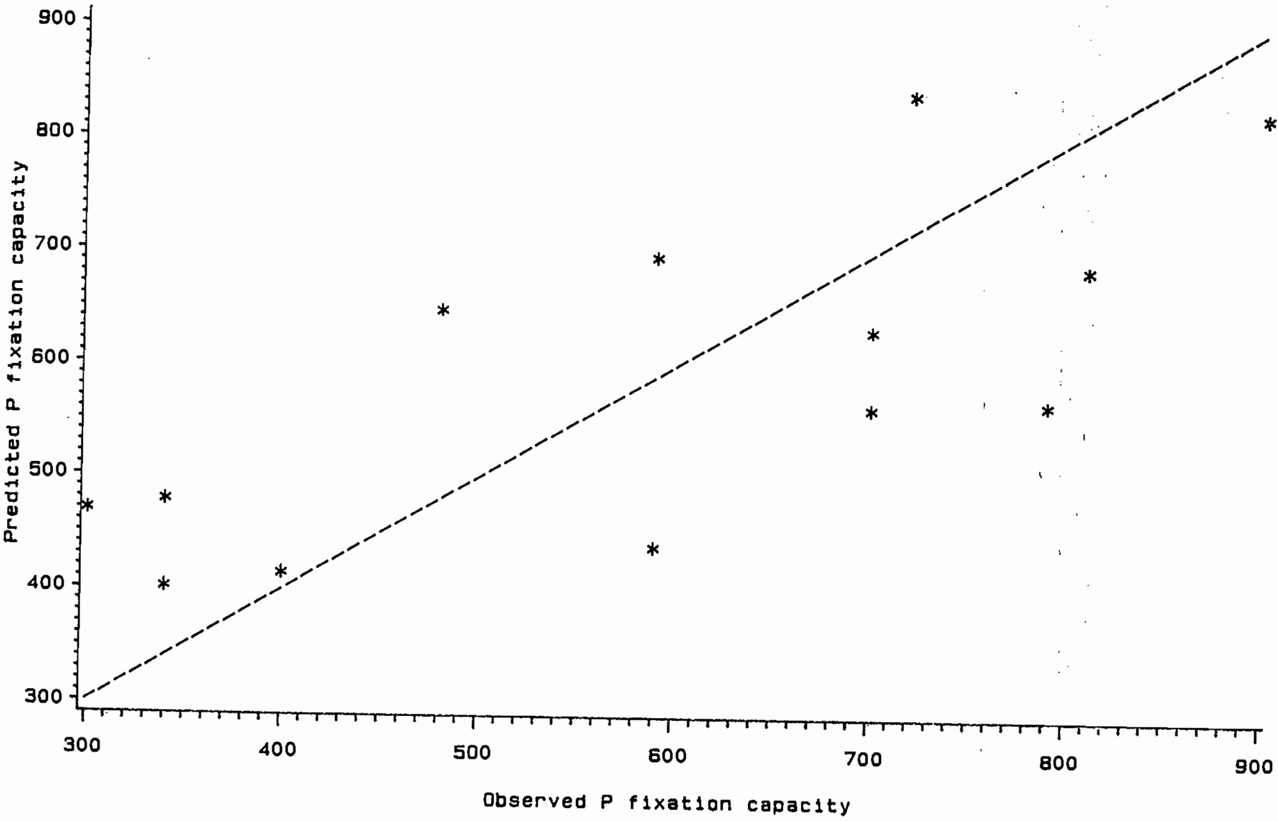
## Peaty Gley

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



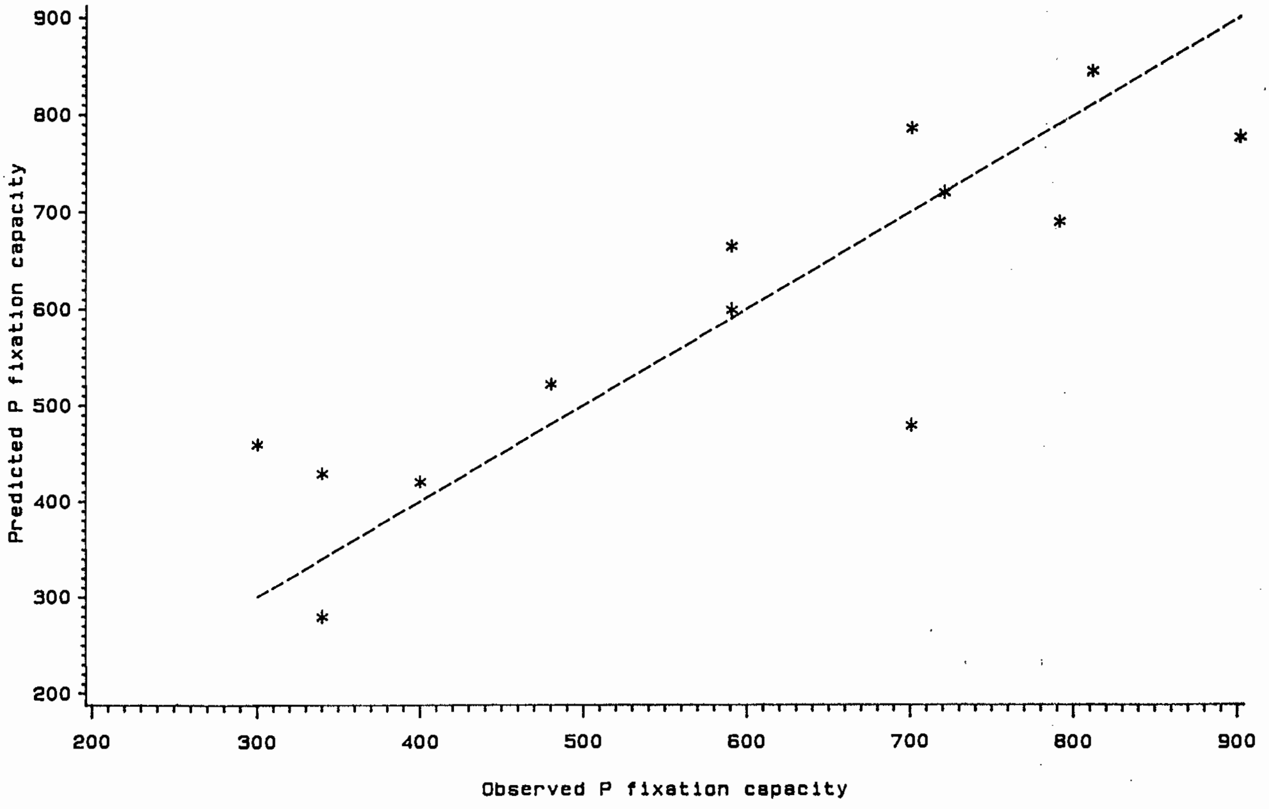
## Gley

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 Michegan | TDP | $16.8^{\#}$ | $0.9^{\#}$ | 95 | Kadlec & Tilton (1979) |
| White Cedar swamp, Michegan | TDP | 3.48 | 0.11 | 97 | Kadlec & Tilton (1979) |
| Deep cattail marsh, Wisconsin | TP | 3.43 | 2.97 | 13 | Fetter et al. (1978) |
| Natural forested swamps, Central Florida | TP | 6.40 | 0.12 | 98 | Boyt et al. (1977) |
| Deep water marsh, Massachusetts | P04-P | 2.2 | 0.7 | 68 | Kadlec & Tilton (1979) |
| Natural carex wetland, Michegan | TDP | 1.57 | 0.07 | 96 | Tilton & Kadlec (1979) |
| Natural marsh, Florida | TP | 8.88 | 0.20 | 98 | Dolan et al. (1981) |
| Forested peatland, Michegan | P04-P | $262^{*}$ | $85^{*}$ | 68 | Richardson et al.(1978) |
| Deep cattail marsh, Wisconsin | P04-P | 3.75 | 1.21 | 68 | Spangler et al.(1976) |
| Natural marshes, Wisconsin | TP |  |  | 0 | Lee et al.(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 et al  (1976) |

$^{\#}$ = kg ; $^{*}$ = kg ha$^{-1}$

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