

YEAR 1

**THE FATE AND TRANSPORT OF INORGANIC
CONTAMINANTS IN NEW JERSEY SOILS**

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Final Report

by

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ABSTRACT

A major problem in the remediation of contaminated sites is frequently the lack of appropriate standards for chemicals in soils. While a few standards exist for organic and inorganic materials for such exposure routes as direct ingestion of soil, there are no standards applicable to the prediction of the potential for groundwater contamination by inorganic materials. Lack of standards can result in subjective judgments regarding the extent of remediation needed. The migration of inorganic materials through the unsaturated zone to groundwater is controlled by sorption to the soil, a highly pH-dependent process, and the hydrological regime. Soil sorption behavior is the criterion upon which to establish a standard based on a maximum permissible concentration in groundwater. The maximum level of metal in soil for which the equilibrium soluble metal does not exceed the drinking water standard has been computed from the measured partition coefficients for Pb(II) and Cd(II) as a function of pH and metal concentration for five New Jersey soils.

INTRODUCTION

The aqueous concentration of an inorganic contaminant in contact with a soil can be predicted from appropriate thermodynamic measurements. At high concentrations, cationic metals will form insoluble hydroxide, carbonate, or sulfide precipitates (Stumm and Morgan 1981; Evans 1989; Sposito 1989). Their solubility can be easily calculated even in situations where the solution may contain complexing agents which result in solubility enhancement (Allen and Unger 1981).

Usually, trace elements, such as those studied in this project, are present at levels below those at which precipitation occurs. Their presence in the solid phase is a result of adsorption to components of the soil. The aqueous phase concentration of the trace element, Me, is related to the mass of adsorbed metal (x) per unit mass of soil (m). A number of adsorption isotherms, including Langmuir and Freundlich, have been developed to relate the solution and adsorbed concentrations (Hiemenz 1986; Kinniburgh 1986; Travis and Etnier 1981). The most commonly used equation is the Langmuir equation

$$\Gamma = \frac{x}{m} = \frac{bK[\text{Me}]}{1 + K[\text{Me}]} \quad (1)$$

where [Me] is the equilibrium concentration of metal and b and K are constants. At low concentration of metal the equation simplifies to a linear adsorption isotherm

$$\Gamma = \frac{x}{m} = K_d [\text{Me}] \quad (2)$$

where K_d is the partition coefficient.

The basic limitation of these relationships is that they do not account for changes in the extent of adsorption which occur when the aqueous phase composition is altered in pH, ionic strength, or concentration of chemicals which form complexes with the metal. Neither do they provide

a means to relate soil properties to the extent of adsorption. Nonetheless, these adsorption isotherms are important, particularly in defining the maximum amount of metal which can be bound by a given soil.

Additional information is needed to relate soluble metal concentrations to adsorption if the metal undergoes significant chemical reaction in the solution phase (Evans 1989; Sposito 1985; Stumm and Morgan 1981; Lindsay 1979; Sposito 1981). Important inorganic ligands forming complexes with metal cations include hydroxide and chloride ions. The computation of solution speciation, which has been reviewed by Jenne (1979), is generally accomplished by use of chemical equilibrium computer programs such as MINEQL (Westall et al. 1976) or MINTEQA (Brown and Allison 1987). These programs are being coupled to hydrologic transport models (Allen et al. in preparation).

This pH dependence of adsorption of metals onto soils has been frequently reported (Kuo and Baker 1980; Harter 1983; Elliott et al. 1986). Christensen (1989) found that the K_d values for 63 samples of Danish agricultural soils correlated very well ($r^2 = 0.72$) with soil pH. For anions, such as chromate, a reverse trend, in which adsorption is maximum at low pH and decrease with increasing pH is found (Zachara et al. 1989).

The binding of metals by soluble complexing agents is similarly highly dependent on pH. Knowledge of the stability constant for metal reacting with the complexing agent is insufficient to permit one to calculate the free metal ion concentration. For example, the concentration of free copper in a solution containing Cu-EDTA increases 25-fold as the pH is decreased from 7 to 6 (Ringbom 1963). To predict the extent of reaction of copper with EDTA, it is necessary to also have equilibrium constants for the reaction of EDTA with protons. The same situation is true for solid phase reactions. It is also necessary that equilibrium constants of the reaction sites on the solid phase with protons be available. In the absence of such information, it would be necessary to measure the extent of adsorption at each pH of interest!

The high degree of adsorption dependency on pH results from the surface chemistry of soil materials. Soils have pH-dependent, or variable, charge associated with the reaction of protons with oxide and hydroxide minerals and with certain functional groups of humic substances (Evans 1989; Sposito 1984). A common surface group which reacts with protons is

hydroxide. A surface hydroxide, $\equiv\text{S-OH}^0$, can undergo two protolysis reactions:



The corresponding conditional stability constants are

$$K_{\text{cond},a1} = \frac{[\equiv\text{S-OH}^0] \{ \text{H}^+ \}}{[\equiv\text{S-OH}_2^+]} \quad (5)$$

$$K_{\text{cond},a2} = \frac{[\equiv\text{S-O}^-] \{ \text{H}^+ \}}{[\equiv\text{S-OH}^0]} \quad (6)$$

where the brackets, [], indicate concentration and the braces, { }, indicate the activity of the enclosed chemical species. Because adsorption is a surface phenomena, concentrations of bound metals or of surface sites are expressed on an area, rather than mass, basis to enable one to relate different materials. The surface area is most commonly determined by determining the volume of nitrogen which can be adsorbed. The BET equation enable the calculation of the area for a complete monolayer surface sorption (Hiemenz 1986).

As the surface undergoes ionization, for instance during a titration with base, the surface becomes progressively more negatively charged and it becomes more difficult to remove subsequent protons. Thus, the conditional stability constant varies with the charge on the surface. It is necessary to incorporate a Boltzman, or electrostatic, factor to convert this conditional constant into an intrinsic constant which does not vary with pH (Huang 1981; Stumm and Morgan 1981; Sposito 1984; Hiemenz 1986; Schindler and Stumm 1987). The intrinsic constant, K_{int} , is given by the relationship

$$K_{\text{cond}} = K_{\text{int}} [-\Psi_0 F / RT] \quad (7)$$

where Ψ_0 is the electrical potential at the surface, F is the Faraday, R is the gas constant and T is the absolute temperature.

The surface potential can be calculated from the surface charge, σ_0 (Sposito 1984; Hiemenz 1986; Schindler and Stumm 1987; Westall 1987; Singh and Uehara 1986):

$$\sigma_0 = \kappa \Psi_0 \quad (8)$$

The surface charge is directly determined from the proton or hydroxide consumption by the solid phase in an acid or base titration (Hohl et al. 1980; Huang 1981).

The electrical double layer theory of equation 7 can be extended to account for the adsorption of ions at planes other than at the surface. The triple layer model of surface complexation requires an additional potential at the Stern layer (James and Parks 1982). The zeta potential, which is the potential at the plane of shear, is subject to easy instrumental measurement and is a good approximation of the Stern potential (Hiemenz 1986). Experimental data fit the simpler model as well as the fit the more sophisticated models (Westall and Hohl 1980; Morel 1981).

It is now easy to understand the reason that metal sorption is so highly pH dependent. Protons and metal ions compete with each other for available surface binding sites on a soil. For a divalent metal ion, Me^{2+}



for which the conditional stability constant is

$$K_{\text{cond}} = \frac{[\equiv \text{S-OMe}^+] \{ \text{H}^+ \}}{[\equiv \text{S-OH}] \{ \text{Me}^{2+} \}} \quad (10)$$

This conditional constant is related to an intrinsic constant in a similar fashion to that in equation 7. An analogous reaction to equation 10

can be written for the binding of the metal ion to two soil surface sites with the concurrent release of two, rather than one, protons. The binding of the hydrolyzed metal, MeOH^+ , to $\equiv\text{S-O}^-$ to give $\equiv\text{S-OMeOH}$ with no release of protons can also be described. If one is to be able to predict the adsorption of a metal at any pH, other than that which there is direct experimentally measured data, it is essential to have the acid base equilibrium constants of equations 5 and 6.

The adsorption of anions, such as chromate, can be described in an analogous fashion to that of metal cations (Parfitt 1978; Mott 1981). Binding of the monovalent anion, L^- , by the surface is represented by the reaction



Again, the pH dependency of the reaction is predicted and accounted for by the conditional constants

$$K_{\text{cond}} = \frac{[\equiv\text{S-L}]\{\text{OH}^-\}}{[\equiv\text{S-OH}]\{\text{L}^-\}} \quad (12)$$

which can be converted to an intrinsic constant by equation 7.

While the above approach will adequately describe the binding of cations and anions by a soil, additional efforts have been undertaken in this and other laboratories to further describe adsorption by heterogeneous materials. These approaches are ultimately aimed at the ability to predict the adsorption properties from independent chemical measurements of the soil (Jenne et al. 1986). Such approaches aim at the *a priori* prediction of sorption from determination of the concentrations of chemically active surface components such as organic matter and reactive iron and manganese oxide. These approaches are not inconsistent with those described above. In general, they only require a different treatment of the data.

Within the past half-dozen years there have been significant advances in the description of a related problem, the binding of protons and metals by fulvic acids. Fulvic acids are important materials in affecting the transport and toxicity of metals in natural water (Saar and Weber 1982). These materials a variety of functional groups capable of binding metal

ions (Stevenson 1981). The titration data can be described by fitting to models with a series of discrete ligands (Fish et al. 1986) or a Gaussian distribution of binding sites (Perdue and Lytle 1983). The discrete ligand approach is the more commonly used. Usually the computer program FITEQL (Westall 1982) is used to obtain a set of conditional constants based on a non-linear, least-squares fit of the titration data. Both methods provide adequate description of the data (Dzombak et al. 1986).

Another approach to the mathematical description of binding by such multiligand systems is by a continuous affinity spectrum (Hunston 1975; Thakur et al. 1980). These procedures calculate the probability of finding a binding constant within a given pK range. Shuman et al. (1983) applied this humic acid and Unger and Allen (1988) applied it to metal binding by sediment. There are a number of mathematical methods to obtain the distribution function (Nederlof et al. 1988). In the recent application of the approach to soils (Riemsdijk et al. 1987; Wit et al. 1988), the intrinsic affinity distribution, in which electrolyte effects are considered, has been determined. The drawback of these affinity spectrum approaches is that a binding distribution, as opposed to a series of discrete equilibrium constants, is obtained. The results are not readily amenable for incorporation into the commonly used equilibrium models.

Another approach to describing the titration behavior of heterogeneous systems is discrete affinity spectrum analysis (Tobler and Engel 1983) which has recently been applied to the analysis of environmental materials. This approach, has the advantage of providing a series of discrete equilibrium constants to define binding and thus the constants obtained can easily be incorporated into chemical speciation computer programs.

In addition to the the important topic of how best to describe the binding of a metal to a soil which has been discussed above, there is yet another important topic to discuss. All of the approaches commonly applied to the measurement of proton or metal binding involve either titrations or batch equilibration. In either case the equilibration is accomplished in a slurry. In the field, the soil column is stationary. The laboratory-derived constants must be the same as those applicable to the field situation for the results to be predictive of sorption/desorption behavior.

At low solute concentrations the linear adsorption isotherm of equation 2 should be followed. This equation predicts that the partition coefficient, K_d , should not vary with solids concentration. However, it has been repeatedly reported that the value of K_d decreases by as much as two to three orders of magnitude as the particle concentration is increased to high values (O'Connor and Connolly 1980; Voice and Weber 1985; Di Toro et al. 1985; McIlroy et al. 1986). It has been suggested that actual particle-particle collision interactions are responsible (MacKay and Powers 1987). Therefore, for immobile particles, the partition coefficient which would be obtained at low particle concentrations in mixed systems is that which is appropriate for use.

MATERIAL AND METHODS

I. Soil Pretreatment:

The five soil samples represent a selection of the major soil types present in New Jersey. The soils were air dried and agglomerates were broken by hand and by using a wooden mallet. Those particles larger than 2 mm were removed by sieving. The fraction of materials larger than 2 mm was recorded (Table 1 and Figure 1) so that results can be related to the native soil.

Table 1. The fraction of material larger than 2 mm

Soil Name	< 2 mm (g)	> 2 mm (g)	percentage (%)
Lakewood sand	18777.5	137.6	0.7
Penn silt loam	21666.5	3372.2	15.6
Sassafras sandy loam	25501.7	761.2	3.0
Washington loam	14807.9	4379.4	29.6
Whippany silty clay loam	18370.8	3946.3	21.5

II. Soil Sample Characterization Analysis:

1. Determination of natural metal contamination in soils

We checked for Pb and Cd contamination of soils, and none was found.

2. Particle Size Distribution

Two methods were used to determine particle size. These were sieve analysis and sedimentation (hydrometer)

(1) Sieving procedure (Head, 1980):

- a) Break agglomerates of soil by hand or using a wooden hammer.
- b) Remove all materials with particle size larger than 2 mm by using a 2 mm sieve.
- c) Take 500 grams of each soil with particle size less than 2 mm and sieve for particle size distribution by passing the soil through 12 different sieves from 0.043 to 1.186 mm. The dried soil sample is placed in the top-most of the first 6 sieves and is shaken for 30 minutes.
- d) The soil contained in the receiving pan is placed in the top-most of the second set of 6 sieves, those with the finer openings, and these too are shaken for 30 minutes.
- e) The mass of soil contained on each stage is determined.

In order to draw a particle size distribution curve, it is necessary to calculate the cumulative percentage (by mass) of particles finer than each sieve aperture size (Head, 1980). This is the mass of particles which pass through a sieve. The mass retained on the first sieve is denoted by m_{s1} . The mass passing the first sieve = $m_{init} - m_{s1}$, where m_{init} is the initial mass of soil and m_{s1} is the mass retained on the first sieve. The percentage passing the first sieve is given by

$$P_1 = \frac{(m_{init} - m_{s1})}{m_{init}} \times 100$$

The mass passing the second sieve = $m_{init} - m_{s1} - m_{s2}$. The percentage passing the second sieve is given by

$$P_2 = \frac{m_{init} - (m_{s1} + m_{s2})}{m_{init}} \times 100$$

The percentage remaining on subsequent stages are calculated in a similar manner. The percentage passing any subsequent sieve can be written as

$$P = \frac{m_{init} - \sum m}{m_{init}} \times 100$$

where $\sum m$ denotes the sum of the masses retained on all sieves down to and including the sieve considered, sieve n:

$$\sum m = m_{s1} + m_{s2} + \dots + m_{sn}.$$

Values obtained in the calculation of the particle size distribution of the Lakewood sand (soil 1) are shown in Table 2. The cumulative mass curve of the Sassafras sandy loam sample, which is shown in Fig. 1, uses the data presented in Table 2. The four other particle size curves are shown in Fig. 2 through Fig. 5.

Table 2. Sieving data for Sassafras sandy loam

sieve size (mm)	mass retained (g)	cumulative mass passing (g)	percentage passing (%)
2.000	0.00	500.00	100
1.168	49.93	450.07	90
1.001	19.75	430.32	86
0.841	21.45	408.87	82
0.833	1.18	407.69	81
0.589	37.19	370.50	74
0.500	24.20	346.30	69
0.417	16.15	330.15	66
0.295	40.06	290.09	58
0.249	24.59	265.50	53
0.150	69.82	195.68	39
0.074	76.99	118.69	24
0.043	118.69	0.00	0

The position of a curve on the figure indicates the fineness or coarseness of the grain; the further to the left the curve lies, the finer the grains, and the further to the right, the coarser the grains. This is

expressed by the effective size (D10) which is the particle size for which 10% of the particles are finer, and 90% of the particles are coarser (Head, 1980). The uniformity of particle sizes is given by the slope of the line. This is expressed by the uniformity coefficient (U) which is the ratio of the 60% particle size to the 10% particle size. The values of effective size and uniformity coefficient are given in Table 3. The smallest sized soils, as determined by the effective size parameter, are the Sassafras sandy loam and the Whippany silty clay loam. These soils also have the greatest uniformity of the five soils tested.

Table 3. Effective size and uniformity coefficients

Soil Name	Effective Size D ₁₀	Uniformity coefficient U
Lakewood sand	130	3.2
Penn silt loam	170	3.5
Sassafras sandy loam	53	5.9
Washington loam	300	2.7
Whippany silty clay loam	42	17.4

(2). Sedimentation (Hydrometer) (Sims and Heckendorn, 1991):

A. Procedure:

- a) Break agglomerates of soil by hand or using a wooden hammer.
- b) Remove all materials with particle size larger than 2 mm by using a 2 mm sieve.
- c) Take 50 grams of each soil with particle size less than 2 mm into a 600 mL beaker and add 100 mL of 5% sodium hexametaphosphate.
- d) Transfer the suspension to the sedimentation cylinder and insert plunger and mix contents thoroughly.
- e) About 15 seconds after mixing the suspension, lower the hydrometer into suspension, and after 40 seconds, read the scale at the top of the meniscus. Record the hydrometer value.

- f) Record temperature of sample and blank at 40 seconds.
- g) At 2 hours after suspending the soil in the cylinder, lower the hydrometer into the sedimentation cylinder and record the hydrometer value, then record the temperature of sample and blank at 2 hours.

B. Calculations:

$$\text{Corrected Hydrometer Reading} = (\text{Hydrometer Reading} - \text{Blank}) + (\text{correction value})$$

$$\text{Where: Correction value} = 0.36 (\text{Measured Temperature} - 20^{\circ}\text{C})$$

Particle Size:

$$\% \text{ Sand} = 100 - \left[\frac{(\text{Corrected Hydrometer Reading at 40 Seconds})}{(\text{Corrected Weight of Soil})} \times 100 \right]$$

$$\% \text{ Clay} = \left[\frac{(\text{Corrected Hydrometer Reading at 2 Hours})}{(\text{Corrected Weight of Soil})} \times 100 \right]$$

$$\% \text{ Silt} = 100 - (\% \text{ Sand} + \% \text{ Clay})$$

$$\text{Where: Corrected Weight of Soil} = \frac{(\text{Oven dry weight of subsample} \times 50\text{g})}{(\text{Air-dried weight of subsample})}$$

C. Results:

Table 4 shows the textural class of each soil studied.

Table 4. Particle Size Distribution (by hydrometer)

Soil Name	Sand (%)	Silt (%)	Clay (%)	Textural ^a Class
Lakewood sand	91	3	6	Sand
Penn silt loam	25	48	27	Loam
Sassafras sandy loam	45	37	18	Loam
Washington loam	20	49	31	Clay Loam
Whippany silty clay loam	49	16	57	Silt Loam

^a Based on U. S. Department of Agriculture classification

3. Soil pH (Storer, 1991)

A. Scope:

This measurement determines the degree of acidity or alkalinity in soil materials suspended in water and 0.01 M calcium chloride solution. Measurements in both liquids are necessary to fully define the soil's pH. This variable is useful in determining the solubility of soil minerals, the mobility of ions in the soil, and assessing the viability of the soil - plant environment.

B. Summary of Test Method:

Measurement of the pH of soils in both suspensions of water and calcium chloride solutions are made with a pH sensitive electrode.

C. Significance and Use:

The pH measurements are made in both water and calcium chloride solution. Because the calcium ion can replace the aluminum of soil, the soil pH values obtained in the calcium chloride solution are slightly lower than those measured in water. Apparently, the released aluminum ions undergo hydrolysis. As a result, protons are generated. Therefore, both measurements are required to fully define the character of the soil's pH.

D. Reagent:

- a) Purity of Water - Water should be distilled, deionized water, but not necessarily free of carbon dioxide.
- b) Calcium chloride stock solution (1.0 M) - Dissolve 14.7 g of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in water in a 100 mL volumetric flask. Dilute to volume with water.

- c) Calcium chloride stock solution (0.01 M) - Dilute 10.0 mL of stock 1.0 M CaCl_2 solution to 1 L with water.

E. Procedure:

Both methods begin with an air dried soil that has been sieved through a 2 mm sieve to remove the coarse soil fraction. For both methods, weigh out approximately 10 g of soil and place the soil into 20 mL glass vial and add approximately 10 mL of distilled water and 0.01 M calcium chloride solution. Mix thoroughly and let the sample stand for 1 hr or overnight. An ORION combination pH electrode and a Cole Parmer Digiphasc pH meter were used for measurements. Meters are calibrated using 2 buffer solutions, pH 4 and pH 7. Both pH-value buffer solutions are rechecked after each 5 measurements. If the measured value is not within ± 0.1 pH units of the accepted value, the data for the previously measured samples are rejected. Following the quality check, the pH meter is restandardized using the two buffer solutions.

F. Results:

The pH value of distilled, deionized water was 6.81.

The pH value of 0.01 M calcium chloride solution was 5.80.

Tables 5 - 7 give results of pH measurements for all soil samples studied.

Table 5. Soil pH measurements (30 min. stirring, 1 hr standing)

Soil name	pH of soil (in water)	pH of soil (in CaCl_2)
Lakewood sand	4.18	3.65
Penn silt loam	4.67	4.13
Sassafras sandy loam	5.78	5.31
Washington loam	6.03	5.80
Whippany silty clay loam	6.17	5.72

Table 6. Soil pH measurements (30 min. stirring, overnight standing)

Soil name	pH of soil (in water)	pH of soil (in CaCl ₂)
Lakewood sand	3.91	3.60
Penn silt loam	4.47	4.14
Sassafras sandy loam	5.71	5.29
Washington loam	6.06	5.83
Whippany silty clay loam	6.15	5.74

Table 7. Soil pH measurements (Overnight stirring, followed by 1 hr standing)

Soil name	pH of soil (in water)	pH of soil (in CaCl ₂)
Lakewood sand	3.88	3.62
Penn silt loam	4.49	4.14
Sassafras sandy loam	5.71	5.31
Washington loam	6.06	5.85
Whippany silty clay loam	6.15	5.78

4. Soil Organic Matter (Walkley-Black Wet Combustion Method)
(Sims and Heckendorn, 1991)

A. Procedure:

- a) Weigh 1.50 ± 0.01 g of soil sample into a 250 mL Erlenmeyer flask and add 25 mL of 0.4 N K₂Cr₂O₇ to the soil. Then add 20 mL of concentrated H₂SO₄.
- b) Swirl gently for one minute to thoroughly mix all reagents with soil.
- c) Prepare a blank and a reference soil sample for the standard calibration, and do the same procedures as a and b.

- d) Using a graduated cylinder, add 100 mL distilled, deionized water and 5 drops of Ferroin indicator.
- e) Titrate the solution with 0.4 N $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$.
- f) Record titration volume, and titrate blanks in the same manner.
- g) Calculations:

$$\% \text{ Organic Matter} = (B-T) \times (F)$$

Where: B = mL of FeSO_4 for blank titration.
 T = mL of FeSO_4 for sample titration.

$$F = \frac{(0.74 \times N)}{W} \quad \text{and,} \quad 0.74 = \frac{(3) \times (1.72) \times (100)}{(0.70) \times (1000)}$$

Where: 3 = mg carbon per milliequivalent of carbon
 1.72 = Correction factor, based on assumption soil organic matter is 58% carbon.
 0.70 = Correction factor for incomplete oxidation of soil carbon during acid digestion (i.e. only about 70% of the soil carbon is oxidized)
 1000 = Convert mg to g
 100 = Convert to percentage (%)
 W = Weight of soil sample (g)
 N = Normality of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, calculated as follows:
 $N_1 V_1 = N_2 V_2$
 N_1 = Normality of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$
 V_1 = mL of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ to titrate blank
 N_2 = Normality of $\text{K}_2\text{Cr}_2\text{O}_7 = 0.4 \text{ meq/mL}$
 V_2 = Volume of $\text{K}_2\text{Cr}_2\text{O}_7 = 25 \text{ mL}$

B. Results

Table 8 gives results for soil organic matter for all soil samples studied.

Table 8. Soil Organic Matter (by Walkley Black)

Soil Name	Organic Matter (%)
Lakewood sand	0.5
Penn silt loam	1.3
Sassafras sandy loam	0.6
Washington loam	2.9
Whippany silty clay loam	2.3

5. Soil Effective Cation Exchange Capacity (Sims and Heckendorn, 1991):

A. Procedure:

(1). Determination of Exchangeable Cations

- a) Weigh 10 g of soil sample into a 100 mL polyethylene cup and add 50 mL of 1 N NH_4OAc (for exchanging cations), pH 7.0 to the cup then shake for 30 min.
- c) Filter the suspension into a 100 mL volumetric flask, using medium qualitative grade filter paper and add 25 mL of 1 N NH_4OAc to the soil, swirl by hand and pour onto soil on filter paper. Repeat this step.
- c) Collect a total of 90 to 95 mL of ammonium acetate filtrate. Make the solution to volume with 1 N NH_4OAc and mix well.
- d) Determine K, Ca, and Mg in the solution by atomic absorption spectrophotometry.
- e) Calculations:
Exchangeable Cation

$$\text{Exchangeable Cation (meq / 100g)} = \frac{(C) \times (df) \times (0.100 \text{ L}) \times (1 \text{ meq}) \times (100)}{(S. \text{ Wt.}) \times (\text{Meq. Wt.})}$$

Where:

C = Concentration of Ca, Mg or K in dilute sample, mg/L

df = dilution factor (Ca; Mg = 28; K=10)

0.100 L = volume of original NH_4OAc extract

S.Wt. = Sample weight (10 g)

Meq.Wt. = weight per milliequivalent (Ca = 20 mg; Mg = 12 mg; K = 39 mg)

(2). Determination of Exchangeable Acidity at the pH of the Soil

- a) Weigh 10 g of soil sample into a 125 mL Erlenmeyer flask and add 25 mL of 1 N KCl (for acidity exchange). Swirl well for half hour, then add 25 mL KCl. Repeat 4 times to get a total 150 mL KCl.
- b) Filter the suspension into a 300 mL Erlenmeyer flask.
- c) Add 4 drops of phenolphthalein indicator to the KCl solution.
- d) Titrate the KCl solution with the standard 0.01N NaOH.
- e) Calculations:

$$\text{Exchangable Acidity (meq / 100g)} = \frac{(T - B) \times (N) \times (100)}{(W)}$$

Where:

T = mL of NaOH to titrate sample

B = mL of NaOH to titrate blank

N = Normality of NaOH (meq/mL)

W = Sample weight, g

B. Results

Table 9 gives results of soil effective cation exchange capacity and exchangeable cations for all soil samples studied.

Table 9. Cation Exchange Capacity (meq/100g)

Soil Name	K	Mg (meq/100g)	Ca	Acidity (meq/100g)	ECEC ^a (meq/100g)
Lakewood sand	0.01	0.02	0.05	0.77	0.90
Penn silt loam	0.14	0.42	1.25	2.02	3.80
Sassafras sandy loam	0.14	0.69	2.06	0.20	3.10
Washington loam	0.65	1.63	6.59	0.02	8.90
Whippany silty clay loam	0.05	2.52	6.87	0.03	9.50

^a ECEC: Effective Cation Exchange Capacity

III. Adsorption Equilibrium:

In order to check whether an equilibration time of 24 hours is long enough for metal adsorption onto soil, we conducted an adsorption batch experiment. The experimental data are shown in Table 10 and Fig. 7 - Fig. 10. The other purpose of the experiment was to determine the influence of mixing in the liquid-solid adsorption equilibrium reaction. The experimental procedure was organized into seven steps:

- (1) Two types of soil, Sassafras sandy loam and Washington loam, were chosen for study. The soil samples were 1.00 ± 0.01 g per 100 mL solution. Ionic strength was maintained at 0.01N with NaNO_3 to avoid complexation with cadmium. We added cadmium nitrate at concentrations of 1×10^{-5} M.
- (2) Individually adjust the mixed liquor pH values of Sassafras sandy loam and Washington loam to certain values for end up close to the desired pHs, pH 4 and 7 and shake them on the reciprocating shaker at a speed of 150 stokes, which did not provide uniform suspension of the solids; The temperature was maintained at room temperature ($25 \pm 2^\circ\text{C}$).
- (3) Adjust the pH value of Washington loam to 4 and stir it on a magnetic stirrer at a speed of 150 rpm, which did provide uniform suspension;

- (4) Take samples from each sample container at times of 1 min, 15 min, 30 min, 45 min, 60 min, 3 hrs, 6 hrs, 12 hrs, 24 hrs, 48 hrs, and 72 hrs and filter them;
- (5) Readjust the pH value of each mixed liquor to the original pH value;
- (6) Analyze the Cd concentration of each sample solution by AA;
- (7) Calculate the percent adsorption. All samples reached adsorption equilibrium within the first 24 hours. The shaken and stirred samples also reached the same value within 24 hours. The results are shown in Table 10 and Figures 7 - 10.

Table 10. The percentage of Cd absorbed as a function of time

Time	Sassafras Sandy Loam		Washington Loam		
	(pH 4) ^a	(pH 7) ^a	(pH 4) ^a	(pH 7) ^a	(pH 4) ^b
1 (min)	2.02	9.94	13.33	19.40	24.03
15 (min.)	2.60	9.88	20.00	30.17	31.76
30 (min.)	3.18	43.37	23.94	66.81	32.62
45 (min.)	3.47	51.51	25.76	71.55	33.05
1 (hr.)	4.05	59.64	27.58	83.20	32.62
3 (hr.)	4.91	63.55	28.49	87.50	34.76
6 (hr.)	7.23	71.99	30.91	90.10	34.34
12 (hr.)	8.96	81.93	31.82	91.81	34.34
24 (hr.)	9.83	82.53	33.33	91.81	34.34
48 (hr.)	9.54	82.30	30.03	91.81	33.91
72 (hr.)	9.83	82.30	33.94	91.81	34.34

^a A reciprocating shaker was used for mixing.

^b A stirrer was used for mixing.

IV. Glassware Adsorption Test:

The purpose of this experiment was to determine if there was a significant adsorption of metal onto glassware. We chose Cd and Pb for study. These were tested at two pH values (4 and 7) and two concentrations (1×10^{-5} M and 1×10^{-4} M). We added 100 mL of cadmium nitrate and lead nitrate at concentrations of 1×10^{-5} and 1×10^{-4} M to 125 mL beakers. Samples were shaken for 24 hours. Membrane filtered with the Gelman 25mm diameter, 0.45 μ m pore size membrane filters and unfiltered samples were collected before and after the 24-hour contact period. The data are presented in Table 11 as the percentage of the initial concentration. Comparing the absorbance between filtered and non-filtered sample or between 0 and 24 hours of shaking, it was observed that neither the 0.45 μ m membrane filter nor the glass flask which we used to run our experiment adsorbed any significant amount of metal.

Table 11. The absorbance of Cd and Pb remaining in solution

Sample	pH	Cd	Cd	Pb ^b	Pb ^b
		1×10^{-5} M	1×10^{-4} M	1×10^{-5} M	1×10^{-4} M
t=0 (nf) ^a	4	0.072	0.715	0.123	0.128
t=0 (f)	4	0.070	0.709	0.123	0.130
t=0 (nf)	7	0.071	0.713	0.121	0.124
t=0 (f)	7	0.071	0.704	0.130	0.123
t=24 (nf)	4	0.070	0.719	0.120	0.132
t=24 (f)	4	0.069	0.718	0.118	0.134
t=24 (nf)	7	0.069	0.717	0.126	0.121
t=24 (f)	7	0.067	0.709	0.134	0.119

a. nf = non-filtered, f = filtered by 0.45 μ m membrane filter

b. Absorbance of Pb was determined by Graphite Furnace AA after the solution was diluted 1/50 for 1×10^{-5} M and 1/500 for 1×10^{-4} M.

V. Cadmium and Lead Adsorption:

Batch equilibration studies have been conducted for cadmium (II) and lead (II) for the five New Jersey soils. The soil samples were 1.00 : 0.01 g per 100 mL solution. Ionic strength was maintained at 0.01N with NaNO_3 to avoid complexation with cadmium. We added cadmium or lead nitrate at concentrations of 1×10^{-5} , 3×10^{-5} , and 1×10^{-4} M. Fifteen pH values covering the range from 3 to 10 were used and the temperature was maintained at room temperature (25 ± 2 °C). The pH values of the samples were adjusted by adding NaOH or HNO_3 , as required. Samples were shaken at 150 rpm for 24 hours. The pH values were measured again after the 24 hours shaking. These values were taken to be the reaction values. The samples were then filtered through 25mm diameter, 0.45 μm membrane filters.

The cadmium and lead concentration in the filtered solution was determined by atomic absorption spectrophotometry using a Perkin-Elmer Model 5000 atomic absorption spectrophotometer. The instrument was calibrated with a calibration curve prior to sample analysis. Samples were analyzed in groups of 16, representing a single initial cadmium concentration. The sixteen samples were the 15 which had been equilibrated at different pH values and the initial cadmium solution to which no soil was added. At the end of each group of samples, a standard was reanalyzed. If the concentration displayed for the standard deviated by more than 10% from the correct value, the instrument was restandardized and the entire set of samples was reanalyzed.

A series of curves have been plotted in a series of figures (Fig. 11 - Fig. 26). Data for the 1×10^{-6} and 3×10^{-6} M initial cadmium concentrations have not been included because of scatter in the data. For the 1×10^{-5} , 3×10^{-5} , and 1×10^{-4} M initial cadmium and lead concentrations, virtually all the added cadmium or lead was adsorbed at higher pH. As the pH decreased, the amount of adsorbed cadmium and lead decreased. Also, we find that for the same soil at the same pH, a lower concentration of added cadmium and lead has a higher percentage adsorbed than does a higher concentration (see Fig. 14 - Fig. 18 and Fig. 22 - Fig. 26).

VI. Adsorption Isotherms:

Air dried, sieved soil samples, 1.0 gram, were immersed in 100 mL of 0.01 M NaNO_3 . The pH was adjusted to certain values for ending up close to desired pHs, 4.0, 5.5, and 7.0, by addition of NaOH or HNO_3 for the tests with cadmium and lead. The temperature was maintained at room temperature (25 ± 2 °C). The initial cadmium and lead concentrations ranged from 1.0×10^{-6} to 1.5×10^{-4} moles/L, and the equilibration time was 24 hours. After 24 hours, the pH was readjusted to the initial value of 4.0, 5.5, or 7.0 and the samples were filtered through 0.45 μm membrane filters. It was found that there are not big changes in pH after 24 hours (all these adjustments were only within ± 0.3 pH). The amount of adsorbed metal was calculated as the difference between the amount added initially and that remaining in solution.

The cadmium and lead concentration of the liquid phase was analyzed by atomic absorption spectrophotometry. Replicate tests were conducted for the lowest and the highest metal concentrations to determine the precision. The adsorption isotherms are presented in Fig. 42 - 51. The results clearly indicate that the pH influenced not only the amount adsorbed, but also the shape of the adsorption isotherms. It can be deduced from the shape of the isotherms that in some cases the partition coefficient (K_d) varied with amount adsorbed.

VII. Computation of Partition Coefficient and Maximum Permissible Amount of Metal in Soil

(1) Computation of partition coefficient:

To convert the percentage of metal adsorbed values into the maximum metal in soil permissible values, we must first calculate the partition coefficient (K_d). The partition coefficients are not directly useful because the soil : water ratio in the laboratory does not equal that in the field.

Example computations are shown for cadmium:

$$K_d = \frac{C_s}{C_w}$$

K_d : adsorption coefficient

C_s : metal concentration in soil ($\mu\text{g/g}$)

C_w : metal concentration in water ($\mu\text{g/mL}$)

For cadmium, molecular weight = 112 g/mole

$$K_d = \frac{\frac{(\text{fraction adsorbed}) \times (112 \text{ g / mole})}{1 \text{ g soil}}}{\frac{(1 - \text{fraction adsorbed}) \times (112 \text{ g / mole})}{100 \text{ mL water}}}$$

$$K_d = \frac{(\text{percentage adsorbed})}{(1 - \text{percentage adsorbed})} \times 100 \text{ (mL / g)}$$

The equation shown above also can be utilized for lead.

Example 1: Cadmium; Sassafras Sandy Loam

pH = 5; $3 \times 10^{-5} \text{ M}$

$3 \times 10^{-5} \text{ M} \times 0.1 \text{ liter solution} = 3 \times 10^{-6} \text{ moles Cd in sample}$

$3 \times 10^{-6} \text{ mole} \times 112 \text{ g/mole} \text{ ----- Cd in sample}$

At pH = 5; roughly 40% absorbed

$3 \times 10^{-6} \text{ mole Cd} \times 112 \text{ g/mole} \times 0.40 \text{ ----- Cd absorbed by soil}$

$3 \times 10^{-6} \text{ mole Cd} \times 112 \text{ g/mole} \times 0.60 \text{ ----- Cd remaining in water}$

$$K_d = \frac{\frac{(3 \times 10^{-6} \text{ mole}) \times (112 \text{ g / mole}) \times 0.40}{1 \text{ g soil}}}{\frac{(3 \times 10^{-6} \text{ mole}) \times (112 \text{ g / mole}) \times (1 - 0.40)}{100 \text{ mL water}}} = 67 \text{ mL / g}$$

Example 2: Cadmium; Sassafras Sandy Loam

pH = 7; $3 \times 10^{-5} \text{ M}$

$3 \times 10^{-5} \text{ M} \times 0.1 \text{ liter solution} = 3 \times 10^{-6} \text{ moles Cd in sample}$

$3 \times 10^{-6} \text{ mole} \times 112 \text{ g/mole} \text{ ----- Cd in sample}$

At pH = 7, roughly 90% absorbed

$3 \times 10^{-6} \text{ mole Cd} \times 112 \text{ g/mole} \times 0.90 \text{ ----- Cd absorbed by soil}$

$3 \times 10^{-6} \text{ mole Cd} \times 112 \text{ g/mole} \times 0.10 \text{ ----- Cd remaining in water}$

$$K_d = \frac{\frac{(3 \times 10^{-6} \text{ mole}) \times (112 \text{ g / mole}) \times 0.90}{1 \text{ g soil}}}{\frac{(3 \times 10^{-6} \text{ mole}) \times (112 \text{ g / mole}) \times (1 - 0.90)}{100 \text{ mL water}}} = 900 \text{ mL / g}$$

Example 3: Lead; Whippany silty clay loam

pH = 3; $1 \times 10^{-4} \text{ M}$

$1 \times 10^{-4} \text{ M} \times 0.1 \text{ liter solution} = 1 \times 10^{-5} \text{ moles Pb in sample}$

$1 \times 10^{-5} \text{ mole Cd} \times 112 \text{ g/mole} \text{ ----- Pb in sample}$

At pH = 3, roughly 25% absorbed

1×10^{-5} mole Pb x 207 g/mole x 0.25 ----- Pb absorbed by soil

1×10^{-5} mole Pb x 207 g/mole x 0.75 ----- Pb remaining in water

$$K_d = \frac{\frac{(3 \times 10^{-5} \text{ mole}) \times (207 \text{ g / mole}) \times 0.25}{1 \text{ g soil}}}{\frac{(3 \times 10^{-5} \text{ mole}) \times (207 \text{ g / mole}) \times (1 - 0.25)}{100 \text{ mL water}}} = 33 \text{ mL / g}$$

Example 4: Lead; Whippany silty clay loam

pH = 4; 1×10^{-4} M

1×10^{-4} M x 0.1 liter solution = 1×10^{-5} moles Pb in sample

1×10^{-5} mole Cd x 112 g/mole ----- Pb in sample

At pH = 4, roughly 70% absorbed

1×10^{-5} mole Pb x 207 g/mole x 0.70 ----- Pb absorbed by soil

1×10^{-5} mole Pb x 207 g/mole x 0.30 ----- Pb remaining in water

$$K_d = \frac{\frac{(3 \times 10^{-5} \text{ mole}) \times (207 \text{ g / mole}) \times 0.70}{1 \text{ g soil}}}{\frac{(3 \times 10^{-5} \text{ mole}) \times (207 \text{ g / mole}) \times (1 - 0.70)}{100 \text{ mL water}}} = 230 \text{ mL / g}$$

B: Computation of Maximum Permissible Amount of Metal in Soil

Partition relationship:

$$C_s = K_d \times C_w$$

C_s : maximum permissible metal concentration in soil ($\mu\text{g/g}$)

C_w : drinking water standard ($\mu\text{g/mL}$)

Mass balance of metal in soil including solid phase and soil water:

$$T = S + W$$

T : total contaminants in soil

S : contaminants bound by dry soil solids

W : contaminants dissolved in soil water

The total amount of metal in the soil is the concentration of metal in the soil times the mass of the soil.

$$S = (K_d \times C_w) \times M_s$$

M_s : mass of dry soil solids

Substituting the product of the density of soil particles times the volume of soil particles we obtain:

$$S = (K_d \times C_w) \times (D_s \times V_s)$$

D_s : density of soil particle (2.65g/mL)

V_s : volume of soil particle (mL) = $(1-n) \times V$

V_v : void volume of soil

V : volume of soil ($V_s + V_v$)

$$n : \text{porosity of soil} = V_v/V$$

The total amount of metal in the pore water is the concentration of metal in the pore water times the volume of the pore water. The maximum permissible concentration of metal in the pore water is the drinking water concentration of the metal, C_w :

$$W = C_w \times V_w$$

V_w : volume of pore water

$$p : \text{degree of water saturation in soil} = V_w/V_v$$

The total amount of metal in the soil is the sum of the mass of metal on the particles and that in the pore water.

$$T = (K_d \times C_w \times D_s \times V_s) + (C_w \times V_w)$$

$$T = \{K_d \times C_w \times D_s \times (1-n) \times V\} + (C_w \times V_w)$$

We can use this expression for the total amount of contaminants to calculate the allowed soil concentration since:

$$\text{Maximum allowed soil concentration} = \frac{(\text{Total contaminants})}{(\text{Total weight of soil})}$$

Since:

$$\text{Total weight of soil} = D_s \times (1-n) \times V$$

We can now write the allowed soil concentration as:

$$\text{Maximum allowed soil concentration} = \frac{\{K_d \times C_w \times D_s \times (1-n) \times V\} + (C_w \times V_w)}{D_s \times (1-n) \times V}$$

$$\text{Maximum allowed soil concentration} = C_w \left\{ K_d + \frac{n \times p}{D_s \times (1 - n)} \right\}$$

Since $\frac{n \times p}{D_s \times (1 - n)}$ is much less than the value of K_d for a highly partitioned material, the maximum allowed concentration $\cong K_d \times C_w$

As n or / and p increases, $\frac{n \times p}{D_s \times (1 - n)}$ increases.

We can evaluate the maximum allowable soil concentration which will not cause an exceedence of the drinking water standard

(a) Drinking Water Standard for cadmium is $10 \mu\text{g/L}$.

$$10 \mu\text{g/L} = 1 \mu\text{g Cd}/100 \text{ mL H}_2\text{O}$$

(b) Drinking Water Standard for lead is $50 \mu\text{g/L}$

$$50 \mu\text{g/L} = 5 \mu\text{g Pb}/100 \text{ mL H}_2\text{O}$$

(c) Assuming $n = 0.4$, $p = 100\%$, $D_s = 2.65 \text{ g/mL}$

we can calculate $\frac{n \times p}{D_s \times (1 - n)}$:

$$\frac{n \times p}{D_s \times (1 - n)} = \frac{(0.3) \times (1.0)}{(2.65) \times (1 - 0.3)} = 0.16 \text{ mL/g}$$

Recalling the equation of total allowed soil concentration

$$\text{Total allowed soil concentration} = C_w \left\{ K_d + \frac{n \times p}{D_s \times (1-n)} \right\}$$

$$\begin{aligned} &\text{Maximum permissible amount of cadmium (mg Cd/Kg soil)} \\ &= (1 \mu\text{g Cd}/100 \text{ mL H}_2\text{O}) \times (1 \text{ mg Cd}/10^3 \mu\text{g Cd}) \\ &\quad \times (K_d + 0.16 \text{ mL H}_2\text{O}/\text{g soil})(10^3 \text{ g soil}/\text{Kg soil}) \\ &= [(K_d + 0.16)/100] \text{ mg Cd/Kg soil} \end{aligned}$$

$$\begin{aligned} &\text{Maximum permissible amount of lead (mg Pb/Kg soil)} \\ &= (5 \mu\text{g Pb}/100 \text{ mL H}_2\text{O}) \times (\text{mg Pb}/10^3 \mu\text{g Pb}) \\ &\quad \times (K_d + 0.16 \text{ mL H}_2\text{O}/\text{g soil})(10^3 \text{ g soil} / \text{Kg soil}) \\ &= [(K_d + 0.16)/20] \text{ mg Pb/Kg soil} \end{aligned}$$

Example 1: Cadmium; Sassafras Sandy Loam; $C_w = 1 \mu\text{g Cd}/100 \text{ mL H}_2\text{O}$;
 $\text{pH} = 5$; $3 \times 10^{-5} \text{ M}$; $K_d = 67 \text{ mL/g}$
Maximum permissible amount of Cd/Kg soil
 $= (67+0.16)/100$
 $= 0.67 \text{ mg Cd/Kg soil}$

Example 2: Cadmium; Sassafras Sandy Loam; $C_w = 1 \mu\text{g Cd}/100 \text{ mL H}_2\text{O}$
 $\text{pH} = 7$; $3 \times 10^{-5} \text{ M}$; $K_d = 900 \text{ mL/g}$
Maximum permissible amount of Cd/Kg soil
 $= (900+0.16)/100$
 $= 9.00 \text{ mg Cd/Kg soil}$

Example 3: Lead; Whippany silty clay loam; $C_w = 5 \mu\text{g Pb}/100 \text{ mL H}_2\text{O}$
 $\text{pH} = 4$; $3 \times 10^{-5} \text{ M}$; $K_d = 33 \text{ mL/g}$
Maximum permissible amount of Pb/Kg soil
 $= (33+0.16)/20$
 $= 1.66 \text{ mg Pb/Kg soil}$

Example 4: Lead; Whippany silty clay loam; $C_w = 5 \mu\text{g Pb}/100 \text{ mL H}_2\text{O}$

$\text{pH} = 5$; $3 \times 10^{-5} \text{ M}$; $K_d = 230 \text{ mL/g}$

Maximum permissible amount of Pb/Kg soil

$$= C_w \times (K_d + 0.16)$$

$$= (230 + 0.16)/20$$

$$= 11.5 \text{ mg Pb/Kg soil}$$

QUALITY CONTROL-QUALITY ASSURANCE PROCEDURES

1. Data Quality Objectives:

The QA/QC objective level will be "Level 4". The results of this research will be used to establish environmental standards which could be used to establish clean-up levels. Such actions on the part of a regulatory agency are frequently subjected to litigation.

2. Monitoring Network Design and Rationale:

The field samples were collected by NJDEP at five sites which had been chosen to represent a distribution of the major soil types present in New Jersey.

3. Sampling Procedure:

The surfacial soil layer, as well as the vegetation, was removed with a spade. The B horizon was collected with the spade. The soil was placed in a 10-gallon opaque plastic container.

4. Sample Custody Procedures:

The soil samples were placed in the 10-gallon opaque plastic containers. These were labeled prior to the soil being placed in them. The soil was kept in the same container during transportation and storage prior to use.

5. Monitoring Sites and Frequency of Sample Collection:

The five soils were collected in June and July 1990 by NJDEP personnel. One sample of each soil was collected. The soils collected for use in this study are Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam, and Washington loam.

6. Data Quality Requirements:

Parameter	Sample Matrix	Detection Limit	Quantitation Limit	Precision	Accuracy
pH	wastewater	±0.01	1.00 - 14.00	±1%	99%
Cd	wastewater	(Details in Standard Methods)			
Cr (III)	wastewater	(Details in Standard Methods)			
Cr (VI)	wastewater	0.01 mg/L	0.5 mg/L	±5%	99%
Pb	wastewater	(Details in Standard Methods)			
Soil pH	soil-wastewater	±0.01	1.00 - 14.00	±1%	99%
Organic matter	soil	0.1%	100%	±10%	95%
Inorganic carbon	soil	0.1%	10%	±10%	95%
Extractable Al, Fe, Mn & Si	soil	(Details in Standard Methods for metal analysis)			
Surface area	soil	0.1 m ² /g	---	±5%	99%
CEC	soil	0.1 meq/kg	5 meq/kg	±5%	95%
Particle size	soil	38 µm	25 mm	±5%	95%
pH _{zpc}	soil	0.1 mV	100 mV	±5%	95%

Note: Method detection limit, quantitation limit, precision, and accuracy are calculated by the methods in ASTM D1687-86 p. 366, 1990.

The most pertinent data to the project are pH and the concentrations of the four metals. The criteria by which the data for these parameters

will be judged are described in Section 8. Calibration Standards and Preventive Maintenance.

7. Data Quality Assessments:

Only data which fall in the stated precision range and accuracy limit will be selected to represent that characteristic of the population.

8. Calibration Standards and Preventive Maintenance:

Commercially prepared and certified metal and pH standards are routinely utilized in the laboratory. Instruments are calibrated each time they are used.

For pH, meters are calibrated using 2 buffer solutions. Depending on the pH of the samples to be measured, the buffers are pH 4 and pH 7 or pH 7 and pH 10. The higher pH-value buffer solution is rechecked after each 15 measurements. If the measured value is not within ± 0.1 pH units of the accepted value, the data for the previously measured samples are rejected. If the measured value of the buffer solution is within ± 0.1 pH units of the accepted value, the data for the previously measured samples are accepted. Following the quality check, the pH meter is restandardized using the two buffer solutions.

For the metal analyses, a calibration curve which covers the entire working range of the method is prepared. At least five concentrations are prepared for the curve. One of these is near the upper limit (quantitation limit) and the remainder are approximately evenly distributed. For atomic absorption analyses, a blank is run after each sample. Analyses for adsorption experiments are run in groups of 18 samples. These 18 represent one initial metal concentration. Fifteen of the the samples are the fifteen different pH values used in the experiment. A mid-pH sample is run in duplicate to assess precision. Another portion of that sample is spiked by the method of standard additions to test recovery. The last sample of the 18 in the group is the initial solution used in the adsorption test. This analysis is for the purpose of ascertaining the exact metal concentration used in the experiment. For both atomic absorption and colorimetric analyses, a standard is run after each group of 18 samples. If the value of

this standard differs from its stated value by more than $\pm 10\%$, the data for the previous set of 18 samples is rejected and the samples are reanalyzed. If the standard does not differ from its stated value by more than $\pm 10\%$, the data are accepted. If the analysis is by flame atomic absorption, the instrument is also restandardized using this standard. If the analysis is by electrothermal atomization atomic absorption or by colorimetric analysis, the value of the slope of the calibration curve used for the subsequent 18 samples is assumed to have changed by the same amount as for the standard.

Instruments are maintained and calibrated according to manufacturers recommendations. Balances are calibrated on an annual basis.

9. Quality Control Checks:

Spiked samples and replicates are an important part of our quality control procedures. These have been discussed in the preceding section.

10. Documentation, Data Reduction, and Reporting:

Depending on the type of data, results are recorded on data sheets or in permanent notebooks. Data are also stored in a computer file and are graphed and subjected to statistical analyses. Data will be reported to NJDEP by quarterly reports.

11. Performance and System Audits:

The data for samples and for quality control samples are regularly checked by the Project Quality Assurance Officer.

12. Project Operations and Responsibility:

Sampling operations	P.F. Sanders and H.E. Allen
Sampling QC	P.F. Sanders
Laboratory analysis	J. Lee, B. Chen, H.E. Allen, C.P. Huang
Laboratory QC	J. Lee, B. Chen, H.E. Allen, C.P. Huang
Data processing activities	J. Lee, B. Chen, H.E. Allen, C.P. Huang
Data processing QC	J. Lee, B. Chen, H.E. Allen, C.P. Huang
Data quality review	H.E. Allen, C.P. Huang, D.L. Sparks

Performance evaluation/auditing	H.E. Allen, C.P. Huang, D.L. Sparks
Overall QA	H.E. Allen
Principal investigators	H.E. Allen, C.P. Huang, D.L. Sparks

DISCUSSION, CONCLUSIONS AND RECOMMADATION

(1) Adsorption kinetics

Generally, it is a problem to mix the adsorbate and adsorbent when using the batch equilibration technique. If mixing is inadequate, the rate of reaction is limited and the rate is controlled by mass transfer. However, vigorous mixing can cause abrasion of soil constituent particles leading to high rates of reaction and even changes in the surface chemistry of particles (Sparks, 1989). Thus, the mixing style and mixing speed could be a potential problem in our batch technique. Fortunately, by checking the adsorption experimental data shown in Table 10 and the plots of adsorption percentage vs. time shown in Fig. 6 - 9. there was no apparent effect of mixing. Furthermore, all of the adsorption reactions approached equilibrium within 24 hours.

(2) Glassware adsorption test

As evident from Table 11, there was no significant adsorption of lead or cadmium to container walls or on the membrane filters in our adsorption equilibrium experiments.

(3) Metal adsorption

Lead and cadmium had similar adsorption behavior but lead had stronger adsorption than cadmium (Fig. 27 - Fig. 41). The soils vary in their strength and capacity for metal binding. Metal adsorption was highly pH dependent. The Whippany silty clay loam and Washington loam displayed almost the same extent of adsorption. They adsorbed metals much more than did the other three soils (Fig. 11 - 13 and Fig. 19 - 21). Lakewood sand had the poorest adsorption capacity. The percent of metal adsorbed increased with rising pH and decreased with increasing initial metal concentration (Fig. 14 - 18 and Fig. 22 - 26).

Adsorption of heavy metals on soils can be described by two molecular mechanisms: (a) nonspecific adsorption - the metallic cations behave as counter cations in the diffuse layer; and (b) specific adsorption resulting from surface complexation (Msaky and Calvet, 1990). The

importance of the second mechanism increases with the stability of hydroxo complexes.

The pH may influence adsorption in several ways: (a) ionization of surface groups; (b) displacement of the equilibrium of surface complexation reactions (Davis et al., 1979); (c) competition with H_3O^+ and Al^{3+} for negative sites; and (d) variation of metal speciation.

(4) Adsorption isotherm

The shapes of adsorption isotherms as a function of the pH at a constant ionic strength are seen in Fig. 42 - 51. The pH greatly affects the shape of adsorption isotherms. There are four main types of isotherms corresponding to different solute/adsorbent interactions: S, L, H, and C (Sposito, 1984).

The S-curve isotherm, less frequently reported in the literature, is characterized by an initial slope that increases with the concentration of substance in the soil solution. This property suggests that the relative affinity of the soil solid phases for the substance at low concentration is less than the affinity of the soil solution. It was speculated that natural organic compounds in the soil solution form strong, nonadsorbing complexes with metals. After the complexing capacity of these compounds is exceeded through an increase in the amount of metals added to the soil solution, the solid particles begin to adsorb metal ions (Reddy and Dunn, 1986).

The L-curve isotherm (e.g. Fig. 42), an isotherm that is concave to the concentration axis because of the combination of affinity and steric factors, is characterized by an initial slope that does not increase with the concentration of a substance in the soil solution. This property is the result of a high relative affinity of the soil solid phases for the substance at low concentrations coupled with a decreasing amount of adsorbing surface as the surface excess of the adsorbate increases.

The H-curve isotherm (e.g. Fig. 47, pH 5.5) is an extreme version of the L-curve isotherm. Its characteristic large initial slope (in comparison with the L-curve isotherm) suggests a very high relative affinity of the soil solid phases for an adsorbing substance. This condition is usually produced either by highly specific interactions between the solid phase and the adsorbing substance or by significant van der Waals interactions contributing to the adsorption process. For both L-curve and H-curve

isotherms, the partition coefficient decreases as the adsorbed amount increases.

The C-curve isotherms (e.g. Fig. 49 - 51, pH 5.5 and pH 7.0) correspond to adsorbent surfaces whose adsorption energies are of the same magnitude as the hydration energy of the cations. In this situation, the partition coefficient does not depend on the amount adsorbed. This kind of isotherm is characterized by an initial slope that remains independent of the concentration of substance in the soil solution until all adsorption sites are saturated and can be produced either by a constant partitioning of a substance between the interfacial region and an external solution or by a proportional increase in the amount of adsorbing surface as the surface excess of an adsorbate increases.

Thus, the shape of adsorption isotherms greatly depends on the pH. In addition, the overall slope of adsorption isotherms increase as pH increases, which reflects an increase in surface affinity for the metal with rising pH values.

(5) Partition coefficient

The adsorption coefficient (K_d), which is related to the percentage metal adsorbed, increased with increasing pH and decreased with increasing initial metal concentration (Fig. 52 - 67). Whippany silty clay loam had the highest K_d values and Lakewood sand had the lowest K_d values (Fig. 34 - 36). The higher the K_d values, the higher the ratio of lead bound by soil to that remaining in solution.

(6) Maximum permissible amount of metal in soil

Data for partition coefficients can be used to compute maximum permissible metal concentrations in soil which will not result in an exceedence of the Drinking Water Standard. These maximum permissible metal concentrations could be used as soil clean-up criteria and to predict the effect of metal addition to soil. It should be noted that these criteria are based on simple partitioning, with no transport of metal through the vadose zone to the groundwater. Such transport would dramatically decrease the maximum concentration of metal actually found in the groundwater. These calculations are very conservative. Furthermore, the partitioning relationships are based on a soil-to-water ratio of 1g soil/100 mL water,

which is quite different from ratios observed in the field (e.g. ~ 1.3 g soil to 0.5 mL water). Also, this is based on initial solution concentrations of metals; and K_d varies with amount of metal in the soil water system.

The maximum permissible level of cadmium and lead in soil increases dramatically with increasing pH. Different soils have very different absorption abilities. For example, at a given pH, Whippany silty clay loam could have a relatively high cadmium and lead concentration whereas Lakewood sand would allow relatively low concentration (Fig. 68 - 73).

At any pH, lead could have a higher soil concentration than cadmium without causing an exceedence of the Drinking Water Standard because (1) lead has stronger adsorption ability than cadmium and (2) lead has higher Drinking Water Standard than cadmium (Fig. 74 - 88).

At the natural soil pH, Whippany silty clay loam and the Washington loam have much higher allowed cadmium and lead concentrations and Lakewood sand has the lowest cadmium and lead concentration without causing an exceedence of the Drinking Water Standard because Whippany silty clay loam and Washington loam have higher soil pH, organic matter (Table 8) and finer particle size (Table 4) whereas Lakewood sand has the lowest soil pH, organic matter and coarser particle size of the soils studied.

Table 12. Comparison of the maximum permissible level of cadmium and lead for five different soils at the natural soil pH for 1×10^{-4} M initial concentration.

Soil Name	Soil pH	Cd in Soil (mg/kg)	Pb in soil (mg/kg)
Lakewood sand	3.88	0.09	0.35
Penn silt loam	4.49	0.35	7.10
Sassafras sandy loam	5.71	0.90	85.00
Washington loam	6.06	3.50	205.00
Whippany silty clay loam	6.15	4.50	250.00

ACKNOWLEDGEMENTS

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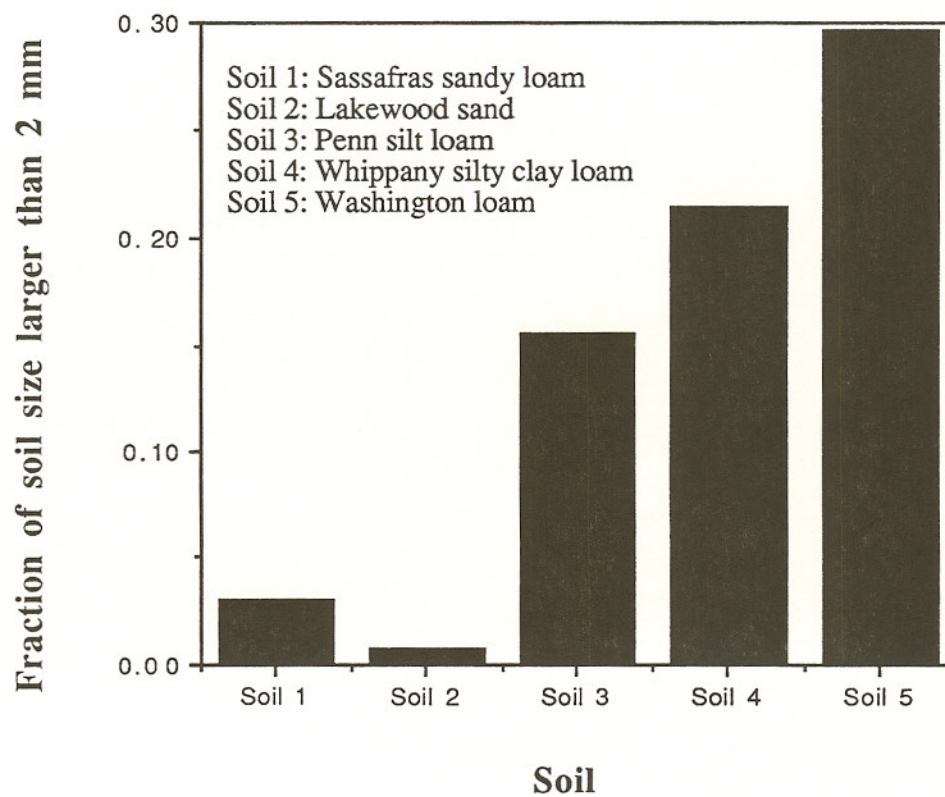


Figure 1. Fraction of soil with particle size greater than 2 mm.

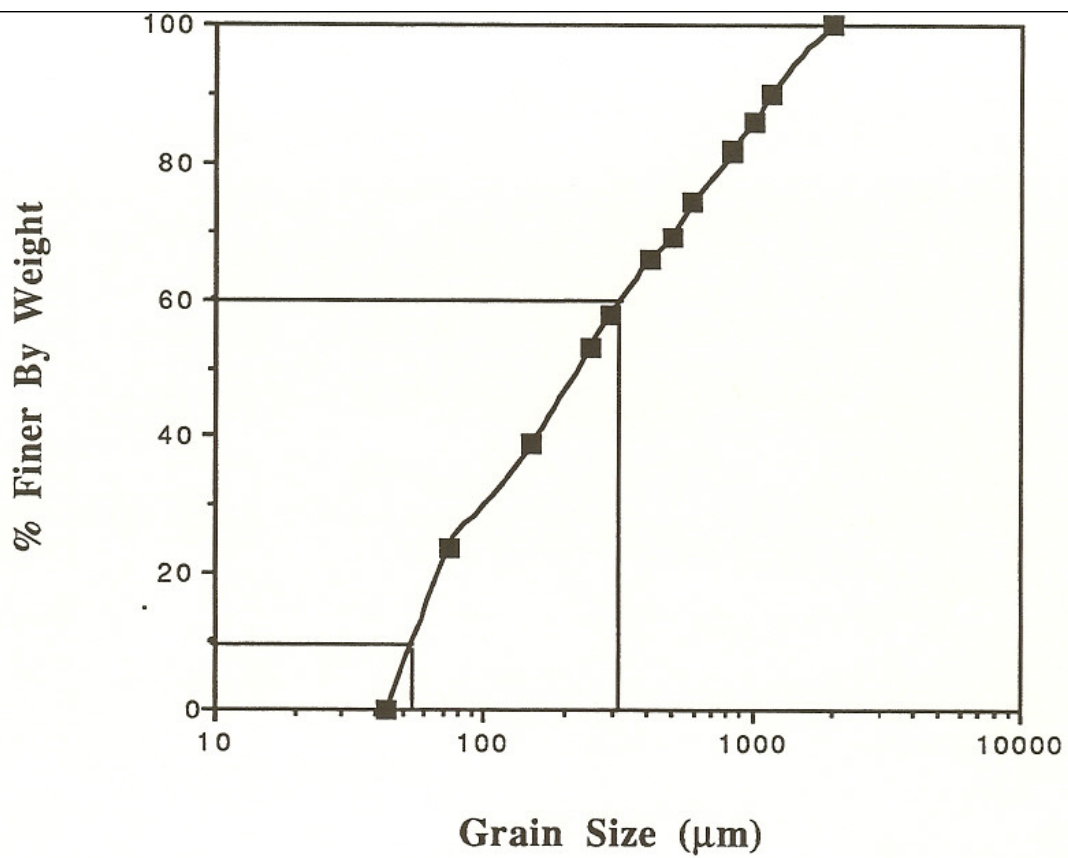


Figure 2. Cumulative particle size distribution for Sassafras sandy loam.

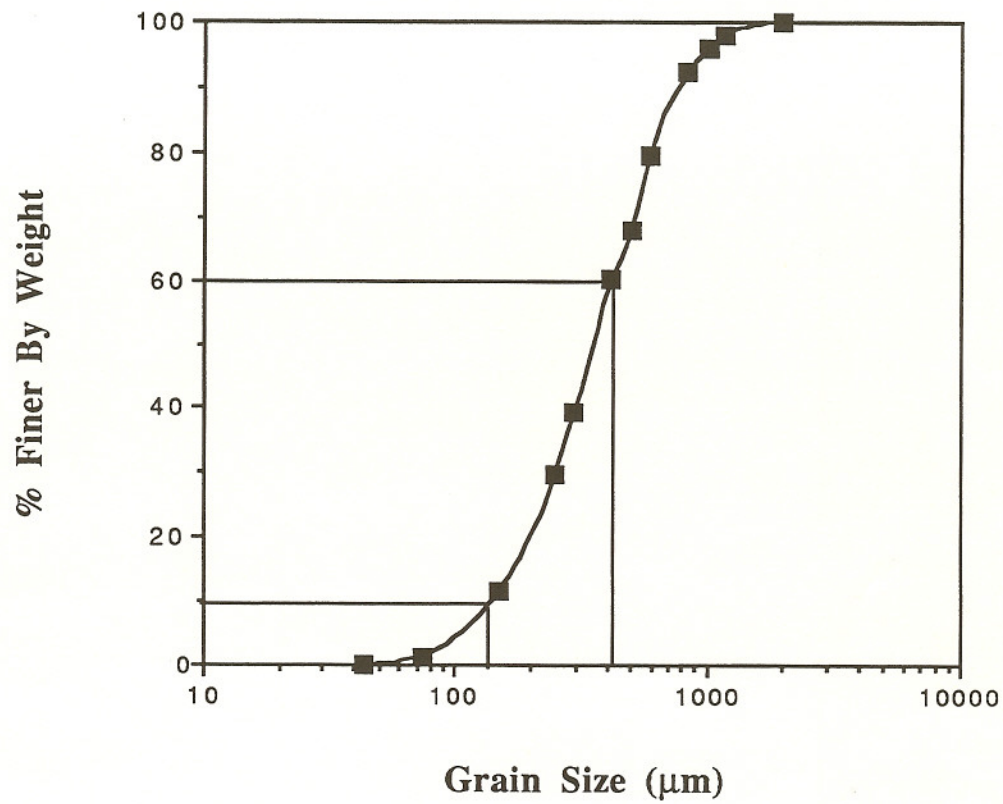


Figure 3. Cumulative particle size distribution for Lakewood sand.

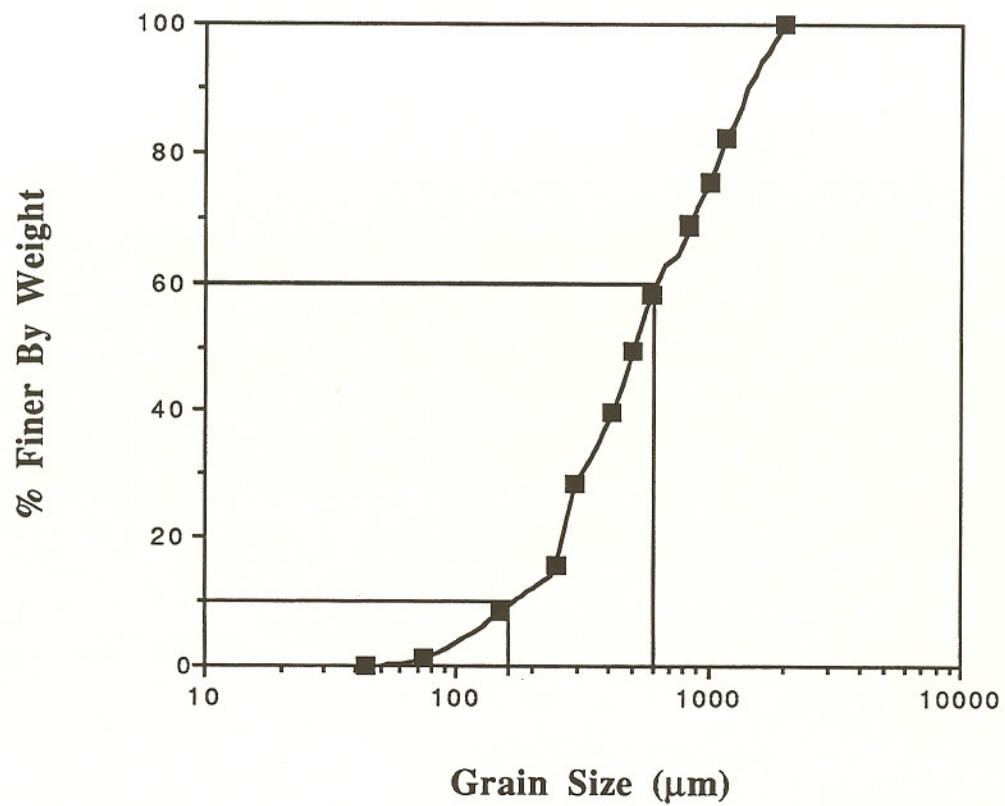


Figure 4. Cumulative particle size distribution for Penn silt loam.

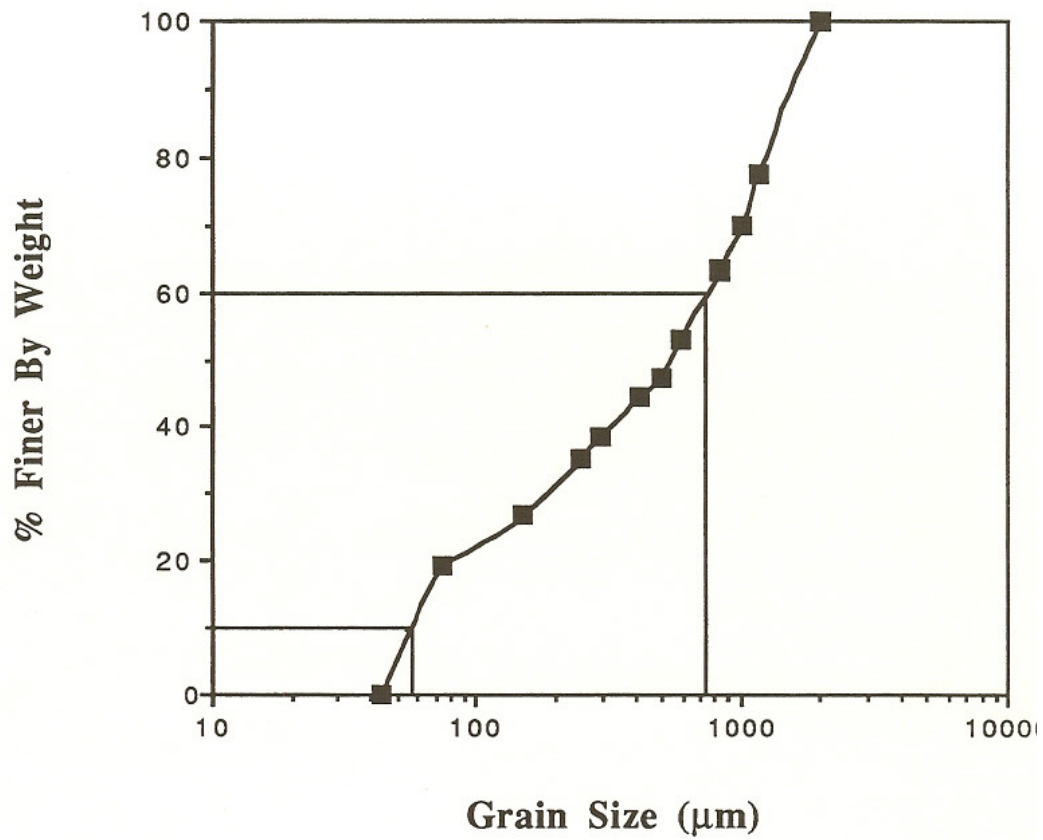


Figure 5. Cumulative particle size distribution for Whippany silty clay loam.

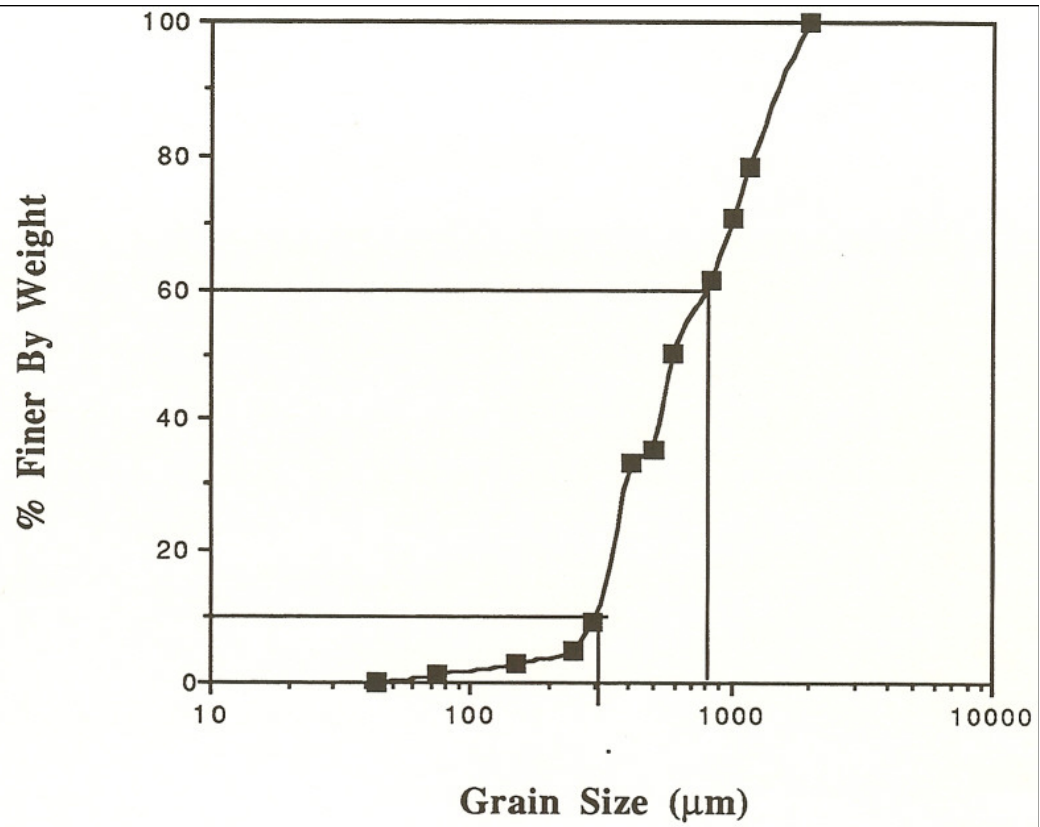


Figure 6. Cumulative particle size distribution for Washington loam.

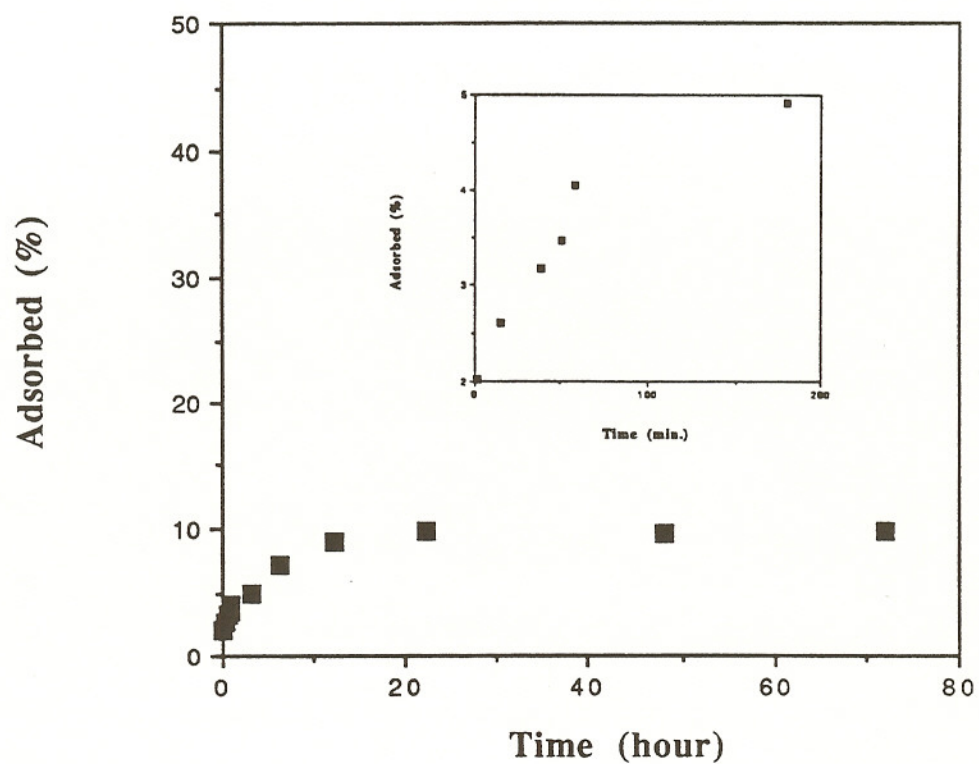


Figure 7. Kinetics of cadmium adsorption onto Sassafras sandy loam at pH 4 (by shaking). Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C, with inset showing the initial 200 min reaction time.

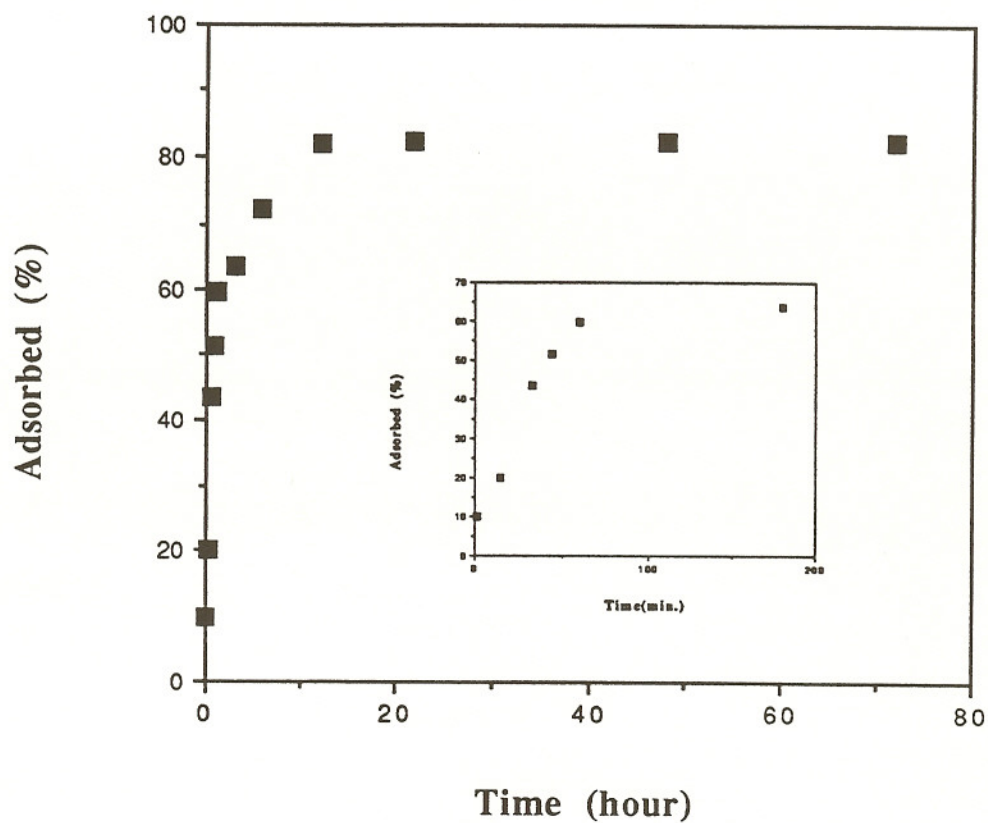


Figure 8. Kinetics of cadmium adsorption onto Sassafras sandy loam at pH 7 (by shaking). Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C, with inset showing the initial 200 min reaction time.

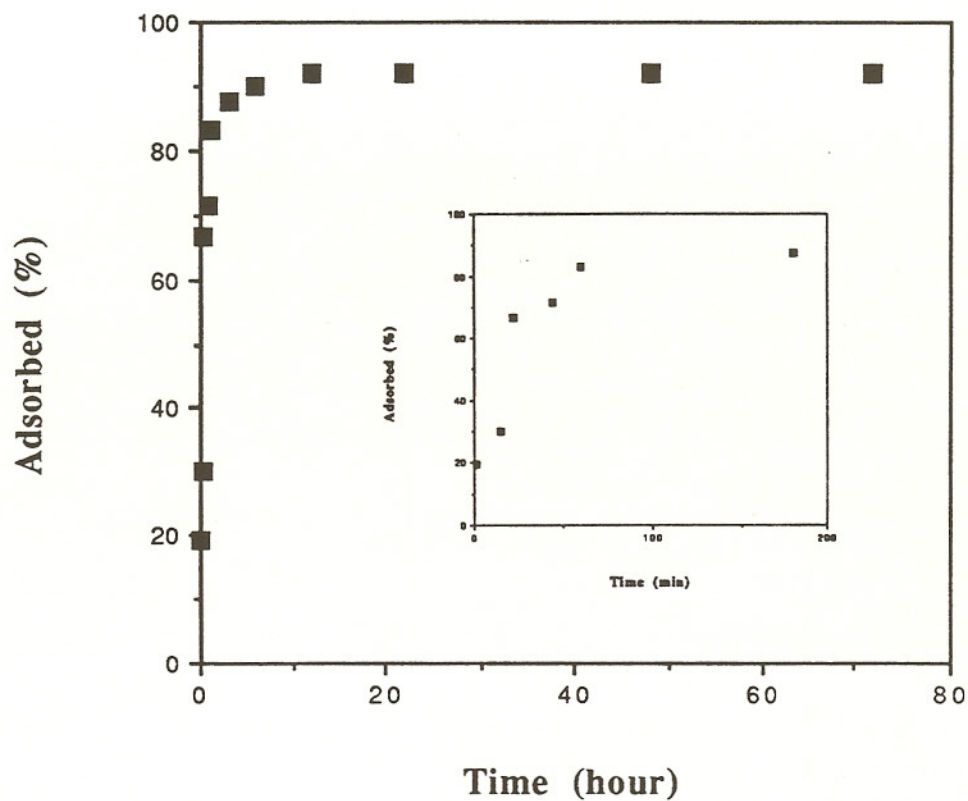


Figure 9. Kinetics of cadmium adsorption onto Washington loam at pH 7 (by shaking). Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C, with inset showing the initial 200 min reaction time.

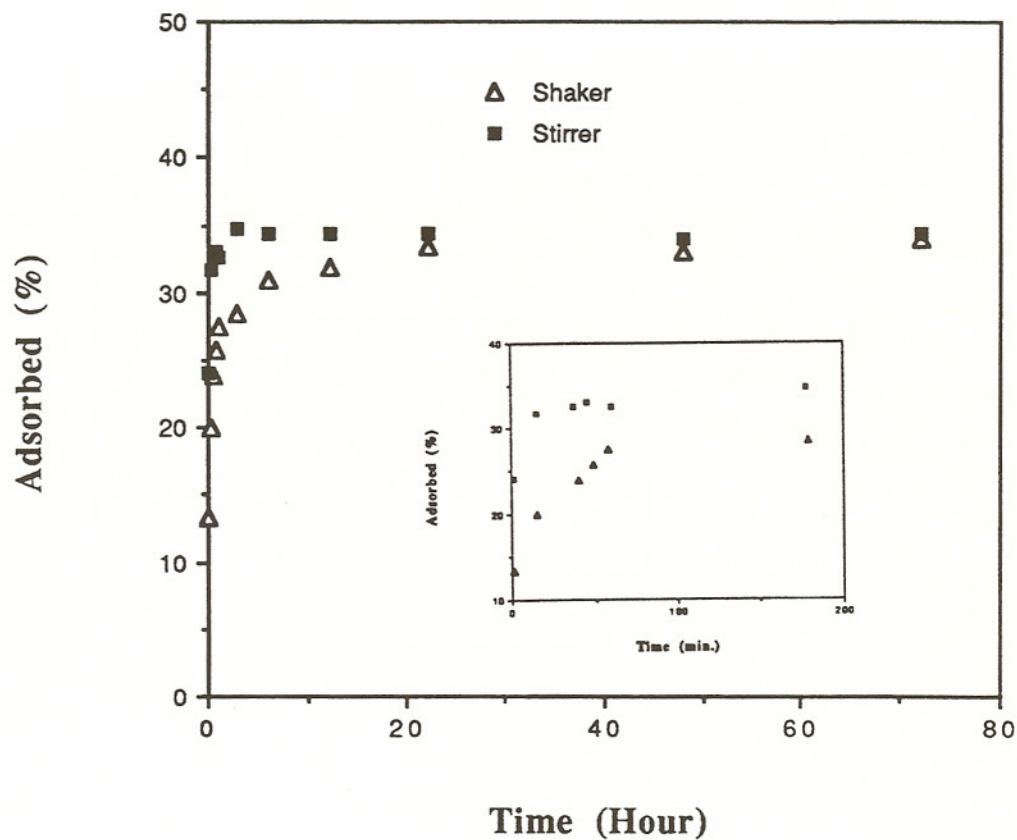


Figure 10. Kinetics of cadmium adsorption onto Washington loam at pH 4 (by shaking and stirring). Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C, with inset showing the initial 200 min reaction time.

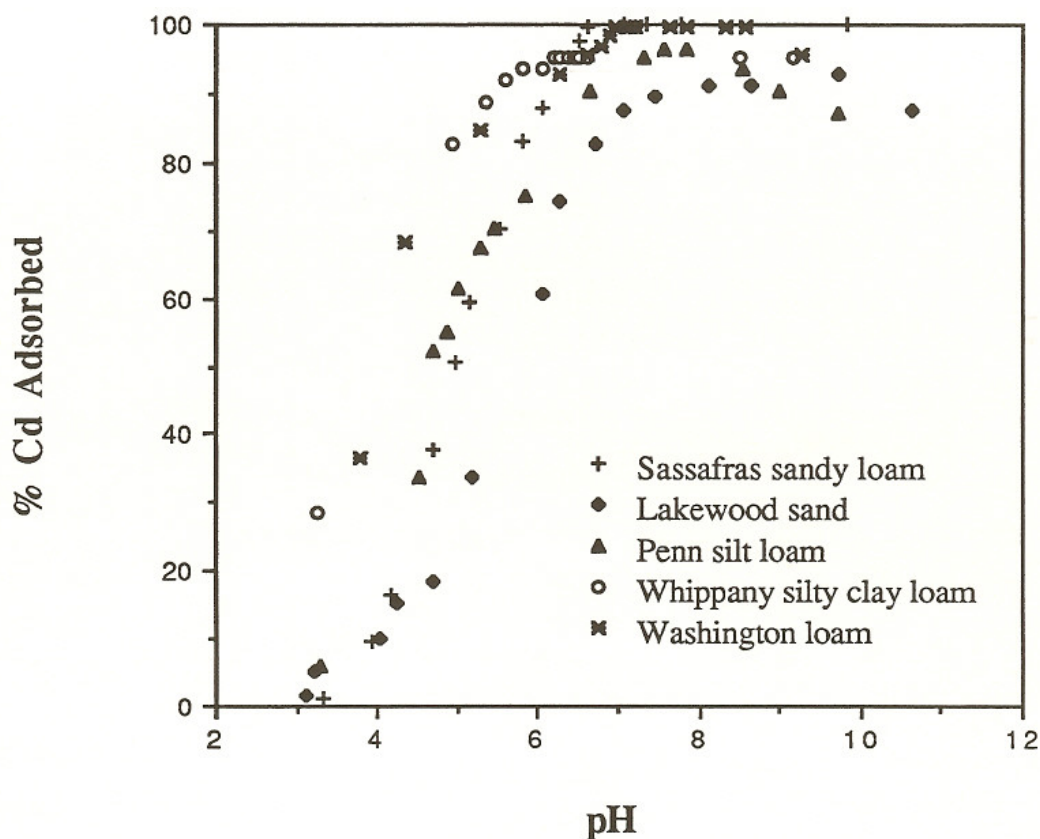


Figure 11. Adsorption of 1×10^{-5} M cadmium onto Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C .

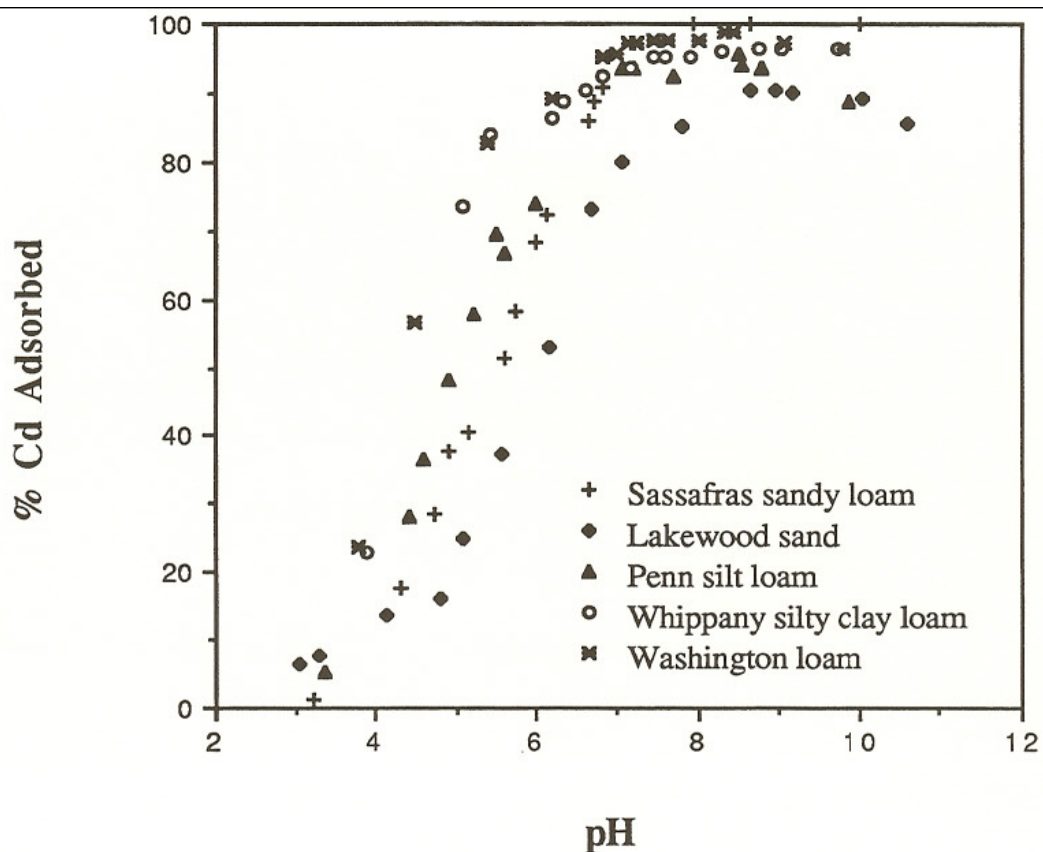


Figure 12. Adsorption of 3×10^{-5} M cadmium onto Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C .

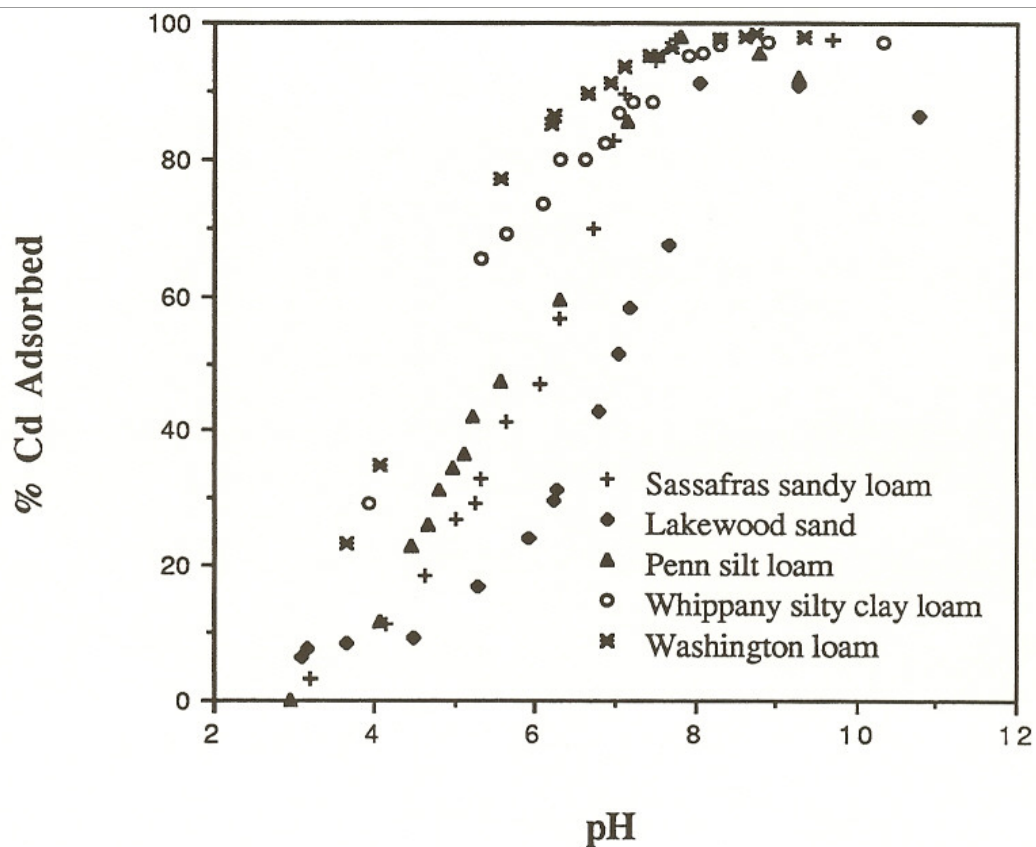


Figure 13. Adsorption of 1×10^{-4} M cadmium onto Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C .

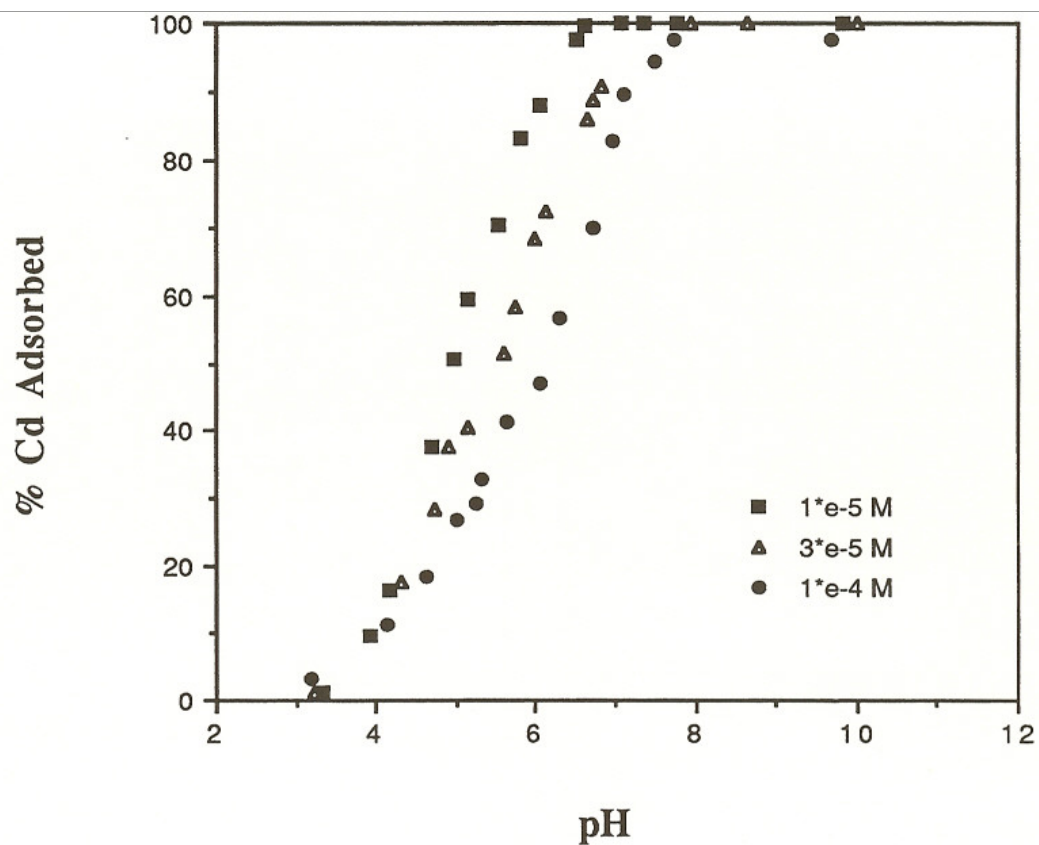


Figure 14. Adsorption of cadmium onto Sassafras sandy loam
Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

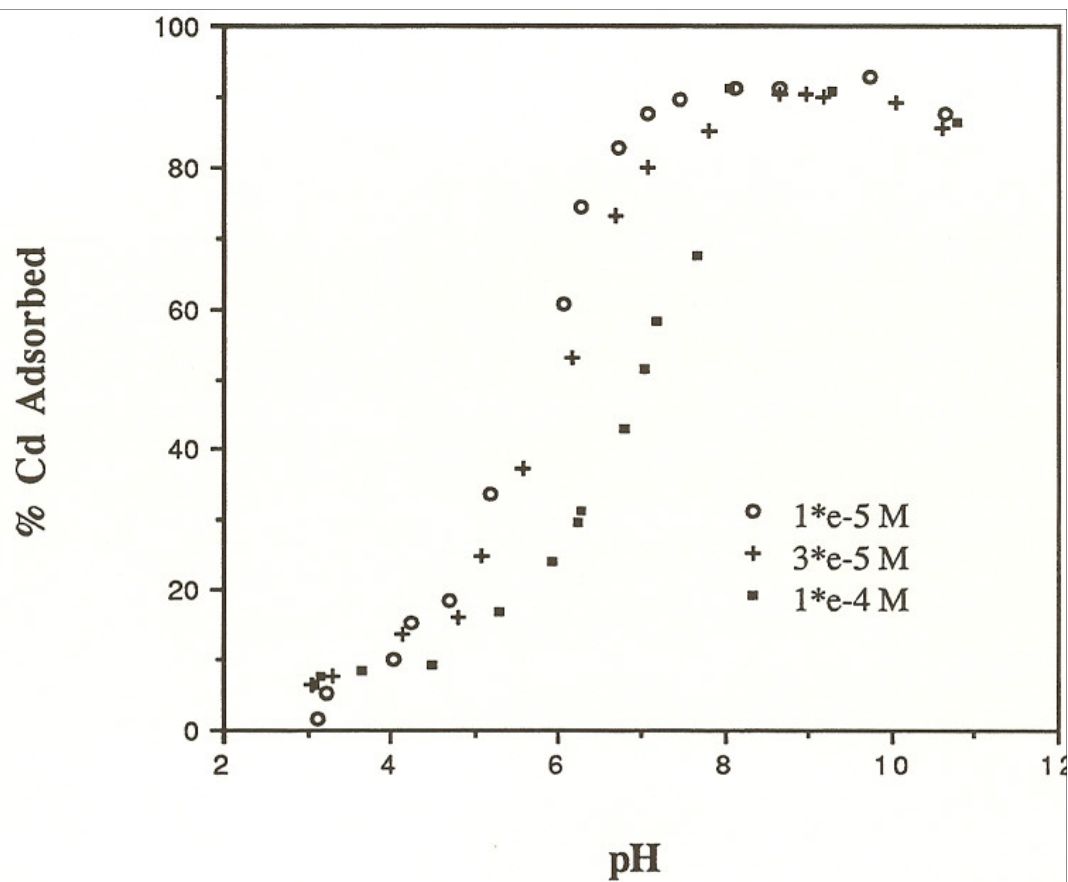


Figure 15. Adsorption of cadmium onto Lakewood sand; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

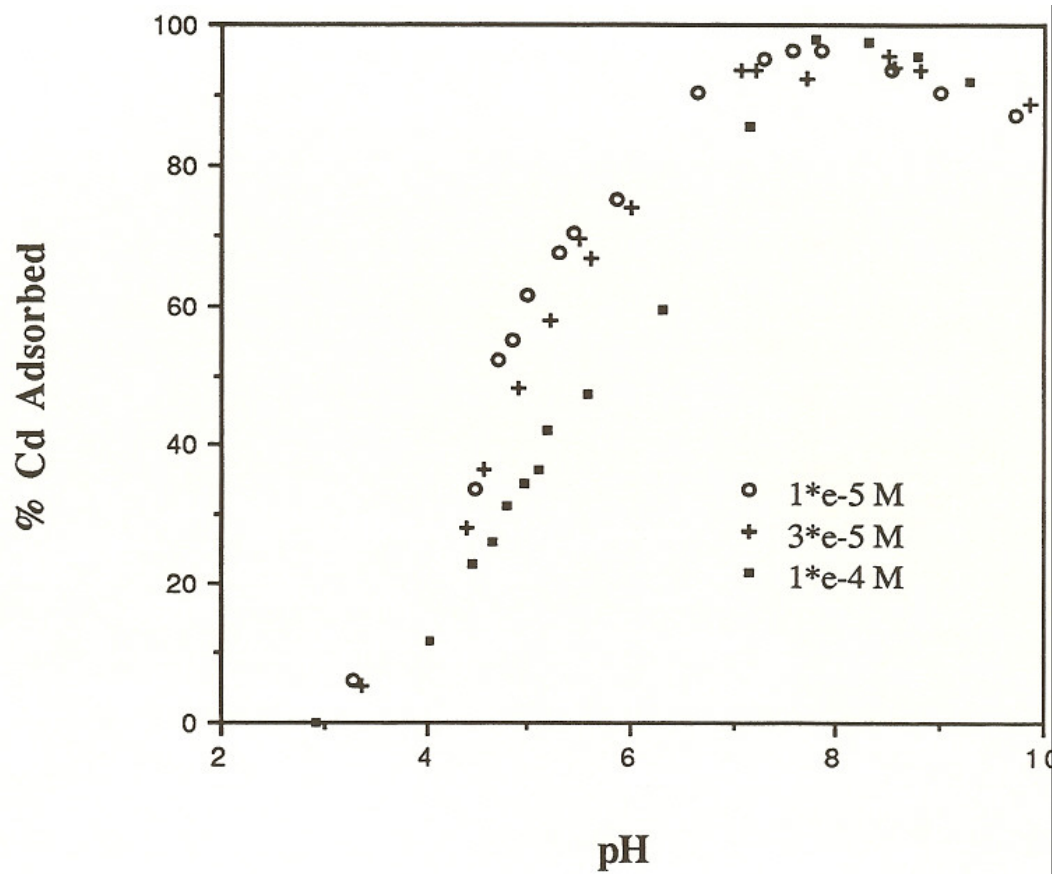


Figure 16. Adsorption of cadmium onto Penn silt loam;
Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

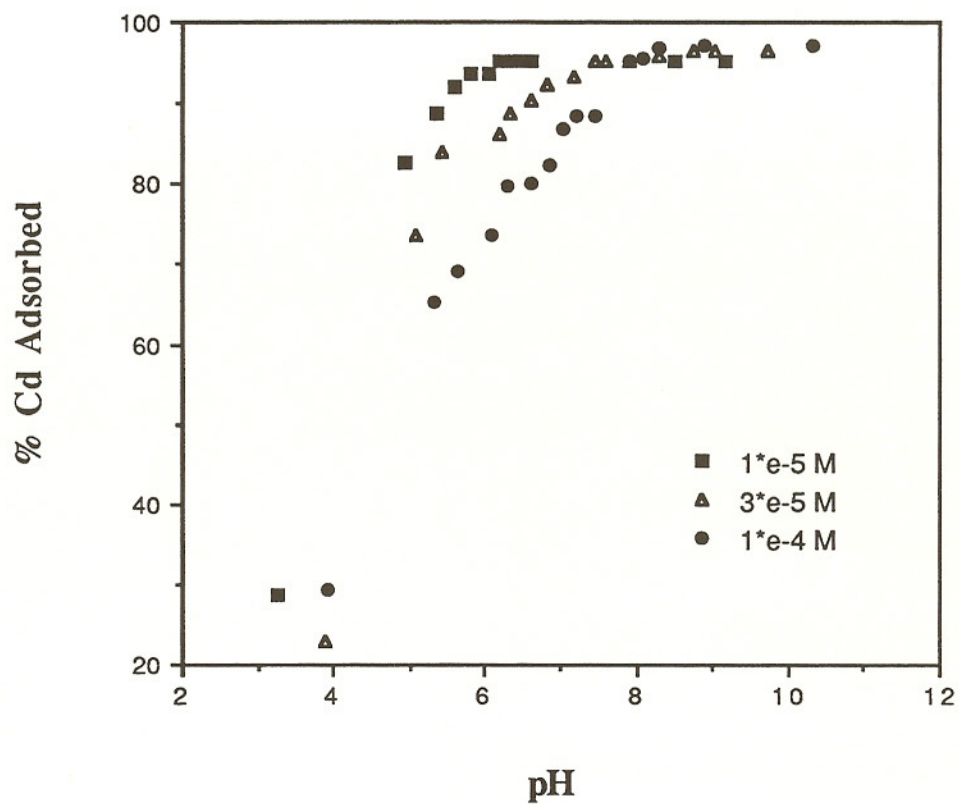


Figure 17. Adsorption of cadmium onto Whippany silty clay loam; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

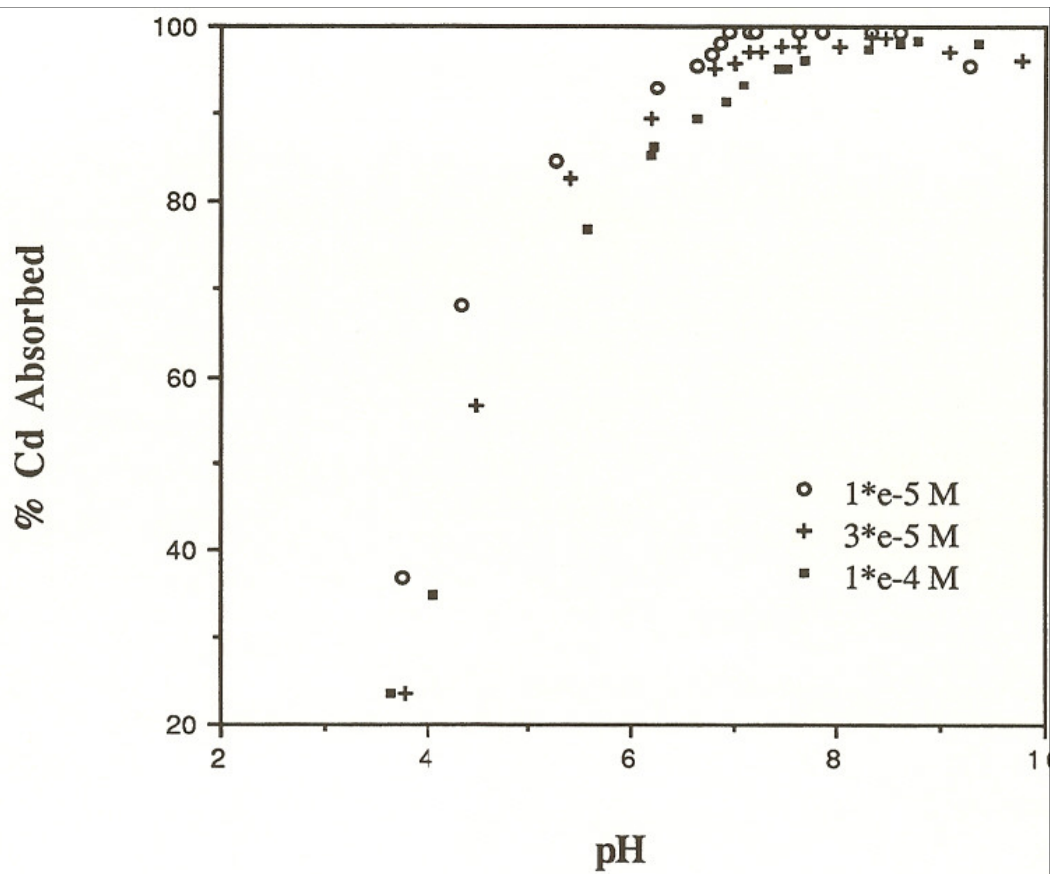


Figure 18. Adsorption of cadmium onto Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

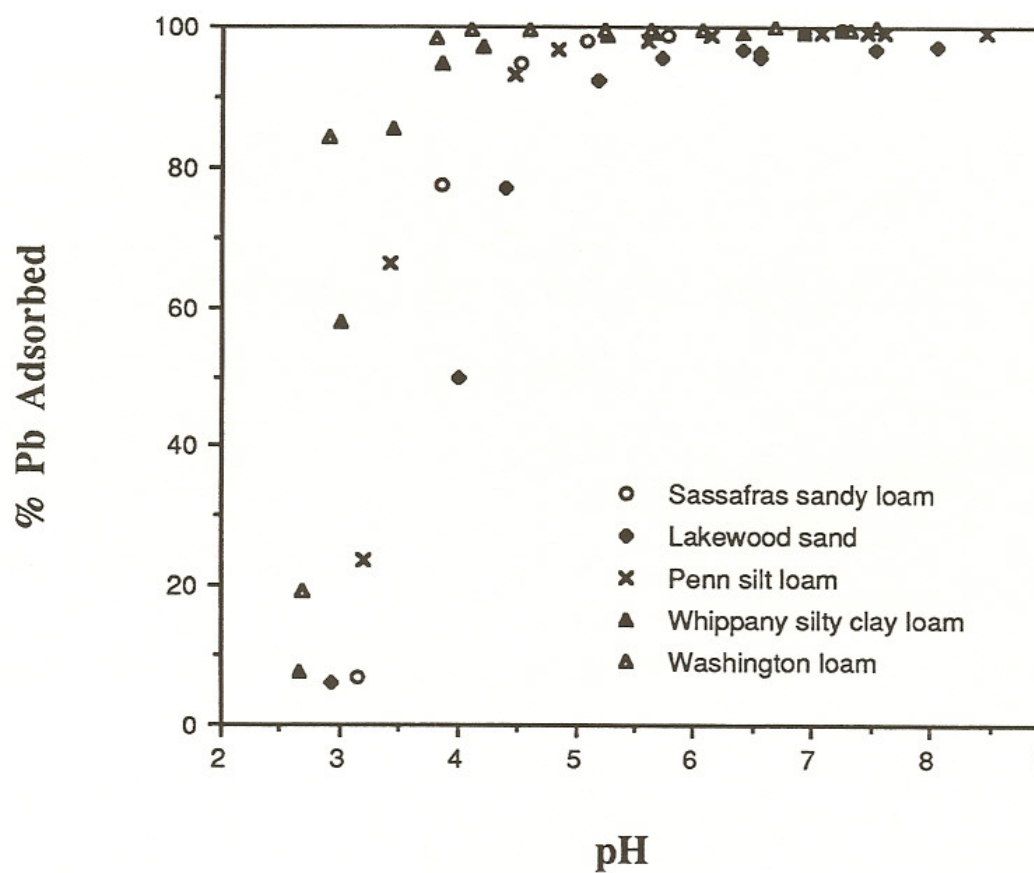


Figure 19. Adsorption of 1×10^{-5} M lead onto Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T : 25°C .

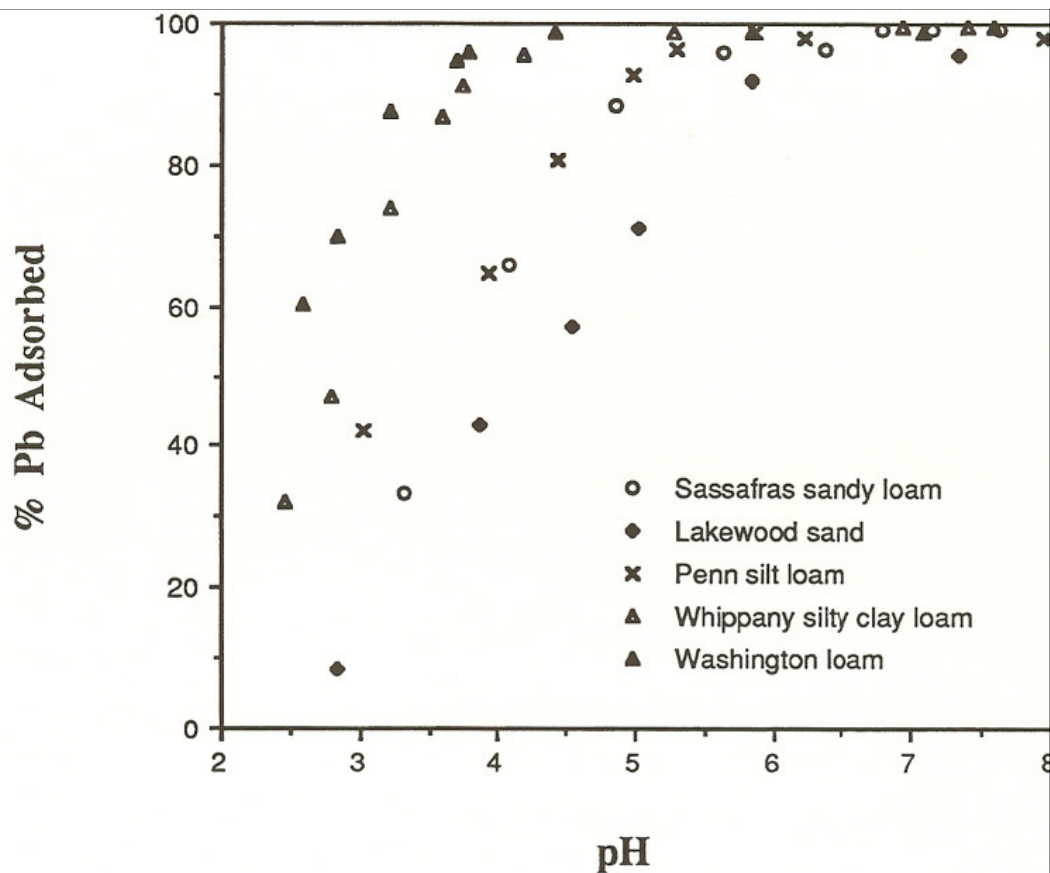


Figure 20. Adsorption of 3×10^{-5} M lead onto Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam. Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

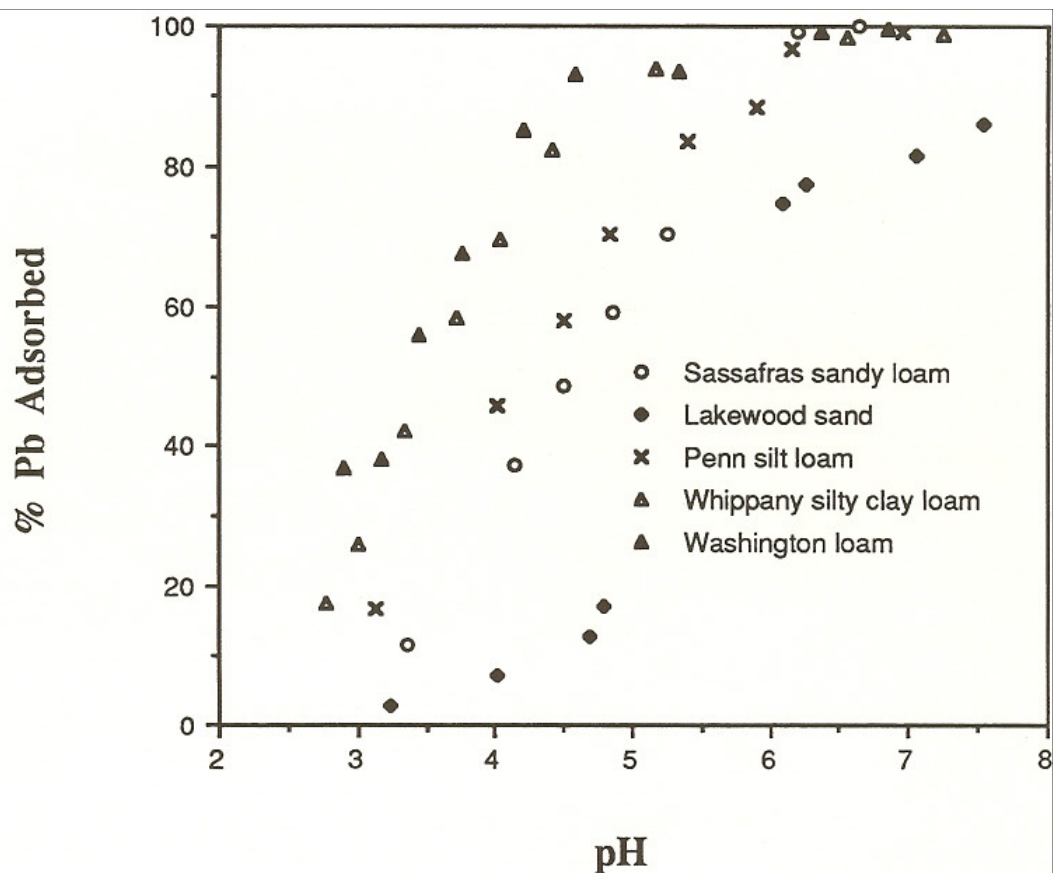


Figure 21. Adsorption of 1×10^{-4} M lead onto Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam. Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

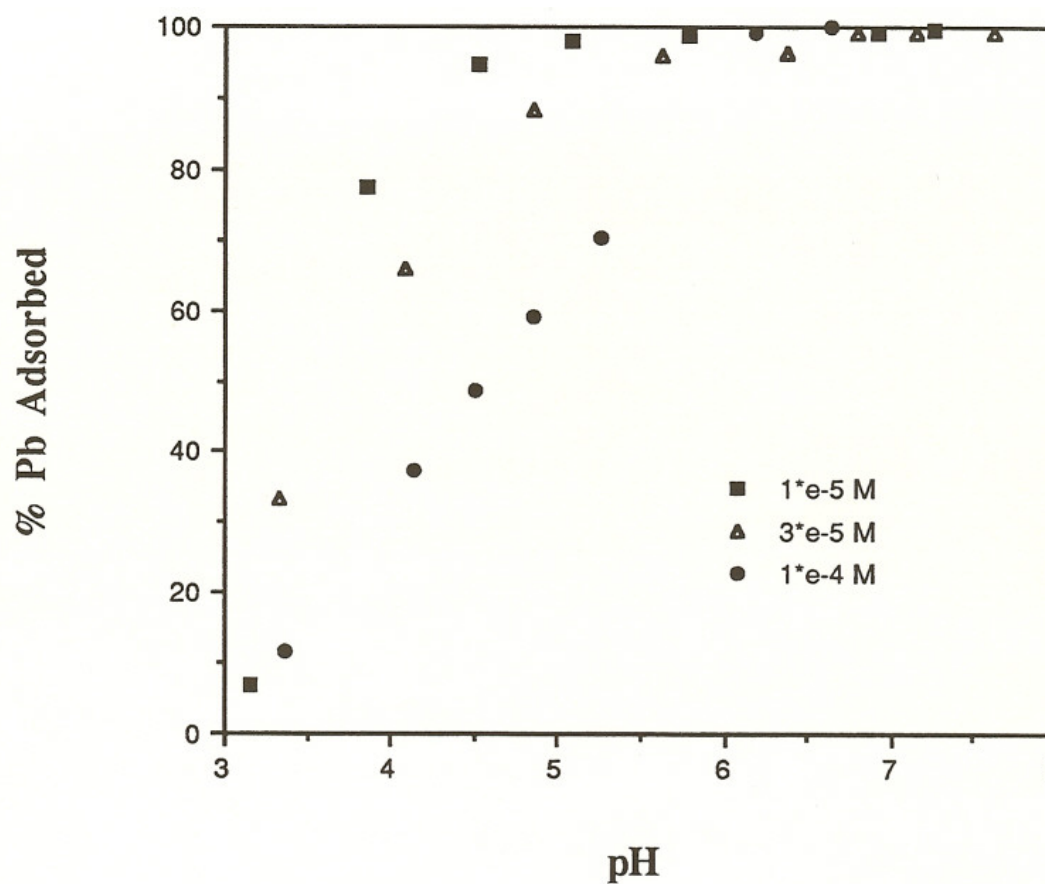
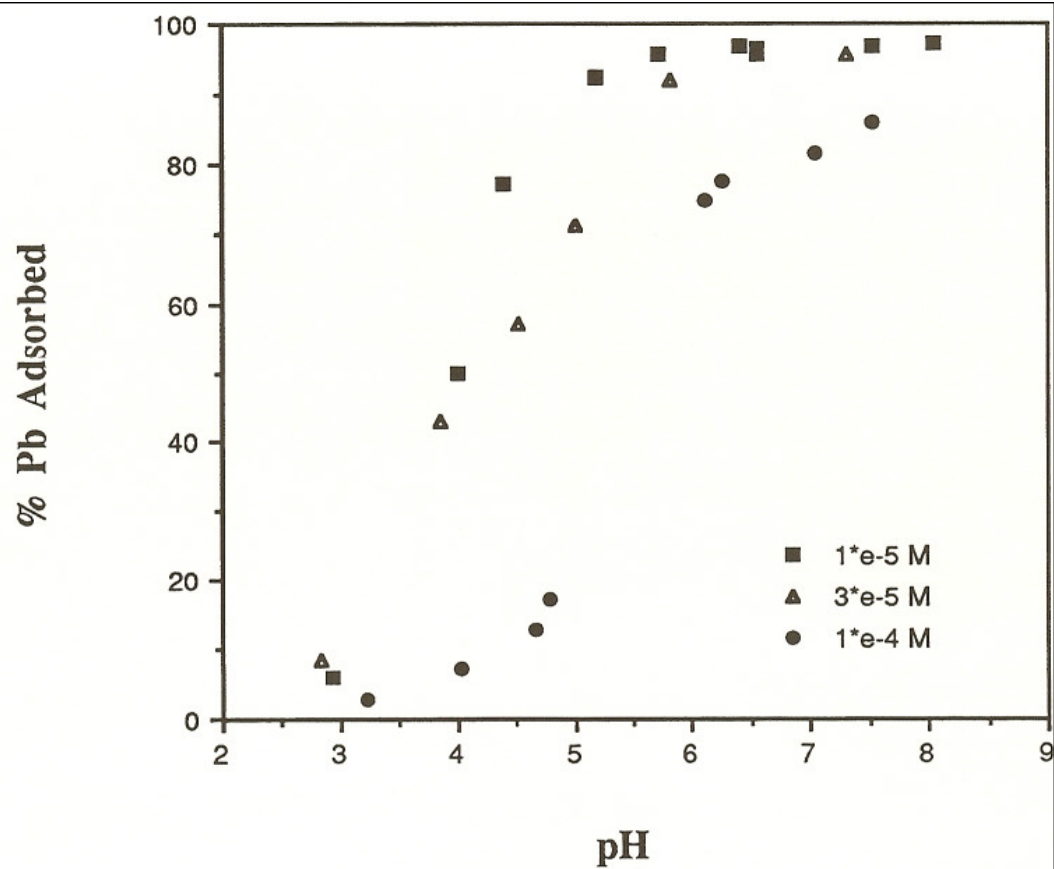
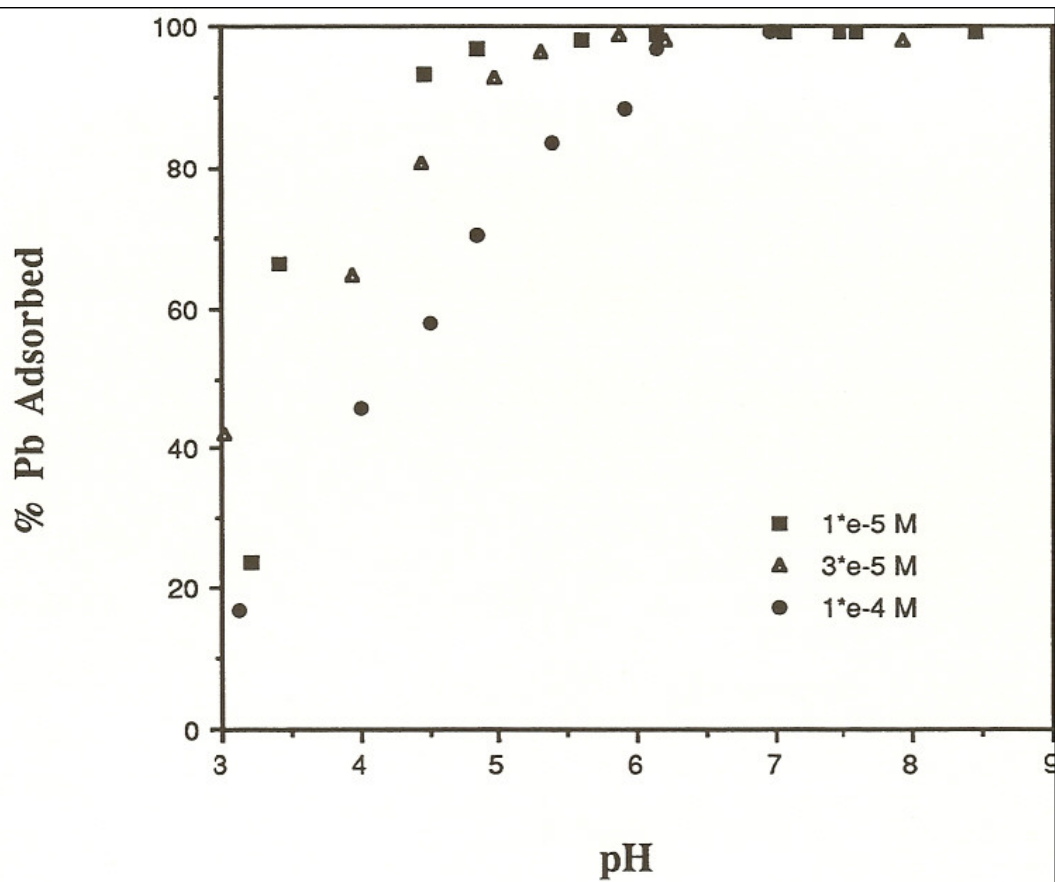


Figure 22. Adsorption of lead onto Sassafras sandy loam; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T : 25°C.



**Figure 23. Adsorption of lead onto Lakewood sand;
Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T =
25°C.**



**Figure 24. Adsorption of lead onto Penn silt loam;
Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T =
25°C.**

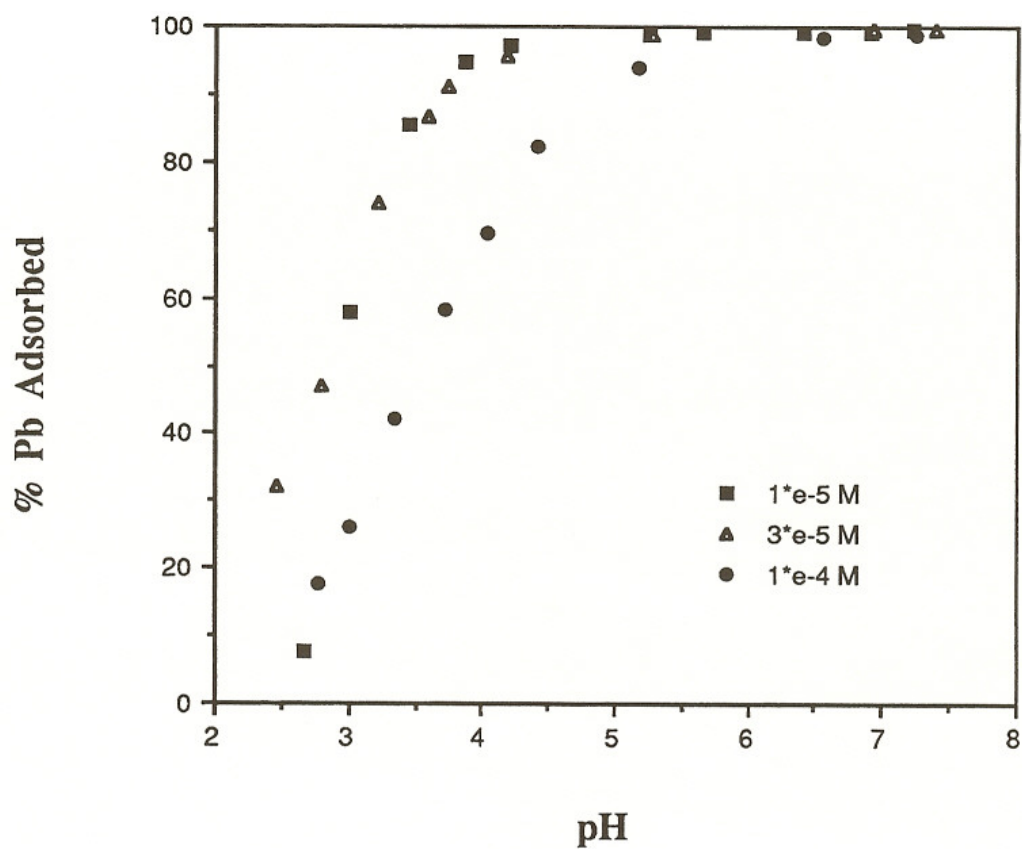
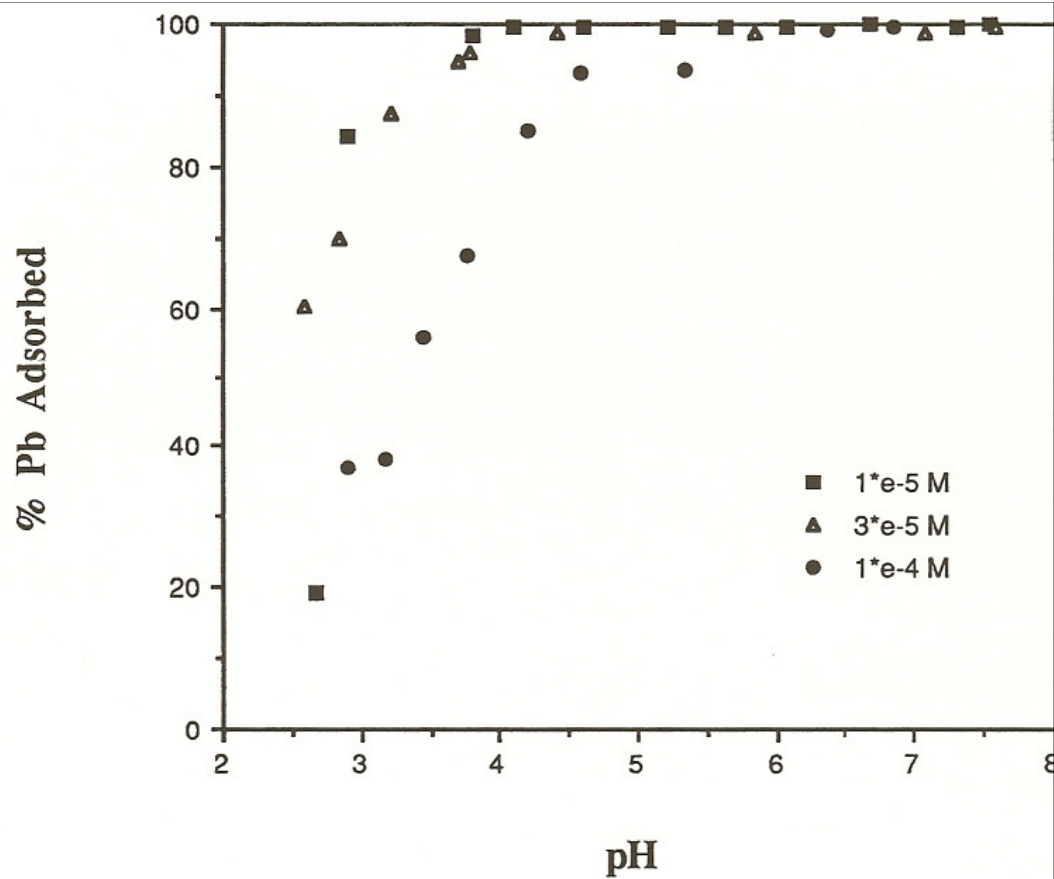


Figure 25. Adsorption of lead onto Whippany silty clay loam; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.



**Figure 26. Adsorption of lead onto Washington loam;
Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T =
25°C.**

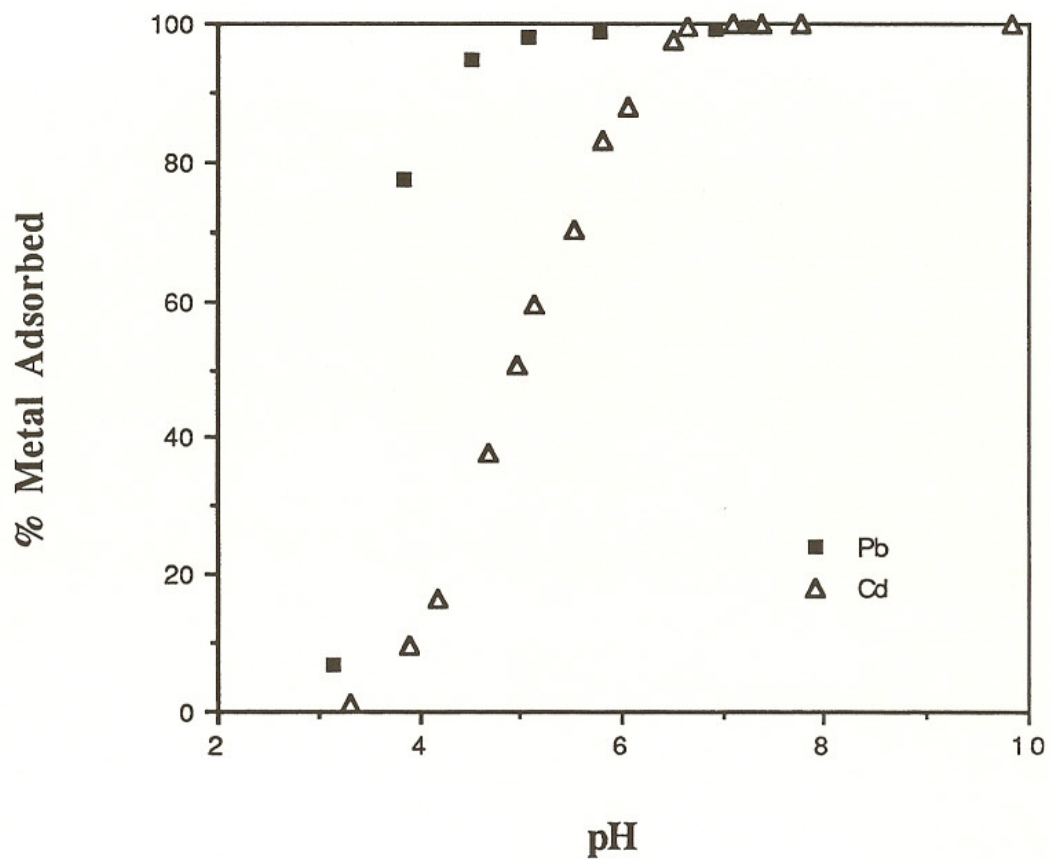


Figure 27. Adsorption of 1×10^{-5} M cadmium and lead onto Sassafra sandy loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

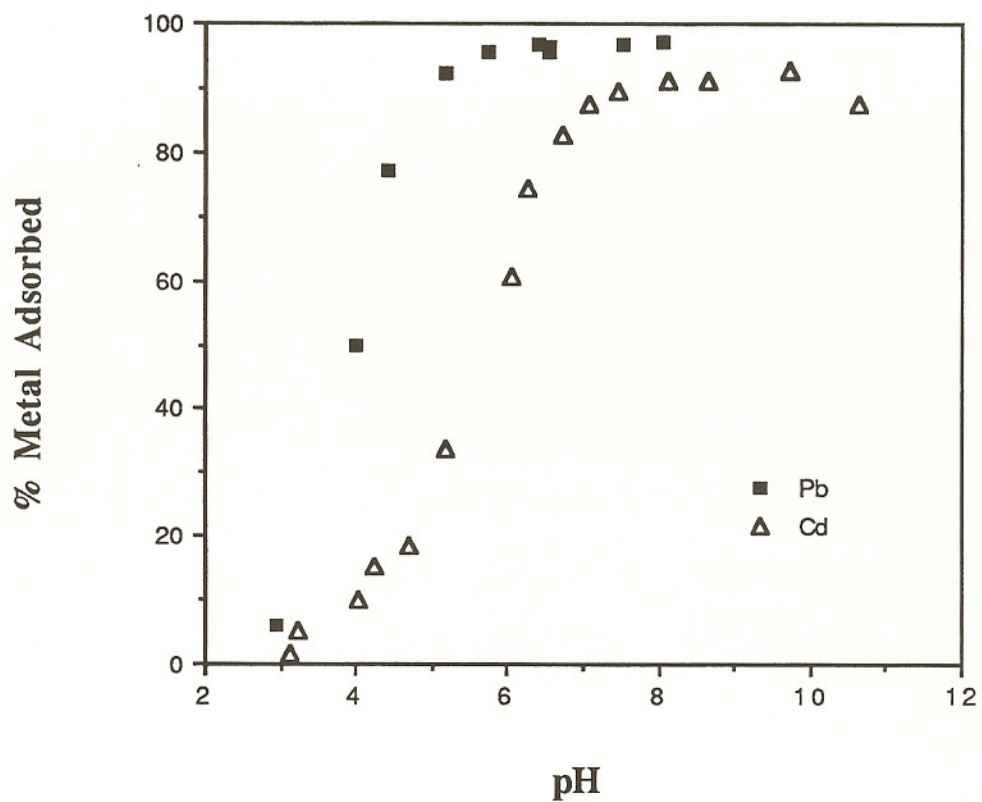


Figure 28. Adsorption of 1×10^{-5} M cadmium and lead onto Lakewood sand; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; $T=25^\circ\text{C}$.

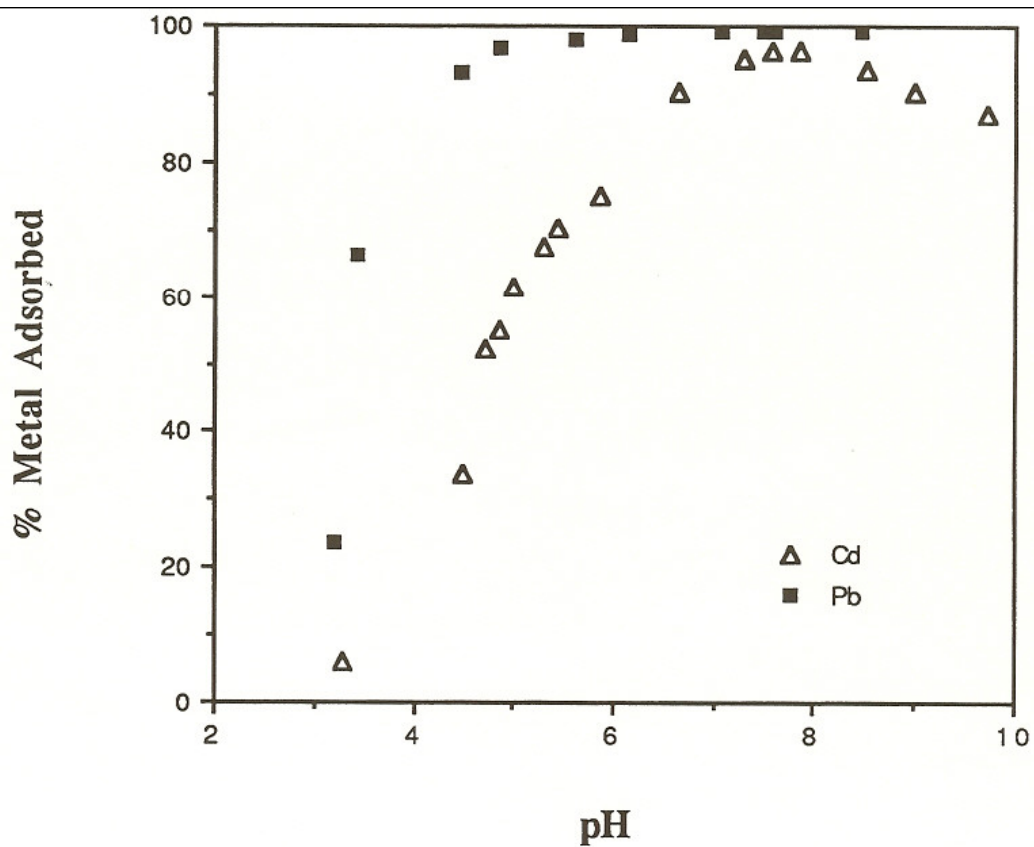


Figure 29. Adsorption of 1×10^{-5} M cadmium and lead onto Penn silt loam; Soil:water = 1g/100mL; I = 0.01 N NaNO_3 ; T=25°C.

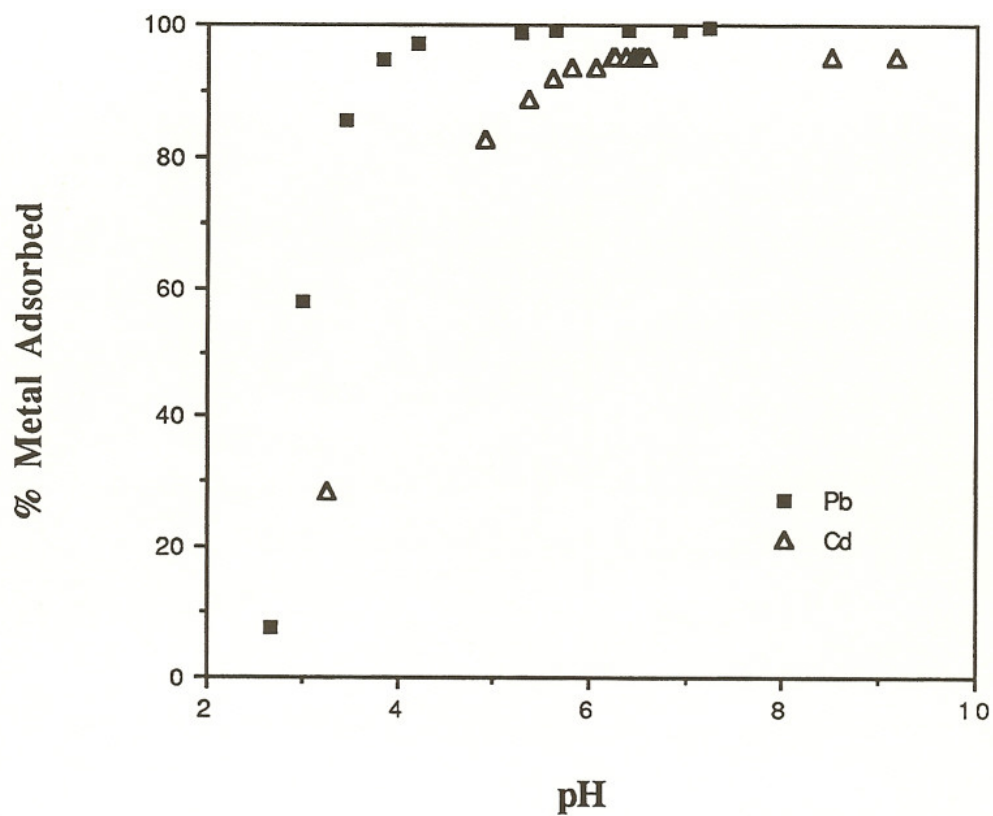


Figure 30. Adsorption of 1×10^{-5} M cadmium and lead onto Whippany silty clay loam; Soil:water = 1g/100mL; $I = 0.01$ M NaNO_3 ; $T=25^\circ\text{C}$.

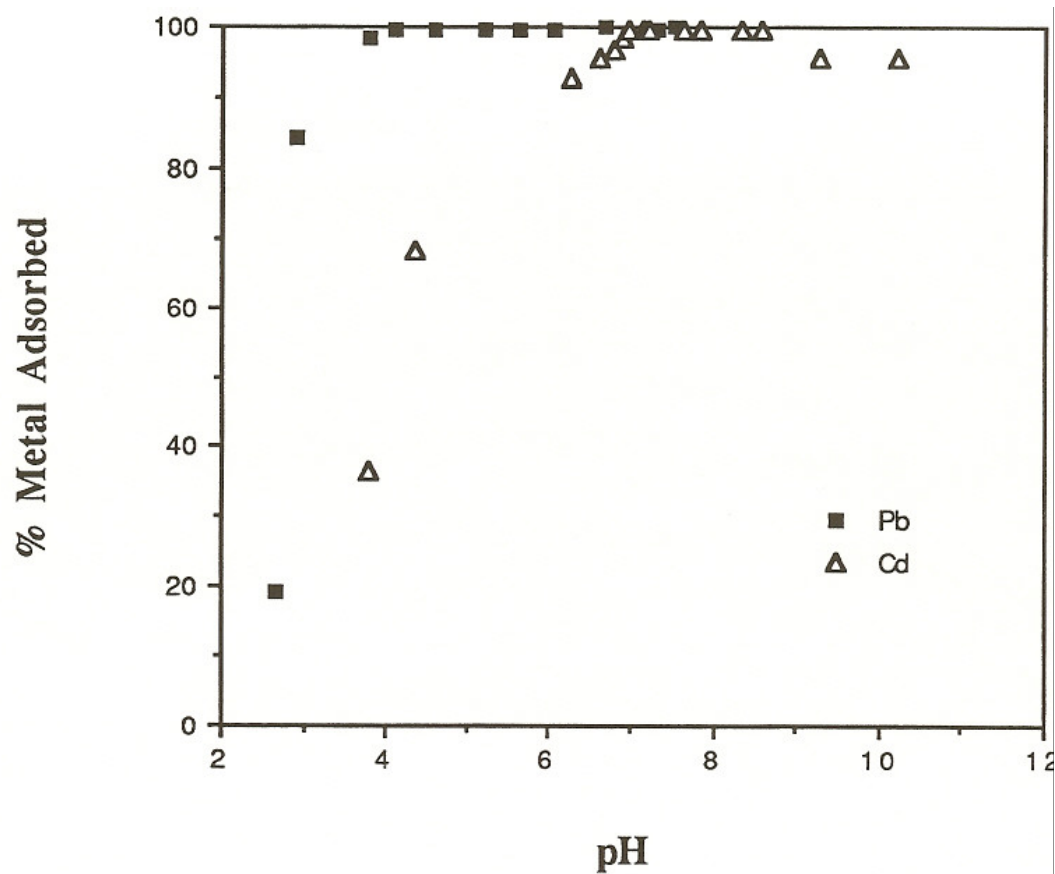


Figure 31. Adsorption of 1×10^{-5} M cadmium and lead onto Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; $T=25^\circ\text{C}$.

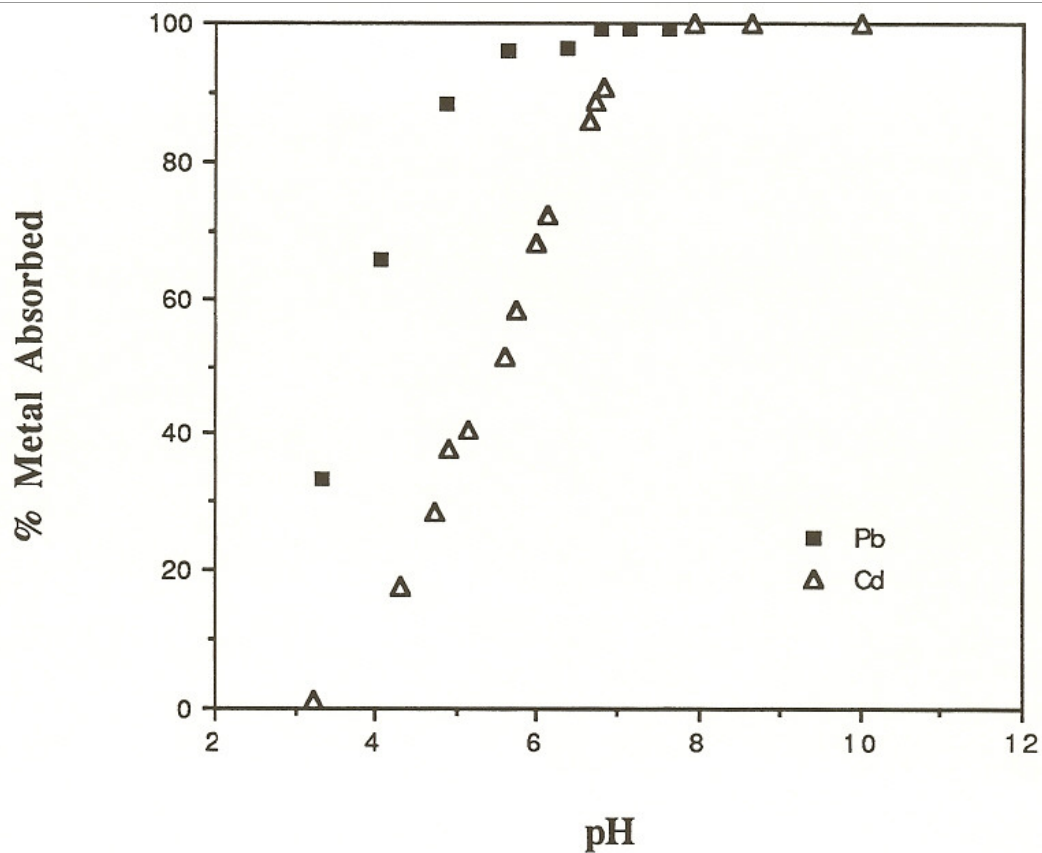


Figure 32. Adsorption of 3×10^{-5} M cadmium and lead onto Sassafra sandy loam; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

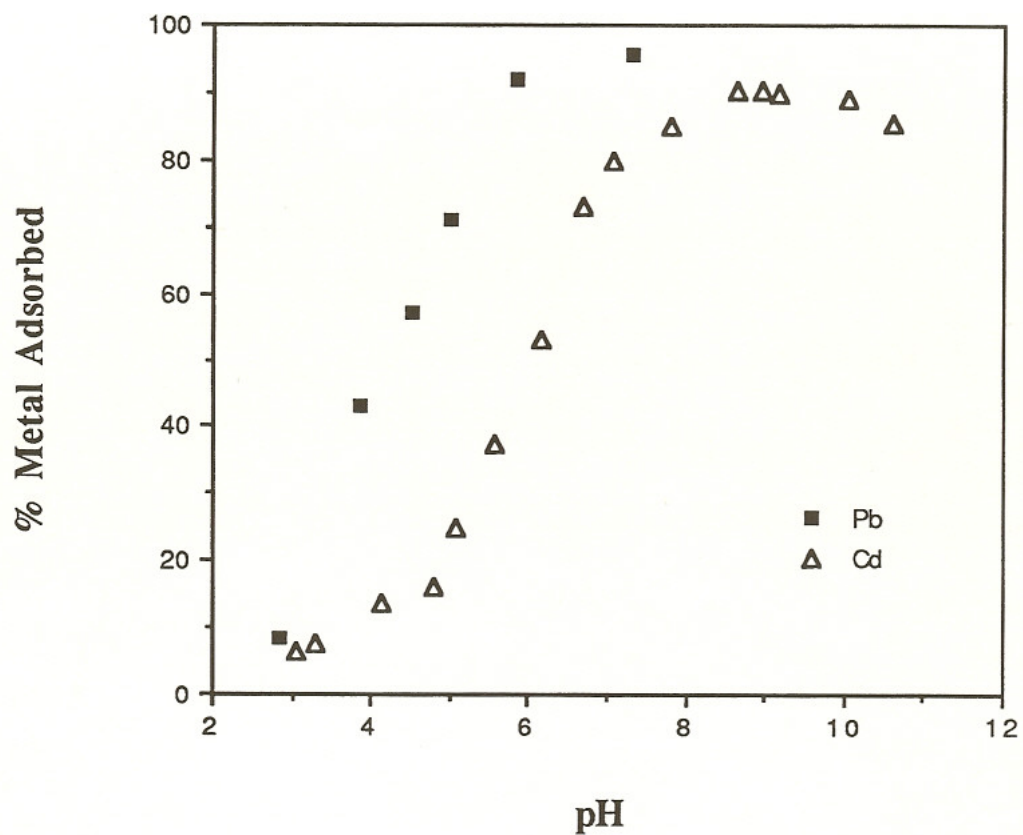


Figure 33. Adsorption of 3×10^{-5} M cadmium and lead onto Lakewood sand; Soil:water = 1g/100mL; I = 0.01 N NaNO_3 ; $T=25^\circ\text{C}$.

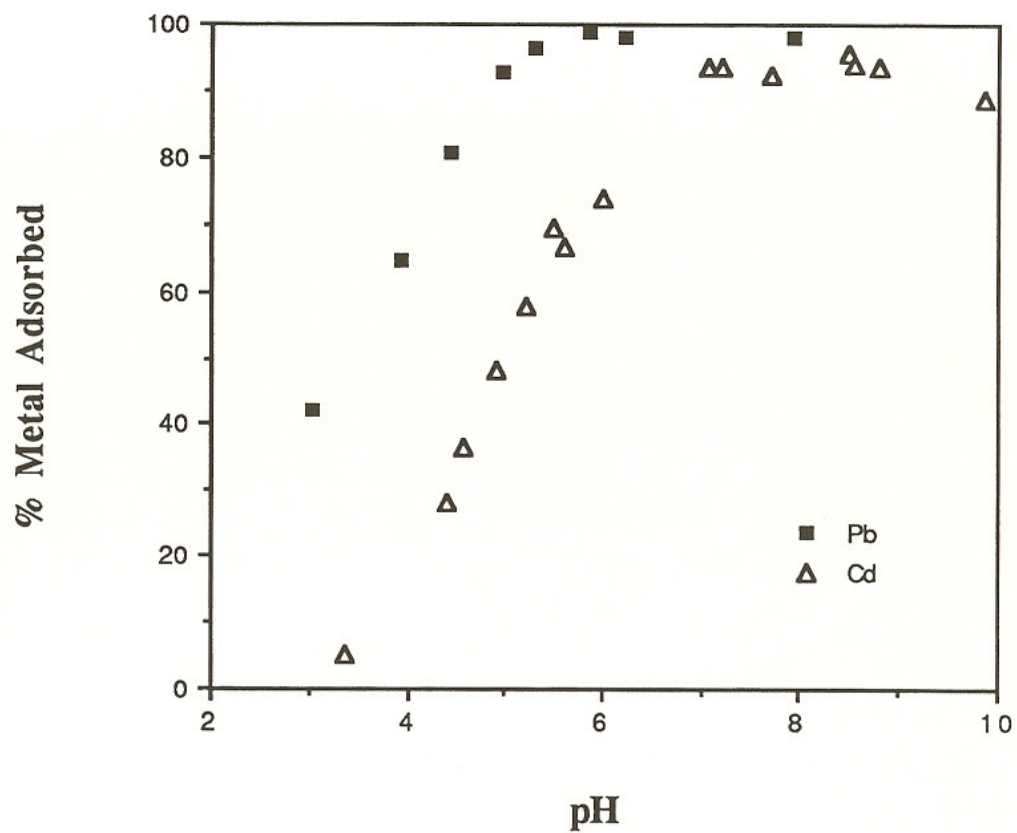


Figure 34. Adsorption of 3×10^{-5} M cadmium and lead onto Penn silt loam; Soil:water = 1g/100mL; I = 0.01 N NaNO_3 ; T=25°C.

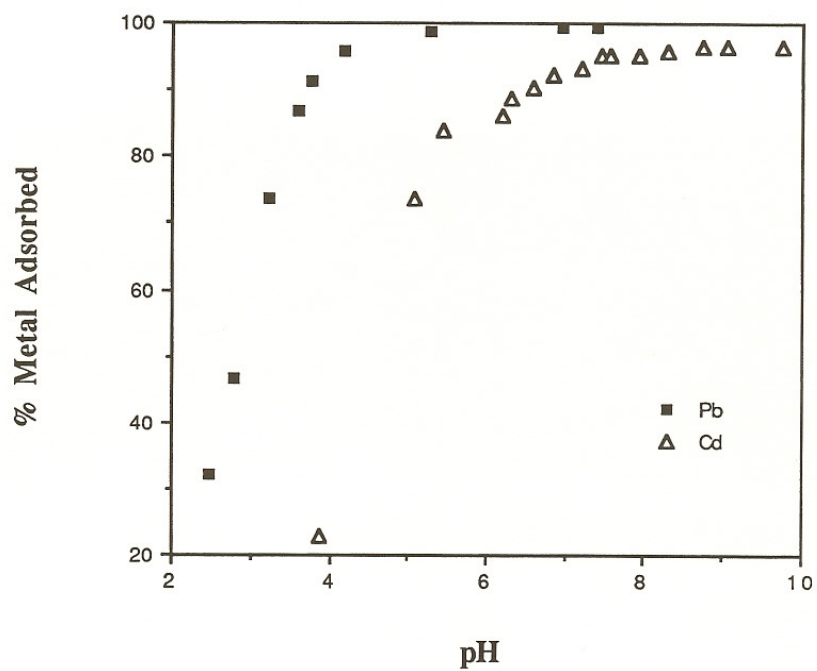


Figure 35. Adsorption of 3×10^{-5} M cadmium and lead onto Whippany silty clay loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T=25°C.

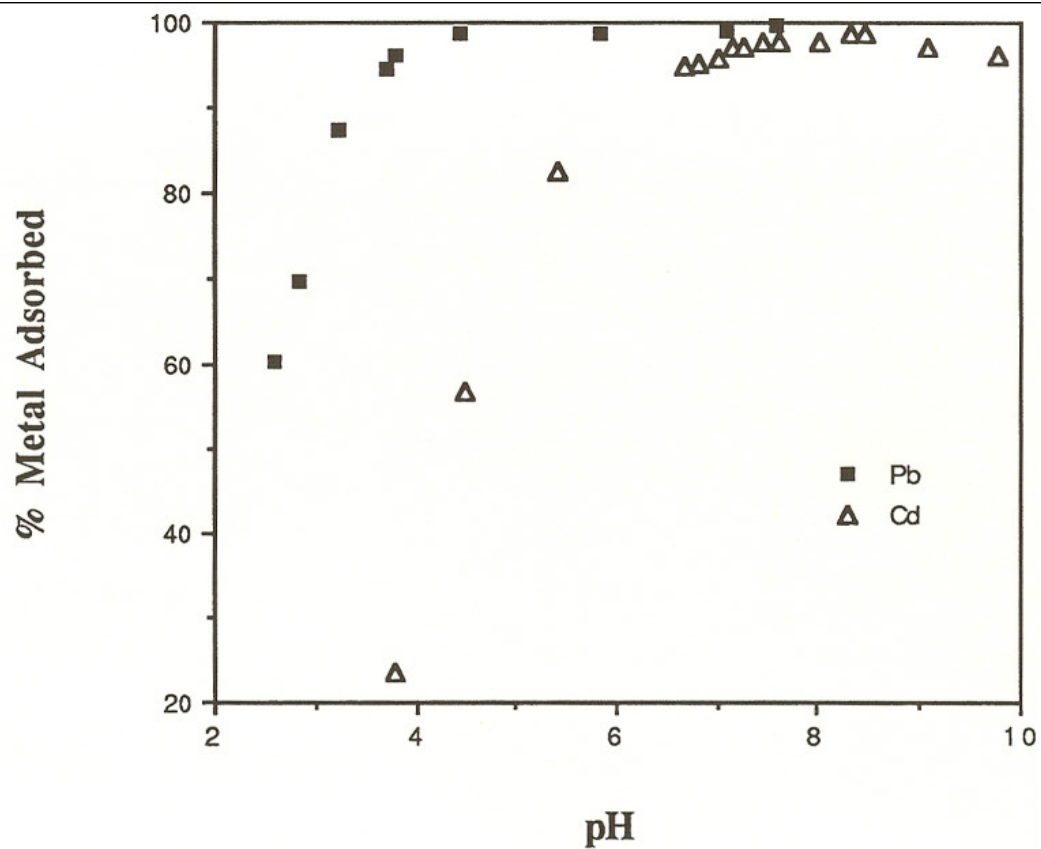


Figure 36. Adsorption of 3×10^{-5} M cadmium and lead onto Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T=25°C.

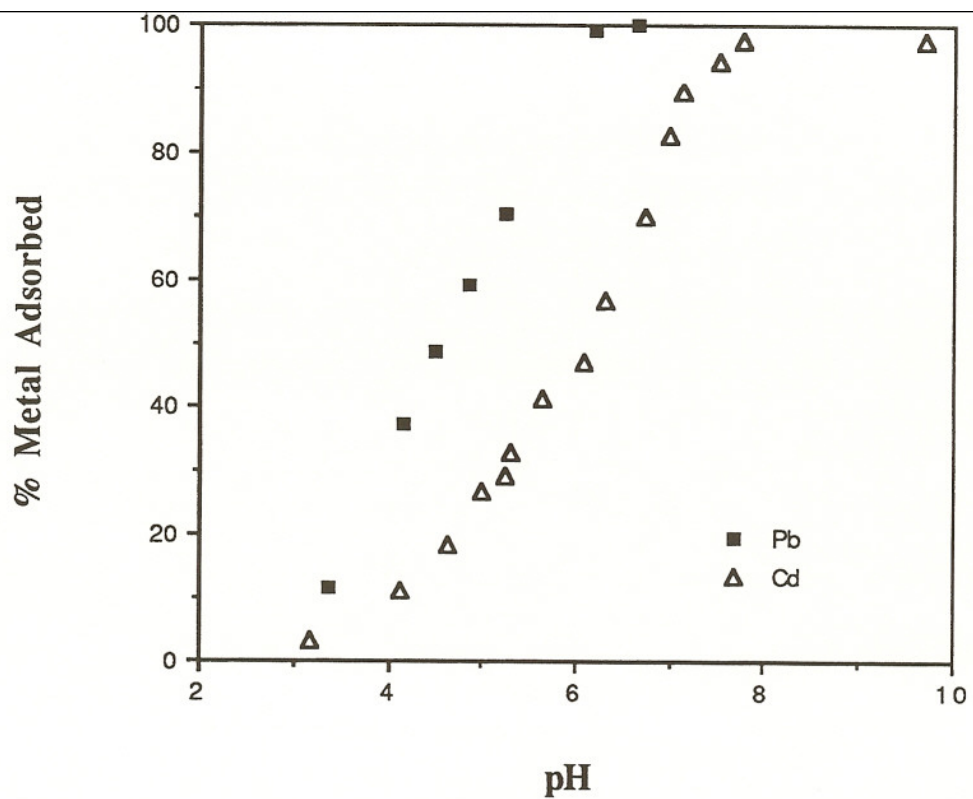


Figure 37. Adsorption of 1×10^{-4} M cadmium and lead onto Sassafras sandy loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

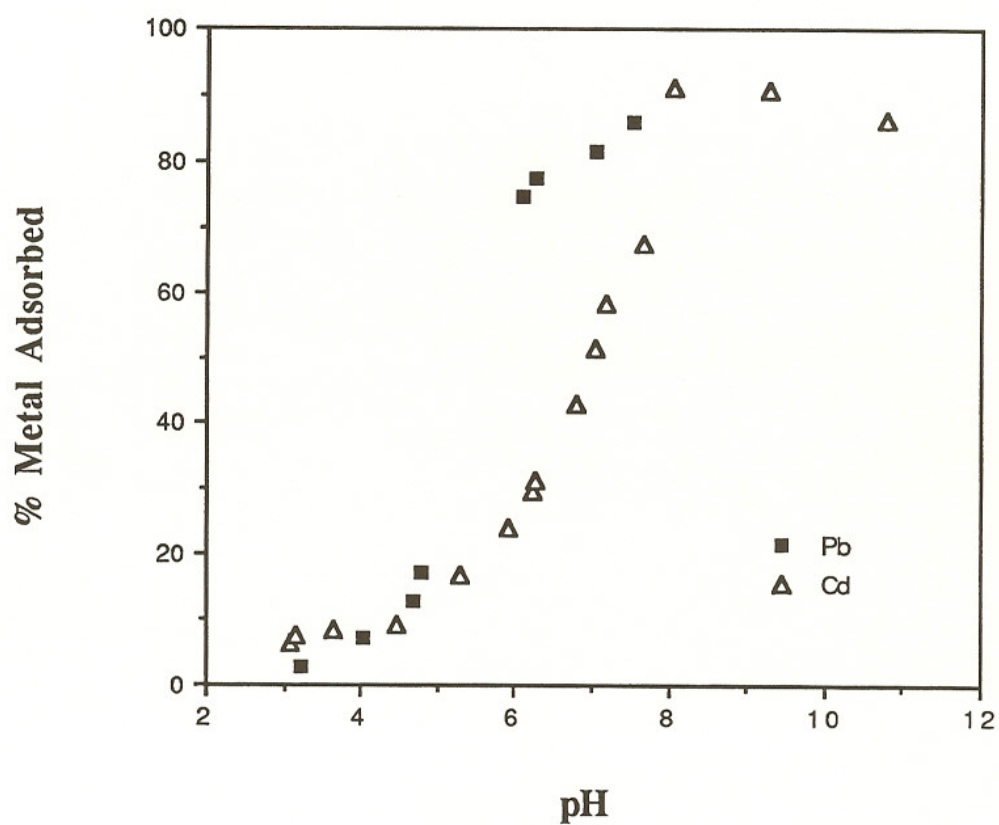


Figure 38. Adsorption of 1×10^{-4} M cadmium and lead onto Lakewood sand; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; $T=25^\circ\text{C}$.

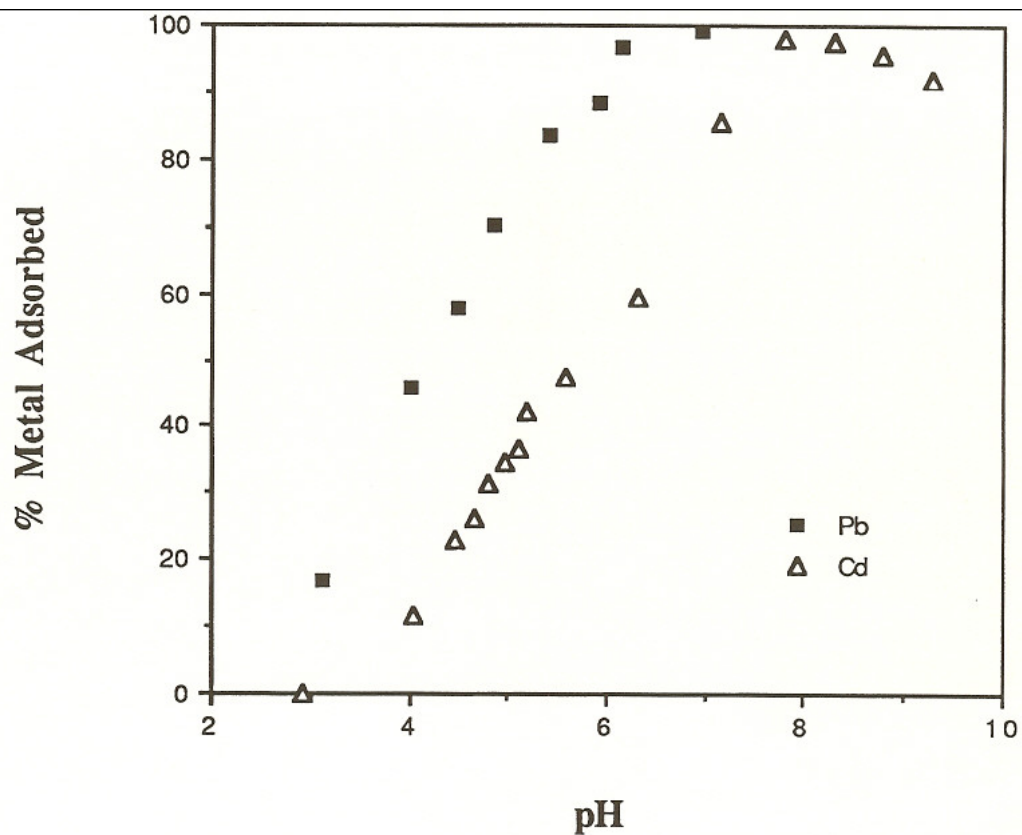


Figure 39. Adsorption of 1×10^{-4} M cadmium and lead onto Penn silt loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T=25°C.

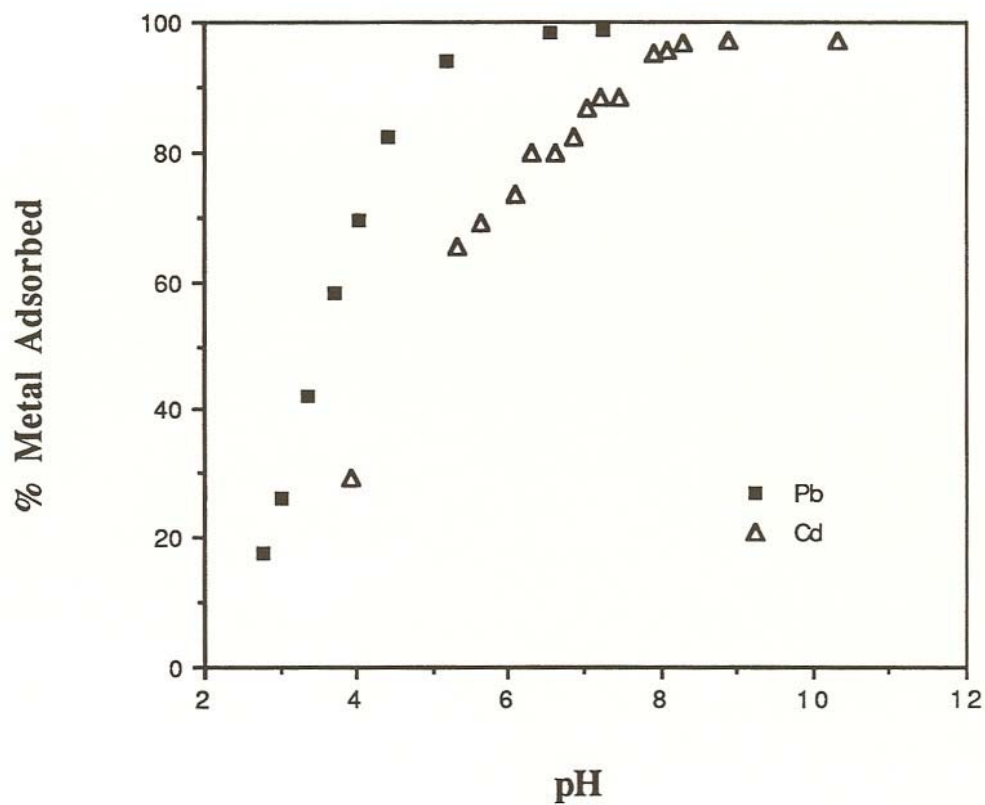


Figure 40. Adsorption of 1×10^{-4} M cadmium and lead onto Whippany silty clay loam; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T=25°C.

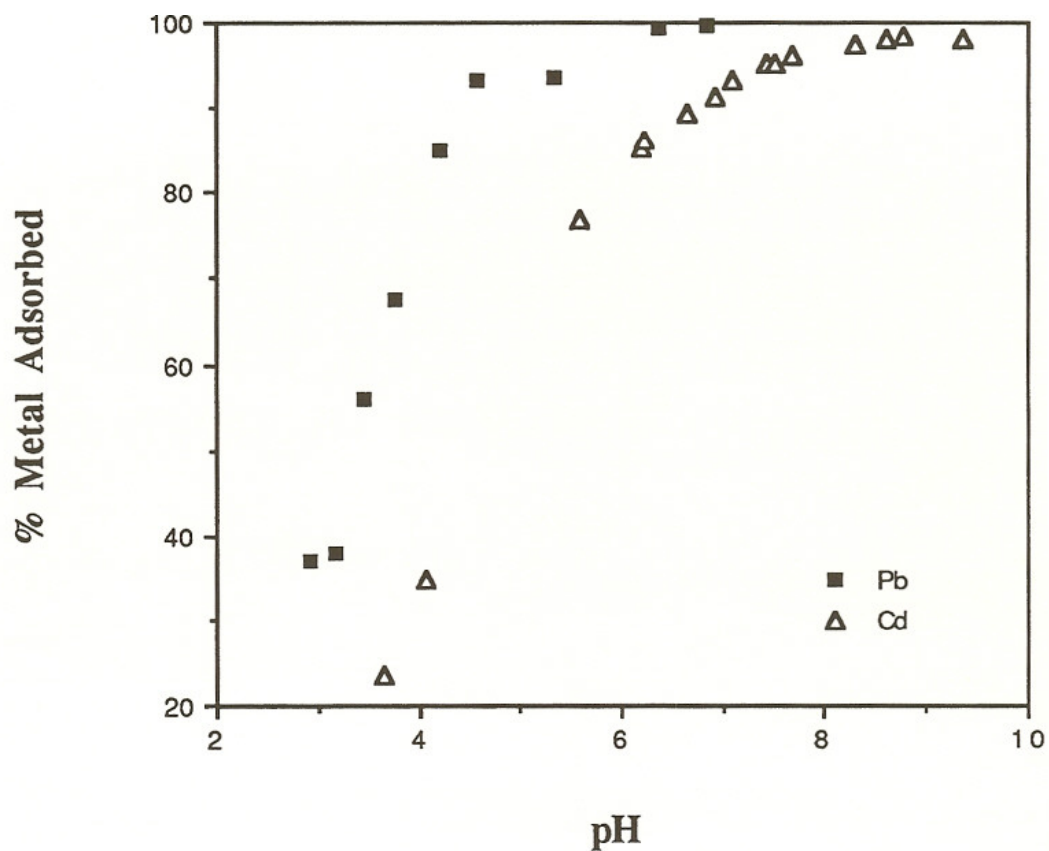


Figure 41. Adsorption of 1×10^{-4} M cadmium and lead onto Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T=25°C.

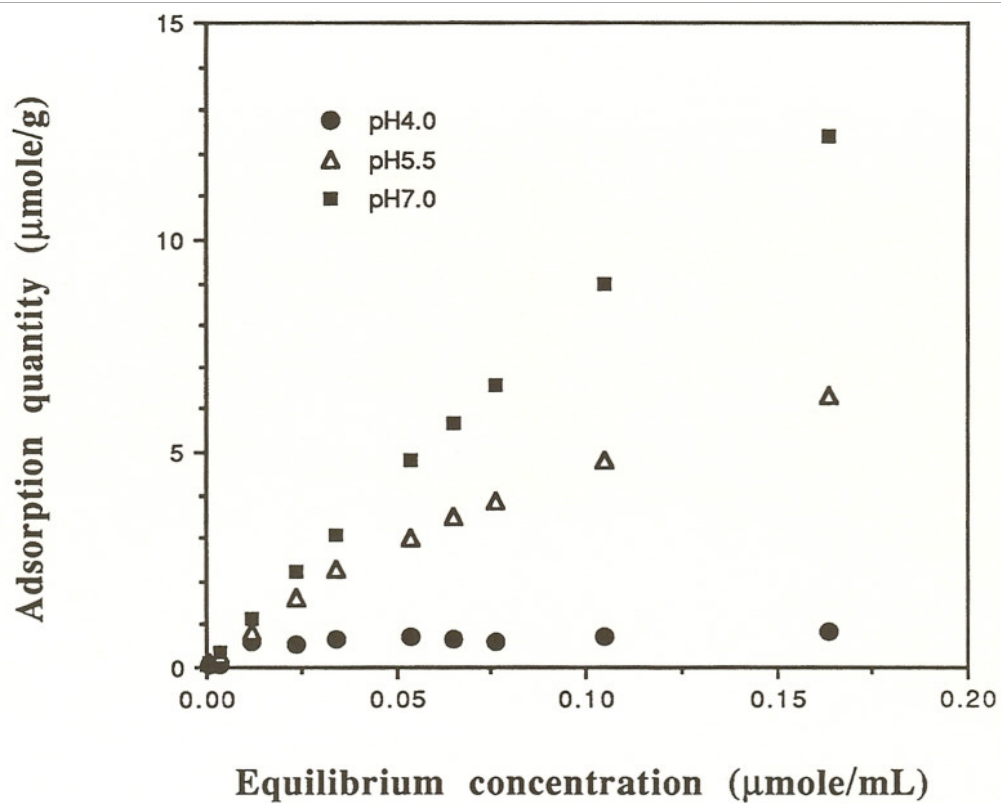


Figure 42. Adsorption isotherms of cadmium at three pH values for Sassafras sandy loam; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

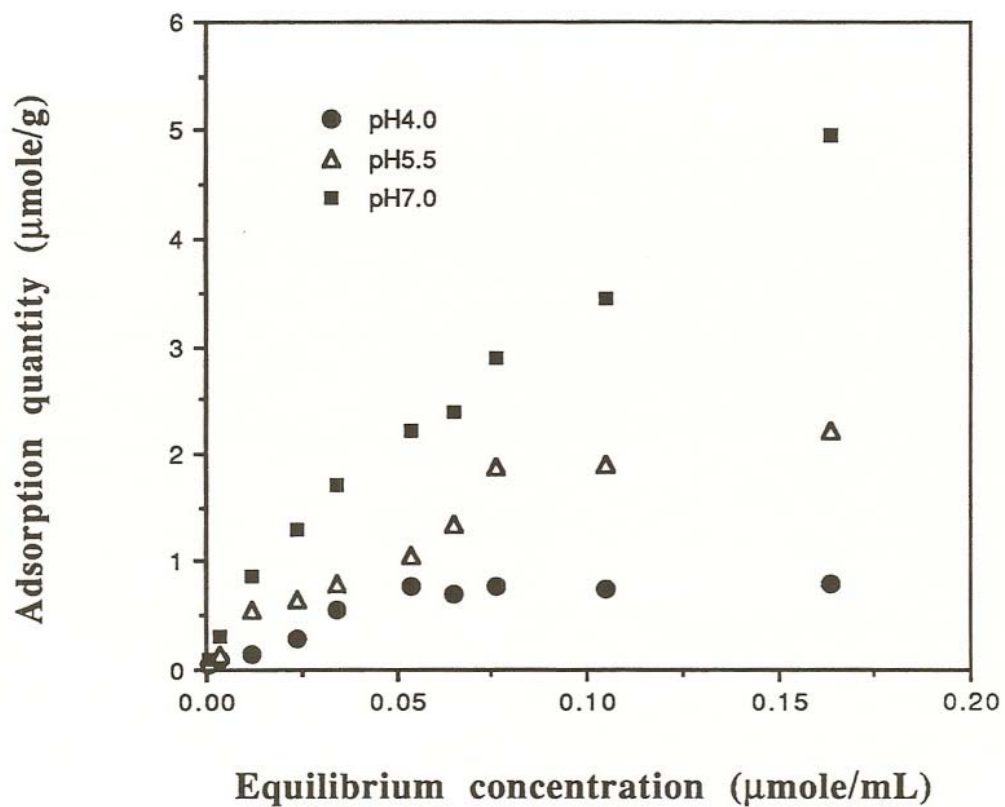


Figure 43. Adsorption isotherms of cadmium at three pH values for Lakewood sand; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

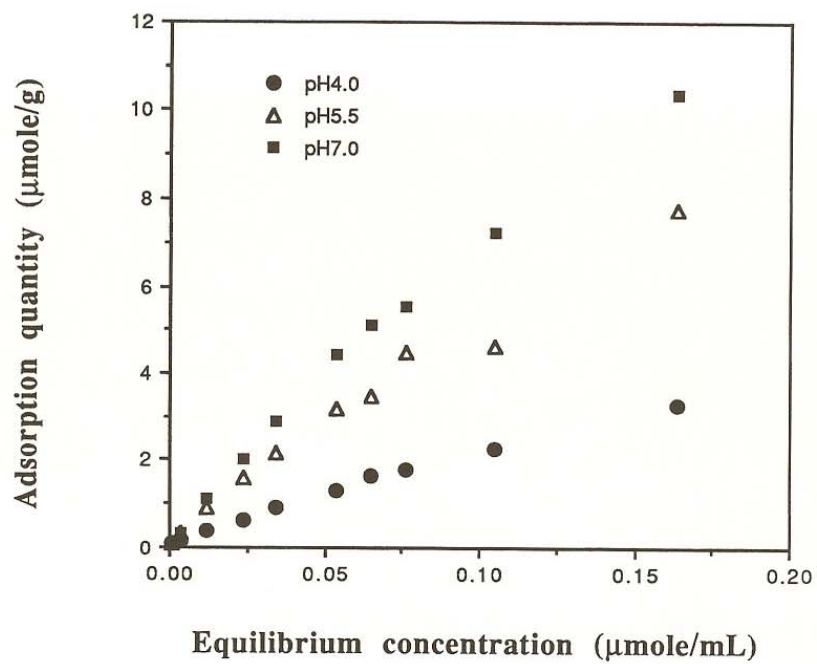


Figure 44. Adsorption isotherms of cadmium at three pH values for Penn silt loam; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

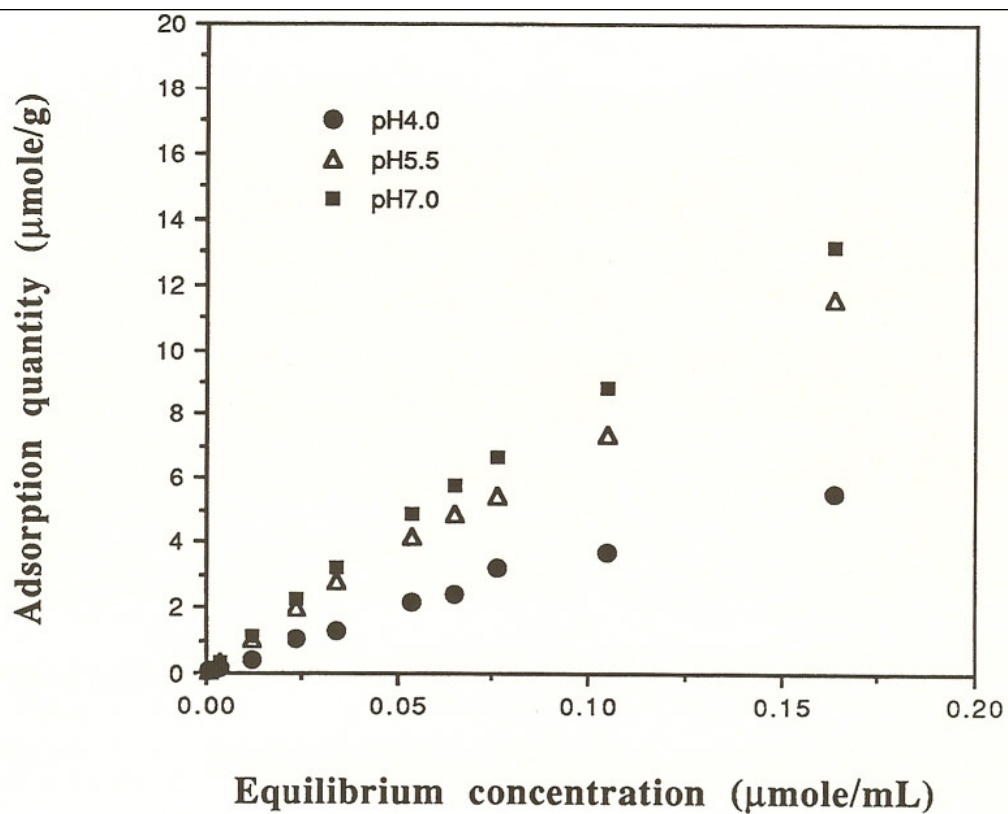


Figure 45. Adsorption isotherms of cadmium at three pH values for Whippany silty clay loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

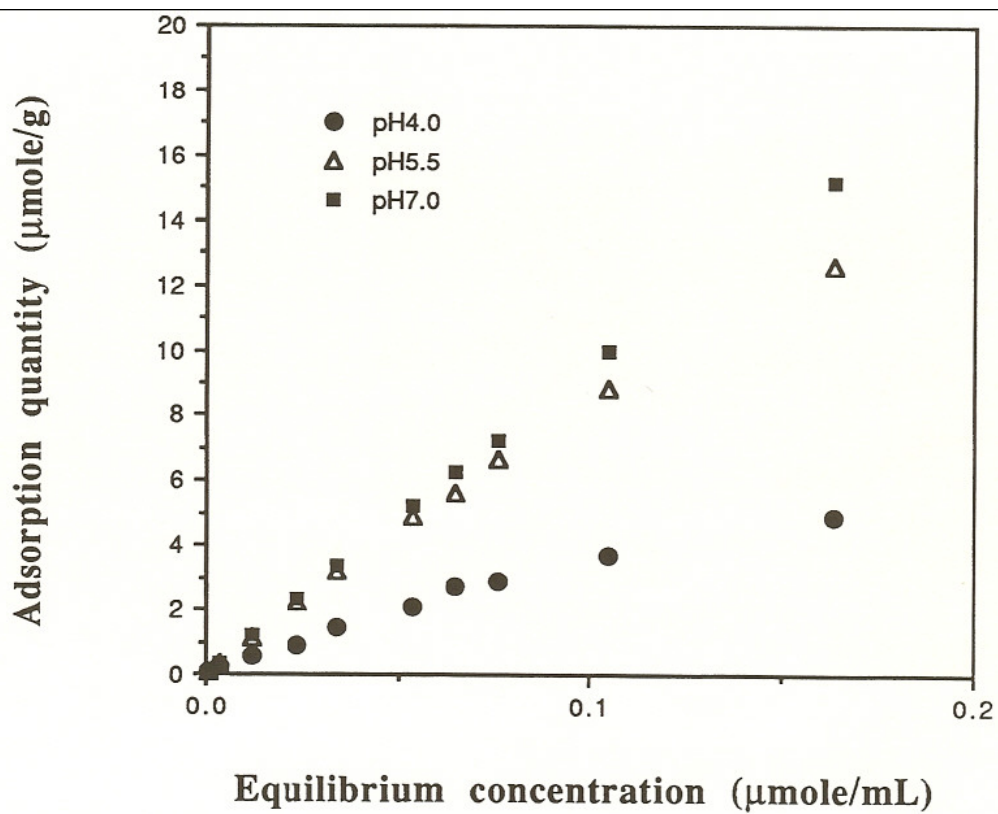


Figure 46. Adsorption isotherms of cadmium at three pH values for Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

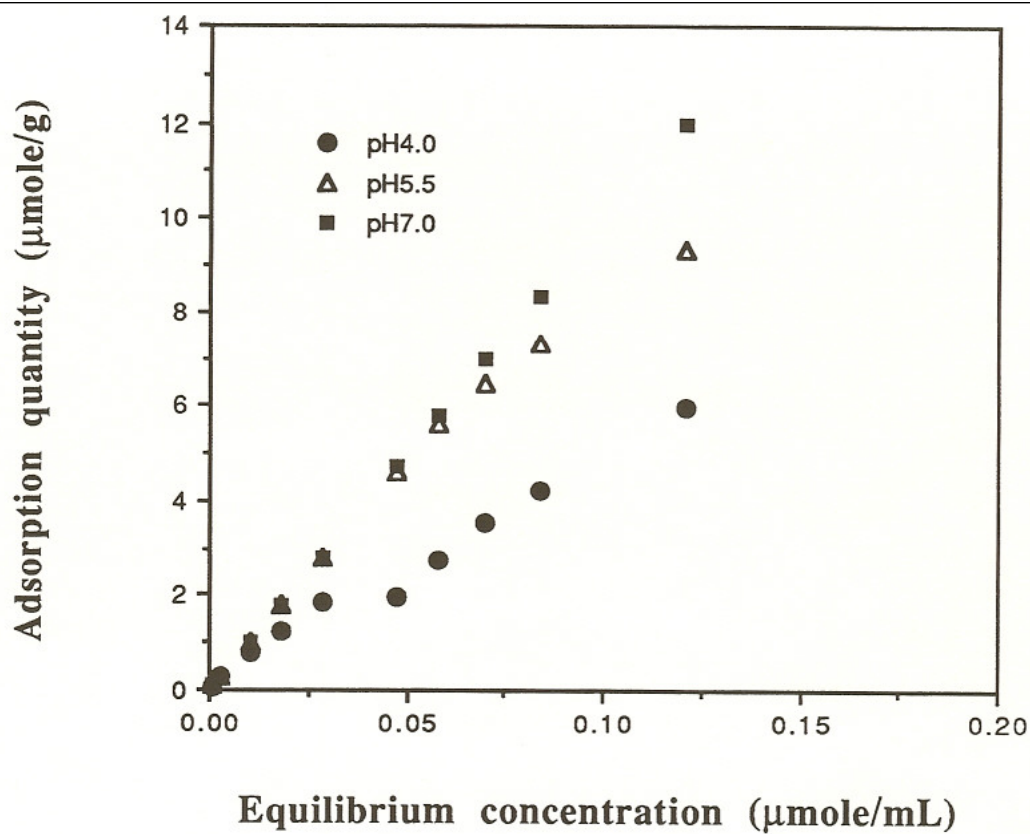


Figure 47. Adsorption isotherms of lead at three pH values for Sassafra sandy loam; Soil:water = 1g/100mL; $I = 0.01 \text{ M NaNO}_3$; $T = 25^\circ\text{C}$.

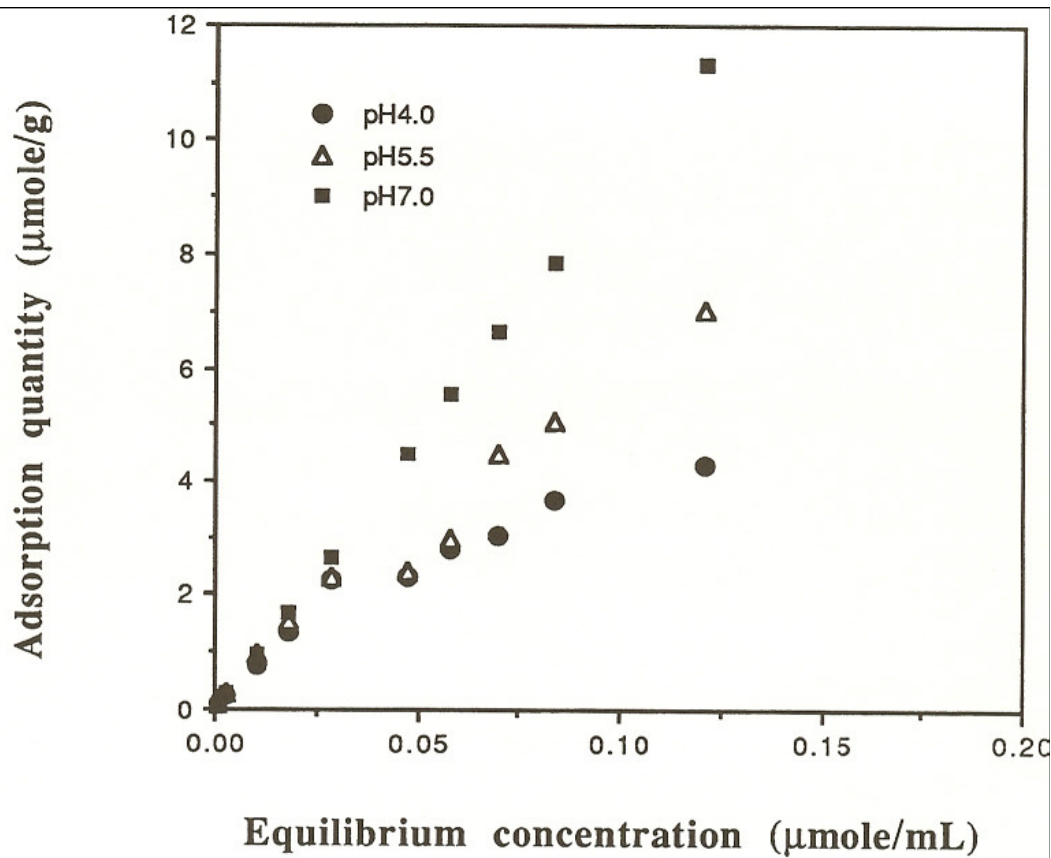


Figure 48. Adsorption isotherms of lead at three pH values for Lakewood sand; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

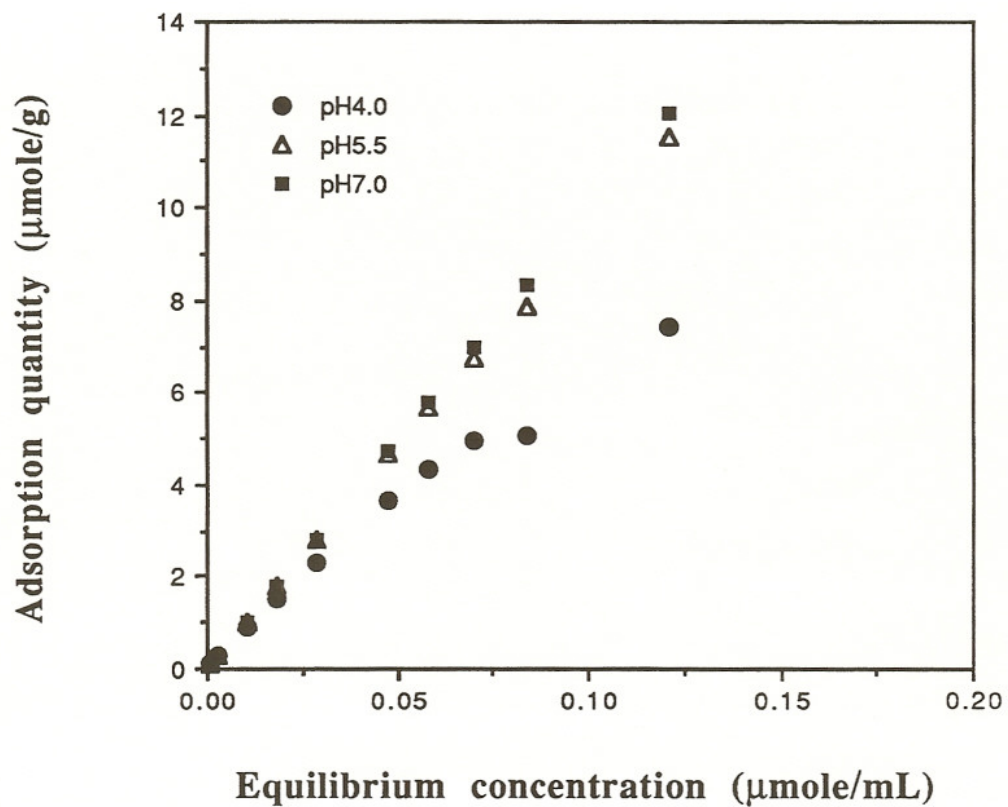


Figure 49. Adsorption isotherms of lead at three pH values for Penn silt loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

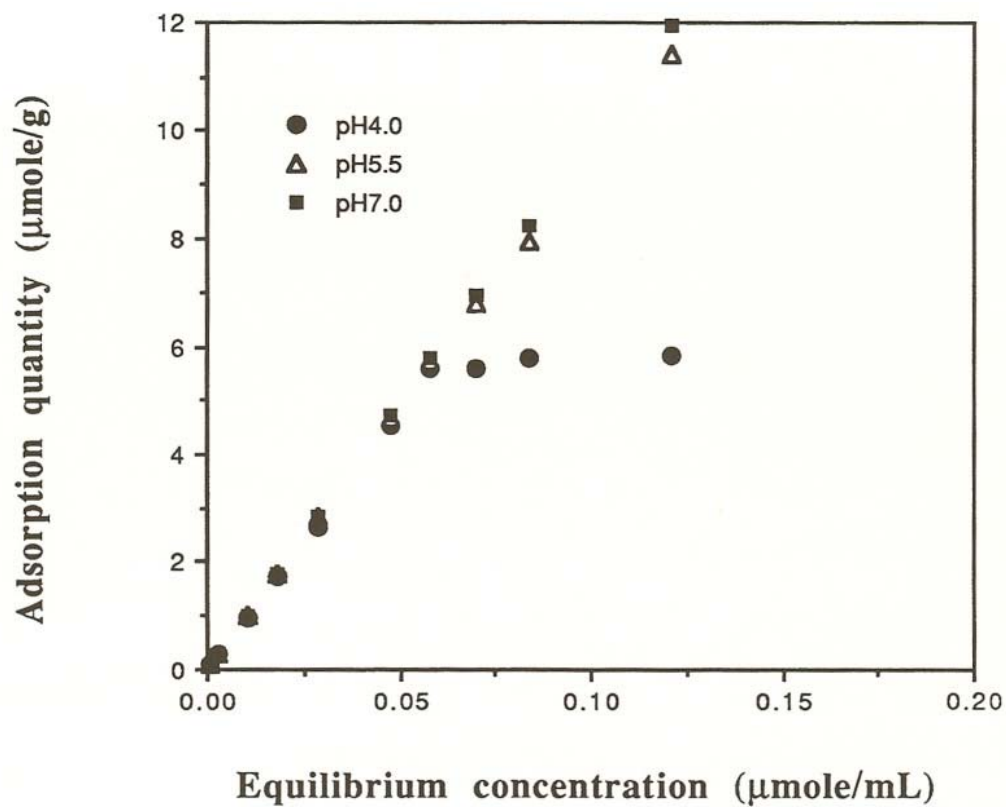


Figure 50. Adsorption isotherms of lead at three pH values for Whippany silty clay loam; Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

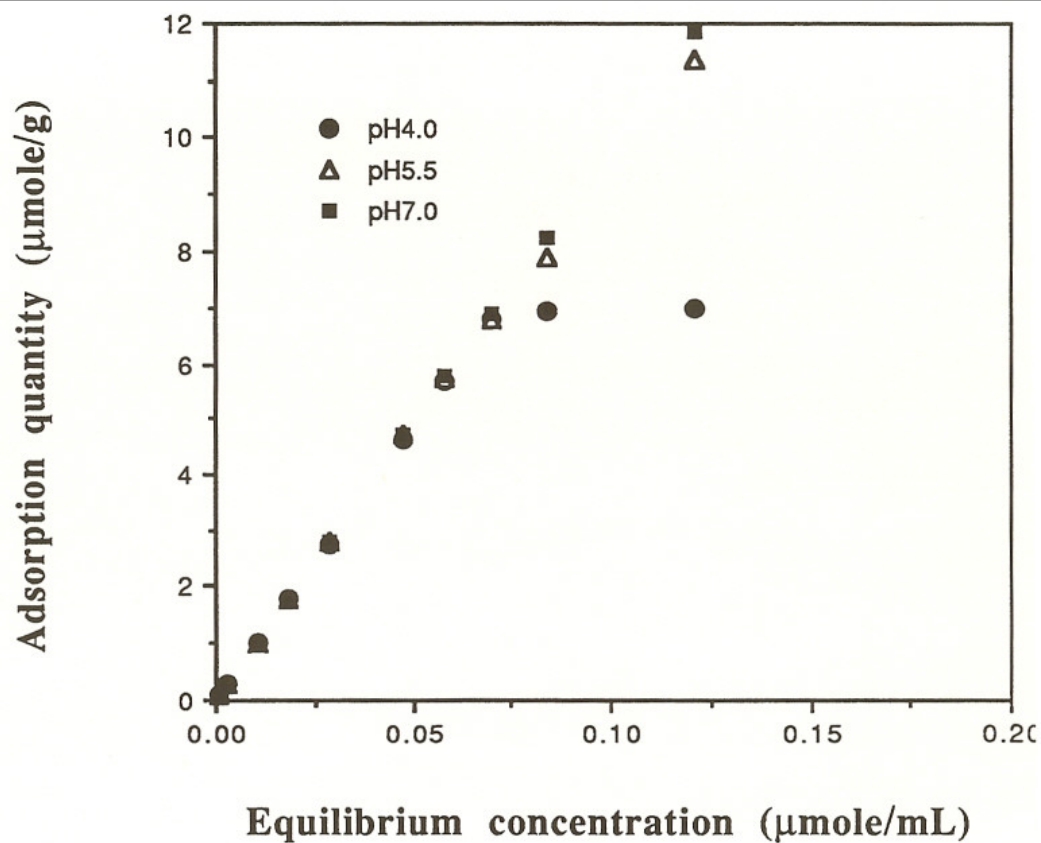


Figure 51. Adsorption isotherms of lead at three pH values for Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

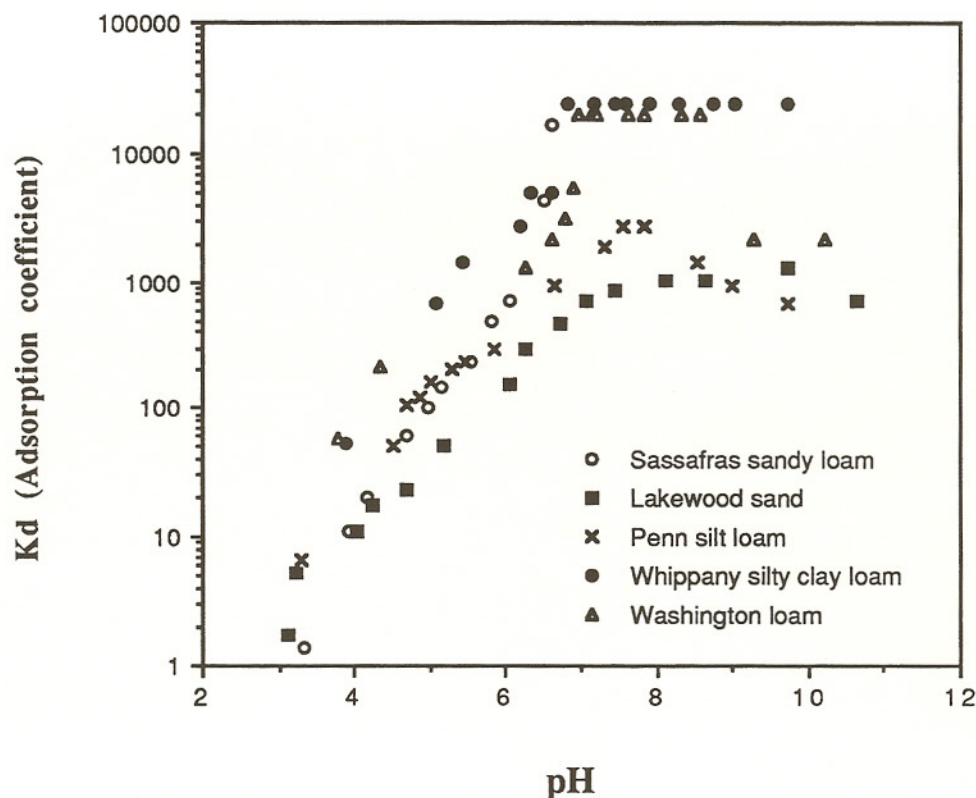


Figure 52. Adsorption coefficient (K_d) for the adsorption of 1×10^{-5} M cadmium onto Sassafra sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

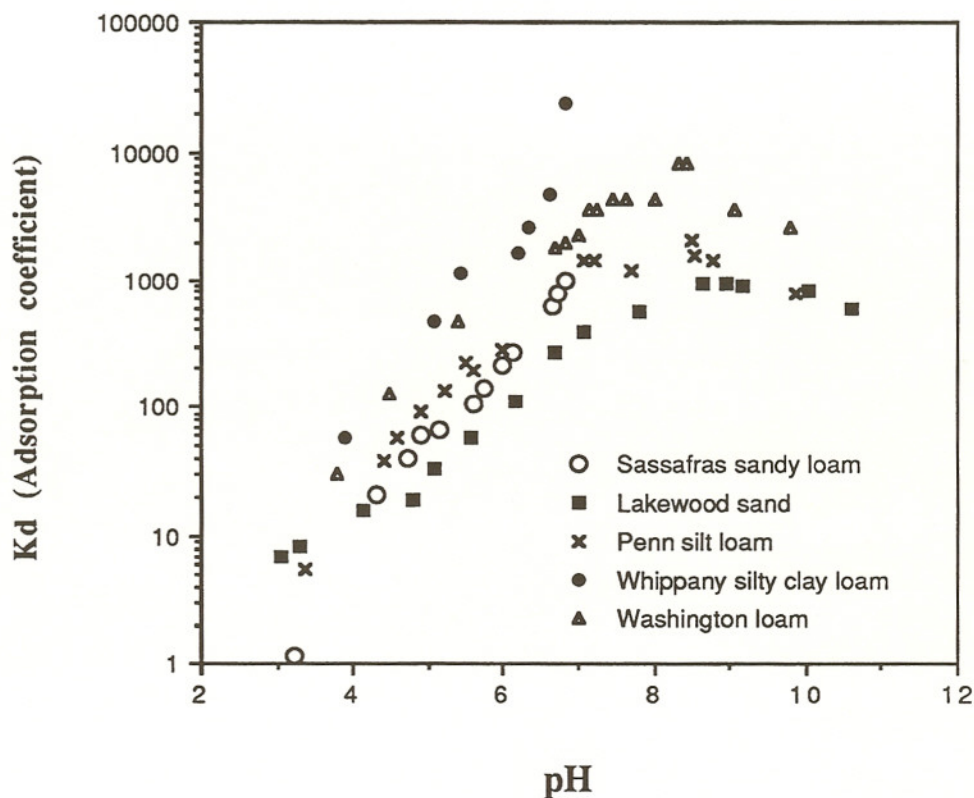


Figure 53. Adsorption coefficient (K_d) for the adsorption of 3×10^{-5} M cadmium onto Sassafra sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam Soil:water = 1g/100mL; I = 0.01 M NaNO₃; T = 25°C.

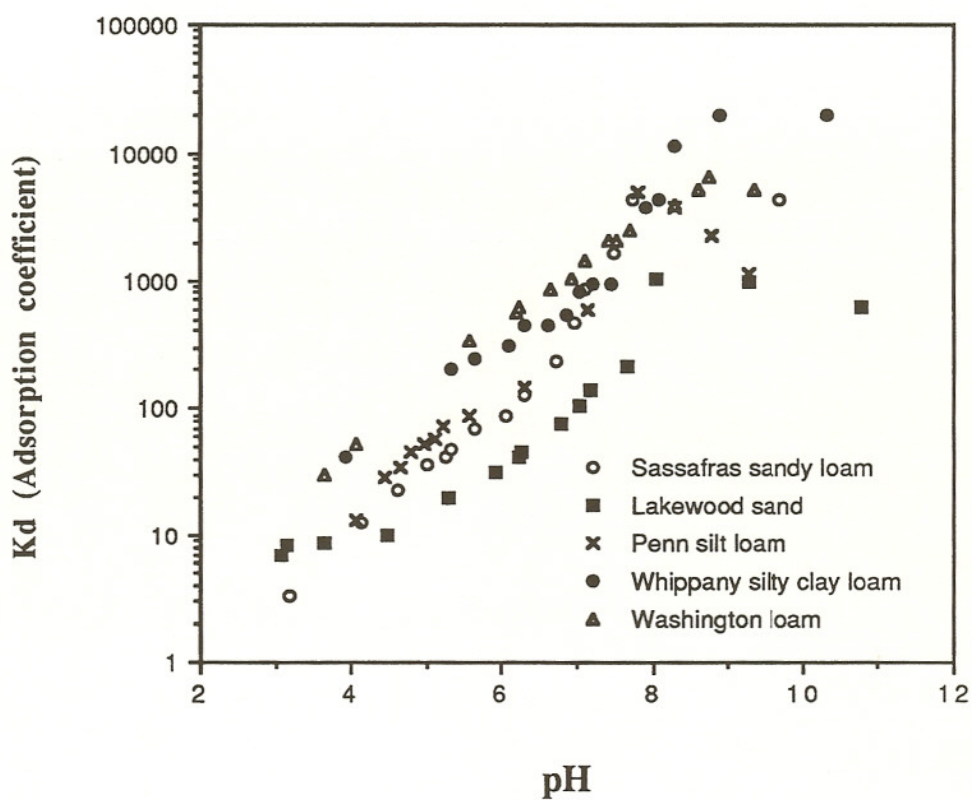


Figure 54. Adsorption coefficient (K_d) for the adsorption of 1×10^{-4} M cadmium onto Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

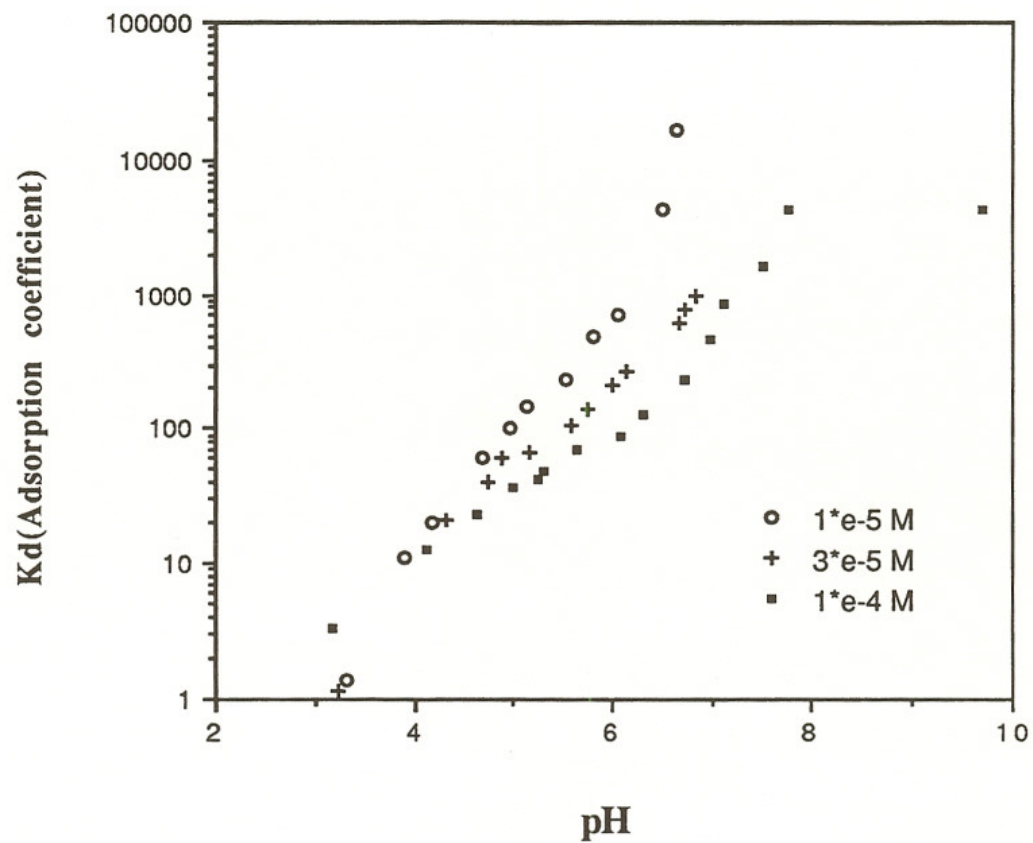


Figure 55. Adsorption coefficient (K_d) for the adsorption of cadmium onto Sassafras sandy loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

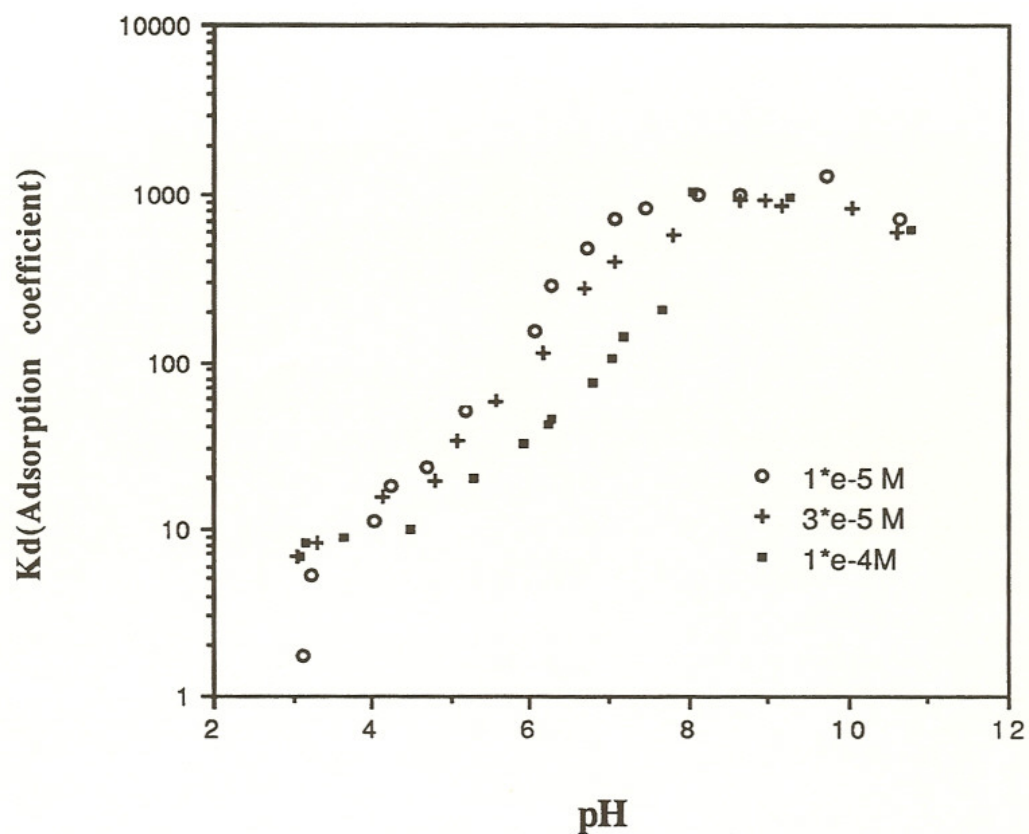


Figure 56. Adsorption coefficient (K_d) for the adsorption of cadmium onto Lakewood sand; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

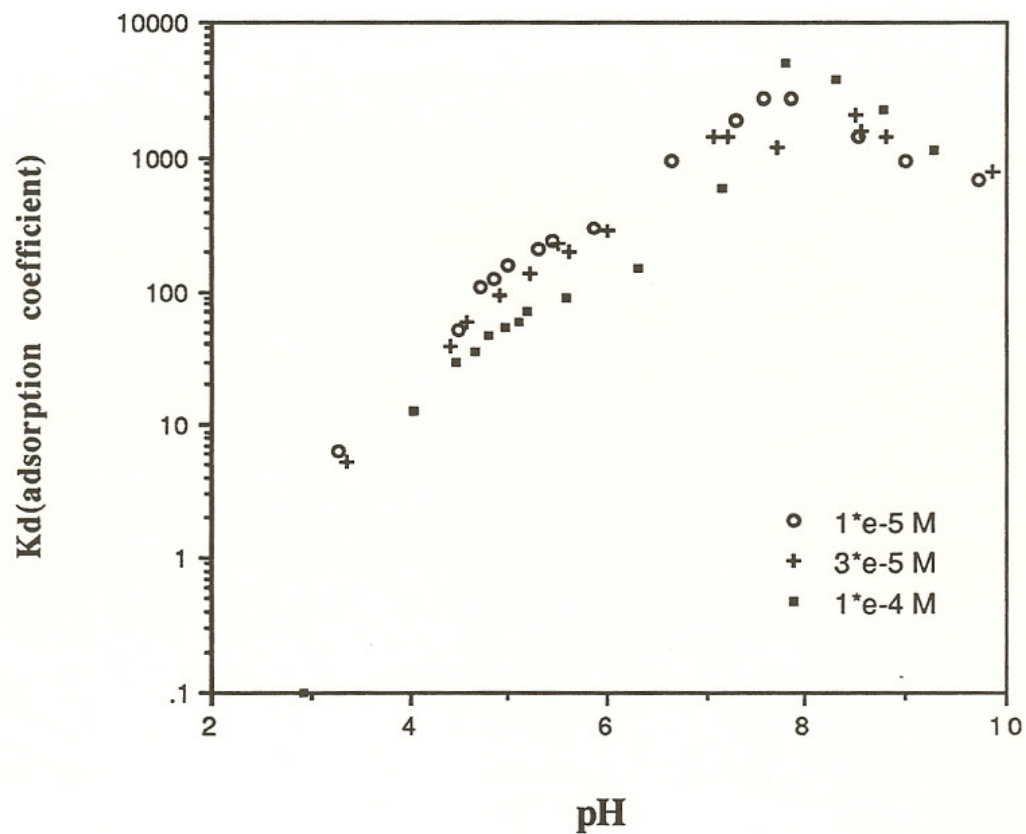


Figure 57. Adsorption coefficient (K_d) for the adsorption of cadmium onto Penn silt loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

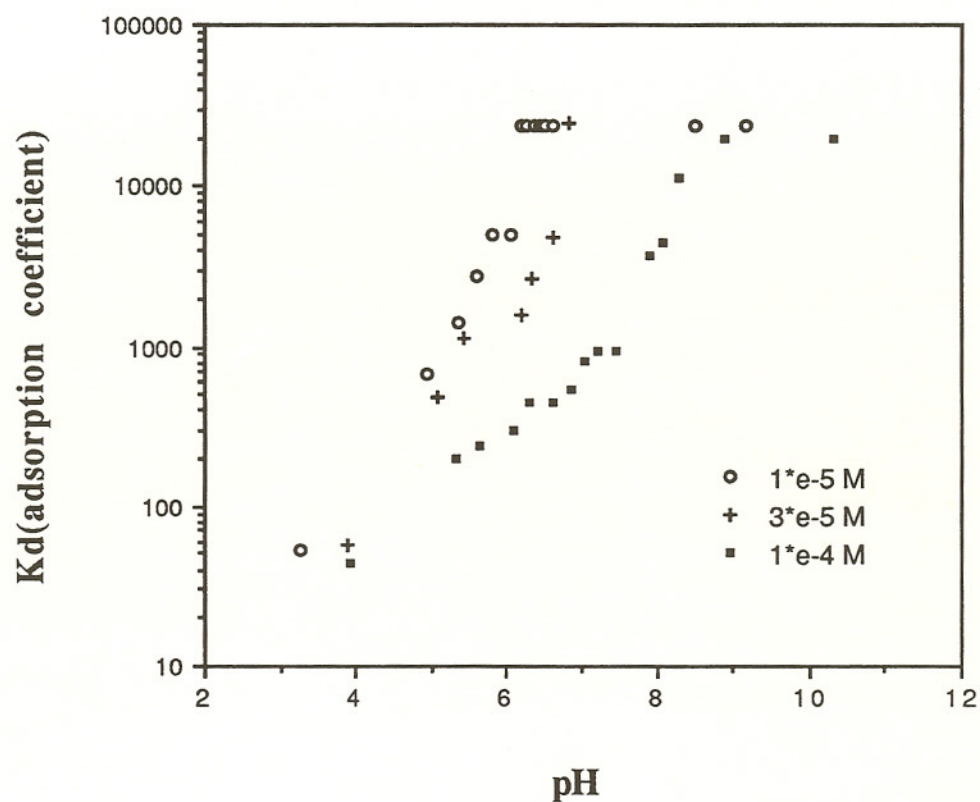


Figure 58. Adsorption coefficient (K_d) for the adsorption of cadmium onto Whippany silty clay loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

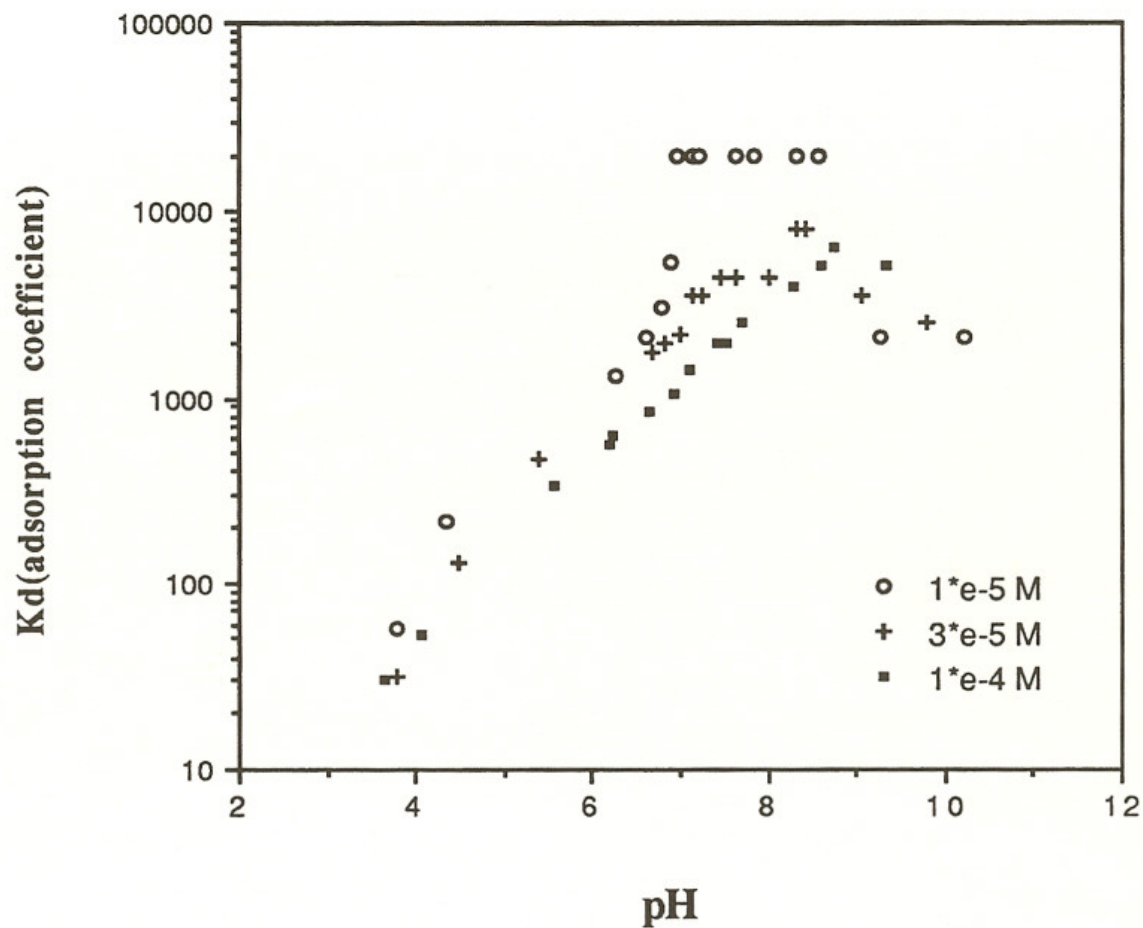


Figure 59. Adsorption coefficient (K_d) for the adsorption of cadmium onto Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

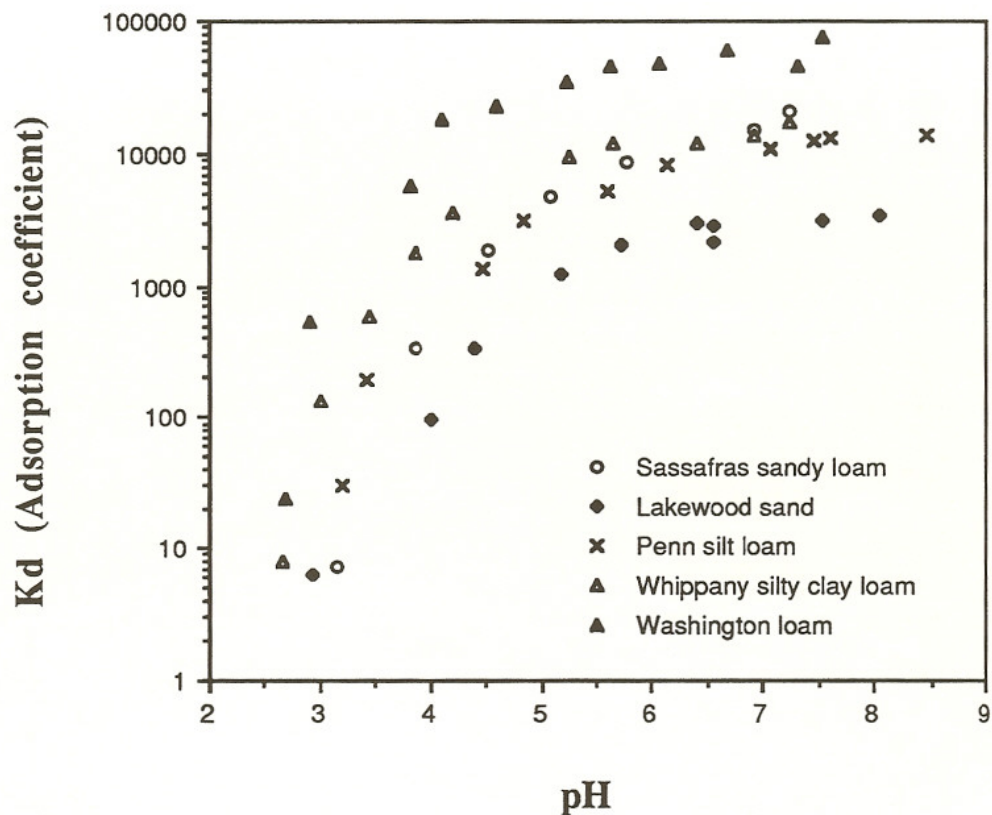


Figure 60. Adsorption coefficient (K_d) for the adsorption of 1×10^{-5} M lead onto Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam, Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

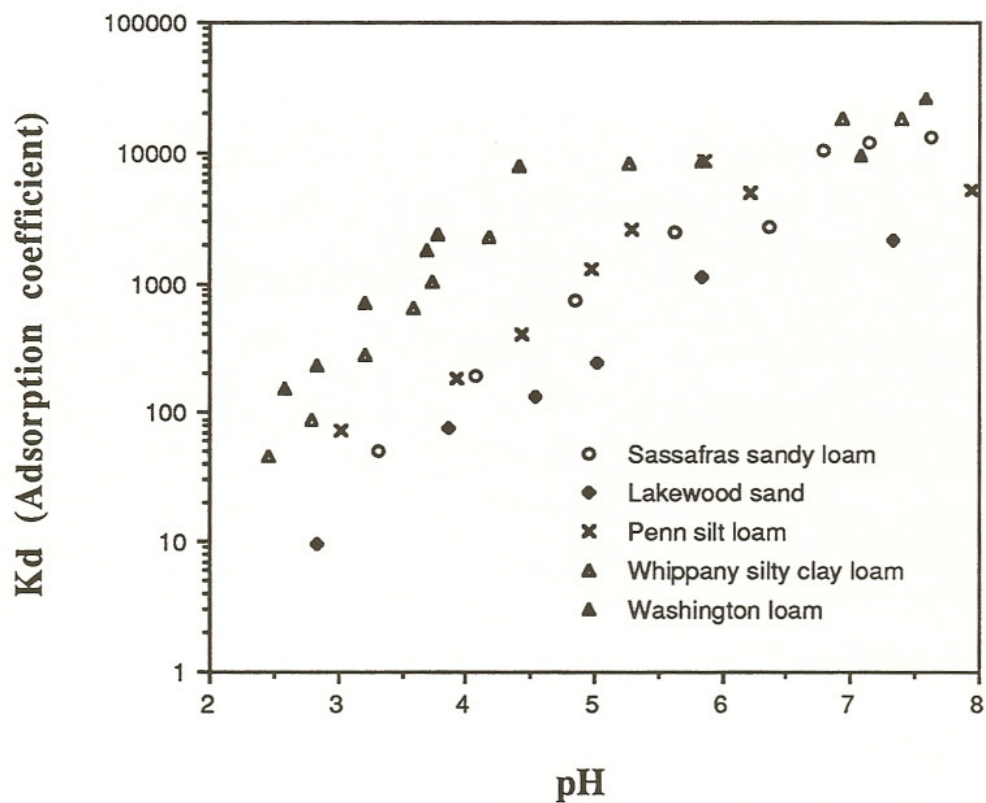


Figure 61. Adsorption coefficient (K_d) for the adsorption of 3×10^{-5} M lead onto Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam, Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

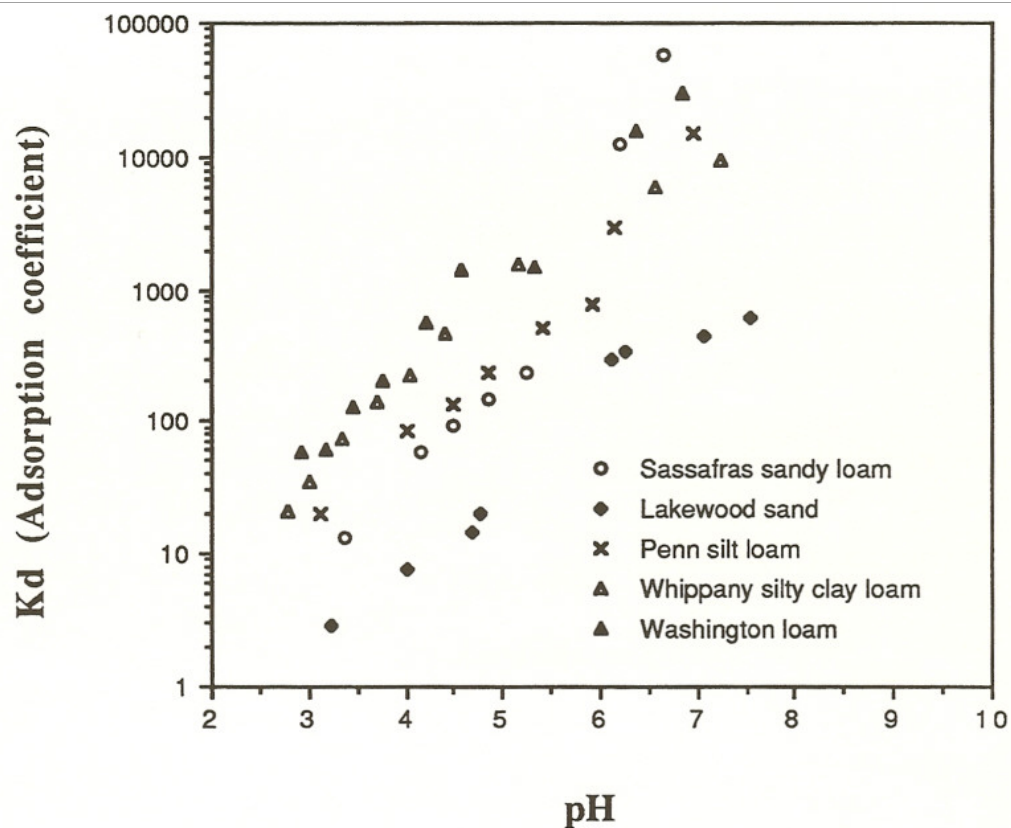


Figure 62. Adsorption coefficient (K_d) for the adsorption of 1×10^{-4} M lead onto Sassafra sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam, Soil:water = 1g/100ml $I = 0.01$ M NaNO_3 ; $T = 25^\circ\text{C}$.

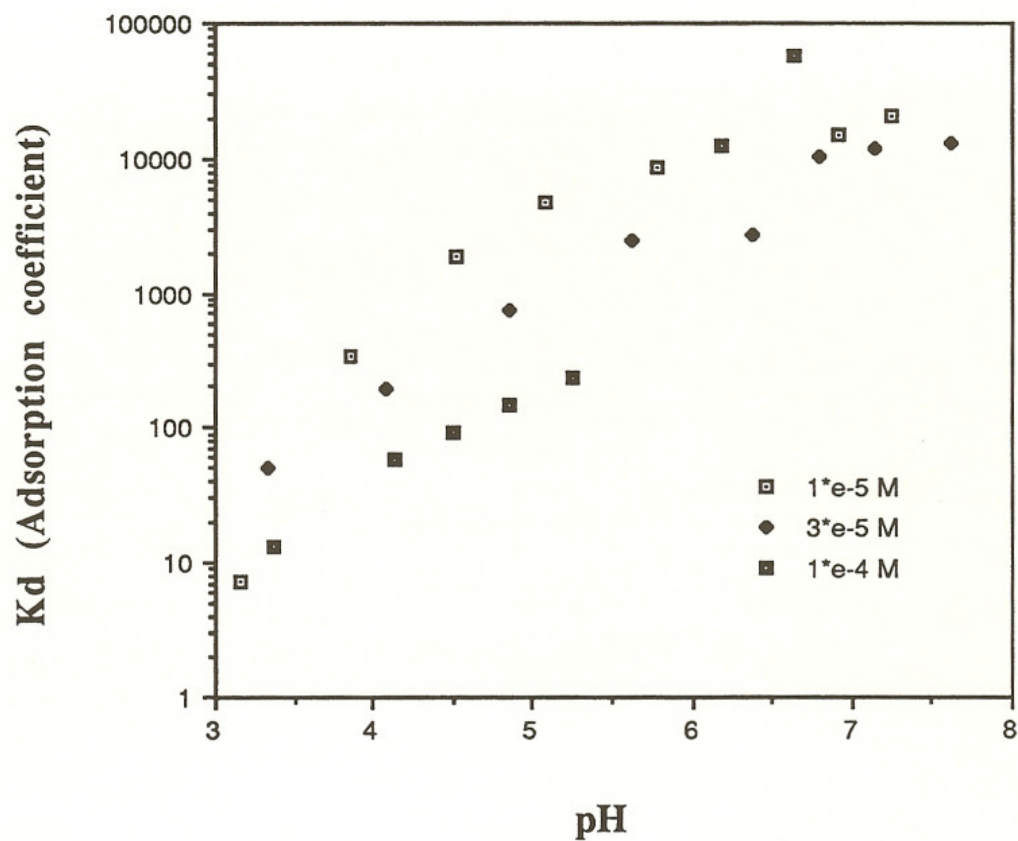


Figure 63. Adsorption coefficient (K_d) for the adsorption of lead onto Sassafras sandy loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

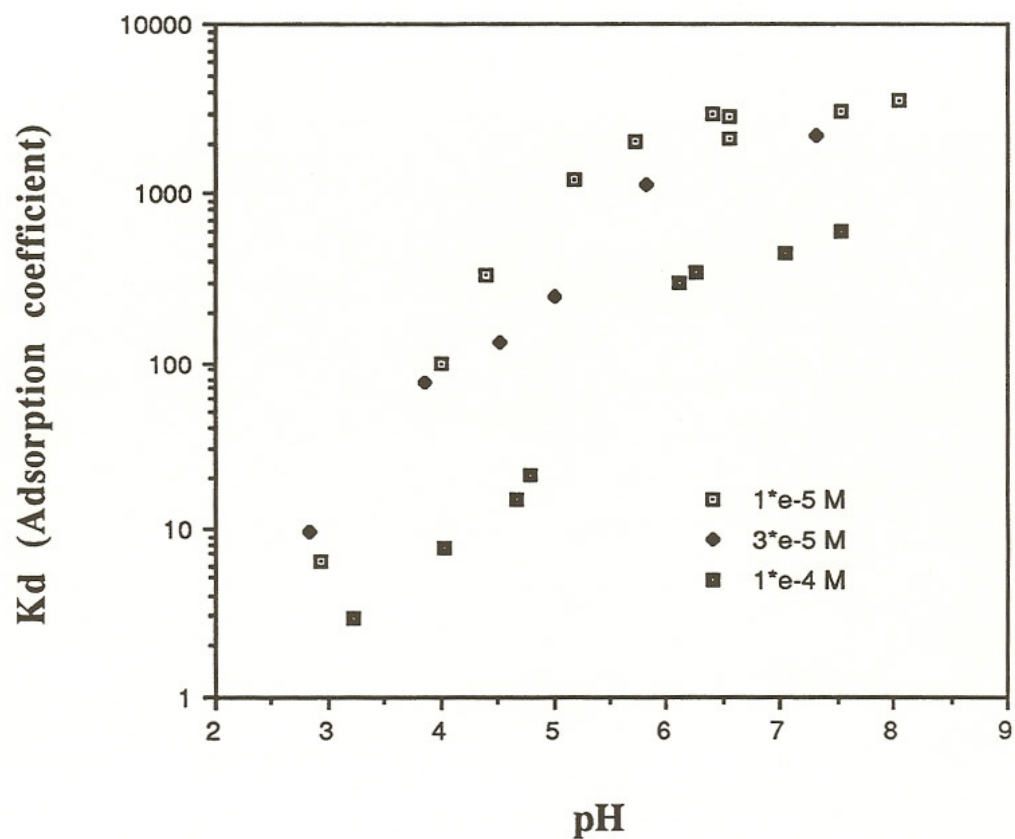


Figure 64. Adsorption coefficient (K_d) for the adsorption of lead onto Lakewood sand; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

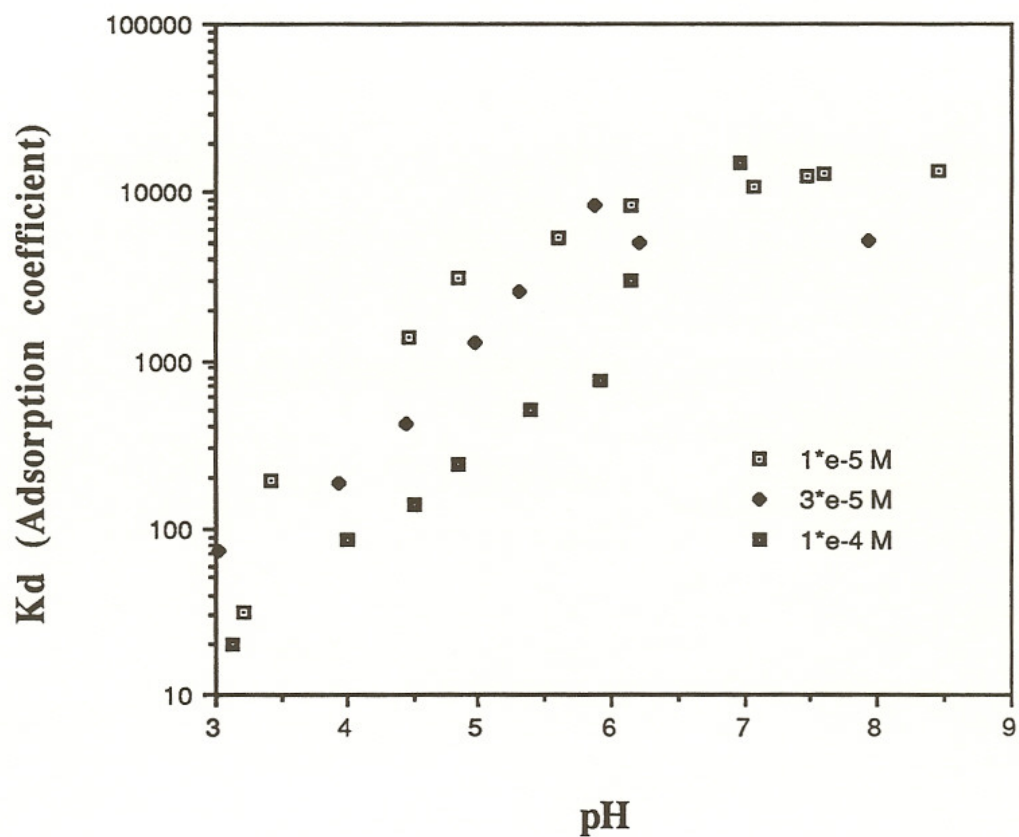


Figure 65. Adsorption coefficient (K_d) for the adsorption of lead onto Penn silt loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

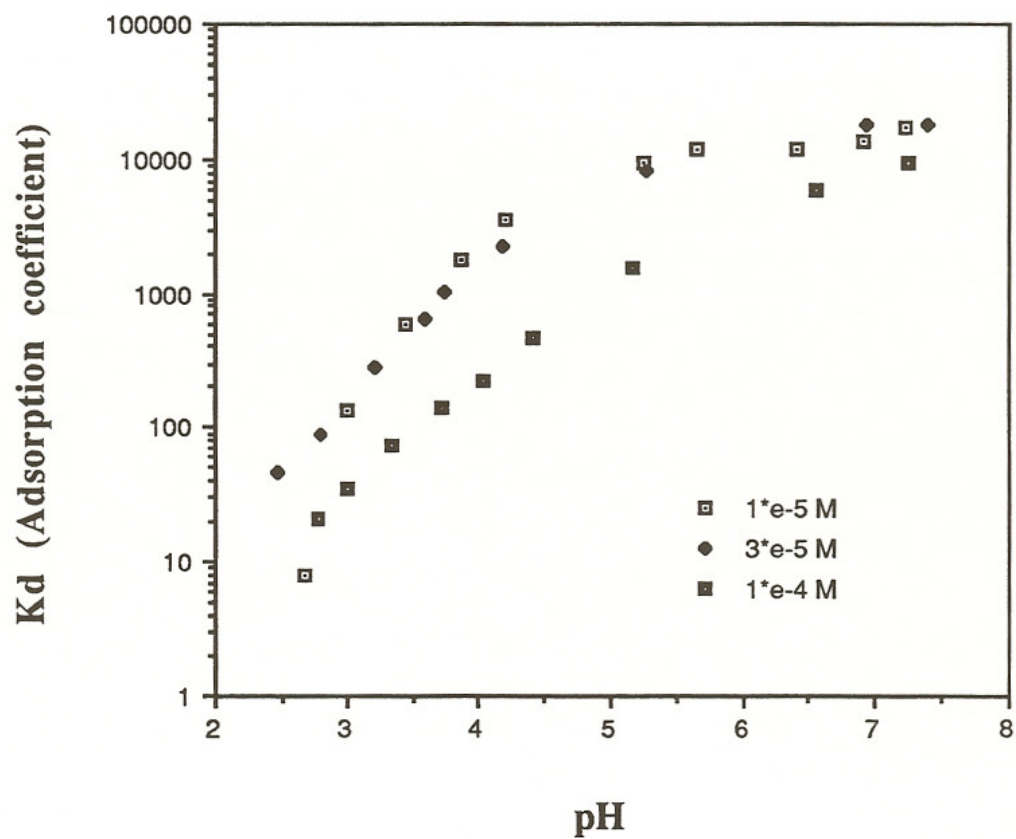


Figure 66. Adsorption coefficient (K_d) for the adsorption of lead onto Whippany silty clay loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

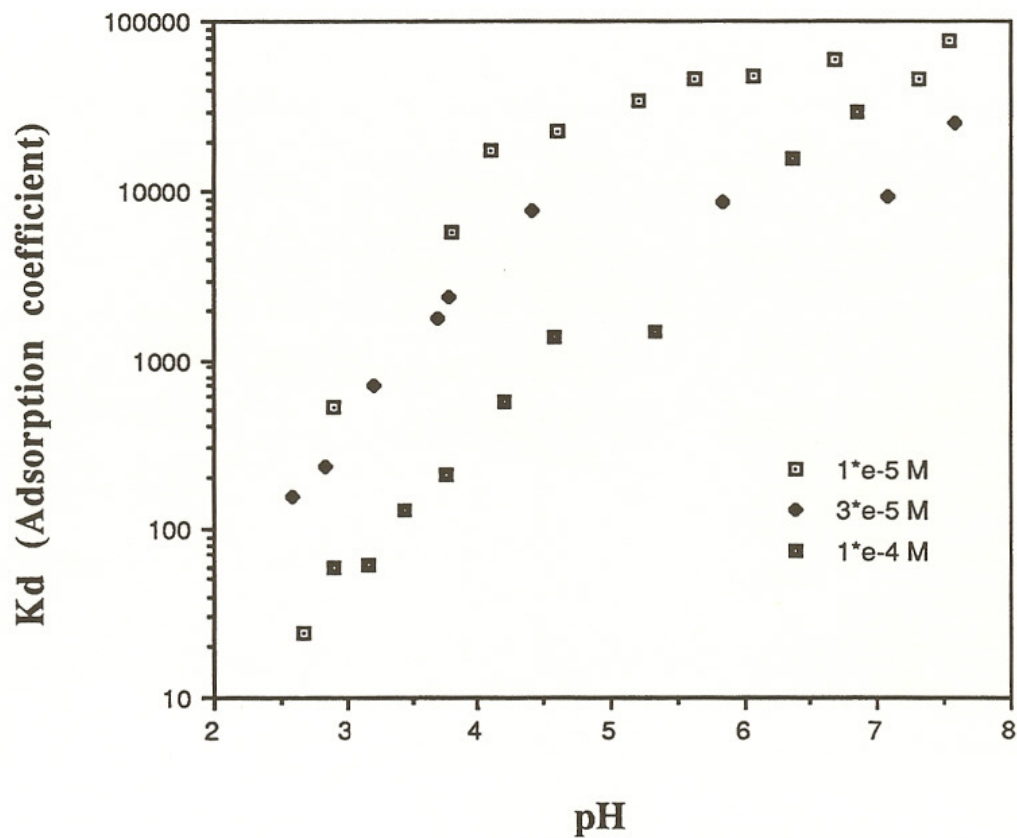


Figure 67. Adsorption coefficient (K_d) for the adsorption of lead onto Washington loam; Soil:water = 1g/100mL; I = 0.01 M NaNO_3 ; T = 25°C.

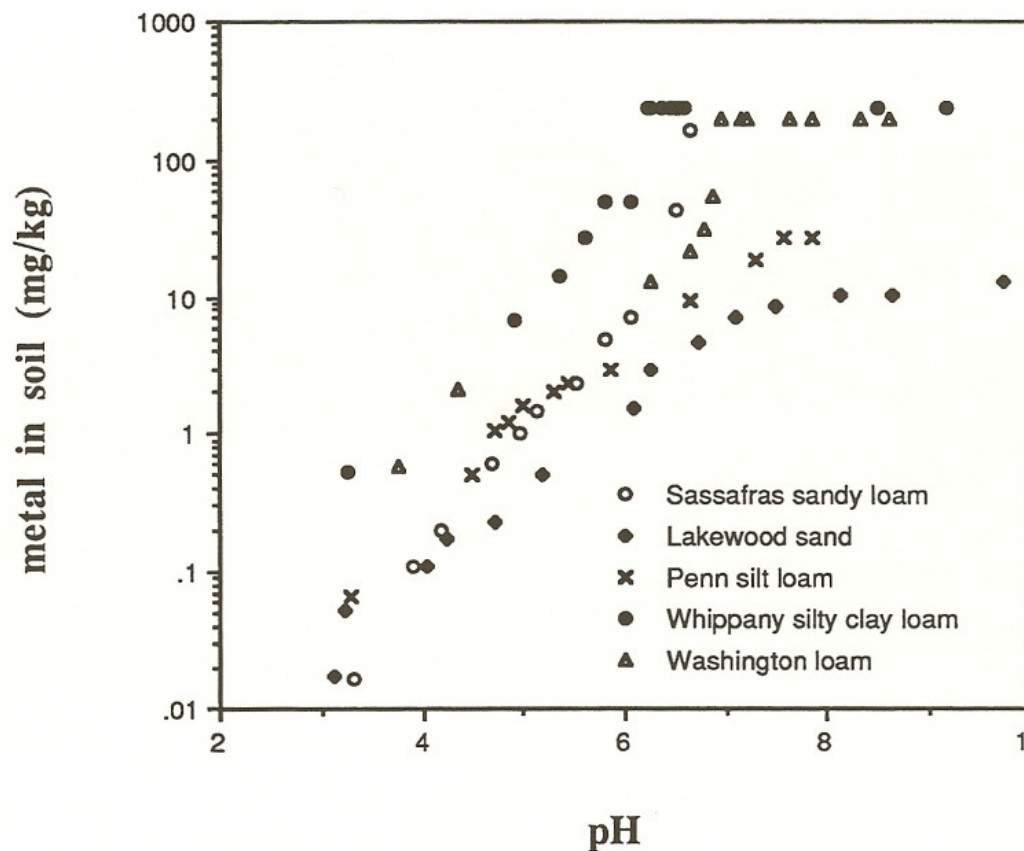


Figure 68. The maximum permissible level of cadmium for Sassafra sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam for 1×10^{-5} M cadmium.

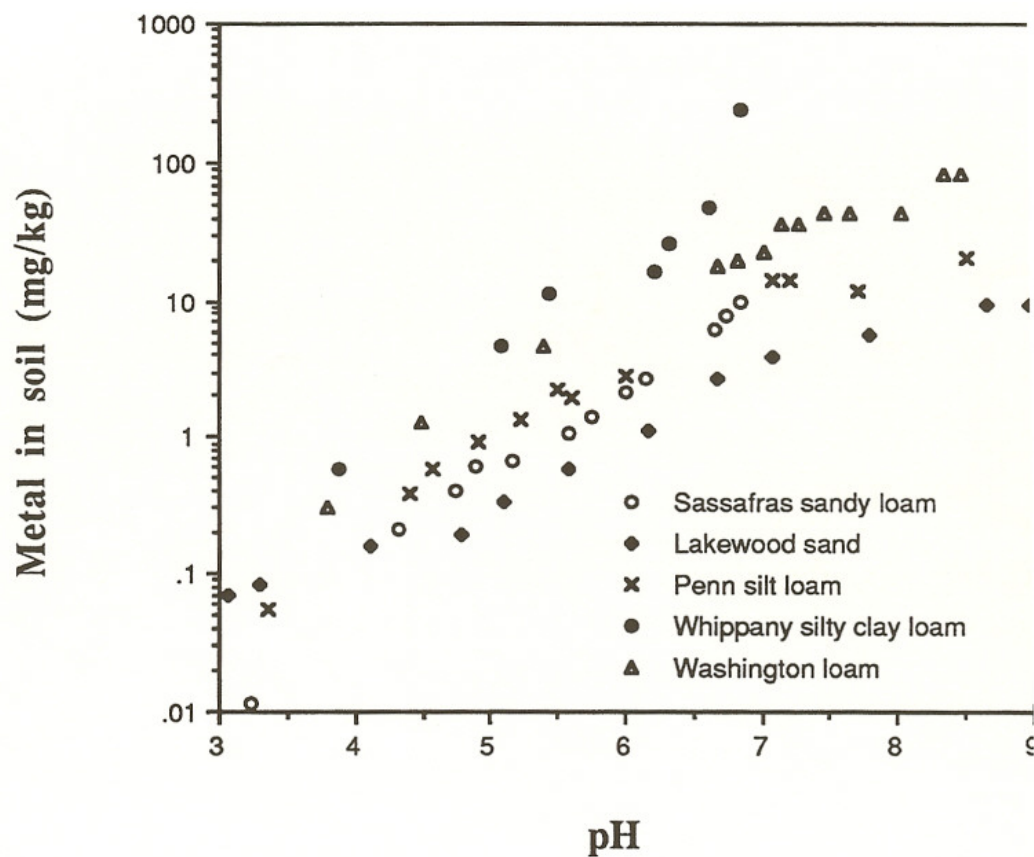


Figure 69. The maximum permissible level of cadmium for Sassafra sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam for 3×10^{-5} M cadmium.

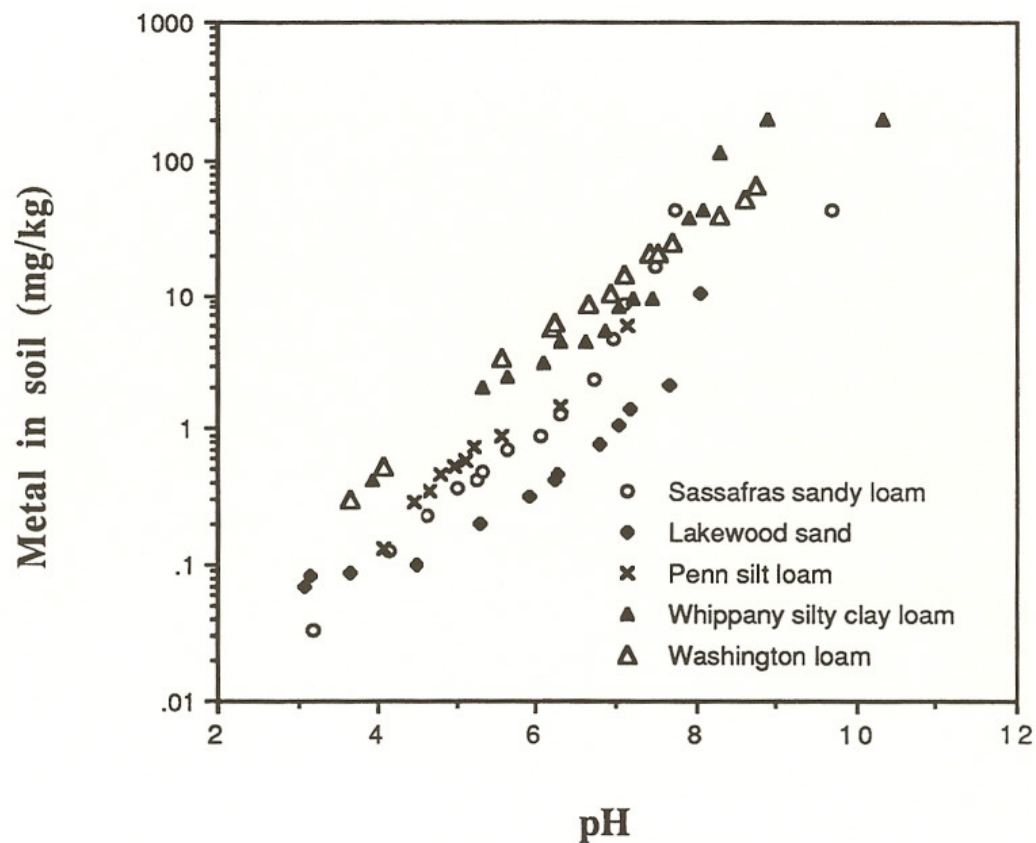


Figure 70. The maximum permissible level of cadmium for Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam for 1×10^{-4} M cadmium.

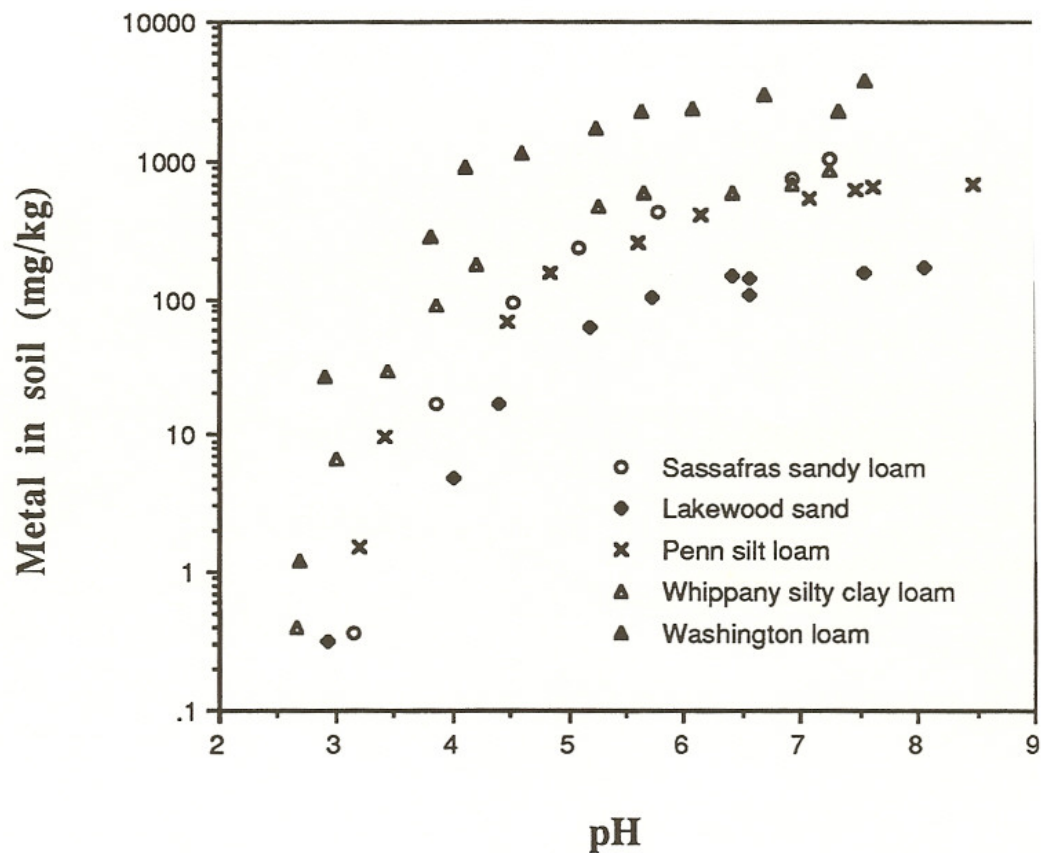


Figure 71. The maximum permissible level of lead for Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam for 1×10^{-5} M lead.

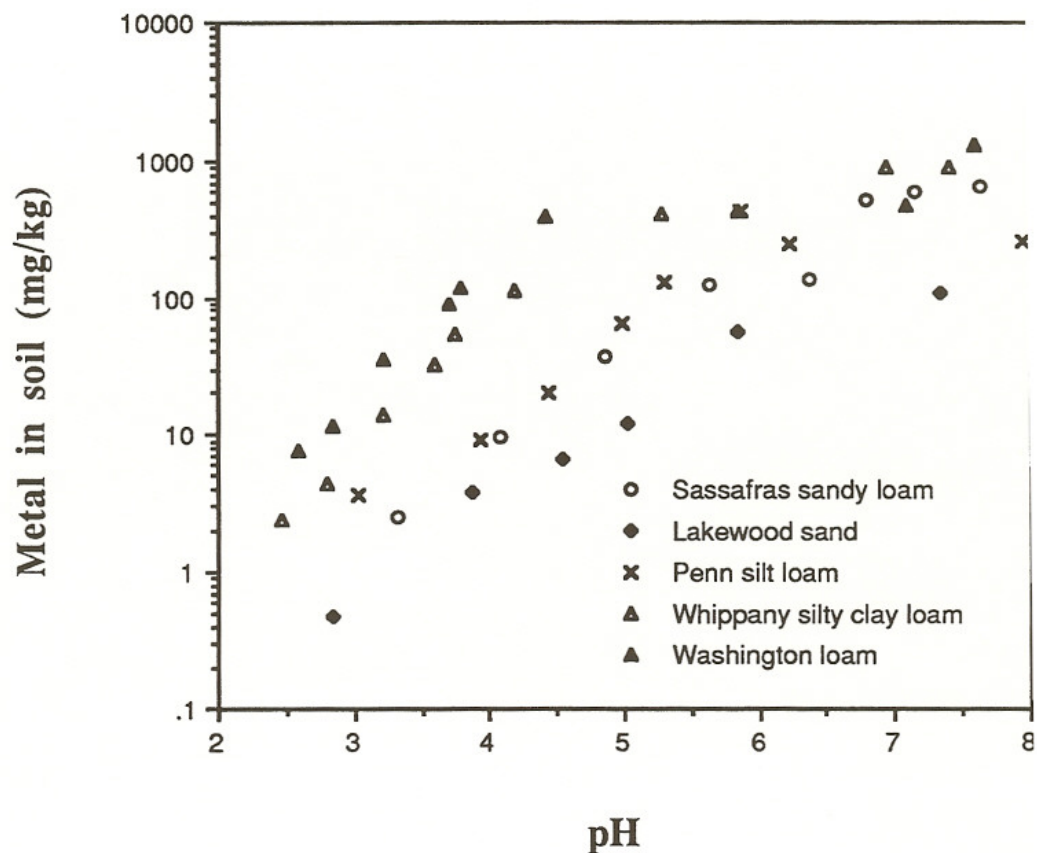


Figure 72. The maximum permissible level of lead for Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam for 3×10^{-5} M lead.

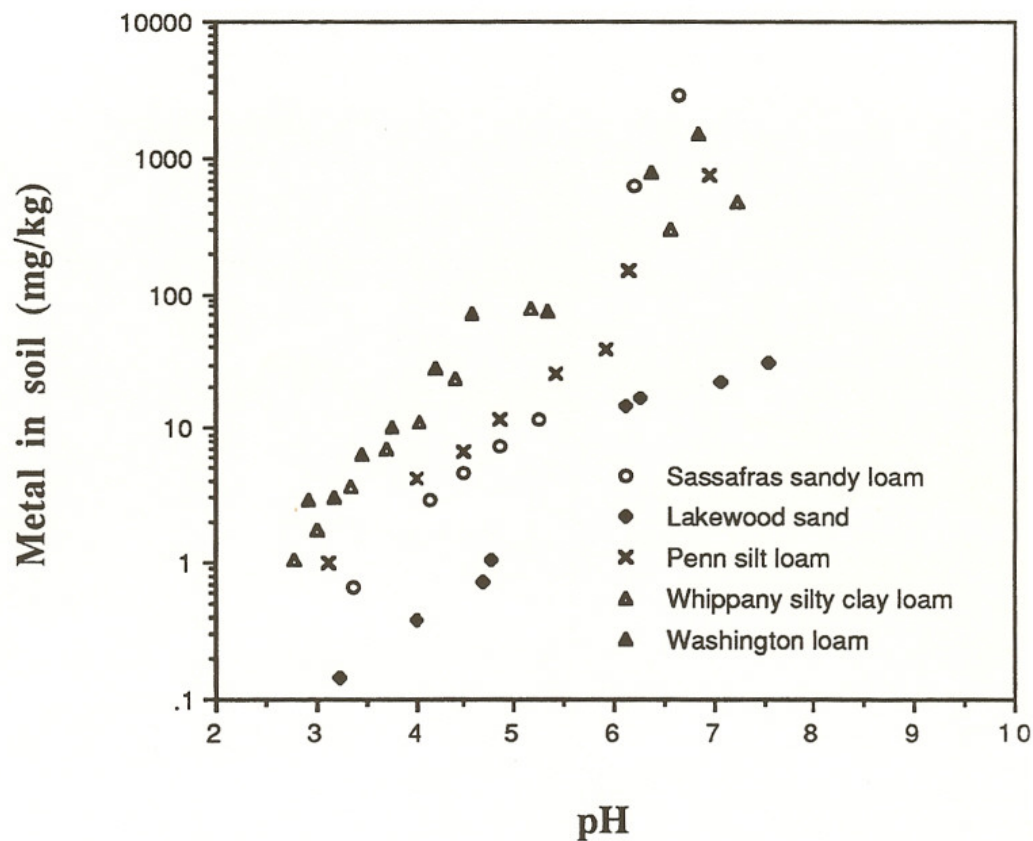


Figure 73. The maximum permissible level of lead for Sassafras sandy loam, Lakewood sand, Penn silt loam, Whippany silty clay loam and Washington loam for 1×10^{-4} M lead.

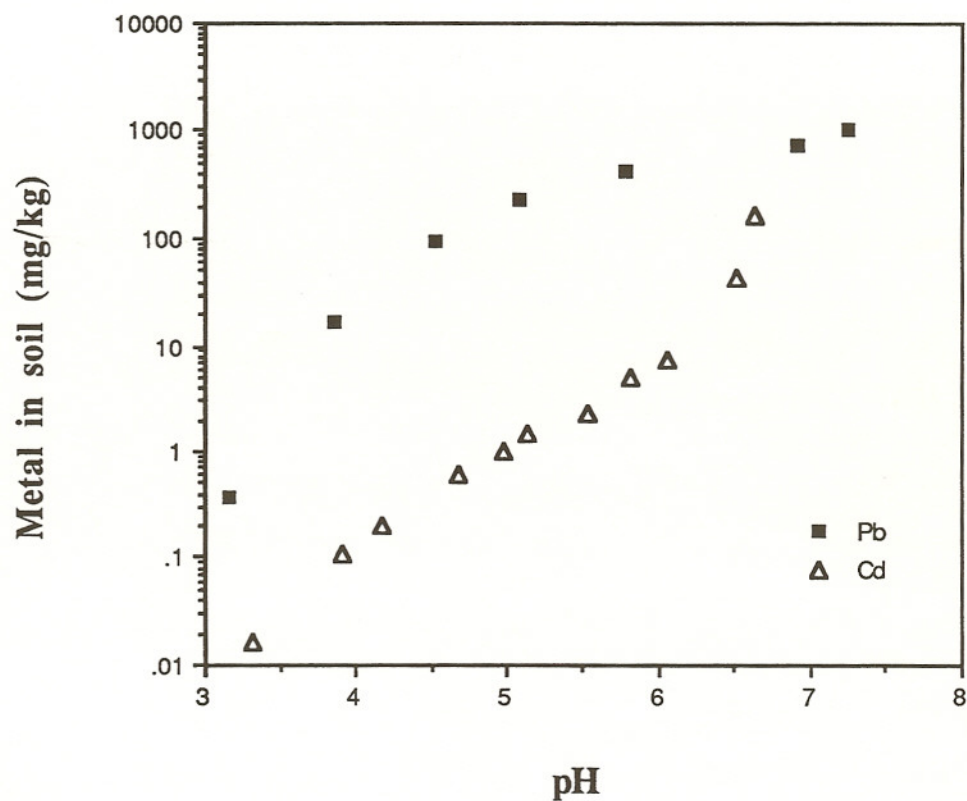


Figure 74. The maximum permissible level of cadmium and lead for Sassafras sandy loam for 1×10^{-5} M initial concentration.

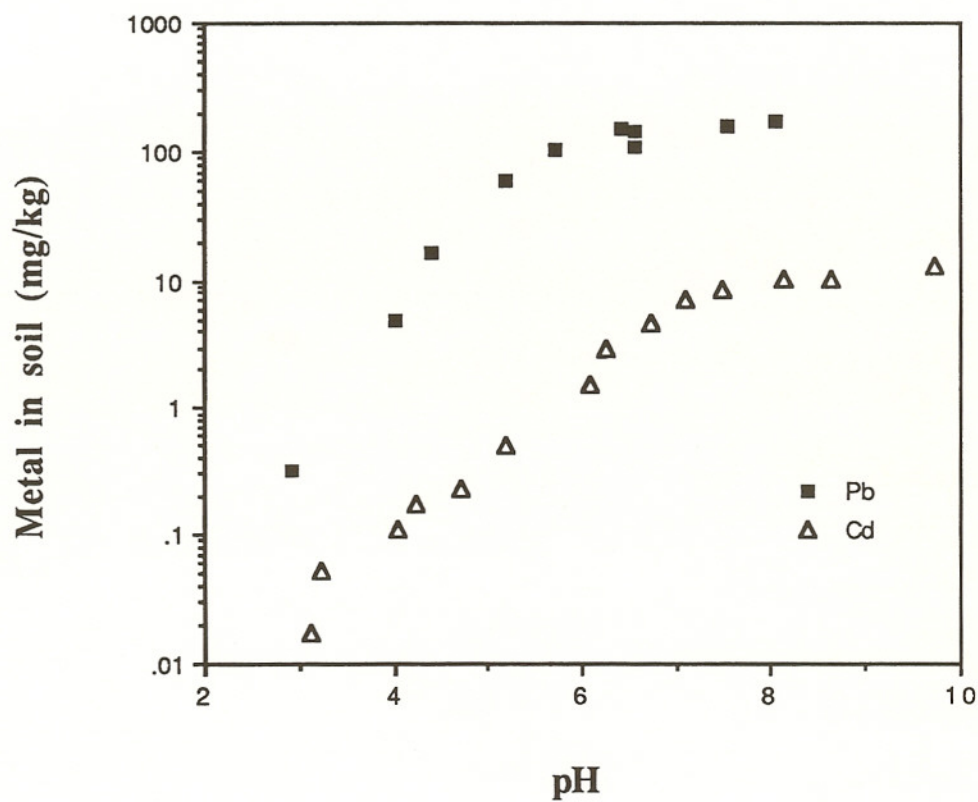


Figure 75. The maximum permissible level of cadmium and lead for Lakewood sand for 1×10^{-5} M initial concentration.

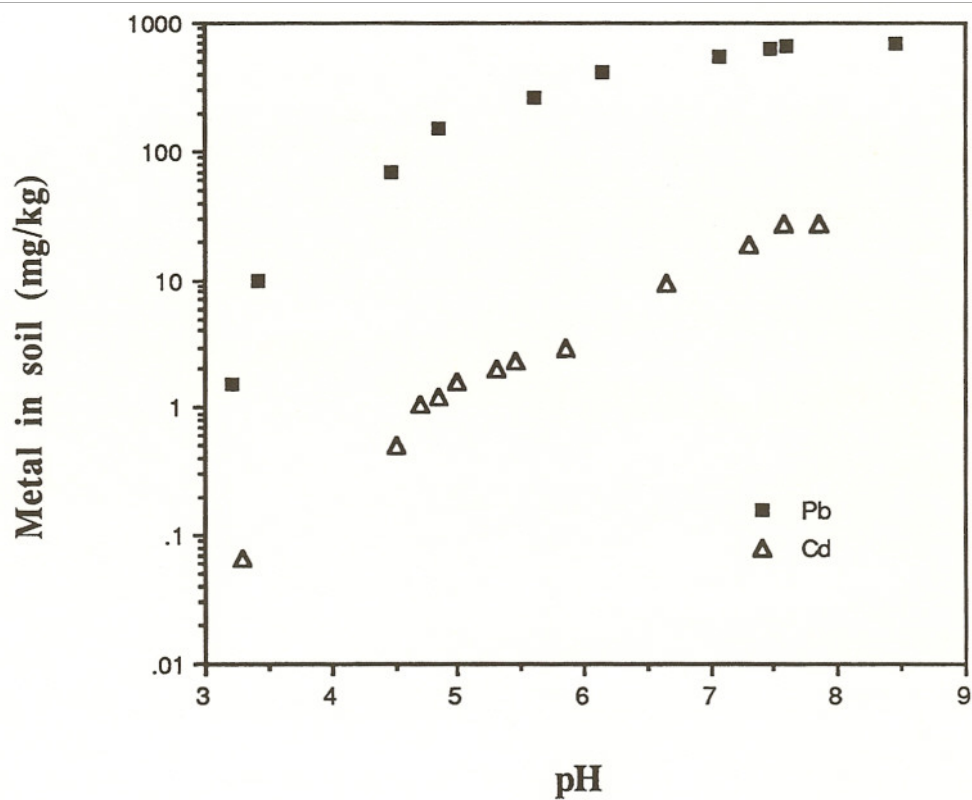


Figure 76. The maximum permissible level of cadmium and lead for Penn silt loam for 1×10^{-5} M initial concentration.

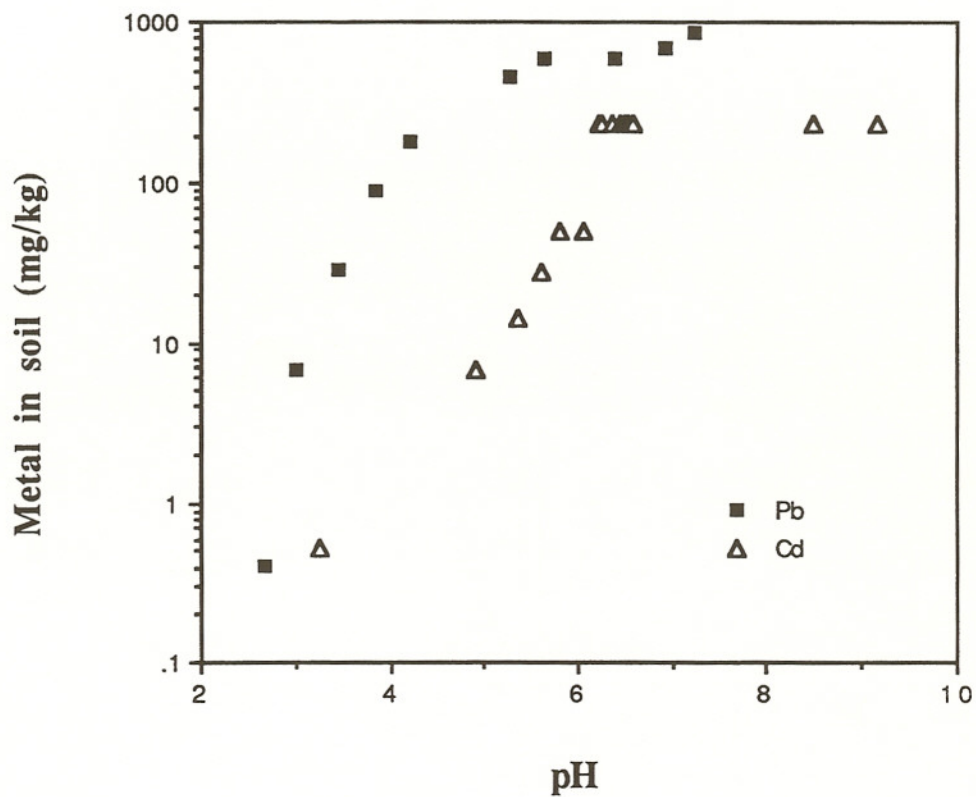


Figure 77. The maximum permissible level of cadmium and lead for Whippany silty clay loam for 1×10^{-5} M initial concentration.

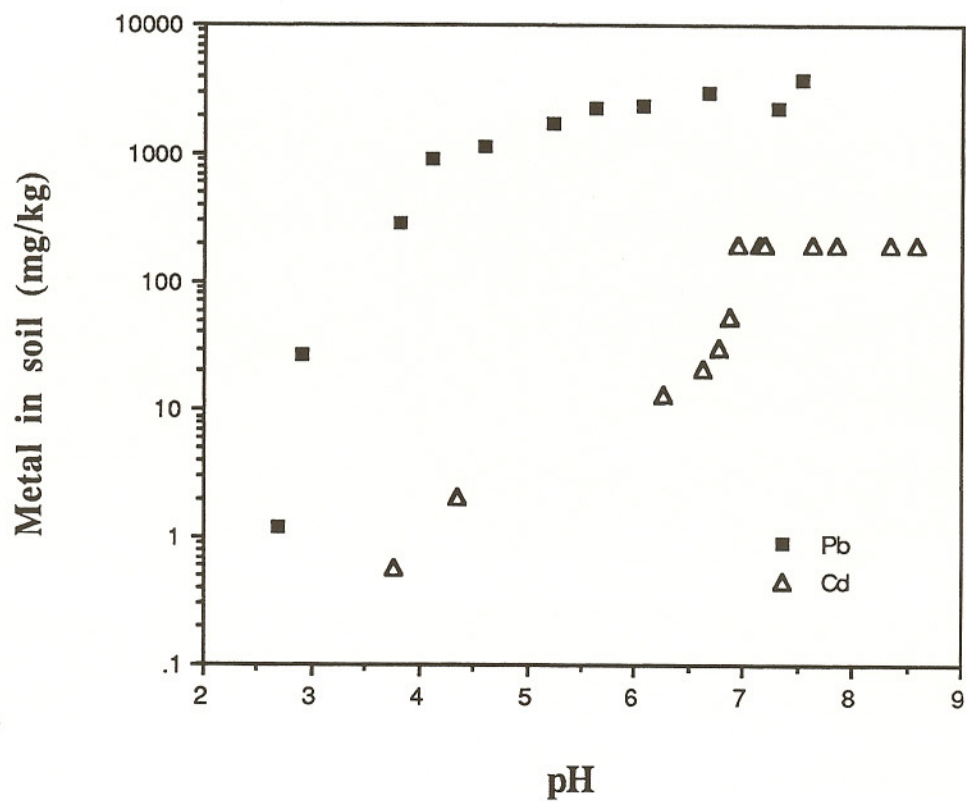


Figure 78. The maximum permissible level of cadmium and lead for Washington loam for 1×10^{-5} M initial concentration.

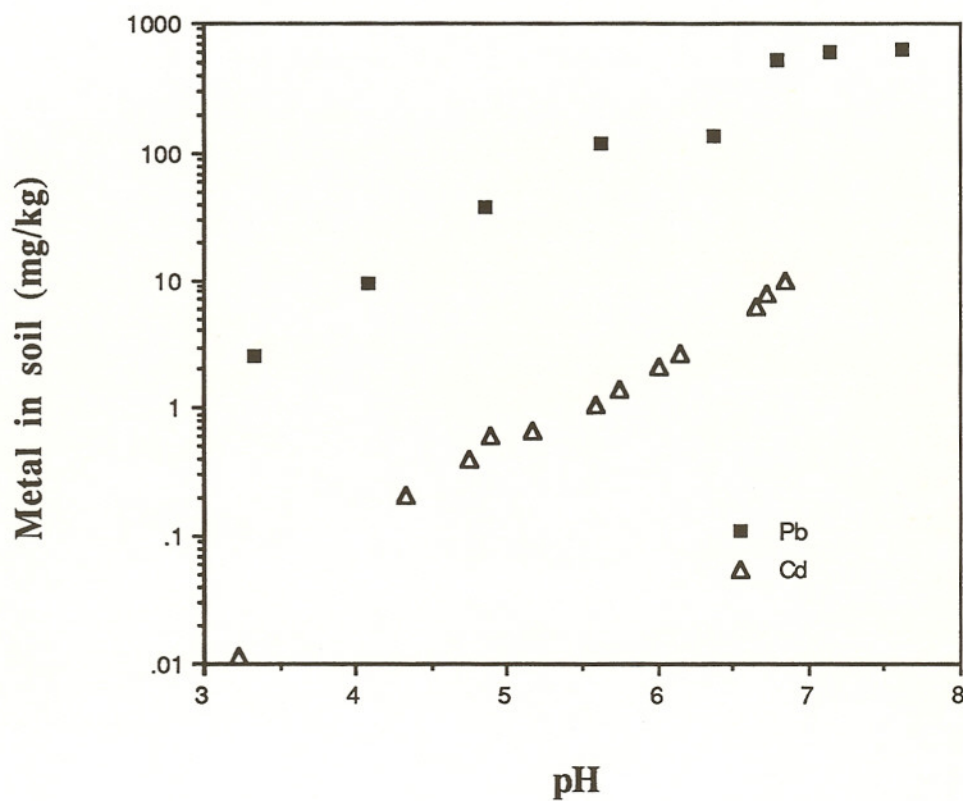


Figure 79. The maximum permissible level of cadmium and lead for Sassafras sandy loam for 3×10^{-5} M initial concentration.

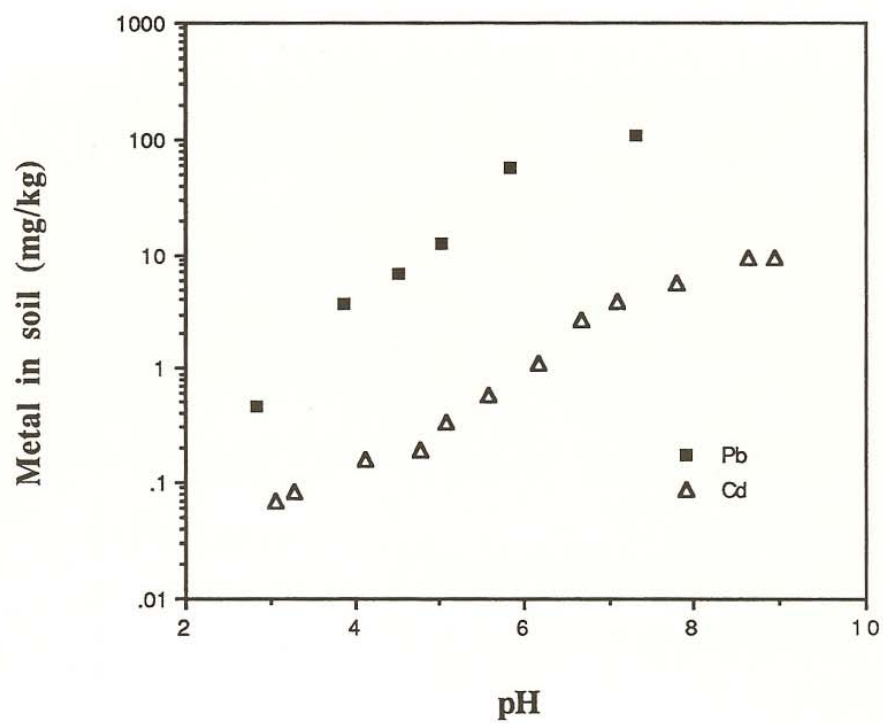


Figure 80. The maximum permissible level of cadmium and lead for Lakewood sand for 3×10^{-5} M initial concentration.

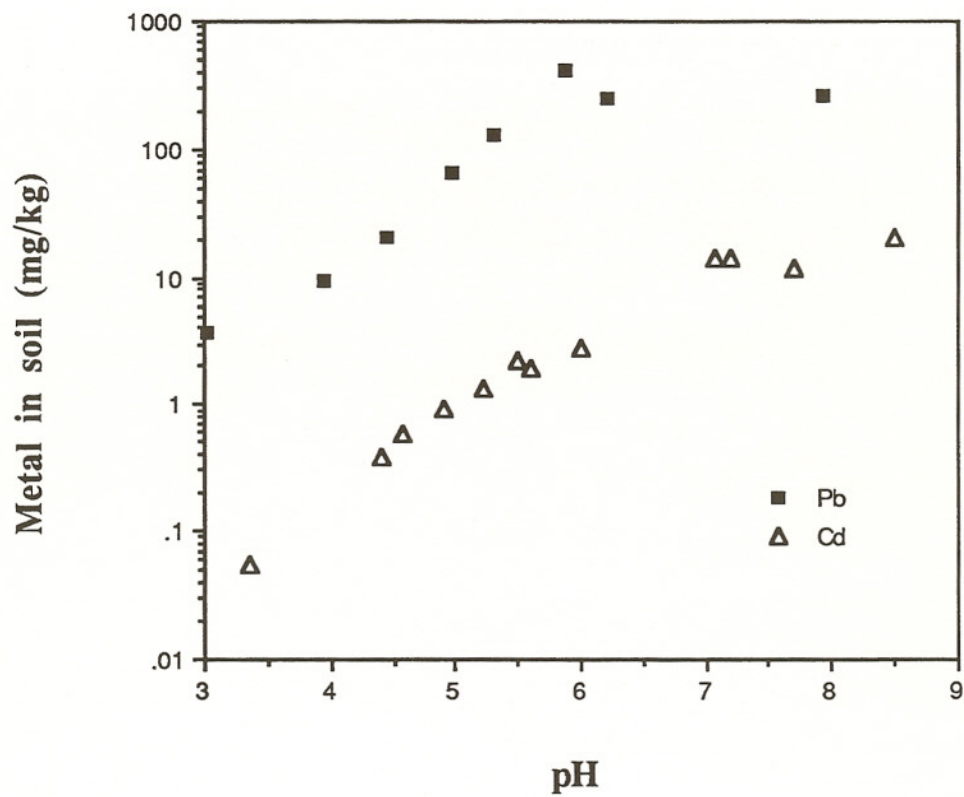


Figure 81. The maximum permissible level of cadmium and lead for Penn silt loam for 3×10^{-5} M initial concentration.

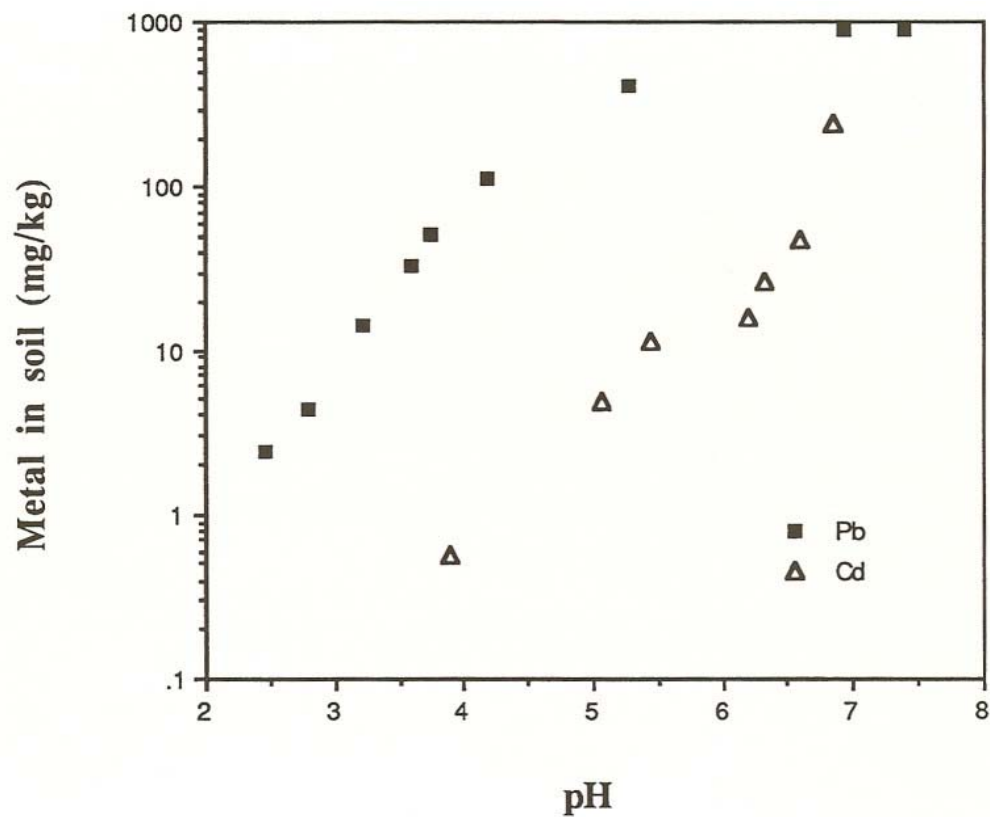


Figure 82. The maximum permissible level of cadmium and lead for Whippany silty clay loam for 3×10^{-5} M initial concentration.

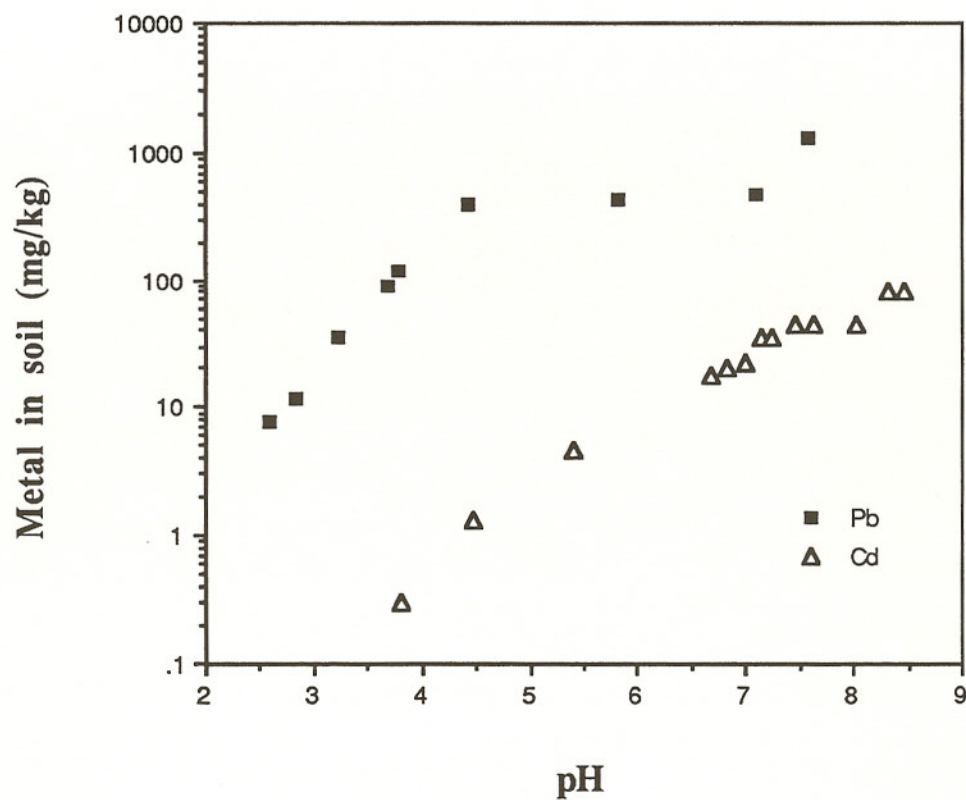


Figure 83. The maximum permissible level of cadmium and lead for Washington loam for 3×10^{-5} M initial concentration.

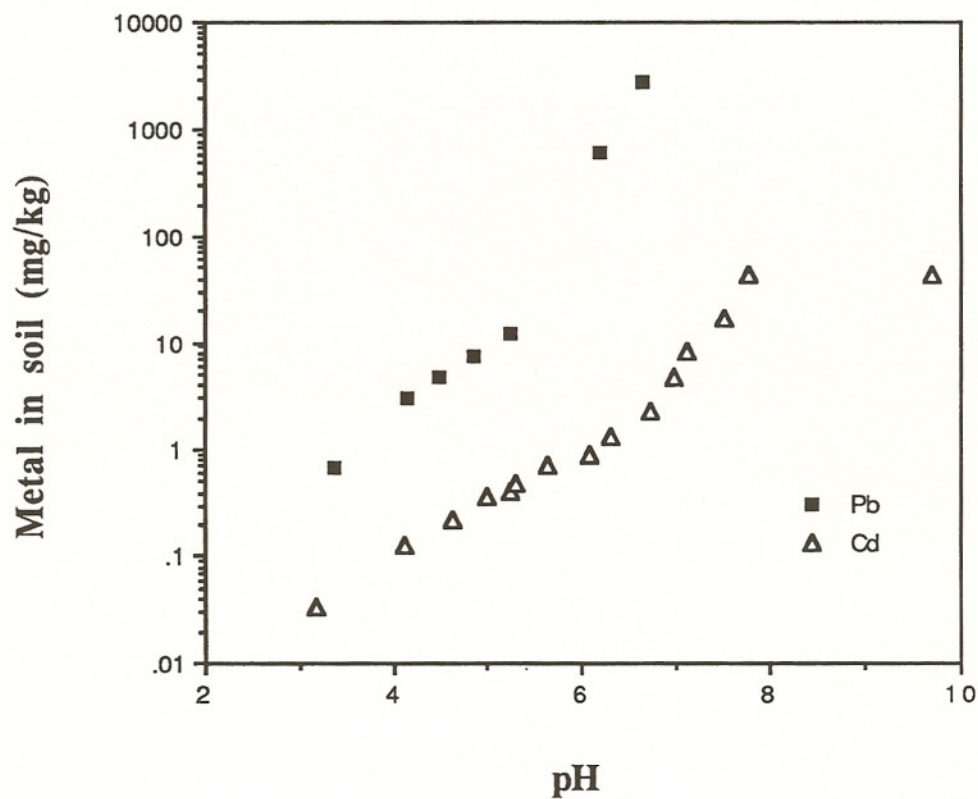


Figure 84. The maximum permissible level of cadmium and lead for Sassafras sandy loam for 1×10^{-4} M initial concentration.

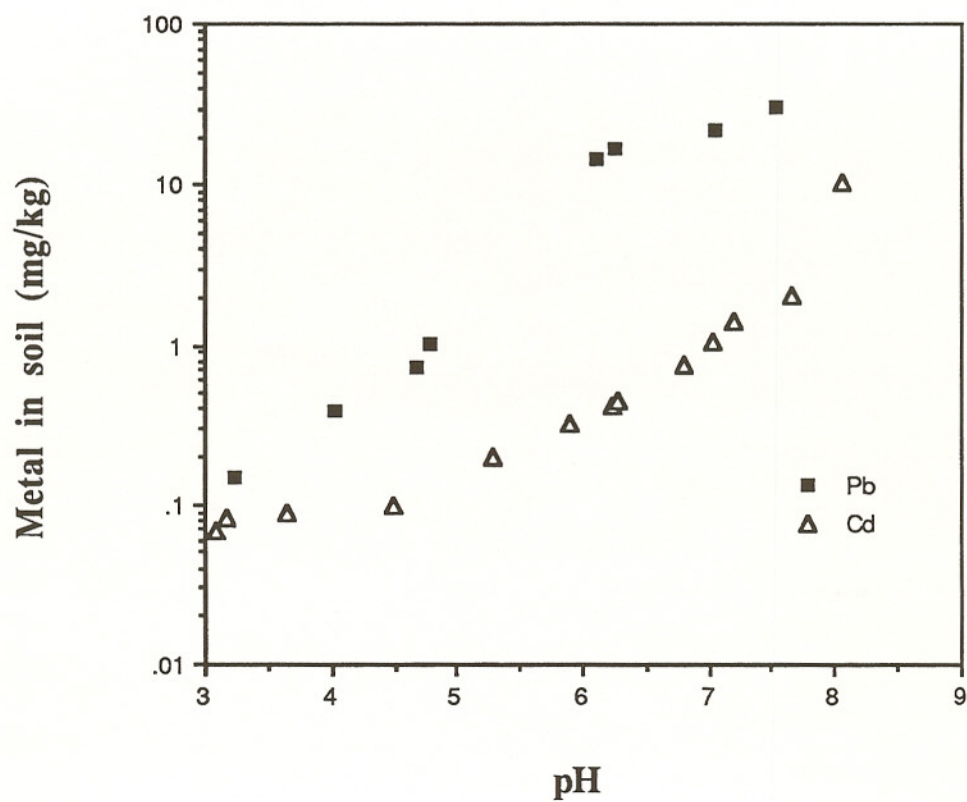


Figure 85. The maximum permissible level of cadmium and lead for Lakewood sand for 1×10^{-4} M initial concentration.

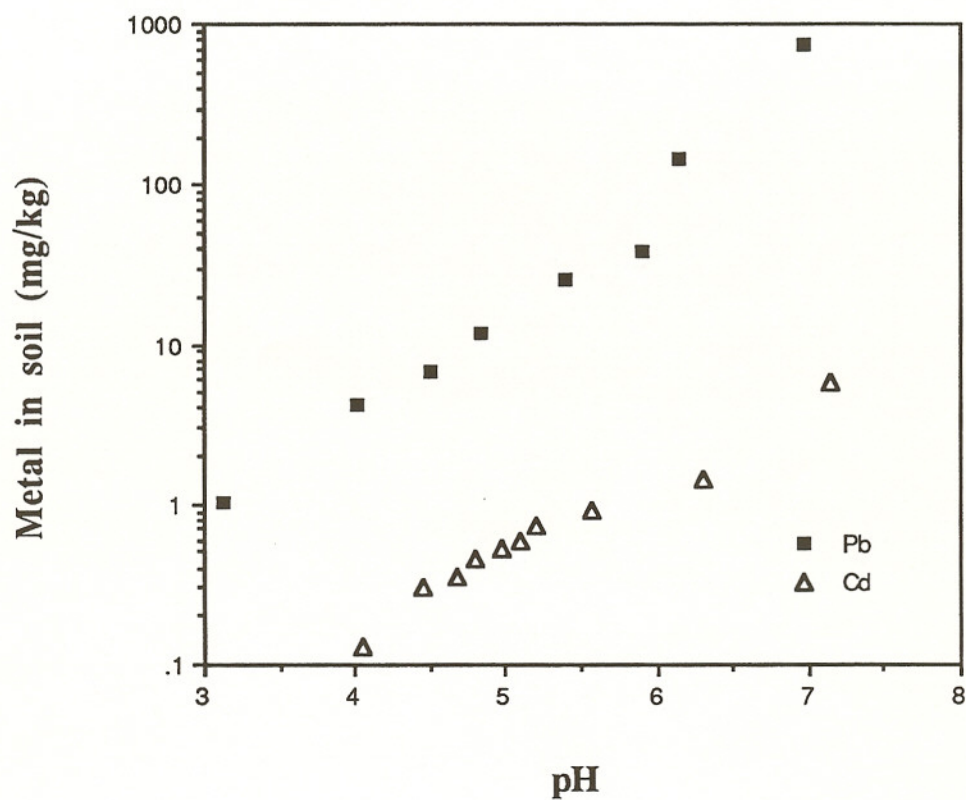


Figure 86. The maximum permissible level of cadmium and lead for Penn silt loam for 1×10^{-4} M initial concentration.

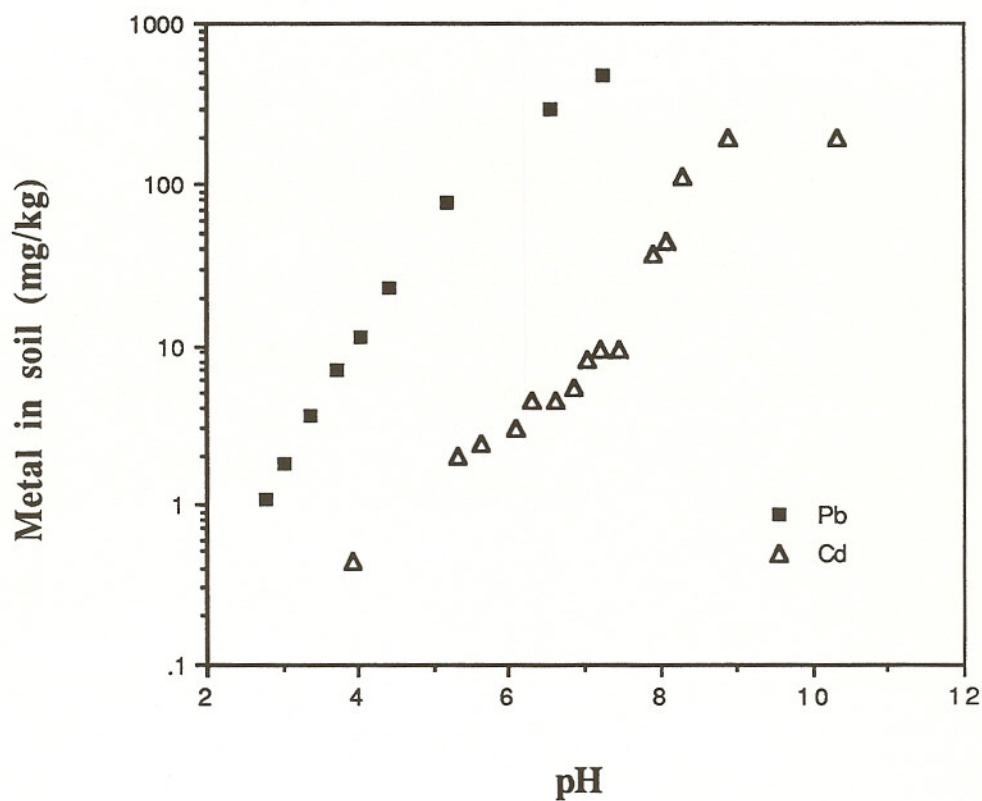


Figure 87. The maximum permissible level of cadmium and lead for Whippany silty clay loam for 1×10^{-4} M initial concentration.

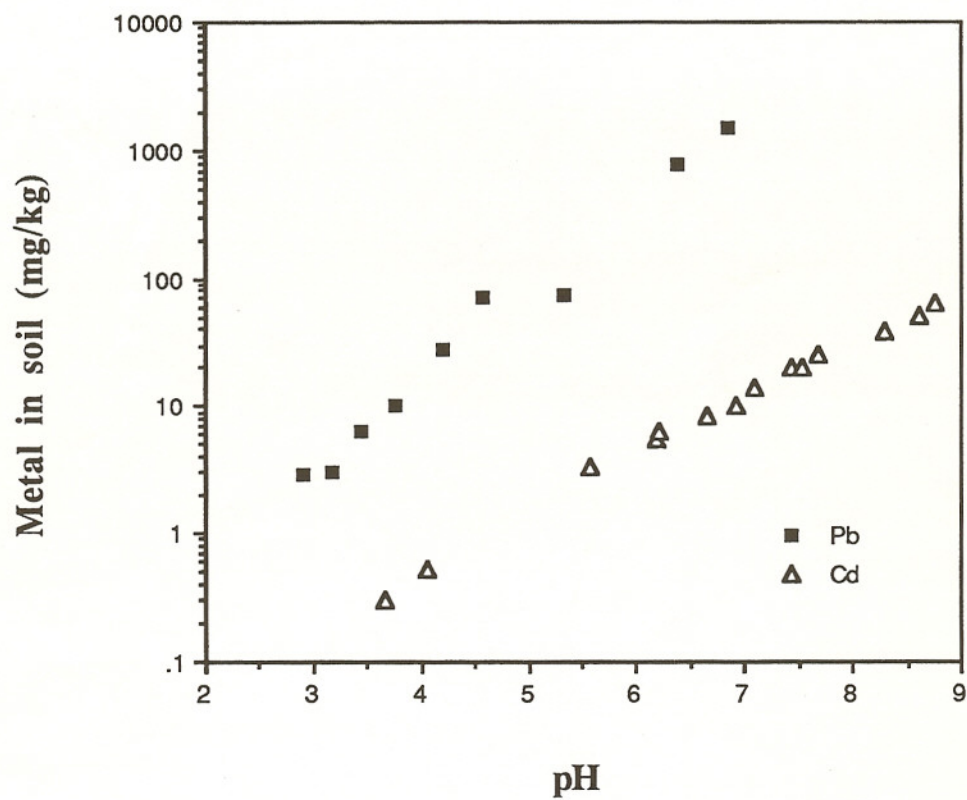


Figure 88. The maximum permissible level of cadmium and lead for Washington loam for 1×10^{-4} M initial concentration.