

Phosphorus
Accumulation
and Loss from
Alabama Soils
Receiving
Poultry Litter



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to race, color, sex, or national origin.*

Phosphorus Accumulation and Loss from Alabama Soils Receiving Poultry Litter

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INTRODUCTION

Each year, Alabama's broiler industry produces an estimated 1.5 million tons of litter, containing approximately 14,645 tons of phosphorus (P). Poultry litter is an excellent source of plant-available P for pasture and row crop lands if properly managed, but excess application rates can pose an environmental threat. Excess P can move from the soil into natural water bodies and lead to eutrophication.

Broiler litter application to cropped and grassed agricultural land has increased the level of extractable P in soils (40). Increasing levels of litter application can increase the amount of P in runoff water (19, 20). Chemical fertilizer or manures come into direct contact with the soil; however, contact between litter P and the soil is reduced by the bedding portion of poultry litter and the practice of applying litter without incorporation. As a result, high percentages of P can be found in dissolved forms.

In areas of concentrated broiler production, such as North Alabama, poultry litter may be more of a disposal problem than a resource management issue. Under these conditions, one may be more interested in the maximum amount of P that can be safely added to a given soil without harming the environment. An Alabama Agricultural Experiment Station (AAES) study was conducted to refine the best management practices for applying broiler litter to farmland. Objectives of the study included:

(1) Determining the P adsorption characteristics and the maximum P adsorption capacity of selected soils in North Alabama as affected by the addition of poultry litter and fertilizer P;

(2) Evaluating P desorption characteristics of North Alabama soils as affected by the addition of poultry litter and fertilizer P;

(3) Evaluating and predicting P uptake by plants and P concentrations in soil water leaching through poultry litter incorporated and spread on soil surfaces, in runoff waters, through the soil profile, and below the root zone;

(4) Evaluating environmentally acceptable P loading limits for North Alabama soils; and

(5) Examining previous related research in relation to results of this study and in relation to P runoff losses.

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Phosphorus Retention and Buildup

In soils with high phosphorus retention capacities, surface water eutrophication can occur from the erosion of P-rich soil material and from runoff water with high phosphorus concentrations. There is no reason for long-term commercial fertilizer use to cause problems of accumulation of excess soil P either in surface water or in ground water. What is needed is the use of P rates consistent with plant needs and with conservation-based management to minimize erosion and runoff. Management should include a regular soil testing program to prevent over application and buildup. Most inorganic P forms in soils are so insoluble that only a small fraction (less than 10%) is available at any one time for plant uptake (15).

There is a large body of literature on the loss of P from fields due to erosion and runoff (70). However, literature on losses from fields receiving animal wastes is limited (40). Phosphorus loss from pastures can be significant for periods soon after application since it is not incorporated by plowing. Phosphorus loss can be significant even if erosion is slight. Best management practices for application of poultry litter should focus on controlling and reducing runoff and erosion. In addition to controlling overland transport, management practices that limit soil test P buildup to excessive levels should be developed (70). Estimating buildup of soil test P levels is a simple test available from all agronomic soil testing laboratories.

Several studies have shown that soil test P and soluble P in runoff are related (68). This has led to state and federal water quality management agencies attempting to identify “cut-off-levels” based on soil test P. Proposed “phosphorus indexing” methods have been developed to plan management strategies when fields receiving P fertilizers approach the cut-off-level (41).

In the Netherlands, animal-based agriculture has resulted in high soil P levels such that regulations have been set to limit the additional application of P. A critical degree of P accumulation in a soil has been set and defined as 25% of the P adsorption capacity of the soil, calculated as follows:

$$\text{DPS} = (\text{Pact}/\text{PSCa}) \times 100$$

DPS is the degree of P saturation, Pact is the oxalate extractable P, and PSCa is the P sorption capacity. All values are expressed on the basis of soil surface area (70).

In Alabama, the Auburn University Soil Testing Laboratory uses an “extremely high” soil test P rating as an environmentally critical level. The level is based on Mehlich-I extractable P. It is defined as four times the amount of a nutrient considered to be adequate for optimum plant growth (2). This level is considered excessive and further additions could be detrimental to the crop and may contribute to pollution of ground and surface waters.

Soil Properties

Goethite and gibbsite sorb phosphates through ligand exchange on exchange sites located on the crystalline edges of gibbsite and the surface of goethite (44). The adsorption of phosphate onto kaolinite, usually the dominant mineral in clay fractions of southeastern U.S. soils, has been proposed to consist of three types of binding sites which correspond to three regions of kaolinite-phosphate adsorption isotherms: Region I involves P adsorption at low P concentration (less than 10^{-4} M P) onto high affinity sites; Region II begins at P concentrations at approximately 10^{-4} M P; and Region III is the linear portion of the isotherm from medium to high P concentrations (10^{-3} to 10^{-1} M P).

Phosphorus is first sorbed onto sites in regions I and II. These are proposed to represent two-OH sites associated with Al at the edge of a kaolinite crystal octahedral sheet and the Al associated with exchange sites (47). Region III may be a poorly crystalline region of the clay surface, or may represent a site that sorbs a small amount of P compared to the number of sites (17).

Several soil chemical and physical properties have been shown to affect P sorption. Jones et al. (37) separated soils into four classes for predicting the P sorption coefficient that is used in the Erosion Productivity Impact Calculator (EPIC). The first separation is between calcareous and non-calcareous soils. In calcareous soils sorption is a function of CaCO_3 content. Non-calcareous soils are classed into slightly, moderately, and highly weathered. In slightly weathered soils the P sorption coefficient (PSP) is considered a function of active and labile P. In moderately weathered soils, PSP is estimated using percent base saturation and pH, and in highly weathered soils clay content is used.

Mullins (48) evaluated the P adsorption characteristics of Benndale, Hartsells, Lucedale, and Dewey soils as affected by long-term fertility treatments. Sorption of P within a soil was affected by the rate of added P and past fertility treatments. P adsorption capacity decreased with decreasing clay content. For example, the Dewey (27% clay) soil had the highest P sorption capacity, and the Benndale (4% clay) soil had the lowest P sorption capacity. In a literature review on the chemistry of soil P, Sanyal and DeDatta (57) summarized P sorption data where correlations had been made between P sorption parameters and soil properties. They showed that several workers have reported a significant correlation of P sorption parameters with clay content. Sanyal and DeDatta (57) speculated that correlation between P sorption and clay content may reflect primarily the effect of surface area on P adsorption. For example, Sanyal et al. (56) reported a high degree of correlation between the Langmuir adsorption maximum and Freundlich K and the clay content of several acid and acid sulfate soils of South and Southeast Asia.

Recently, Schunost and Schwertmann (60) developed pedotransfer functions proposed by Bouma (10) for modeling P availability. They related the P sorption capacity to clay content, citrate-bicarbonate-dithionite extractable iron (CBD iron), and pH. The iron (Fe) content could be replaced by a yellowness component (goethite). In addition, a one-point partition function was required. This relationship was developed for soils that have smectite: goethite soil mineral assemblages.

Alabama is dominated by noncalcareous, highly weathered soils in the Ultisol soil order. Soils with smectite and goethite mineral assemblages are found in Alabama. They would be considered non-calcareous moderately weathered soils. Calcareous soils in Alabama are found in the Blackland Prairie Soil Province (28).

Phosphorus Adsorption and Desorption

When water soluble P fertilizers are applied to soils, most of the added P is converted very quickly to one of many possible low-soluble forms of P. Soil pH is one of the most important factors that affects the forms of P in soil and the solubility and availability of soil P. In acid soils, P is precipitated as insoluble Fe- or aluminum (Al)-phosphates or is adsorbed on the surface of hydrous oxides (75). In calcareous soils, P is precipitated as calcium (Ca)-phosphates of low solubility. When considering adsorption and the solubility of both Fe- and Al-phosphates and Ca-phosphate minerals, a pH of 6.5 generally corresponds to a maximum solubility and availability of soil P.

Adsorption by ligand exchange between phosphate and H₂O and/or OH is believed to be the primary mechanism for P adsorption on hydrous oxide surfaces. Phosphate retained through a single coordinate linkage is considered to be labile (i.e. weakly adsorbed) and readily available to plants. In contrast, P retained through a double coordinate linkage is difficultly available (75).

As summarized by Stevenson (75), Riley and Syers (55) proposed three mechanisms for P adsorption in soils and on the surfaces of Fe-oxide gels. The first mechanism is by chemisorption at protonated surface sites with the surface release of one H₂O for each phosphate ion. A second mechanism is chemisorption by replacement of surface OH groups by adsorbed phosphate ions. The third mechanism is believed to operate at high concentration and represents a physical sorption of P as a potential determining ion.

Phosphate may also interact with the surface of clay minerals (75). At exposed crystal edges, phosphate can be bound by replacement of a OH group from exposed Al atoms. On clay surfaces, phosphate may be held by forming a linkage with exchangeable Ca. This extent of adsorption is considered to be more prevalent for 1:1 type clays

The high affinity of oxide and clay surfaces for soluble P results in a low rate of release of added P. Thus, the release or desorption of adsorbed P is very slow to almost being irreversible, resulting in a large hysteresis effect

(57). Hysteresis effects make the use of P adsorption isotherms unsuitable as a means of estimating the solubility and release of added P.

Models Used to Evaluate P Adsorption

Phosphorus retention by soils has been typically evaluated using adsorption isotherms. Adsorption isotherms are constructed by plotting the amount of P adsorbed per unit weight of soil as a function of the equilibrium P concentration in solution. It is assumed in the use of adsorption isotherms that the P removed from solution is sorbed, that precipitation does not occur or is accounted for and that equilibrium conditions have been reached (9). The two adsorption models most commonly used to study P adsorption include the Langmuir and the Freundlich equations.

The Langmuir equation was developed on the basis of kinetic theory and was initially derived to study the adsorption of gasses on solids (9, 30). It is an attractive model since it produces a theoretical adsorption maximum and a coefficient that is theoretically related to a binding energy. The adsorption maximum is assumed to be a monomolecular layer on all reactive sites. The equation is commonly presented as:

$$x/m = (kXb)/(1 + kX)$$

where x/m is the weight of P per unit weight of soil, X is the equilibrium concentration of P in solution, b is a constant related to the binding strength, and k is the maximum adsorption capacity.

If adsorption data do not conform to the Langmuir equation, the Freundlich equation is often used. The Freundlich equation was originally empirical, and is less demanding since it implies that the energy of adsorption decreases logarithmically as the fraction of covered surface increases. The equation is given as:

$$x/m = kX^{1/n}$$

where k and n are empirical constants and the other terms are defined as for the Langmuir equation.

The Erosion Productivity Impact Calculator (EPIC)

Several soil and plant P models have been developed for specific objectives (36). However, none provide the long-term capability required for evaluating buildup and depletion simulations associated with litter application. A soil and plant model with long-term capability was developed as a component of EPIC, which is a comprehensive model developed for application to erosion-productivity problems (79). EPIC can be used to predict current-year crop yields using measured variables such as climate and soils, or it can be used to predict long-term yields using simulated weather based on nearest station input and various management strategies. The P part of the model simulates plant uptake, attenuation in soil, runoff P losses both in solution and adsorbed to soil particles, mineral P, organic P, labile P, active P, and

fixed P (37). This is the most comprehensive model available to predict the buildup of P based on fertilizer and other management practices for long time periods. In addition, EPIC is an excellent tool to evaluate soil erosion using USLE, MUSLE, and other erosion models. EPIC has an extensive soil and climate data base for all regions of the U.S.

Solubility and Speciation of Solution and Solid P

Measurement and prediction of P concentrations in runoff waters is a key factor in determining mobility and transport of solution P and suspended solid P from fields, pastures, and woodland. MINTEQA2 is a geochemical equilibrium speciation model capable of computing equilibria among the dissolved, adsorbed, solid, and gas phases in an environmental setting (5). Several problems are often encountered in measuring total elemental concentrations in soils and water (43). Often concentrations are below detection limits of the methods used, organic complexes can chelate elements, and fine suspended clays may adsorb some ions that are determined as being soluble. MINTEQA2 can be used to address these and a wide variety of phosphorus solubility problems.

Phosphorus and Suspended Eroded Soil Material

Phosphorus is readily adsorbed onto amorphous oxides and hydroxides of Al and Fe (76) and onto short-range order aluminosilicates (47). The sorption of inorganic P is rapid. Because of the ubiquitousness of Al- and Fe-oxides and hydroxides in soils and their rapid sorption rate of P (32), they have been reported to be associated with up to 50% of the total soil P content (58). Soil P can be carried off-site by water erosion. Suspended solids, particularly the water-dispersible clay, can transport P to receiving waters.

The forms of P entering waterways can be divided into dissolved and particulate P (74). The dissolved forms are those that pass through a 45-micrometer (μm) pore size filter. These include inorganic, condensed, and organic forms. Dissolved forms are more readily available to algae. The particulate forms are less readily available to algae. They also include inorganic, condensed, and organic forms. Of the particulate forms, the inorganic form contributes the most bioavailable P. This form includes P associated with Al and Fe hydrous oxides and non-apatite minerals. Most of the P (75-90%) in runoff from agricultural land is associated with suspended mineral and organic material (45, 63). Phosphorus in runoff from pasture, which contains little suspended material, may be mostly in the soluble form (11, 71).

Excessive P in waterways can lead to plankton blooms and eutrophication. The quantity of P entering waterways is dependent upon quantity of P in the soil, topography, vegetative cover, quantity and duration of runoff, and land use (39). Phosphorus loss from agricultural lands occurs from its leaching from plant material during rainfall, dissolution of fertilizer material, desorption of soil P by runoff, and the erosion of P-laden soil (59, 62).

Scarseth and Chandler (58) reported that 60% of superphosphate applied over a 26-year period was lost by erosion from a nearly level Norfolk loamy sand soil planted to a cotton, corn, oat, and legume rotation. A 63% loss of applied P was attributed to erosion in a Hartsell fine sandy loam of 2-4% slope (21). Schuman et al. (59) applied P at the recommended rate of 39 kilograms per hectare (kg/ha) in Treynor, Iowa, and at 2.5 times this rate to contour-planted corn and pasture. The average P loss for the normally and heavily fertilized plots, over a three-year period, were 0.691 and 1.221 kg/ha per year. They divided P loss into solution P and aggregate-bound P. The solution P for the normally and heavily fertilized plots averaged 0.110 and 0.171 kg/ha per year and the aggregate-bound P averaged 0.581 and 1.050 kg/ha per year.

The concentration of soil-bound P in runoff water tends to be considerably higher than its concentration in the original soil. Enrichment ratios are used to compare the P adsorbed onto an eroded particle or aggregate compared to the amount of P in an equal mass of soil. Enrichment ratios greater than one indicate that the eroded soil material contains more P than the soil from which it eroded (8, 80). Enrichment ratios ranging from 0.95 to 1.96 have been reported for various-size aggregates eroded from plots subjected to different tillage methods in experiments conducted by Alberts and Moldenhauer (4). They observed that the 0.21-0.05-millimeter (mm) and the less than 0.05-mm fractions had the highest enrichment ratios. Sharpley (61) studied the effect of the amount of P applied to a soil and the enrichment ratio of eroded soil material. Enrichment increased with increasing P addition. Enrichment ratios were greatest in the 5-2- μ m and less than 2- μ m fractions.

Barrows and Kilmer (8) hypothesized that low amounts of soluble ions in runoff water may be due to the reabsorption of the ions in solution by the colloidal material in runoff. Sharpley et al. (62) observed that the soluble P concentrations in surface runoff from several cropped and grassed watersheds decreased as the amount of eroded soil material increased. In experiments using soil from these watersheds, soluble P added in rainfall was adsorbed by the eroded soil material transported in the runoff. Their results indicated that suspended eroded soil material may act as a P sink rather than as a P source. They also stated that the magnitude of the sorption was more dependent on the sorptive capacity of the eroded material than that of the surface soil.

Section 319 of the 1990 Water Quality Act gives states the responsibility of developing management plans to limit P pollution from agricultural lands and aquacultural operations. Farmers must have a best management plan developed by the Alabama Department of Environmental Management (2). Currently, the amount of broiler litter that is applied to crop land and pasture is based primarily on nitrogen (N) content of the litter and crop N requirements. However, recent Alabama Cooperative Extension Service publications discourage additional P applications, especially in broiler litter and other animal manures, when soil test P levels reach the "Extremely High" rating.

SUMMARY

In the fall of 1990, soil samples were collected from the Ap and Bt horizon of three major soil series found within the poultry-producing region of North Alabama. The soils sampled included a Hartsells (fine loamy, thermic, siliceous Typic Hapludults), Linker, and Dewey (clayey, kaolinitic, thermic Typic Paleudults) series. According to available records, none of the sites had been treated with poultry litter. The samples were used for laboratory soil characterization and to determine P adsorption-desorption of soils treated with both mineral fertilizer P and broiler litter P.

In 1991, a paired pasture and a paired cotton field were sampled to one meter. One field in each pair had received litter for 18-20 years, and the other was under conventional N and P fertilization. Resident mineral (total and resin extractable) and organic N were determined to sampled depths. EPIC was used to simulate P uptake, leaching and runoff losses under fescue and cotton receiving litter and under conventional fertilization.

Data obtained by adsorption isotherm analysis, incubation of litter, and monocalcium-P-treated samples, analysis of field soil samples, EPIC simulation of P loading, and fitting equilibrium distribution data to various models show these North Alabama soils have high P adsorption capacities. The P adsorption capacity is essentially the same when based on clay content. Following a three-month incubation period of monocalcium-phosphate- (MCP) and broiler-litter-treated soil samples, significantly more P was soluble and leached from MCP-treated soil than from broiler-litter-treated soil with comparable amounts of P added. Measured and predicted results show that large amounts of P are retained on clay (5,000 mg/kg) before dissolved P concentrations reach 1,000 μg per liter, a concentration considered as a limit for disposal of treated water from sewage treatment plants. In watershed studies in North Alabama, dissolved P in runoff water exceeded this limit even when conventional application rates recommend by soil test were used, regardless of P source (litter P or mineral fertilizer P). The dissolved P concentrations are related to date of application, degree of incorporation, management schedules, and time after application when runoff events occurred (29, 72). Reviews of available literature for research conducted outside of Alabama (66, 65) show that dissolved P in surface runoff can exceed this limit under a variety of cropping systems, with and without the addition of fertilizer P. Runoff P losses are more related to management practices than they are to the source of P or, to a point, the amount of resident soil-P. A 20-year EPIC simulation of conventional P application and of annual 7,200 kg/ha litter applications indicated that the annual average dissolved P concentration of runoff does not change appreciably over a 20-year period, while total soil P levels increased from 500 mg/kg to 1,500 mg/kg.

The amount of P that soil can adsorb depends on its P adsorption capacity and its soil mineralogy. Results of particle-size and mineralogy characterization from this study indicate that the P-adsorbing capacity of these soils should be governed by their kaolinite, HIV, gibbsite, and goethite contents. The clay percentage should be a more relevant factor in describing P movement since active P-sorbing minerals are in the clay fraction. Approximately 40% to 60% of the water-dispersible clay fractions in runoff from highly weathered Ultisols in North Alabama should be kaolinitic. Hydroxy-interlayered vermiculite (HIV) would comprise about 15-20% of the water-dispersible clay of suspended solids. Mica, goethite, and gibbsite would make up the rest. More accurate descriptions of P adsorption mechanisms and movement possibly could be attained by utilizing mineral percentages in adsorption models. However, the analysis procedures are complex and not suitable for routine soil tests such as used in the soil testing laboratory. An ion speciation model MINTEQA2 (43), which uses mineralogy input, did not adequately predict soluble P in equilibrium with these soil clays.

Mineralogy and clay content is somewhat accounted for in the EPIC model by use of a P sorption parameter (PSP) obtained by considering classification of the soil and clay content in highly weathered soils and CaCO_3 in relatively unweathered soils (37). The need to consider clay content is evident from results obtained by isotherms and solubility of P from 91-day incubated soil samples with litter P and MCP applied and with no P applied. Hartsells Ap sample has 5.7% clay and Dewey has 20.2%. *When P adsorption was put on a clay percent basis, adsorption and desorption was essentially the same per unit of clay.* This should hold on a regional basis for soils with kaolinitic mineralogy in Ultisol and Alfisol soil orders.

The complex nature of soil:solution P equilibria is well documented (42). Isotherm results in the AAES study show that a single adsorption mechanism does not explain or model adsorption and solution concentration from low to high loading. Several phenomena were found to occur: adsorption on multiple surfaces; higher soil pH at high litter loading rates, and slightly higher pH as MCP rates increased; and precipitation of Al-, Fe-, and Ca-phosphates. These isotherm adsorption curves can be represented by combining an initial Langmuir adsorbing surface followed by a linear representation of equilibrium solid:solution P concentrations (Figures 13-18). The linear nature of this equilibrium concentration distribution also is evident when solid:solution equilibria were evaluated on a clay suspension basis. *In all cases, the linear phase is reached when solution concentrations are greater than 1,000 $\mu\text{g/L}$* (67). Alabama does not have a discharge limit for municipal treatment facilities; however, one facility discharging into a stream flowing into a reservoir for a city water supply uses the 1,000 $\mu\text{g/L}$ limit. At this concentration, MCP data (Figure 23) in the AAES study show that the total mineral P in the solid phase is 5,884 mg/kg of clay, of which 2,878 mg/kg is stable fixed and 128

mg/kg is exchangeable or active P. In the same clays incubated with litter, 9,096 mg/kg of P are in the solid phase, 3,163 are fixed, and 980 are active.

An approximation of exchangeable or active P can also be made by considering all MCP used in developing adsorption isotherms as being active. The tests were made after only 16 hours of shaking. Considering that the linear adsorption region is reached at 1,000 $\mu\text{g/L}$, a linear equation can be developed, and the active or exchangeable solid phase P at 1,000 $\mu\text{g/L}$ can be calculated.

This and other investigations have shown that soil test P (Mehlich-I extractable) gives an indication of dissolved P. At 1,000 $\mu\text{g/L}$ dissolved P, the soil test level is 300 mg/kg. Kingery et al. (40) found that the average soil test P from 11 sites were near 300 mg/kg for surface soil layers of fescue pastures on the Hartsells series receiving litter for about 20 years. A 20-year simulation of soil test P levels using the EPIC model compared favorably to Kingery's measured results.

Many researchers have expressed concern about the level of P buildup in soils receiving high rates of P from poultry litter applications. Critical values for soil test P have been defined on the basis of crop requirements. The rationale has been that the limits proposed are far in excess of crop P requirements, and further applications enhance the risk for P losses in runoff. There is considerable evidence that on soils with moderate levels of soil test P, there are P losses in runoff from P applied at soil test recommended levels. In fact, both Scarseth (58) and Ensminger (21) reported substantial amounts of P losses from applied P fertilizer on Alabama soils. Losses in excess of biological algae limits are not the exception. These losses are management- and rainfall-related and are not totally subject to P inputs from long-term P application. Isotherms show that resident soil test P levels have to exceed 300 mg/kg before equilibrium dissolved P levels greater than 1,000 $\mu\text{g/L}$ are supported. This is a reasonable maximum P limit level based not on crop needs, but on both soil and solution levels obtained from controlled experimentation. Lower soil test critical values ranging from 75 to 200 mg/kg have been proposed (26, 67).

Results from this study show that as the 300 mg/kg critical soil test value is approached or exceeded, best management plans (BMPs) should be evaluated to guide operators in selecting practices to limit further P buildup, minimize erosion and runoff losses, and maintain soil productivity. For fields that currently exceed the 300 mg/kg limit, remediation strategies that will accelerate P depletion should be made a part of management. Evaluating proposed practices or developing recommended practices through the use of models such as EPIC can help provide a comprehensive approach based on real onsite input of climate, soil, agronomic factors, management, and economic returns. Recommendations can be flexible, site specific, and environmentally sound.

METHODS

Soil Characterization

In the fall of 1990, soil samples were collected from the Ap and Bt horizon of three major soil series found within the poultry-producing region of North Alabama. The soils sampled were in the Hartsells, Linker and Dewey series. According to available records, none of the sites had been treated with poultry litter. Approximately 150 kg of soil was collected from each horizon, air-dried and ground to pass a 0.25-inch sieve. Subsamples were obtained for incubation and adsorption isotherm determinations. In addition subsamples were used for soil physical, chemical, and mineralogical characterization.

Physical: Particle-size analysis was performed by the sieve and pipette method (73). Percentages of the various fractions were calculated on an oven-dry weight basis. The samples were treated for removal of organic matter and free Fe oxides.

Chemical: Soil pH was determined on 1:1 soil-water suspensions. Cation exchange capacity (CEC) was determined by \underline{N} NH_4OAc saturation at pH 7.0 and KCl extraction (73). Exchangeable Ca, magnesium (Mg), potassium (K), and sodium (Na) were extracted with \underline{N} NH_4OAc and determined by atomic absorption spectrophotometry. Exchangeable Al and hydrogen (H) were extracted with a \underline{N} KCl solution and determined by titration (73). Free Fe oxides, extracted by the Na-citrate-bicarbonate-dithionite method (34) were determined in solution extracts by X-ray emission spectroscopy (22).

Mineralogical: Clay fractions (less than 2 μm) were obtained for mineralogical analysis by ultrasonic bath dispersion in a pH 9.5 Na_2CO_3 suspension (38). Quantitative interpretations were based on procedures given by Karathanasis and Hajek (38).

X-ray diffraction patterns were obtained for magnesium- and potassium-saturated clay fractions placed on glass slides by a modified filter peel technique (18). A Siemens D5000 diffractometer equipped with a monochromator and Cu tube was used.

Magnesium-saturated clays were analyzed by Thermogravimetry and Differential Scanning Calorimetry. A Thermal Analysis "TA" 1200 controller unit was used for all TG and DSC analyses.

Paired Fields

Paired fescue pasture and paired cotton fields were sampled to one meter. One field in each pair had received litter for 18-20 years, and the other was under conventional N and P fertilization. The collected samples were air-dried and ground to pass a 2-mm sieve. They were analyzed for Mehlich-1 (46) extractable P, K, Ca, Mg, and pH by the Auburn University Soil Testing Laboratory. Organic P was determined using an ignition procedure (52). A 10-gram subsample of soil from each treatment was ground to pass a 60-mesh

sieve. This ground subsample was used in the determination of resin-extractable P (52) and total P. Total P was determined using a nitric-perchloric acid, wet ash digestion procedure (33).

Incubation

Subsamples of soil from each horizon were ground to pass a 2-mm sieve and treated with poultry litter at rates equivalent to 0, 25, and 50 tons per acre (0, 25, and 50 g of litter per kilogram of soil). A rate of 50 tons per acre would represent the approximate amount of litter what would be applied to supply the N needs of a corn crop for a period of 10 years. Litter used in the study was obtained from North Alabama and contained 32.14% carbon (C), 3.5% N, and 1.37% P. The litter was air-dried and ground to pass a 1-mm sieve prior to application. A second series of treatments received P as inorganic, reagent-grade monocalcium phosphate, MCP, $[\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}]$ at rates equivalent to the amount of P applied in the poultry litter treatments (0, 342, and 684 mg/kg).

Treatments consisted of 200 g of air-dried soil that was thoroughly mixed (by hand) with the respective rate of litter or MCP. Treated soil was placed into treatment vessels which consisted of one-pint, wide-mouth mason jars. Deionized water was added to bring the soil to 85% of field capacity. Treatments were incubated at 30°C for 91 days.

In order to measure the amount of CO_2 produced during the incubation, a vial containing 10 mL of 2 N NaOH was placed into each treatment vessel. Two treatment vessels without soil were included as checks. Residual NaOH in the vials was titrated (in the presence of BaCl_2) periodically throughout the incubation study using 1 N HCl. Data from the titrations were used to determine the amount of CO_2 that was produced during the incubation study. Treatment vessels were aerated 10 minutes each time the NaOH vials were removed for titration and once a week when the time between titration was extended to 14 days.

At the end of 91 days, the samples were air-dried and ground to pass a 2-mm sieve. Organic P was determined using an ignition procedure (52) and pH using a 1:1 soil to water (V:V) ratio (33). A 10-gram subsample of soil from each treatment was ground to pass a 60-mesh sieve. This ground subsample was used in the determination of resin-extractable P (52) and total P. Total P was determined in soil from selected treatments using a nitric-perchloric, wet ash digestion procedure (33).

Phosphorus desorption in each treatment was evaluated using a batch equilibrium method where soil was extracted with 0.01 M CaCl_2 . Subsamples of soil (5 g) from each treatment were weighed into 50 mL centrifuge tubes and equilibrated with 20 mL of 0.01 M CaCl_2 . One drop of toluene was added to reduce microbial activity. Each tube was weighed before and after the addition of the CaCl_2 solution. The tubes were placed in a 30°C shaking water bath for 24 hours at approximately 25 rpm; tubes were then centrifuged, and

10 to 15 mL of solution was removed. The tubes were reweighed and enough CaCl_2 solution was added to bring the solution back to 20 mL. A vortex mixer was used to resuspend the soil, and the samples were shaken for an additional 24 hours. This process was repeated for six days. Leachates were analyzed using the Murphy and Riley (49) procedure. The amount of P released was calculated by knowing the concentration of P in the leachate, the amount of leachate removed each day, and the amount of leachate that was carried over to the next sampling.

Adsorption Isotherms: Phosphorus adsorption isotherms were constructed for soil from each repetition of each treatment. Subsamples (1 g) of soil from each treatment were weighed into 50-mL centrifuge tubes and equilibrated with 30 mL of 0.01 M CaCl_2 containing various levels of P. Phosphorus was supplied as KH_2PO_4 at rates of 0, 5, 10, 25, 75, 150, 250, and 500 mg/kg soil. One drop of toluene was added to each tube to reduce microbial activity. Treated samples were shaken for 18 hours in a reciprocating, shaking water bath (30°C), centrifuged, and filtered through Gelman SUPOR-200 membrane filters (0.2 μm pores). Phosphorus in the filtrates was determined by the Murphy and Riley (49) procedure. Adsorbed P was calculated as the difference between the amount of P added and the resulting equilibrium solution concentration. The Langmuir, cumulative, Freundlich, and linear equations were applied to isotherm data. Adsorption capacities were needed as input into a soil P simulation model. An additional subset was equilibrated in 0.01 M CaCl_2 for 30 days, with no P added to the background solution. Following equilibration the suspensions were centrifuged and filtered to obtain clear solutions for P analysis. This set was used to determine the relation of P sorption to clay content and the solution P concentrations were used to evaluate an ion speciation model.

MINTEQA2/PRODEFA2 Ion Speciation

The concentration of P in solution was evaluated relative to soil mineral and soluble ion composition by submitting equilibrium solution P concentrations to the MINTEQA2 ion speciation model (5). Equilibrium P concentrations were obtained by suspending enough soil in solution to achieve clay suspensions of 500 and 1,000 mg/L. The Hartsells and Dewey soils were obtained from an incubated set with the equivalent of 25 and 50 tons of litter added and with equivalent amounts of MCP added and incubated for 91 days at 30°C. Check samples were also included (no litter or MCP added). The suspensions were allowed to equilibrate for 30 days with occasional shaking. A microbial inhibitor was added. Following equilibration the suspensions were centrifuged, filtered, and analyzed for soluble P and other major soluble ions.

The data required to predict the equilibrium P in these suspensions include: (1) dissolved concentrations of P and other relevant ions, such as Ca, Mg, Fe, Al, pH, SO_4 , and anions, to nearly maintain neutrality and to simulate the ionic strength of the solution; (2) dissolved CO_2 ; and (3) minerals, espe-

cially kaolinite, gibbsite, quartz, and iron oxyhydroxides. Initial soil mineral and total P composition was available from analysis done in other parts of this study. MINTEQA2/PRODEFA2 was installed on a 486/33 PC, and the equilibrium constant data furnished with the program was replaced by a database sent on request by Lindsay (personal communication). Both the Langmuir and the Kd adsorption equations were included in the simulation.

Erosion Productivity Impact Calculator Simulation

In this study, a paired fescue pasture (Hartsells fine sandy loam) and a paired cotton field (Dewey silt loam) were sampled to one meter. The pasture sites were in DeKalb County, Ala., and the cotton fields were in Cherokee County, Ala. One field in each pair had received litter for 18-20 years, and the other was under conventional N and P fertilization. Isotherms developed from similar soils were used to determine P sorption ratios of surface and subsoils which were input into the model. Resident mineral (total and resin extractable), Mehlich-1 extractable P, and organic P were determined to sampled depths for the four fields. Soil input variables were obtained from available soil data sampled in support of other research and the soil survey program. Management was obtained from farm operator records and from practices recommended by professional agricultural workers in North Alabama. Average fresh broiler litter composition was obtained from an Extension Service survey of litter composition needed to make fertilizer recommendations for litter used on pasture or other crops. Before the model was used, it was evaluated by comparing predicted forage and cotton yields to average yields expected in North Alabama on these or similar soils. Predicted yields were well within the expected range when evaluated for a 10-year period. EPIC was used to simulate P uptake, leaching, buildup, and runoff losses under fescue and cotton receiving litter and under conventional fertilization for 20 years.

RESULTS AND DISCUSSION

Soil Characteristics

The surface and subsoil samples collected from three pedons were characterized to confirm placement into Soil Taxonomy (73). In addition, selected data were obtained that were useful in interpreting differences in P loading and retention.

The data showed that all three soils should be classified as Ultisols, which are considered to be highly weathered (Table 1). Particle-size distribution properties are given in Table 2, and chemical properties are in Table 3. Since clay is the active fraction, particle size data indicate that the clay content of the Ap horizon in Dewey and Linker soils (about 20%) will adsorb more P per unit weight of soil than Hartsells (5.7% clay) (37). This is also evident for subsoil Bt horizons. Other particle-size differences are reflected in higher silt

TABLE 1. CLASSIFICATION OF NORTH ALABAMA SOILS SAMPLED FOR P ADSORPTION AS AFFECTED BY THE APPLICATION OF POULTRY LITTER

Soil	Classification
Dewey	Clayey, kaolinitic, thermic, Typic Paleudults
Linker	Fine-loamy, siliceous, thermic, Typic Hapludults
Hartsells	Fine-loamy, siliceous, thermic, Typic Hapludults

in the Dewey and corresponding lower sand. Chemical properties, OM, CEC, and pH are also similar for Dewey and Linker, but the higher gibbsite and Fe_2O_3 of the Linker clay fraction (Table 4) should enhance P adsorption and fixation. Although all soils were classified in the Ultisol soil order, differences in clay content and mineralogy should be reflected by substantially higher P fixation and sorption in Dewey and Linker. This is supported by total P content and organic P (Table 3) but not by soil test P. The soil test P was higher in Hartsells and Dewey because they were collected in cultivated fields. The Linker was collected in mixed pasture-woodland that had received no fertilizer P.

Phosphorus Adsorption

Although P was the primary interest of this study, CO_2 production was measured in order to evaluate the relative degree of litter decomposition that occurred during the 91-day incubation study (Figures 1-3). As expected, C released as CO_2 increased with litter rate (Figures 1-3 and Table 5). A power function was used to describe the cumulative release of C with time from the litter treated soils (Figures 1-3). The amount of added litter-C released ranged from 47-64% of the added C in the Ap horizon samples and from 37-47% of the added C in the Bt horizon samples (Table 5). These levels of decomposition are consistent with other reports evaluating litter decomposition in soils. Sims (69) reported that from 30-60% of the organic N in poultry manure was

TABLE 2. PARTICLE SIZE DISTRIBUTION OF THE THREE SOILS USED TO EVALUATE P ADSORPTION AS AFFECTED BY THE APPLICATION OF LITTER

Soil & Horizon	Particle size distribution			Sand size distribution (mm)				
	Sand	Silt	Clay	2-1	1-.5	.5-.25	.25-.1	.1-.05
	<i>pct.</i>	<i>pct.</i>	<i>pct.</i>	<i>pct.</i>	<i>pct.</i>	<i>pct.</i>	<i>pct.</i>	<i>pct.</i>
Hartsells-Ap ¹	61.0	33.28	5.72	0.66	3.78	32.84	51.56	11.17
Hartsells-Bt ¹	56.8	31.20	12.00	1.06	3.89	31.63	52.30	11.13
Linker-Ap ²	48.8	31.44	19.76	5.57	2.27	17.32	42.89	31.96
Linker-Bt ³	40.1	27.22	32.68	3.50	2.25	13.75	39.25	41.25
Dewey-Ap ⁴	29.9	49.86	20.24	6.10	14.92	27.46	32.54	18.98
Dewey-Bt ⁵	19.0	46.16	34.84	3.72	11.17	25.00	35.11	25.00

¹Sandy loam; ²Loam; ³Clay loam; ⁴Silt loam; ⁵Silty Clay loam.

TABLE 3. CHEMICAL PROPERTIES OF THREE SOIL SERIES USED TO EVALUATE P ADSORPTION CHARACTERISTICS AS AFFECTED BY POULTRY LITTER

Soil & horizon	Organic matter	CEC	pH	Total P	Organic P	Resin ext. P	Mehlich I extractable			
							P	K	Mg	Ca
	<i>pct.</i>	<i>cmol/kg</i>		<i>mg/kg</i>	<i>mg/kg</i>	<i>mg/kg</i>	<i>lb./a.</i>	<i>lb./a.</i>	<i>lb./a.</i>	<i>lb./a.</i>
Hartsells-Ap ...	1.5	4.86	6.6	311	86	27.0	96	70	52	1,470
Hartsells-Bt.....	0.3	4.68	5.1	223	40	1.5	3	44	11	390
Linker-Ap	1.8	6.34	5.8	479	149	0.9	5	74	112	1,290
Linker-Bt	0.7	6.61	4.9	497	113	1.6	2	39	70	780
Dewey-Ap	2.1	6.73	5.3	656	138	5.5	53	413	127	830
Dewey-Bt	0.7	7.35	5.2	488	77	1.0	3	250	157	1,240

mineralized within 90 to 150 days after incorporation. Castellanos and Pratt (13) reported that approximately 45% of the total C in chicken manure was decomposed during a four-week incubation study. Gale and Gilmour (25) reported that C release from litter-treated soil consisted of three phases (rapid, intermediate, slow). In their study, decomposition shifted from a rapid to an intermediate and ultimately to a slow phase. The shift in decomposition phase occurred when approximately 15% and 30% of the added C was mineralized, respectively. Under field conditions, Flynn (24) evaluated the decomposition of peanut-hull- and wood-shaving-based poultry litter. Both sources of litter were applied at a rate of four tons per acre. At 112 days after application, he reported an average release of 52% and 49% of the litter-C on a Wynnville and a Norfolk soil, respectively.

Monocalcium phosphate resulted in higher levels of resin-extractable P, as compared to the litter treatments, since part of the litter P is organic (Table 6). The litter treatments resulted in large increases in organic P in all soils tested. For some unexplained reason, the low-litter treatment to the Ap horizon of the Linker soil resulted in very little change in organic P. If the Ap horizon of the Linker soil is excluded, an average of 37% and 33% of the

TABLE 4. MINERALOGICAL CHARACTERISTICS OF SOILS SAMPLED FOR P ADSORPTION AS AFFECTED BY THE APPLICATION OF POULTRY LITTER

Soil & horizon	Fe ₂ O ₃ equivalent	Surface area, clay	Surface area, soil	Mineralogy				
				HIV	Kaolinite	Mica	Gibbsite	Quartz
	<i>pct.</i>	<i>m²/g clay</i>	<i>m²/g soil</i>	<i>pct.</i>	<i>pct.</i>	<i>pct.</i>	<i>pct.</i>	<i>pct.</i>
Dewey-Ap	2.3	133	27	27	48	5	tr ¹	6
Dewey-Bt	3.5	147	51	32	45	4	tr	2
Hartsells-Ap	0.5	144	8	63	34	--	2	3
Hartsells-Bt.....	1.0	137	16	53	31	--	5	10
Linker-Ap	2.6	183	36	58	39	tr	9	7
Linker-Bt	4.6	166	54	55	44	tr	14	7

¹Trace amount.

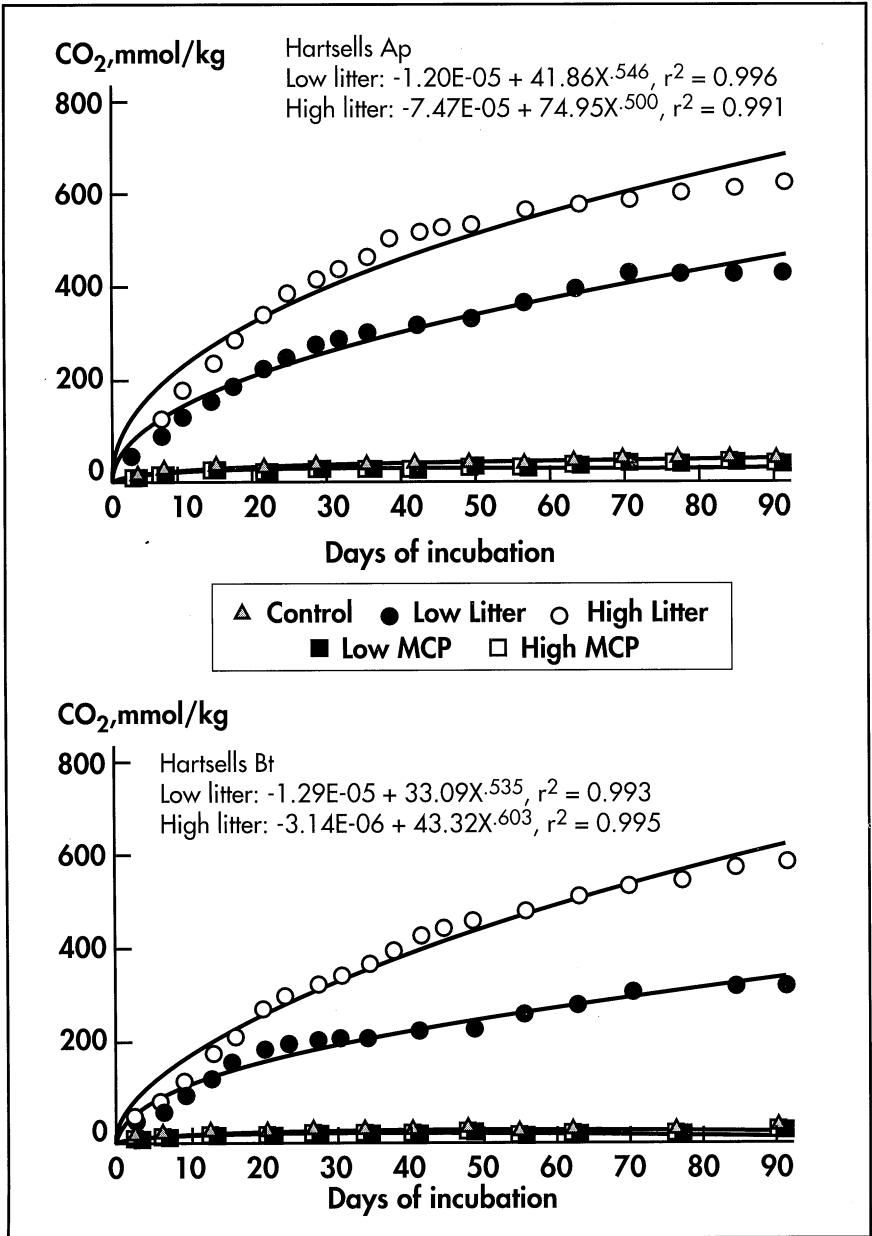


Figure 1. Cumulative production of CO₂ from the Ap and Bt horizon of a Hartsells soil as affected by the application of poultry litter and inorganic fertilizer. Low litter = 25 tons/acre, High litter = 50 tons/acre, Low MCP = monocalcium phosphate applied to equal P in Low litter treatment (342 mg P/kg), High MCP = monocalcium phosphate applied to equal P in High litter treatment (684 mg P/kg).

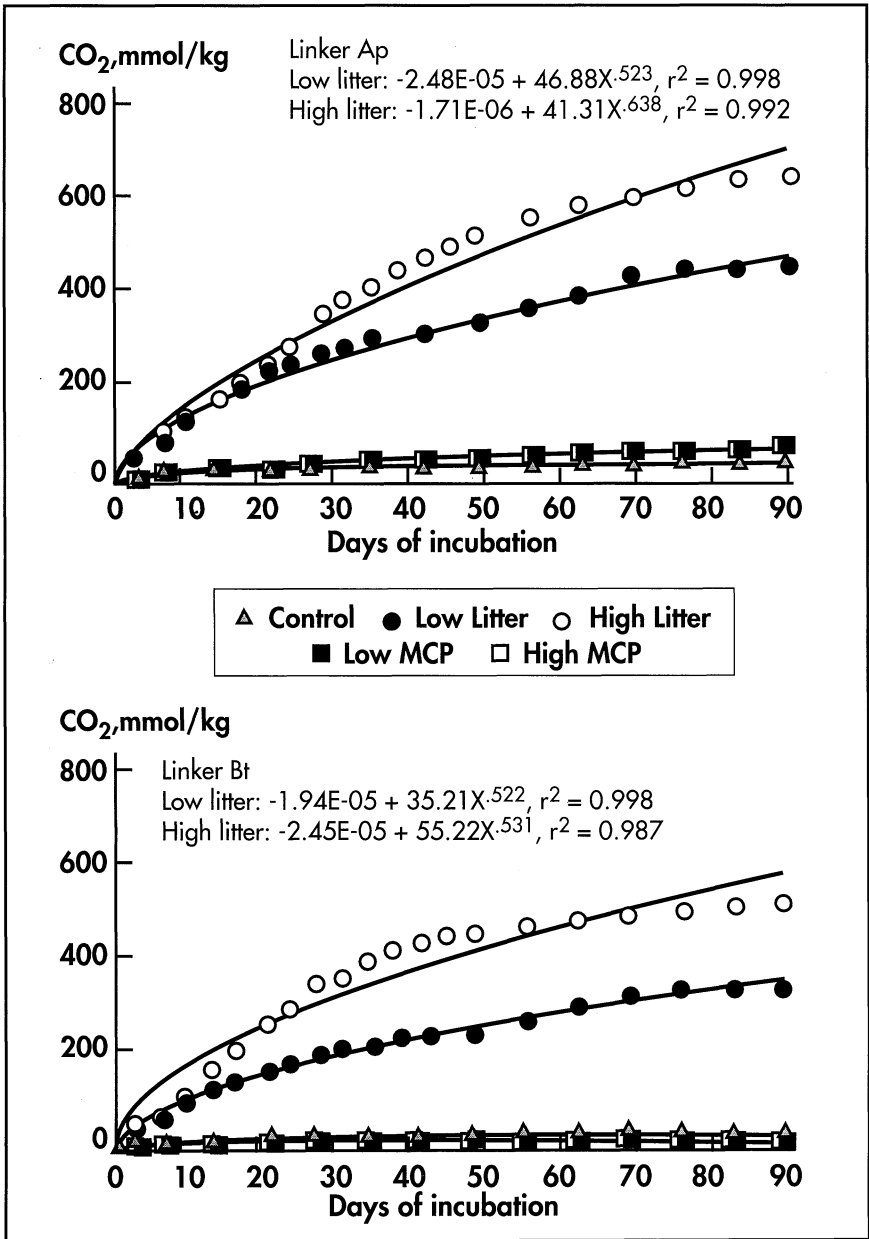


Figure 2. Cumulative production of CO₂ from the Ap and Bt horizon of a Linker soil as affected by the application of poultry litter and inorganic fertilizer. Low litter = 25 tons/acre, High litter = 50 tons/acre, Low MCP = monocalcium phosphate applied to equal P in Low litter treatment (342 mg P/kg), High MCP = monocalcium phosphate applied to equal P in High litter treatment (684 mg P/kg).

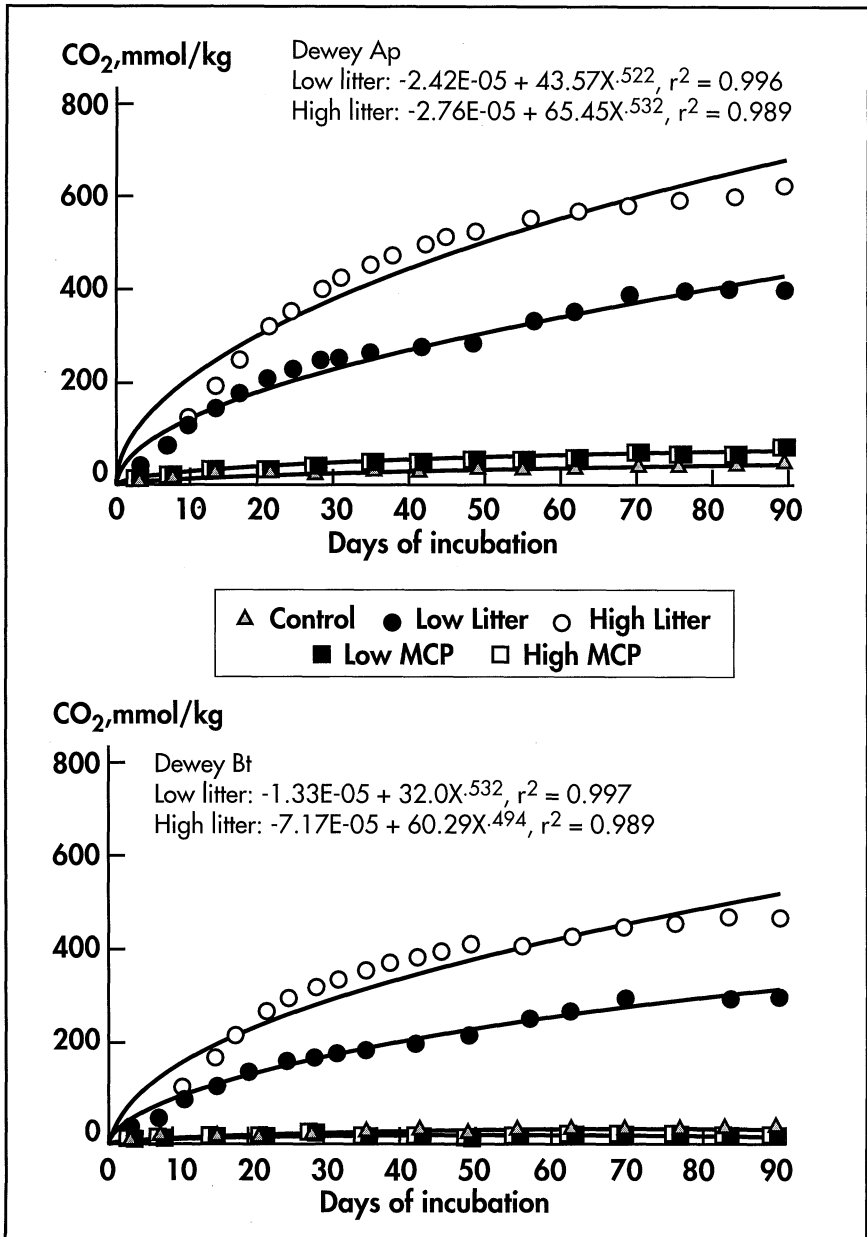


Figure 3. Cumulative production of CO_2 from the Ap and Bt horizon of a Dewey soil as affected by the application of poultry litter and inorganic fertilizer. Low litter = 25 tons/acre, High litter = 50 tons/acre, Low MCP = monocalcium phosphate applied to equal P in Low litter treatment (342 mg P/kg), High MCP = monocalcium phosphate applied to equal P in High litter treatment (684 mg P/kg).

TABLE 5. AMOUNT OF CARBON RELEASED AS CO₂ FROM SOILS DURING 91-DAY INCUBATION AS AFFECTED BY LITTER AND MONOCALCIUM PHOSPHATE

Soil & horizon	Source	P rate	Added C	Carbon release	
				Released C	Pct. added C
		<i>mg/kg</i>	<i>mmol/kg</i>	<i>mmol/kg</i>	<i>pct.</i>
Hartsells-Ap	Check	0	0	31	--
Hartsells-Ap	Litter	342	669	457	64
Hartsells-Ap	Litter	684	1,338	650	46
Hartsells-Ap	MCP	342	0	35	--
Hartsells-Ap	MCP	684	0	36	--
Hartsells-Bt	Check	0	0	14	--
Hartsells-Bt	Litter	342	669	352	51
Hartsells-Bt	Litter	684	1,338	614	45
Hartsells-Bt	MCP	342	0	6	--
Hartsells-Bt	MCP	684	0	22	--
Linker-Ap	Check	0	0	43	--
Linker-Ap	Litter	342	669	472	64
Linker-Ap	Litter	684	1,338	667	47
Linker-Ap	MCP	342	0	66	--
Linker-Ap	MCP	684	0	68	--
Linker-Bt	Check	0	16	--	--
Linker-Bt	Litter	342	669	352	50
Linker-Bt	Litter	684	1,338	538	39
Linker-Bt	MCP	342	0	19	--
Linker-Bt	MCP	684	0	34	--
Dewey-Ap	Check	0	54	--	--
Dewey-Ap	Litter	342	669	433	57
Dewey-Ap	Litter	684	1,338	650	45
Dewey-Ap	MCP	342	0	64	--
Dewey-Ap	MCP	684	0	74	--
Dewey-Bt	Check	0	22	--	--
Dewey-Bt	Litter	342	669	336	47
Dewey-Bt	Litter	684	1,338	511	37
Dewey-Bt	MCP	342	0	19	--
Dewey-Bt	MCP	684	0	25	--

litter P from the low and high litter treatments, respectively, could be accounted for as organic P in the Ap horizon samples. In the Bt horizon samples averages of 40% and 39% of the litter P could be accounted for as organic P in the low- and high-litter treatments. Litter also resulted in an increase in soil pH, as compared to the check treatment. Monocalcium phosphate also resulted in the greatest release of added P during a continuous desorption study that was conducted over a period of six days (Figures 4-6). However, when expressed as a fraction of the added P, relatively small amounts of P were released from the treated soils during the batch desorption study (Table 6). The greatest release on a percentage basis was from the low-MCP treatment (342 mg/kg) on the Hartsells soil, where 20% of the added P was released. Data from the desorption study suggest that the leaching potential for P from the Ap horizon would be greatest for the Hartsells soil and lowest for the

Dewey soil. Leaching potential for P applied as both sources would be very low in the Bt horizon of all three soils (Table 6, Figures 4-6).

Solution P concentrations ($\text{PO}_4\text{-P}$) maintained during the batch desorption study are shown in Figures 7-9. Consistently, the MCP treatments maintained the highest solution P concentrations. In the Ap horizon samples, the high-MCP treatment had solution P concentrations that were always higher as compared to the high-litter treatments. Higher solution concentrations in the MCP treatments were due, in part, to a lower soil pH in the MCP versus the litter treatments (Table 6). For the MCP and high-litter treatments, the highest concentrations were always observed in the first extract followed with a decrease in concentration with each successive extract. In the Ap horizon

TABLE 6. SOIL pH, RESIN EXTRACTABLE P, ORGANIC P, AND THE AMOUNT OF P RELEASED DURING A SIX-DAY DESORPTION STUDY¹

Soil	Source	P rate	Soil pH	Resin P	Organic P	Desorbed P	
						Total	Pct. added P ²
		<i>mg/kg</i>		<i>mg/kg</i>		<i>mg/kg</i>	<i>pct.</i>
Hartsells-Ap	Check	0	6.2	27.00	76	1.04	—
Hartsells-Ap	Litter	342	7.3	110.00	189	11.00	2.80 ²
Hartsells-Ap	Litter	684	7.5	166.00	303	23.00	3.20
Hartsells-Ap	MCP	342	6.0	123.00	—	69.00	20.00
Hartsells-Ap	MCP	684	5.8	216.00	92	132.00	19.20
Hartsells-Bt	Check	0	5.1	1.50	40	0.24	—
Hartsells-Bt	Litter	342	6.8	21.00	173	0.91	0.20
Hartsells-Bt	Litter	684	7.3	108.00	386	5.30	0.70
Hartsells-Bt	MCP	342	4.9	35.00	37	6.40	1.80
Hartsells-Bt	MCP	684	5.1	110.00	54	56.00	8.20
Linker-Ap	Check	0	5.2	0.89	149	0.36	—
Linker-Ap	Litter	342	5.5	16.00	161	1.50	0.30
Linker-Ap	Litter	684	7.3	68.00	325	3.90	0.50
Linker-Ap	MCP	342	5.3	57.00	147	19.00	5.50
Linker-Ap	MCP	684	5.4	118.00	192	65.00	9.50
Linker-Bt	Check	0	5.0	0.48	113	0.21	—
Linker-Bt	Litter	342	4.5	2.40	254	0.34	0.04
Linker-Bt	Litter	684	6.9	31.00	281	1.40	0.20
Linker-Bt	MCP	342	4.9	8.80	92	1.30	0.30
Linker-Bt	MCP	684	5.5	66.00	138	9.30	1.30
Dewey-Ap	Check	0	5.0	5.50	138	0.33	—
Dewey-Ap	Litter	342	6.6	29.00	279	1.30	0.30
Dewey-Ap	Litter	684	6.9	46.00	361	2.50	0.30
Dewey-Ap	MCP	342	5.0	52.00	177	12.00	3.40
Dewey-Ap	MCP	684	5.1	92.00	196	47.00	6.80
Dewey-Bt	Check	0	5.2	0.74	77	0.14	—
Dewey-Bt	Litter	342	5.3	2.10	215	0.19	0.01
Dewey-Bt	Litter	684	7.9	31.00	394	0.94	0.10
Dewey-Bt	MCP	342	5.1	8.30	84	1.44	0.40
Dewey-Bt	MCP	684	5.1	60.00	70	16.00	2.40

¹Measurements were taken on soils that had been incubated for 91 days after being treated with P as either poultry litter or monocalcium phosphate (MCP).

²Percent added P = (desorbed P - desorbed P from check)/added P)x100

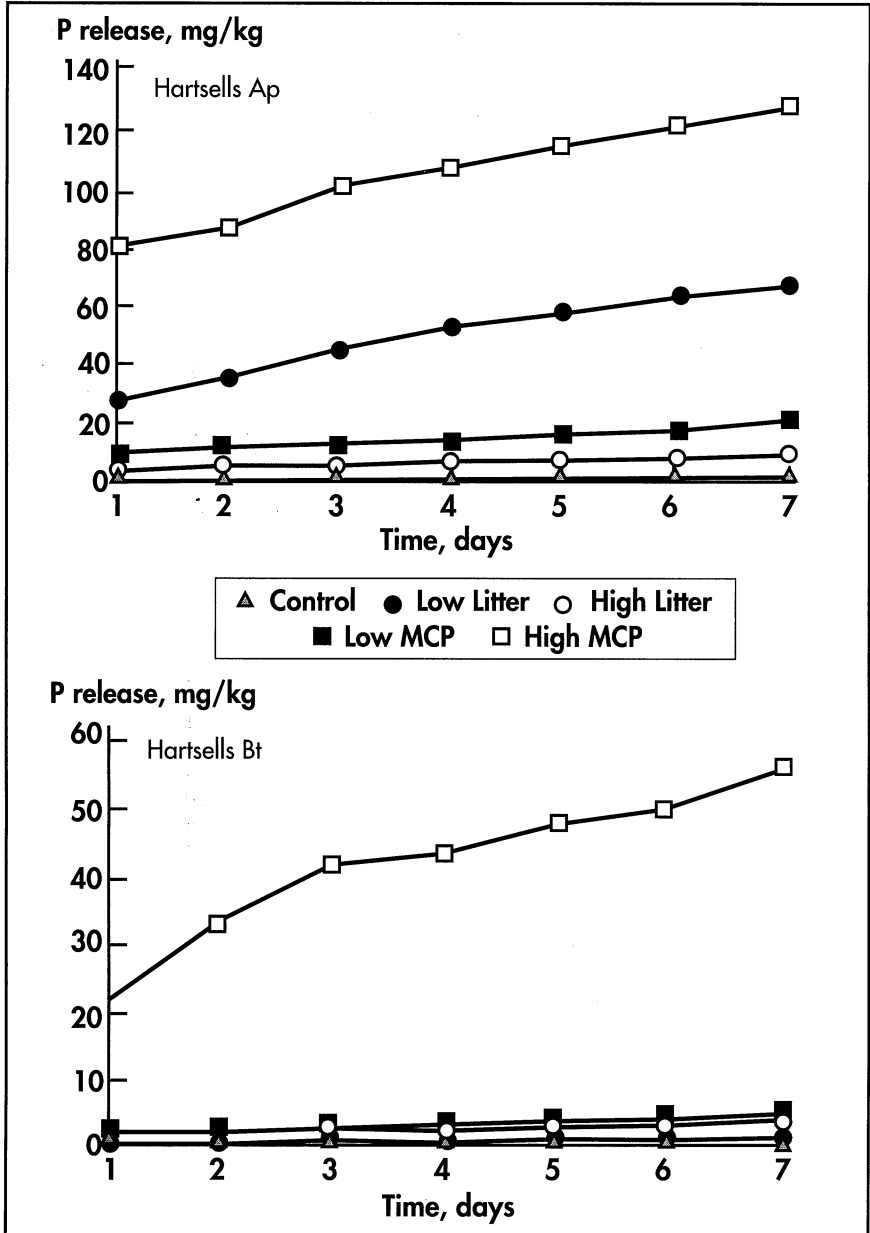


Figure 4. Cumulative P release during a batch desorption study using 0.01 M CaCl_2 . Soil samples were collected from the Ap and Bt horizon of a Hartsells soil and treated with poultry litter and inorganic fertilizer. Solution phase was collected daily and soil resuspended in 0.01 M CaCl_2 . Low litter = 25 tons/acre, High litter = 50 tons/acre, Low MCP = monocalcium phosphate applied to equal P in Low litter treatment (342 mg P/kg), High MCP = monocalcium phosphate applied to equal P in High litter treatment (684 mg P/kg).

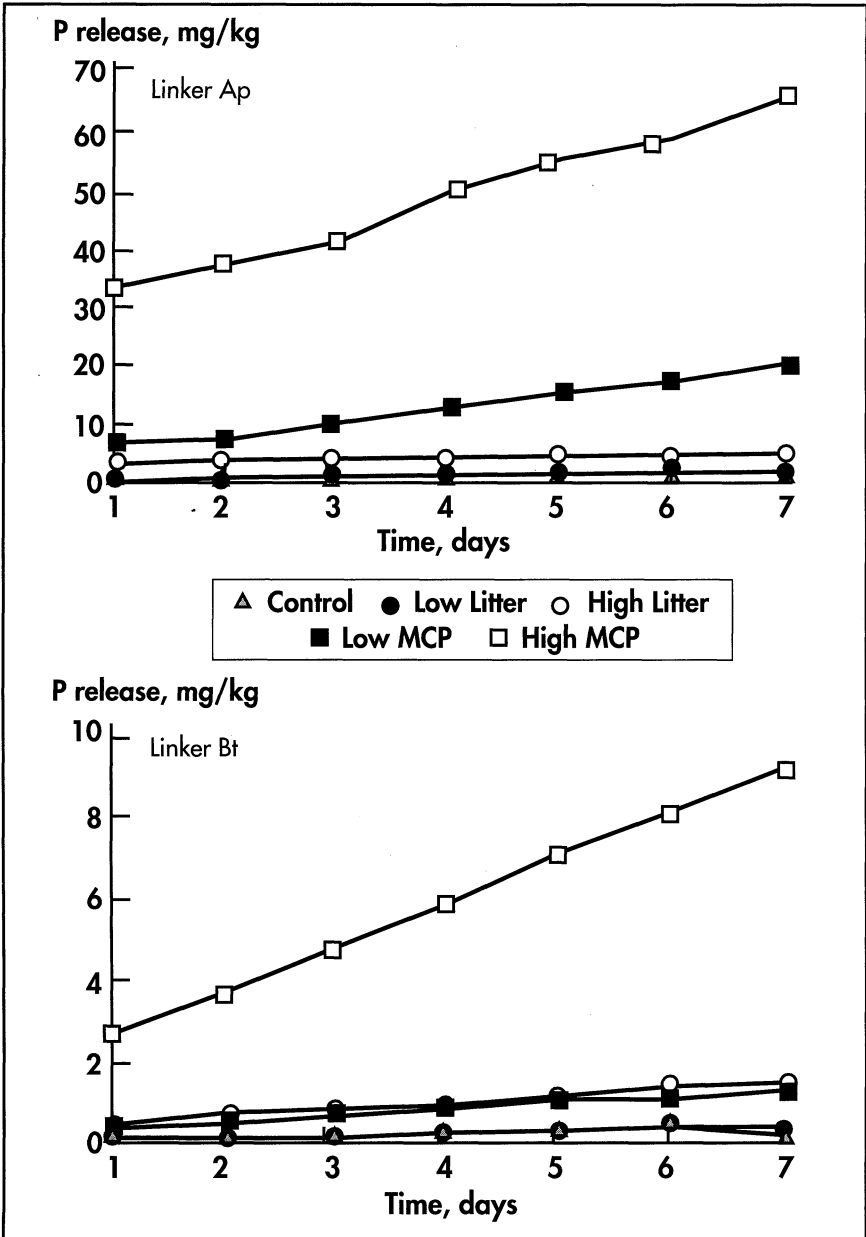


Figure 5. Cumulative P release during a batch desorption study using 0.01 M CaCl₂. Soil samples were collected from the Ap and Bt horizon of a Linker soil and treated with poultry litter and inorganic fertilizer. Solution phase was collected daily and soil resuspended in 0.01 M CaCl₂. Low litter = 25 tons/acre, High litter = 50 tons/acre, Low MCP = monocalcium phosphate applied to equal P in Low litter treatment (342 mg P/kg), High MCP = monocalcium phosphate applied to equal P in High litter treatment (684 mg P/kg).

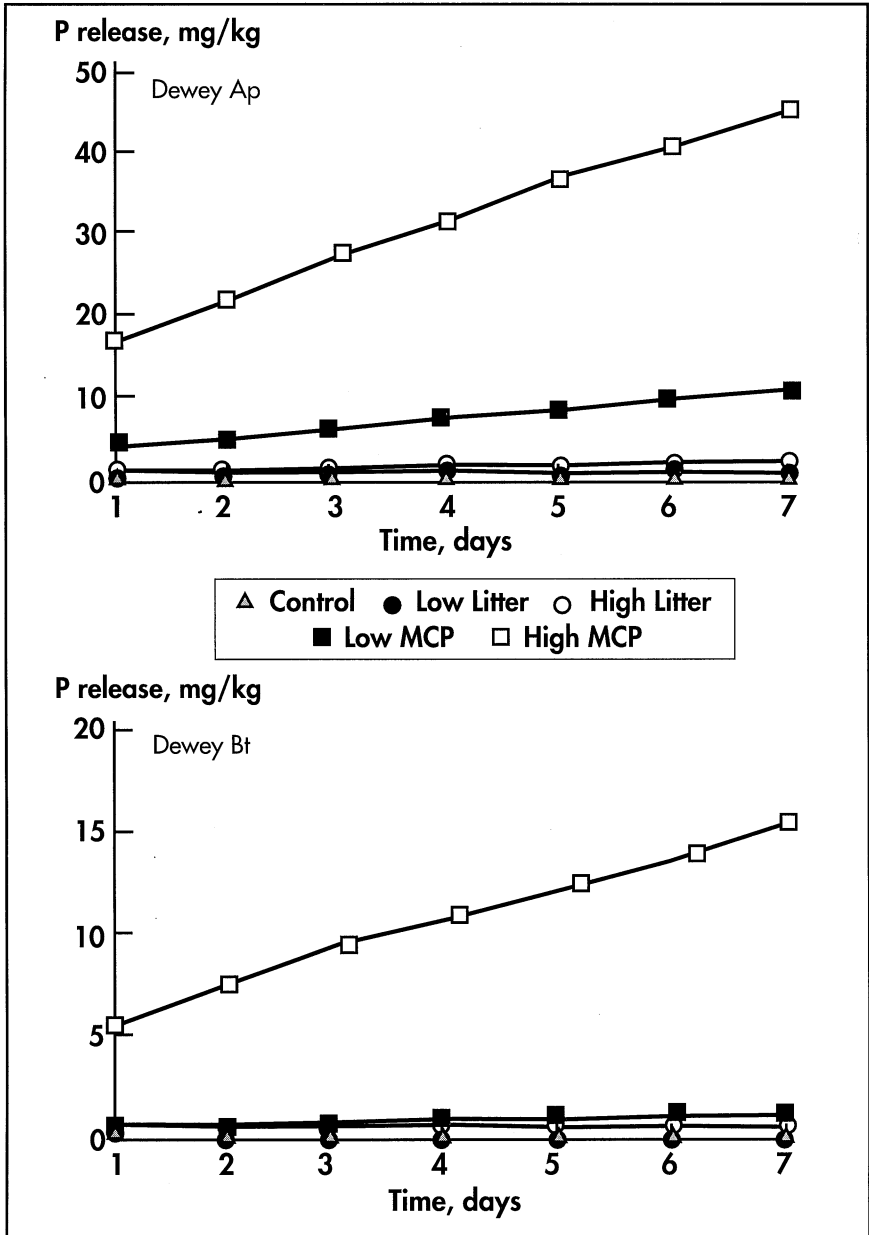


Figure 6 . Cumulative P release during a batch desorption study using 0.01 M CaCl₂. Soil samples were collected from the Ap and Bt horizon of a Dewey soil and treated with poultry litter and inorganic fertilizer. Solution phase was collected daily and soil resuspended in 0.01 M CaCl₂. Low litter = 25 tons/acre, High litter = 50 tons/acre, Low MCP = monocalcium phosphate applied to equal P in Low litter treatment (342 mg P/kg), High MCP = monocalcium phosphate applied to equal P in High litter treatment (684 mg P/kg).

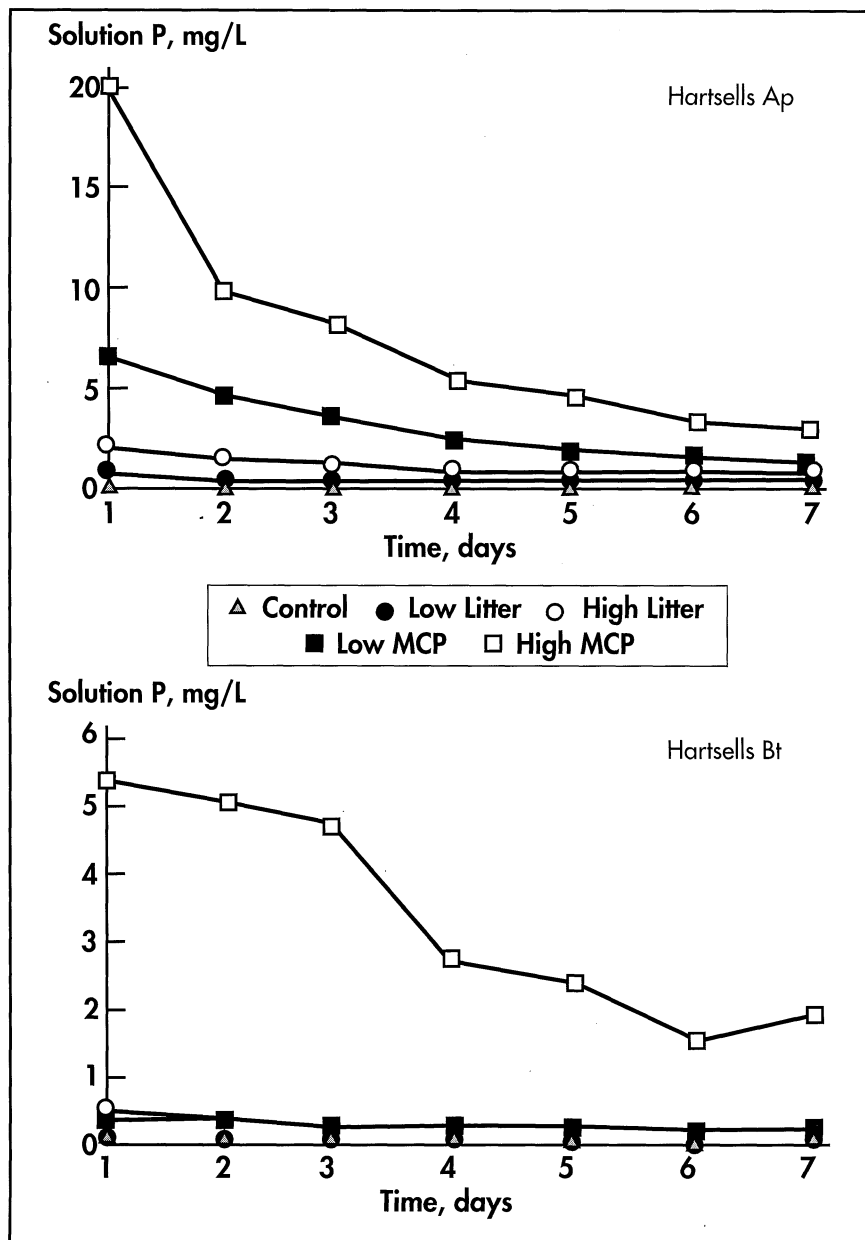


Figure 7. Phosphorus concentration in the equilibrium solution during a batch desorption study using 0.01 M CaCl_2 . Soil samples were collected from the Ap and Bt horizon of a Hartsells soil and treated with poultry litter and inorganic fertilizer. Solution phase was collected daily and soil resuspended in 0.01 M CaCl_2 . Low litter = 25 tons/acre, High litter = 50 tons/acre, Low MCP = monocalcium phosphate applied to equal P in Low litter treatment (342 mg P/kg), High MCP = monocalcium phosphate applied to equal P in High litter treatment (684 mg P/kg).

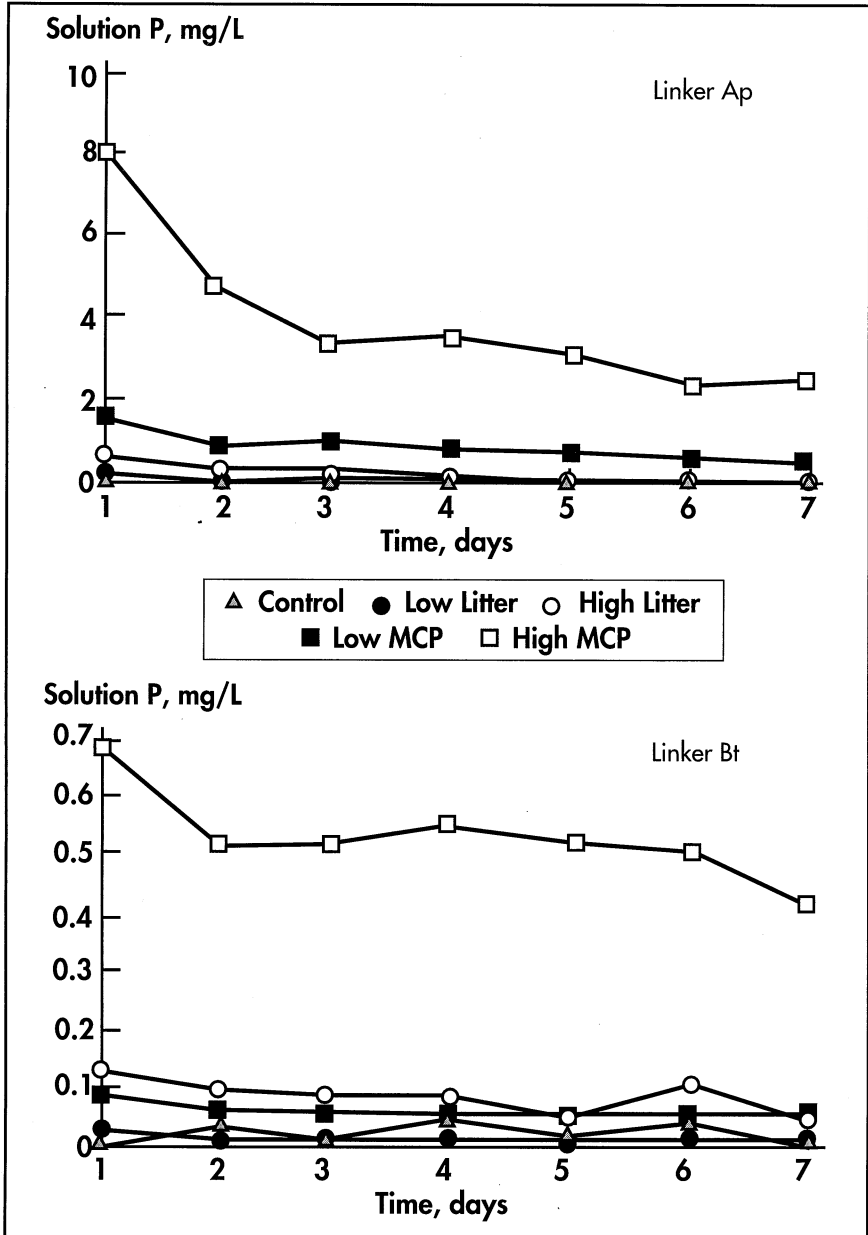


Figure 8. Phosphorus concentration in the equilibrium solution during a batch desorption study using 0.01 M CaCl_2 . Soil samples were collected from the Ap and Bt horizon of a Linker soil and treated with poultry litter and inorganic fertilizer. Solution phase was collected daily and soil resuspended in 0.01 M CaCl_2 . Low litter = 25 tons/acre, High litter = 50 tons/acre, Low MCP = monocalcium phosphate applied to equal P in Low litter treatment (342 mg P/kg), High MCP = monocalcium phosphate applied to equal P in High litter treatment (684 mg P/kg).

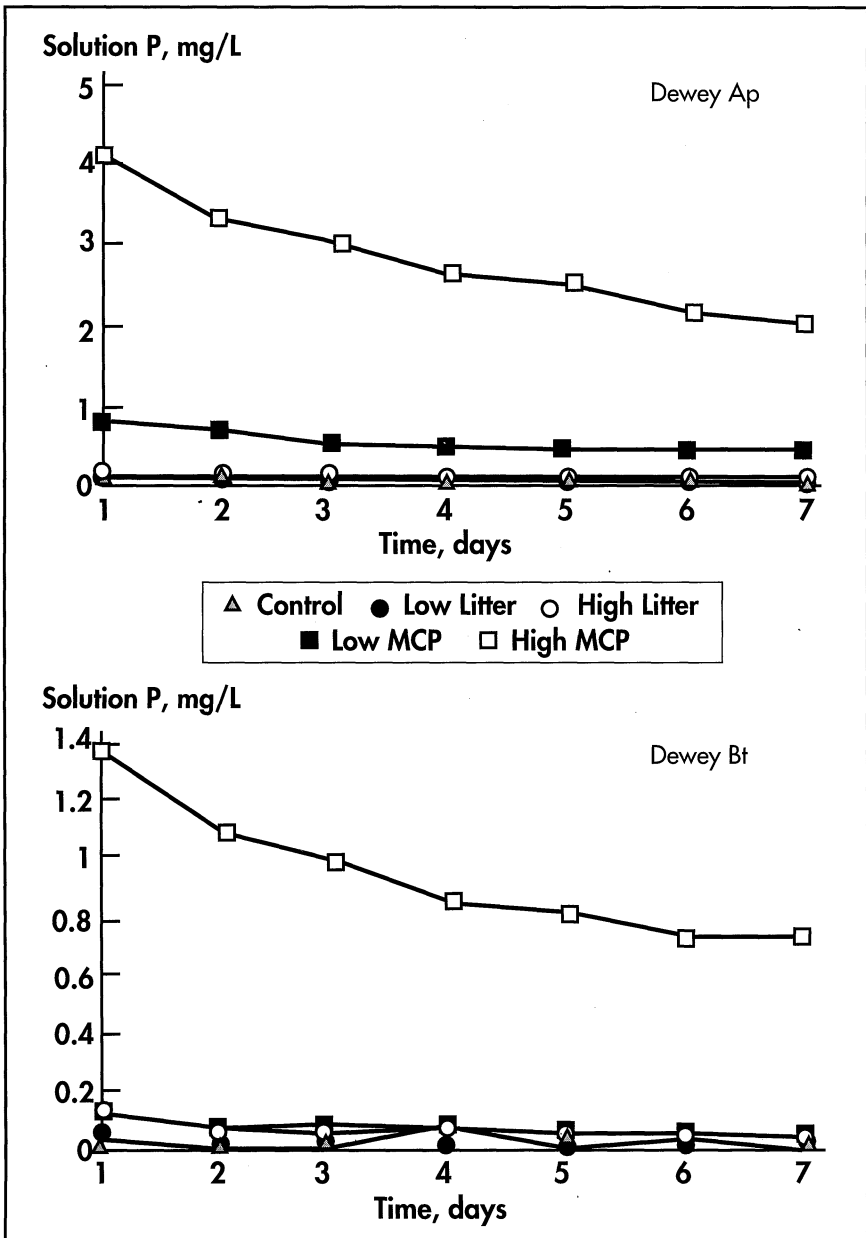


Figure 9. Phosphorus concentration in the equilibrium solution during a batch desorption study using 0.01 M CaCl₂. Soil samples were collected from the Ap and Bt horizon of a Dewey soil and treated with poultry litter and inorganic fertilizer. Solution phase was collected daily and soil resuspended in 0.01 M CaCl₂. Low litter = 25 tons/acre, High litter = 50 tons/acre, Low MCP = monocalcium phosphate applied to equal P in Low litter treatment (342 mg P/kg), High MCP = monocalcium phosphate applied to equal P in High litter treatment (684 mg P/kg).

samples, the Hartsells soil had the highest while the Dewey soil had the lowest concentrations. Surprisingly, the first extract (day 1) from the Ap horizon of the Hartsells soil had a solution P concentration of approximately 20 mg/L. Even the Dewey soil had a solution P concentration of 4.1 mg/L in the first extract from the high-MCP treatment.

Even after the final extract (day 7), solution P concentrations in the MCP and litter treatments would be within or above the minimum concentration that is needed for algae growth (27). These solution values which would be representative of a soil receiving litter for several years are much higher than soluble P concentrations observed in runoff collected from fields treated with annual applications of poultry litter (29, 31). A higher solution P concentration in the MCP treatments is in agreement with the results of Nichols et al. (50). They looked at runoff P concentrations (rainfall simulator) from fescue pasture at seven days after being treated with two tons of poultry litter per acre and an equivalent rate of fertilizer P. Concentrations of $\text{PO}_4\text{-P}$ from the litter treatment averaged 10.5 mg/L, while runoff from the fertilizer treatment averaged 26.1 mg/L.

Adsorption Isotherms

Five point isotherms were developed for the three soils following incubation for 91 days. An isotherm in which P concentration is plotted vs. concentration in the solid phase was developed for all treatments of all soils. Representative isotherms for surface and subsoil horizons of each soil are shown in Figures 10-12.

Several P isotherm models have been proposed for predicting the P adsorption capacity of soils. Most P adsorption data are compared to a fit to the Langmuir type isotherm (9) which was initially derived for the adsorption of gases and vapors on surfaces. Two constants are obtained from a best fit of the adsorption data to a linear form of the Langmuir equation.

$$yI = \frac{kbX}{1+kX}$$

The constant b is related to energy of adsorption, the constant k is the adsorption capacity, yI is the solid phase P concentration, and X is the solution P concentration. The fit generally is good at lower adsorption levels and under-predicts at very high solution-sorbed concentrations. Figure 13 shows an example in which the Langmuir fit is good to approximately 15 mg/L in solution and about 400 mg/kg on the solid phase. However, the distribution becomes essentially linear from 200 to the last point at 600 mg/kg adsorbed P.

Other models can be used and in some cases can be useful in predicting adsorption capacities. A cumulative model was considered because the equation has an adsorption maximum and a nonlinear distribution at lower adsorption amounts. In the cumulative equation:

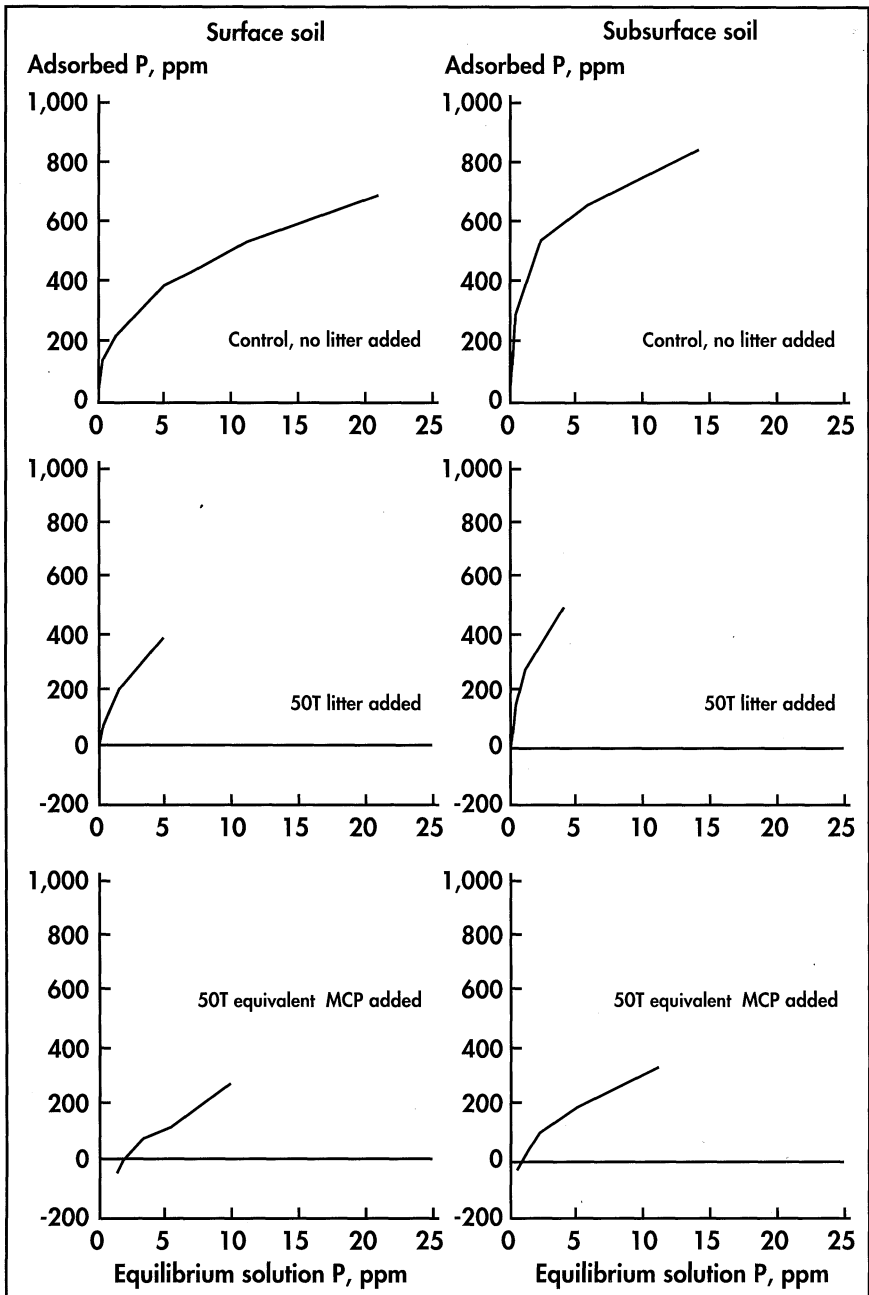


Figure 10. Phosphorus adsorption isotherms of Dewey surface and subsurface soil following addition of poultry litter and monocalcium phosphate and incubation for 91 days.

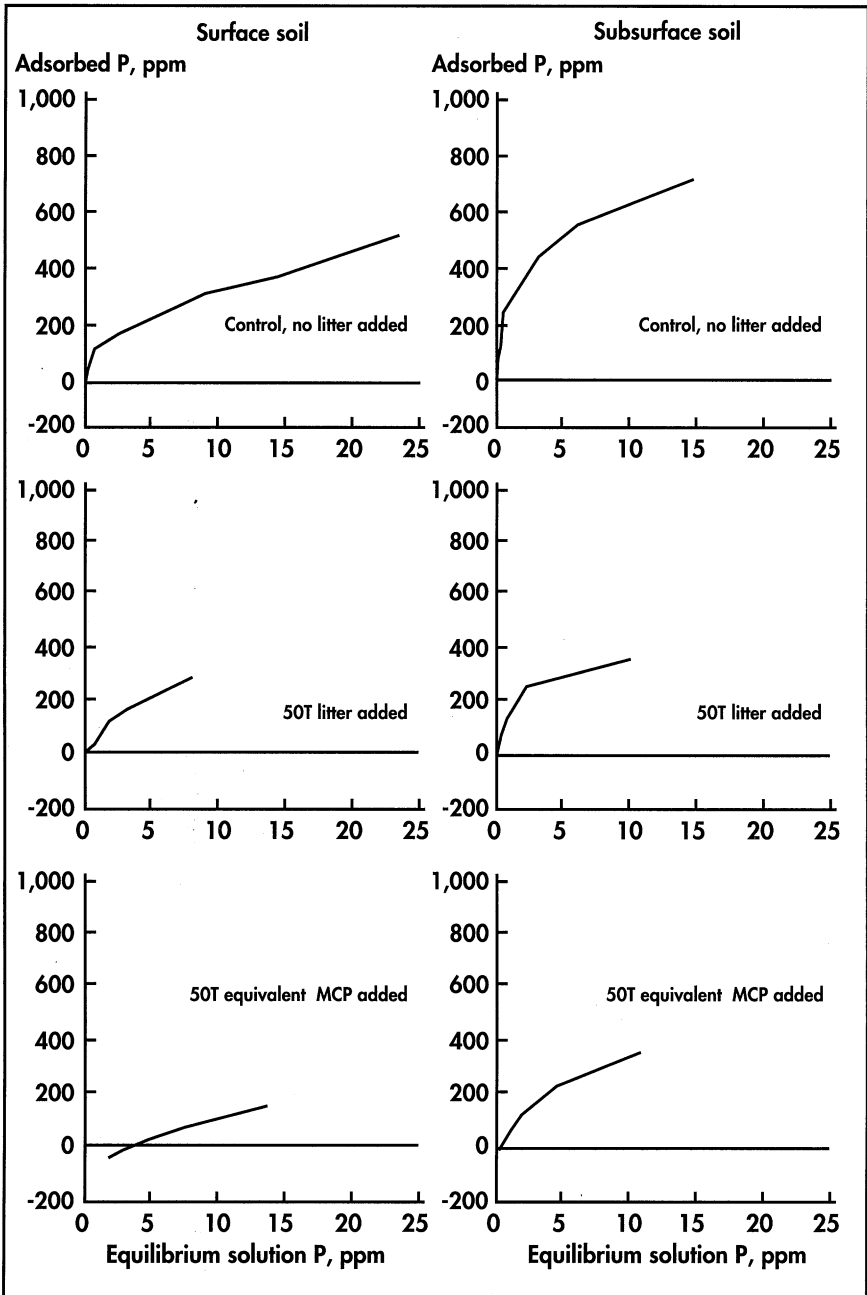


Figure. 11. Phosphorus adsorption isotherms of Linker surface and subsurface soil following addition of poultry litter and monocalcium phosphate and incubation for 91 days.

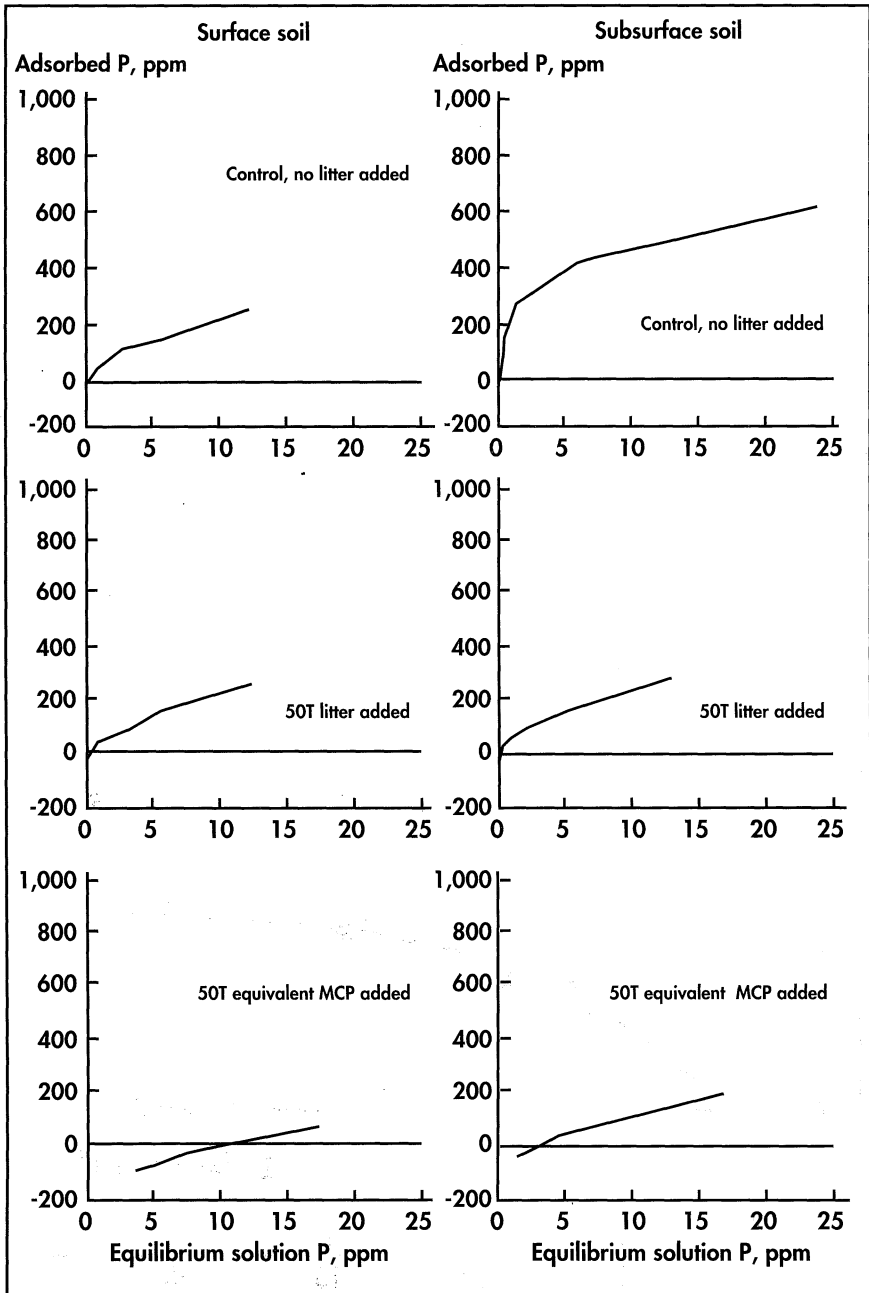


Figure 12. Phosphorus adsorption isotherms of Hartsells surface and subsurface soil following addition of poultry litter and monocalcium phosphate and incubation for 91 days.

$$y_2 = 0.5a_0 \left[1 + \operatorname{erf} \left(\frac{X - a_1}{a_2 \sqrt{2}} \right) \right]$$

y_2 is the amount adsorbed on soil, a_0 is the adsorption capacity, a_1 is the cumulative midpoint, and a_2 is the width from no adsorption to capacity. Figure 14 shows that a cumulative curve can be drawn that passes near most points.

It is obvious that a single linear equation would not improve the fit of a line that would include all data points. However, a linear equation gives a good fit to adsorption data points at high concentrations. In the linear expression:

$$y_3 = a + K_d X$$

y_3 is the amount of P in the solid phase, a is the intercept, and K_d (equilibrium distribution coefficient) is the slope. If only the solution concentration points greater than 5 mg/L are used, a reasonable fit is obtained (Figure 15) in which the intercept is the amount of P in the solid phase that is "fixed" and/or that is tightly bound.

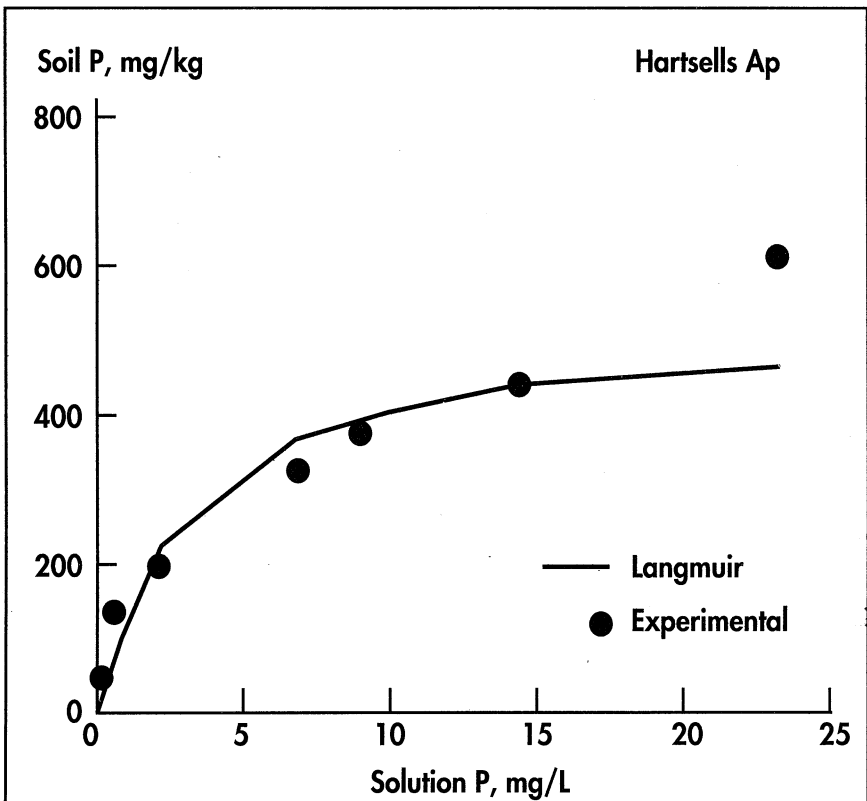


Figure 13. An example of the Langmuir equation applied to equilibrium phosphorus adsorption data for a Hartsells surface soil.

To include all data points, the Langmuir and cumulative equations can be summed to create the following equation:

$$y1 = \frac{a0a1X}{1+a1X} + (0.5a2[1 + \operatorname{erf}\left(\frac{X-a3}{\sqrt{2a4}}\right)])$$

in which $a0$ and $a1$ are Langmuir constants, $a2$ corresponds to the cumulative maximum, and $a3$ and $a4$ set width and cumulative curve midpoint. Figure 16 shows the resulting fit using a spreadsheet to generate the curve (Hartsells Ap) and Peakfit software (Figure 17; Linker Ap). A summation of the Langmuir and linear equations gives a comparable data fit (Figure 18).

Using a model developed by combining equations to simultaneously model multiple P sorption reactions allows interpretation of the entire isotherm in terms of different adsorbing surfaces, precipitation, and fixation (47); or in terms of initially tightly bound P during initial loading and linear distribution between solid and solution phases after initial tightly bond sites are filled.

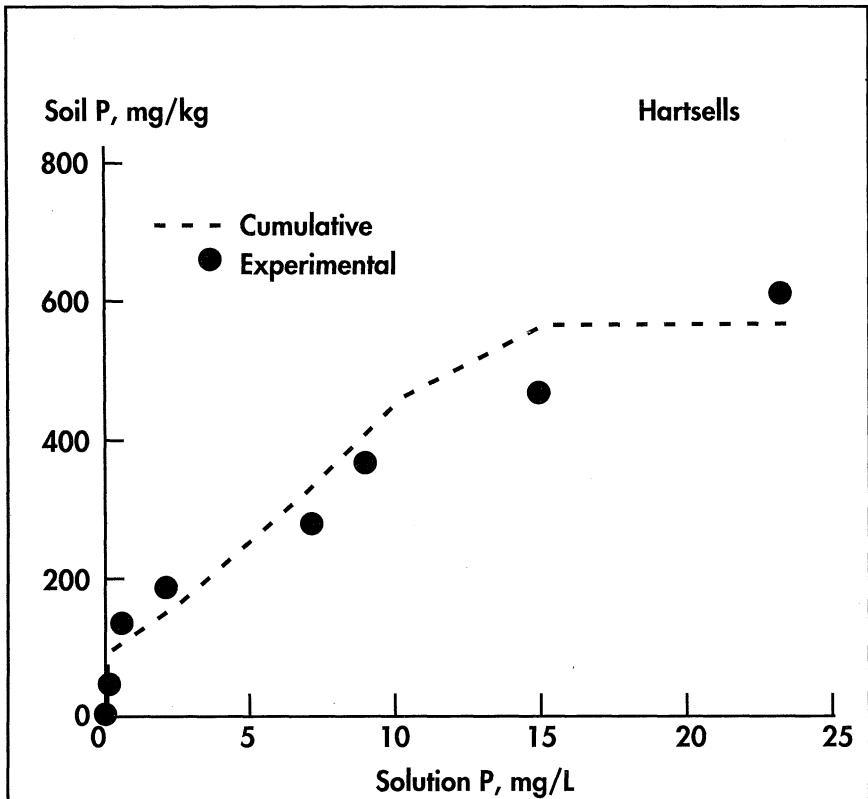


Figure 14. An example of the cumulative equation applied to equilibrium phosphorus adsorption data for a Hartsells surface soil.

In Figures 19-21 (showing P adsorption isotherms following incubation), these isotherms show that resident mineral P following incubation was added to that retained from solution to give the total solid-phase mineral P. The relatively linear soil:solution concentration distribution is evident for Ap horizons of all soils. Solution concentrations of Ap horizons also indicate that after 91 days of incubation, more P was in solution when MCP was applied than from the addition of litter. In both P treatments on surface soil, the Langmuir capacity was exceeded, and adsorption distribution between solid and solution phases was essentially a linear function at high-solution concentrations.

Phosphorus adsorption in soils is not a simple process, and it is not surprising that no one equation can be successfully used to model a complete adsorption isotherm from none adsorbed or in solution, to complete capacity loading. Excellent Langmuir representation is possible at initial loading to about 5 mg/L in solution or less. These points were used from all check samples represented by examples in Figures 10-12. The constants in Table 7 were calculated from this set of four repetitions for each surface and subsoil. The R^2 indicated the "goodness of fit." The Langmuir capacities from this set of control samples were com-

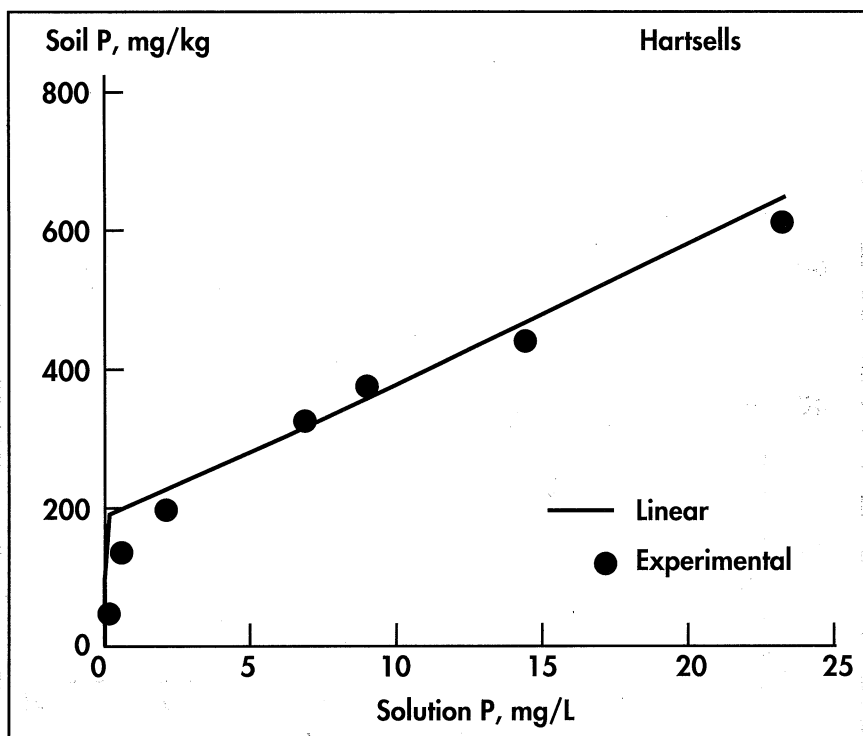


Figure 15. An example of the linear equation applied to equilibrium P adsorption data for a Hartsells surface soil.

pared to soil clay content of the sample. The Langmuir P sorption capacity relationship to clay can be considered good (Figure 22), despite mineralogy differences between soils, and lends support to the use of clay content in the EPIC model (37).

Soluble Phosphorus Determinations Following Incubation

The samples in which the equivalent of 0, 25, and 50 tons of litter were applied and an equivalent sample set that were treated with monocalcium phosphate and equilibrated for 91 days were selected for solubility determinations. Only the Ap horizon samples of the Hartsells and Dewey soils were selected since litter and fertilizer P are applied to the surface layers only and these are the most extensive soils being used for pasture and cropland in North Alabama. Two soil:solution ratios were used for each soil. The two suspensions of both soils and all treatments contained approximately 500 and 1,000 mg of clay per L. This is within the range of suspended solids in runoff studies from small watersheds on the Tennessee Valley Substation (29) and from a cotton field in Colbert County, Ala. (72). The suspensions were allowed to equilibrate for 30 days with daily

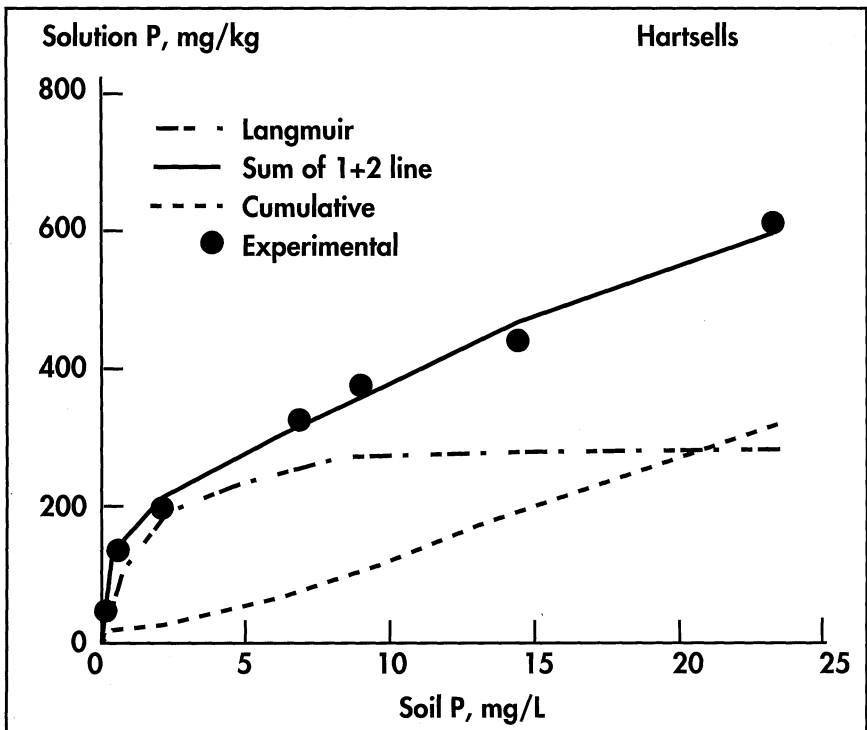


Figure 16. An example of the Langmuir and cumulative equations summed and applied to equilibrium phosphorus adsorption data for a Hartsells surface soil.

shaking, centrifuged, filtered, and soluble P determined. The suspension clay concentrations, pH, initial and final adsorbed phosphorus, measured and simulated solution phosphorus are shown in Table 9. The initial resident (total) P in the soils is given in Table 8.

MINTEQA2 soluble ion speciation model did not satisfactorily predict solution P concentrations. In most cases, but not all, the model over-predicted solution P concentration. The model included both an adsorption distribution coefficient and a Langmuir exchange component. Input could be adjusted to make any one sample fit the data. However, the adjustments could not be applied across all soils and treatments. The simulated concentration values reported were calculated using Langmuir and K_d constants calculated from isotherm data, final suspension pH, and mineralogy of each soil clay. The differences from measured were not consistent enough to suggest possible modification of model parameters.

Soluble P was also evaluated with respect to clay suspension concentration, equilibrium adsorbed P concentrations, and litter-applied and monocalcium-P treat-

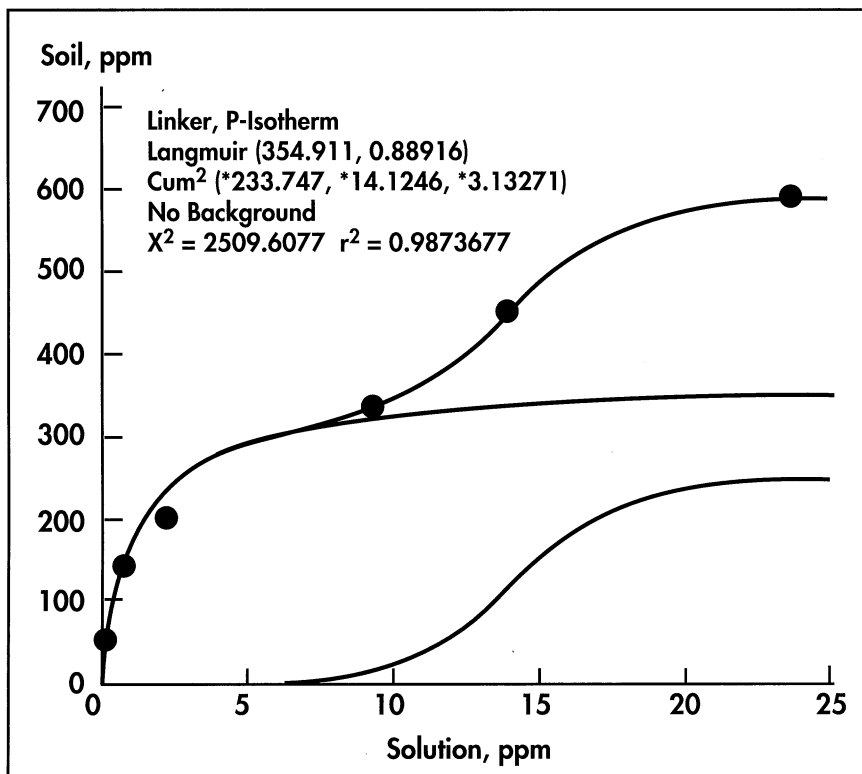


Figure 17. An example of the Langmuir and cumulative equations summed and applied to equilibrium P adsorption data for a Linker surface soil developed with Peakfit software.

ments. The data were grouped into litter-treated and monocalcium-P treated samples. Each group was plotted by individual soil and both soils combined into one graph. The monocalcium-P treatments are shown in graphs in Figure 23. The figures show the linear relation between P adsorbed on clay and "in solution." The slope, approximately 3,000 mL/g, corresponds to an equilibrium distribution coefficient that is essentially a constant throughout the concentration range of the experiment. Extrapolating to zero concentration in solution should be an approximation of "fixed" or very tightly held P. The extrapolated constant 2,884 mg/kg clay corresponds to 583 mg/kg for fixed P in the Dewey soil and 164 mg/kg in Hartsells. Similar linear relationships resulted from litter-applied equilibrium experiments (Figure 24). The slope in this group is approximately 6,000 mL/g, twice that of the MCP test. This indicates more litter P in the suspended solid phase and also in the "fixed" phase as indicated by higher extrapolated values. Since samples receiving litter had higher pH following incubation, this difference could reflect the effect of pH on solution complexes of Ca, Al, and Fe phosphates (42).

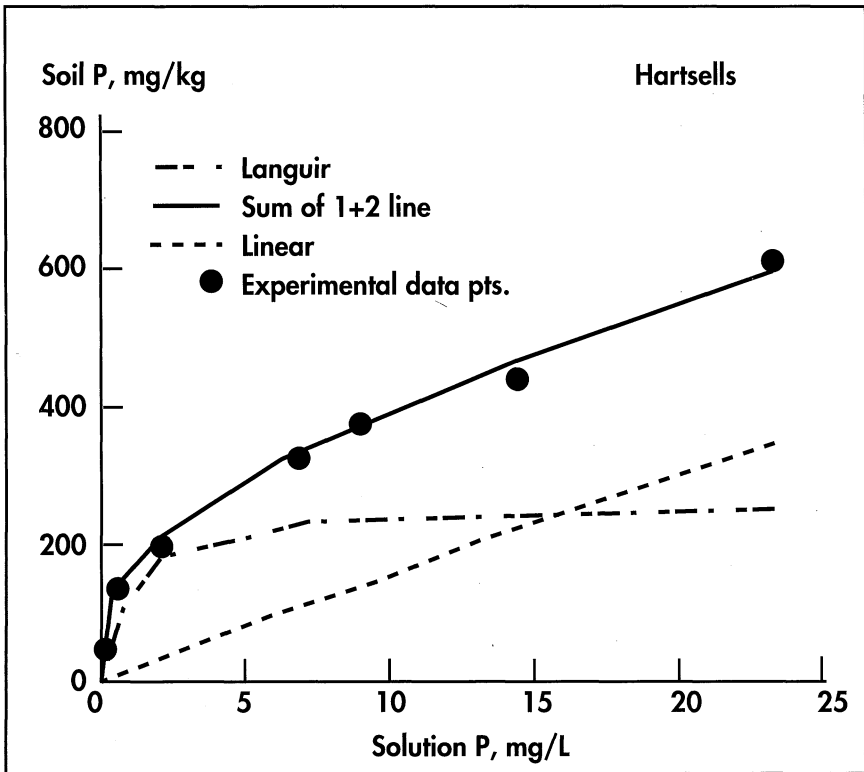


Figure 18. An example of the linear and Langmuir equations applied to equilibrium phosphorus data for a Hartsells surface soil.

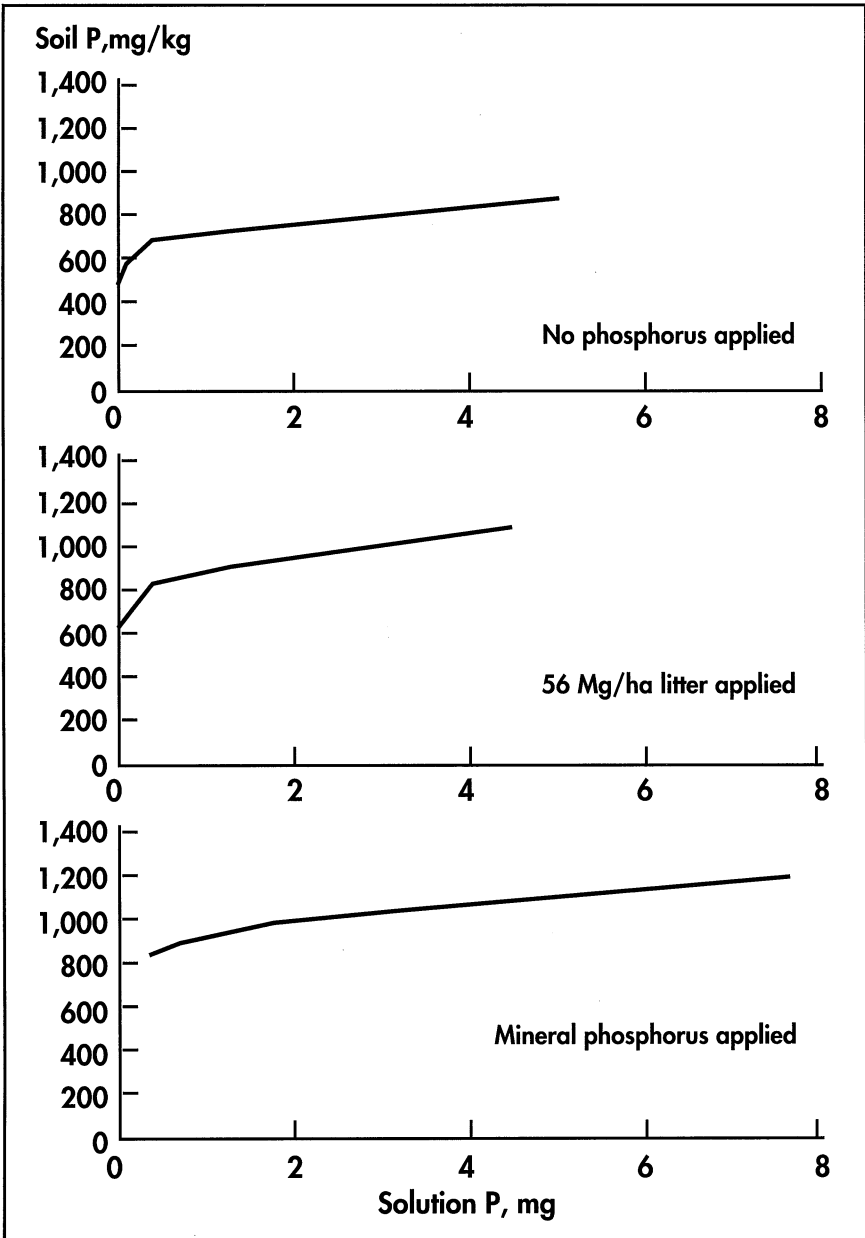


Figure 19. Dewey surface soil equilibrium P adsorption from solution following poultry litter and monocalcium phosphate addition and incubation for 91 days.

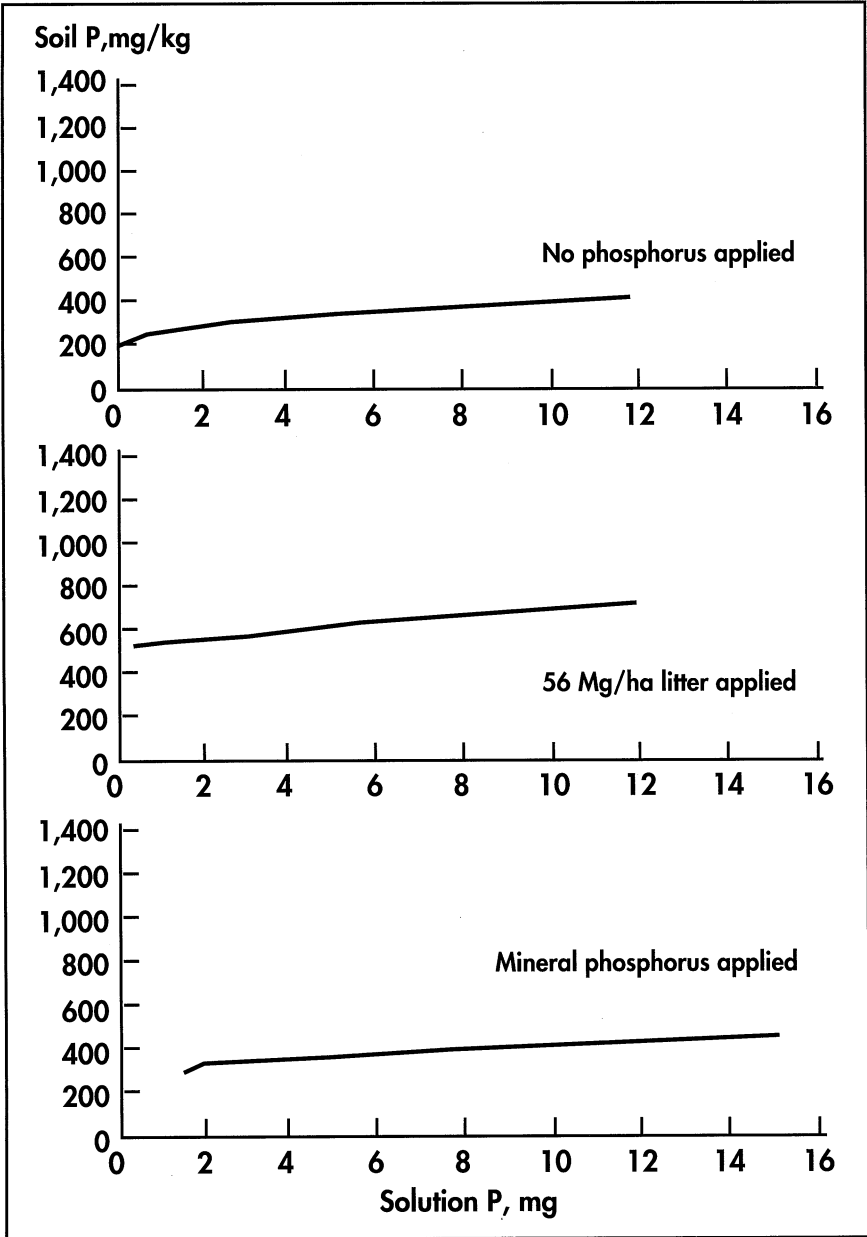


Figure 20. Hartsells surface soil equilibrium P adsorption from solution following poultry litter and monocalcium phosphate addition and incubation for 91 days.

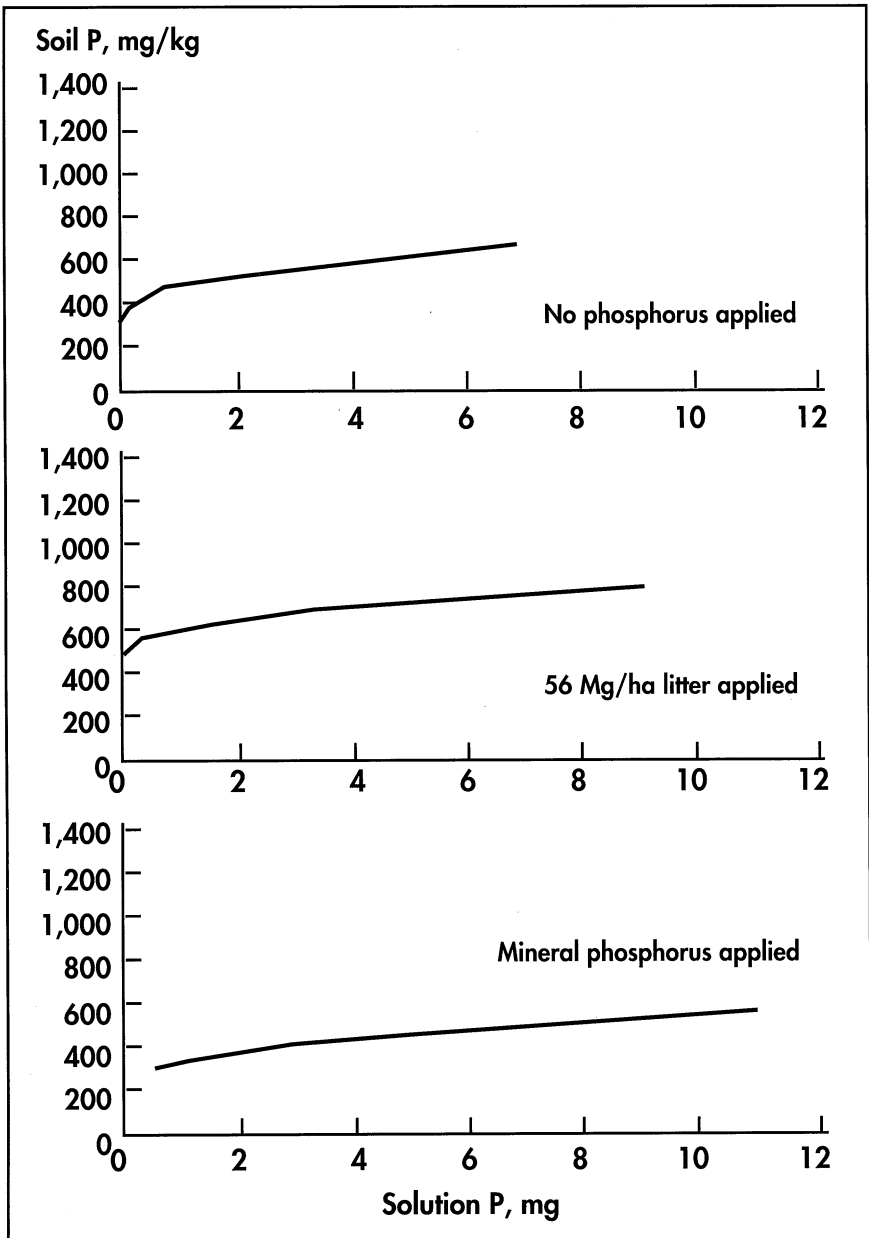


Figure 21. Linker surface soil equilibrium P adsorption from solution following poultry litter and monocalcium phosphate addition and incubation for 91 days.

The solution:soil P distribution is also affected by the suspended clay concentration (Figure 25). More clay in suspension resulted in more P remaining on the clay and yielding more P into solution.

Several studies have documented a relationship between soil test P concentration and dissolved, runoff, and soil solution P (67, 1). All show that there is a potential for enrichment in dissolved P as soil test values increase. This approximately linear relationship was also observed in this study (Table 10). Figure 26 shows dissolved P and soil test values from surface samples collected from paired cotton fields, paired pastures, and incubated samples of Dewey and Hartsells soils following addition of litter. Dissolved P was obtained by suspending an equivalent amount of clay from the different soils and shaking overnight. According to these data 300 mg/kg Mehlich-1 extractable P would predict a dissolved P concentration of 1,000 $\mu\text{g/L}$. A solution concentration of 1,000 $\mu\text{g/L}$ has been accepted as a limit for treated municipal water discharged into streams and suggested as a possible limit for runoff P concentration (67).

**TABLE 7. LANGMUIR CAPACITY CONSTANTS
CALCULATED FROM EQUILIBRIUM
ISOTHERM DETERMINATIONS USING SOIL CHECK SAMPLES**

Soil	P capacity	R-squared ¹	Avg. capacity
	<i>mg/kg</i>		<i>mg/kg</i>
Hartsells-Ap	292	0.90	300
Hartsells-Ap	334	0.83	--
Hartsells-Ap	291	0.93	--
Hartsells-Ap	281	0.92	--
Hartsells-Bt	612	0.97	610
Hartsells-Bt	606	0.98	--
Hartsells-Bt	607	0.98	--
Hartsells-Bt	612	0.96	--
Linker-Ap	631	0.91	608
Linker-Ap	595	0.94	--
Linker-Ap	600	0.94	--
Linker-Ap	604	0.94	--
Linker-Bt	850	0.98	856
Linker-Bt	844	0.98	--
Linker-Bt	865	0.98	--
Linker-Bt	865	0.98	--
Dewey-Ap	722	0.95	733
Dewey-Ap	729	0.95	--
Dewey-Ap	741	0.95	--
Dewey-Ap	738	0.95	--
Dewey-Bt	855	0.98	861
Dewey-Bt	864	0.98	--
Dewey-Bt	859	0.98	--
Dewey-Bt	865	0.98	--

¹R² for fit of data to the linear form of the langmuir equation, four reps.

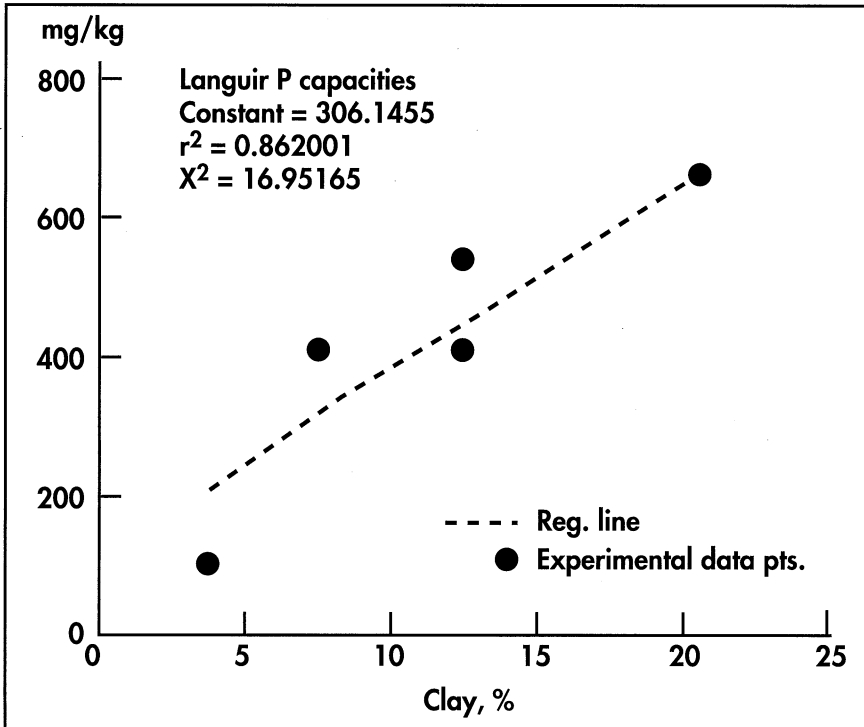


Figure 22. Surface and subsurface Langmuir P adsorption capacities obtained from Hartsells, Dewey and Linker soils. Each observation is the average of four replicate isotherms.

TABLE 8 . INITIAL AMOUNTS OF MINERAL P IN SOILS BEFORE BATCH EQUILIBRIUM TEST FOR ION SPECIATION MODEL VALIDATION (MINTEQ)

Soil & horizon	Treatment	Total P
		<i>mg/kg</i>
Dewey, Ap	Check, 0 added	656
Hartsells, Ap	Check, 0 added	311
Dewey, Ap	25 tons/acre litter ¹	969
Hartsells, Ap	25 tons/acre litter ¹	702
Dewey, Ap	50 tons/acre litter ¹	1,938
Hartsells, Ap	50 tons/acre litter ¹	1,404

¹Soil samples were also incubated with equivalent amounts of mineral fertilizer P added.

TABLE 9. MEASURED AND PREDICTED EQUILIBRIUM SOLUTION P CONCENTRATIONS IN DILUTE CLAY SUSPENSIONS FOLLOWING INCUBATION

Soil & treatment	Soil	Clay	Initial P	Final P	Solution P ¹	MINTEQ ²	pH
	<i>g/L</i>	<i>g/L</i>	<i>mg/kg</i>	<i>mg/kg</i>	<i>mg/L</i>	<i>mg/L</i>	
Decatur-Ap, check	2.50	0.51	2,559	2,520	0.02	0.04	5.15
Decatur-Ap, check	5.00	1.01	2,559	2,539	0.02	0.04	5.09
Decatur-Ap, 25 tons litter	2.50	0.51	3,409	3,271	0.07	0.33	6.62
Decatur-Ap, 25 tons litter	5.00	1.01	3,409	3,330	0.08	0.42	6.68
Decatur-Ap, 50 tons litter	2.50	0.51	4,258	4,001	0.13	0.36	6.74
Decatur-Ap, 50 tons litter	5.00	1.01	4,258	4,080	0.18	--	6.47
Decatur-Ap, MCP, 25T equiv.	2.50	0.51	4,249	3,775	0.24	0.39	5.21
Decatur-Ap, MCP, 25T equiv.	5.00	1.01	4,249	3,903	0.35	0.75	5.12
Decatur-Ap, MCP, 50T equiv.	2.50	0.51	5,939	4,852	0.55	1.20	5.22
Decatur-Ap, MCP, 50T equiv.	5.00	1.01	5,939	5,050	0.90	2.19	5.19
Hartsells-Ap, check	10.00	0.57	3,934	3,742	0.11	0.56	5.93
Hartsells-Ap, check	20.00	1.14	3,934	3,803	0.15	0.04	6.22
Hartsells-Ap, 25 tons litter	10.00	0.57	8,969	7,990	0.56	0.31	6.97
Hartsells-Ap, 25 tons litter	20.00	1.14	8,969	8,209	0.87	0.31	6.95
Hartsells-Ap, 50 tons litter	10.00	0.57	14,003	11,853	1.23	0.51	7.07
Hartsells-Ap, 50 tons litter	20.00	1.14	14,003	12,360	1.88	0.46	7.28
Hartsells-Ap, MCP, 25T equiv.	10.00	0.57	9,913	7,728	1.25	3.08	6.29
Hartsells-Ap, MCP, 25T equiv.	20.00	1.14	9,913	8,069	2.11	4.72	6.10
Hartsells-Ap, MCP, 50T equiv.	10.00	0.57	15,892	11,924	2.27	2.51	6.42
Hartsells-Ap, MCP, 50T equiv.	20.00	1.14	15,892	12,535	3.84	3.35	6.31

¹Measured.

²Predicted equilibrium solution P.

Predicting Long-term Phosphorus Accumulation, Leaching, and Runoff

A paired pasture and a paired cotton field were sampled to one meter. One field in each pair received litter for 18-20 year and the other was under conventional N and P fertilization. Phosphorus adsorption isotherms from the previous studies, and the constants in Table 7 were used to determine P sorption ratios for the Hartsells and Dewey surface and subsoils. Resident mineral (total and resin extractable) P and organic P were determined to sampled depths. EPIC (Erosion/Productivity Impact Calculator) was used to simulate P uptake, leaching and runoff losses under fescue and cotton receiving litter and under conventional mineral fertilization. The EPIC model has a P component that simulates uptake, leaching, and runoff losses both soluble and on sus-

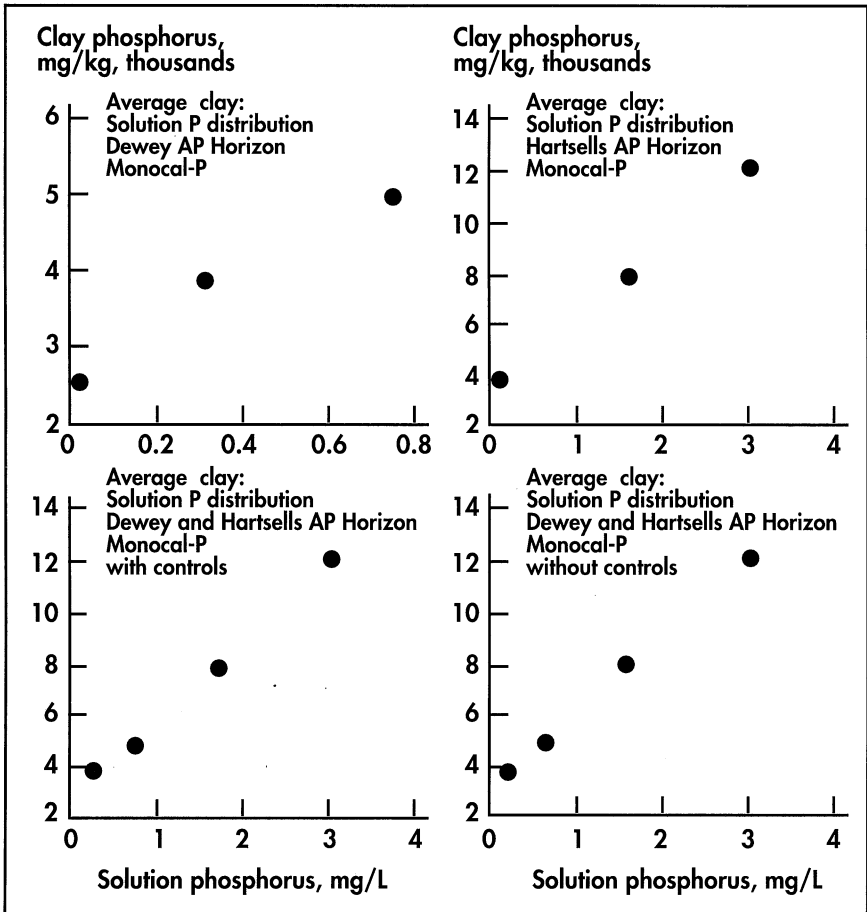


Figure 23. Equilibrium solution:clay P distribution following high levels of monocalcium phosphate addition, 91 days incubation, and 30 days in a 0.01M CaCl₂ suspension.

pended solids. At equilibrium, P is considered to exist in three pools: labile, active, and stable. The stable form is four times the active and labile is about one-tenth of the active but has a temperature and time relationship. Additions or losses from any phase causes the equilibrium to adjust back to these limits (79). Figure 27 shows a flow chart of P partitioning as simulated by EPIC.

Soil, climate, management, and crop input was obtained from various sources. EPIC's climate generator was driven by weather data from the station nearest to the pastures and fields selected for study (Cullman and Birmingham, Ala.; and Chattanooga, Tenn.). Soil layer information was obtained from EPIC's soil database and modified with on-site data when available (Hartsells #309, and Dewey #186). Management was obtained from land managers, the farmers managing the selected fields. Tables 11 and 12 give the

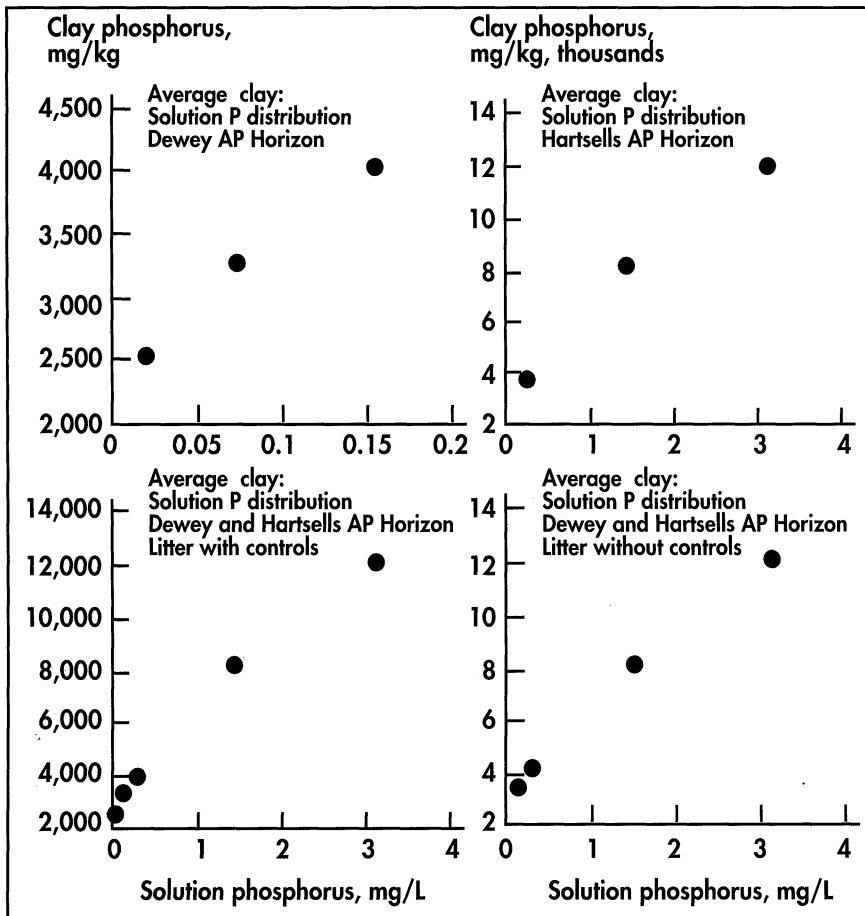


Figure 24. Equilibrium solution:clay P distribution following high levels of poultry litter addition, 91 days incubation, and 30 days in a 0.01M CaCl₂ suspension.

EPIC operation schedules for grazed fescue pastures and cotton. Tables 13 and 14 give background soil test and P partitioning data for input and comparison with EPIC predictions.

The comparisons of EPIC-simulated, litter-applied, conventional-fertilizer-applied, and sampled-soil-layer P concentrations are presented as total mineral P distributions with depth in Figures 28 and 29. The distributions after 20 years of litter application compare favorable with actual concentra-

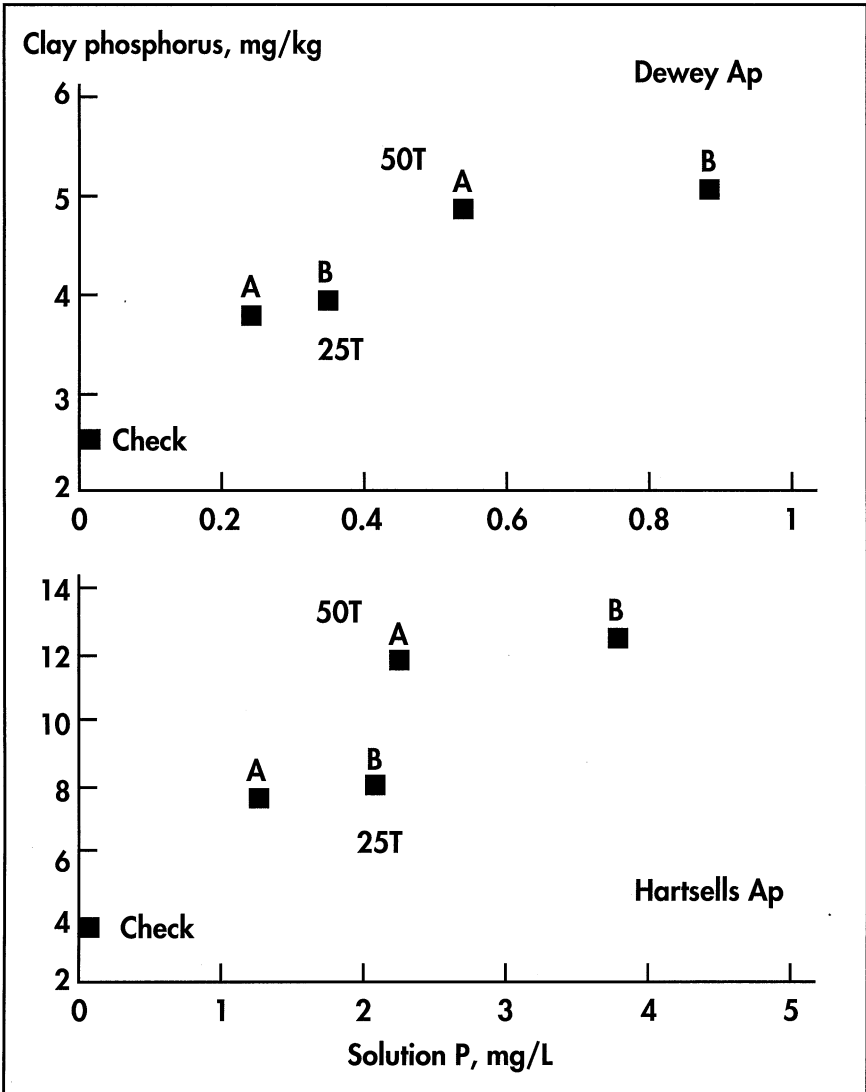


Figure 25. Effect of clay suspension concentration on equilibrium P in solution; A = 0.5, B = 1.0 g/L.

TABLE 10. SOIL TEST AND SOLUTION P FROM PAIRED-FIELD, FESCUE-PASTURE, AND INCUBATED LITTER-TREATED SURFACE SOIL SAMPLES

Series	Treatment	Clay	pH	Soil-test P	Dissolved P
		<i>pct.</i>		<i>mg/kg</i>	<i>mg/L</i>
Dewey	cotton, no litter	23.20	4.99	13	0.14
Dewey	cotton, litter	13.92	6.56	120	0.48
Dewey	check	20.41	6.38	27	0.03
Dewey	25 tons litter	20.41	6.56	61	0.15
Dewey	50 tons litter	20.41	6.88	91	0.20
Hartsells	fescue, no litter	6.99	5.48	59	0.14
Hartsells	fescue, litter	11.23	6.74	163	0.59
Hartsells	check	5.71	6.47	48	0.16
Hartsells	25 tons litter	5.71	6.89	205	0.69
Hartsells	50 tons litter	5.71	7.18	305	0.93

tions for both fescue pasture and cotton. In both cropping systems, measured and simulated P accumulated to over 1,000 g per ton of soil in the littered treatments. Under conventional cotton, P buildup was approximately 500 g per ton at the surface and in the 1-15 cm layer. EPIC simulates high concentrations at the surface when conventional P is used because it is not incorporated. Considering the many assumptions required to run the model, simulated results predict actual measured concentrations well and support the use

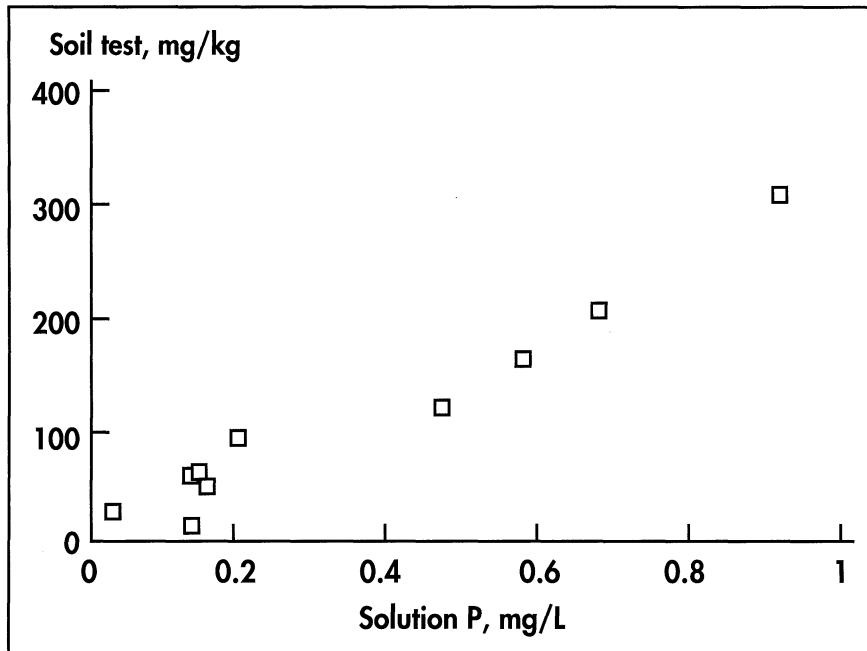


Figure 26. Relationship between soil test P and dissolved P of Hartsells and Dewey surface soil samples from paired cotton fields and fescue pastures and incubated samples.

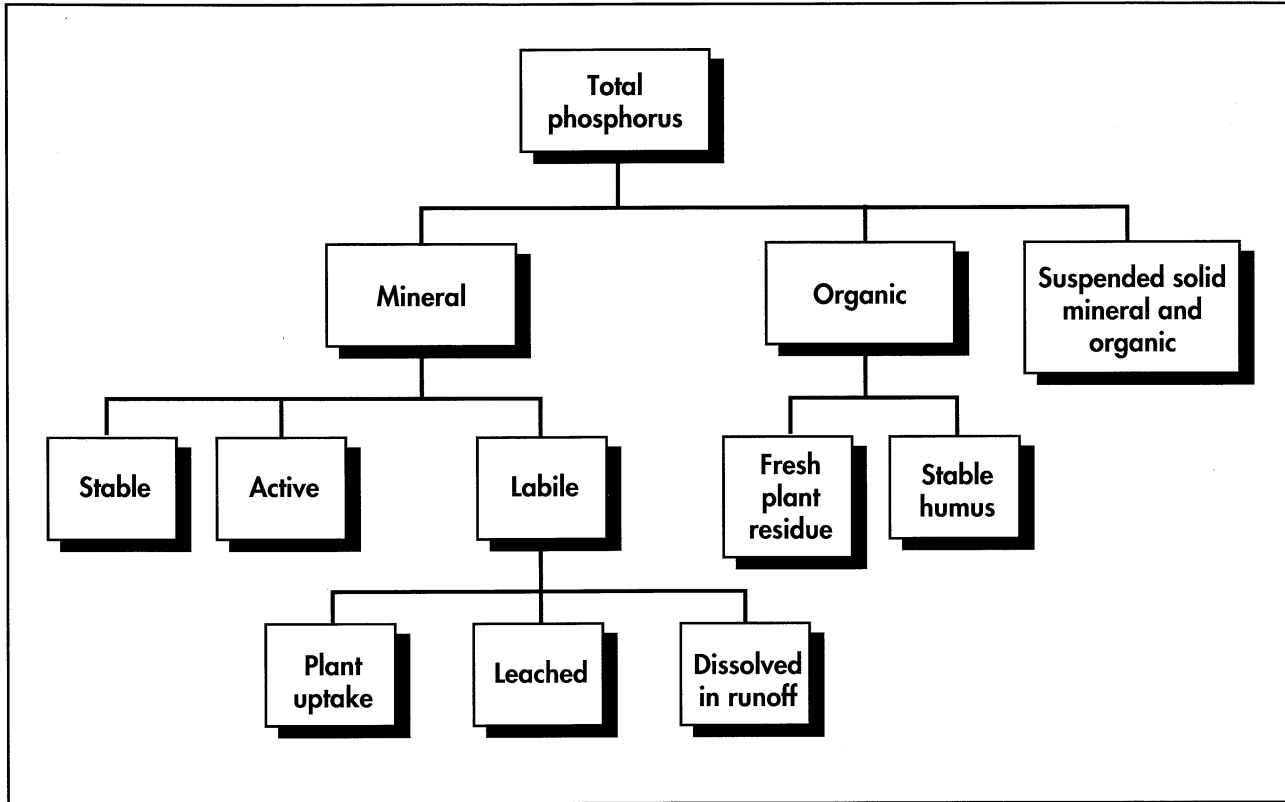


Figure 27. Phosphorus partitioning as simulated in the EPIC model.

TABLE 11. FESCUE PASTURE MANAGEMENT INPUT USED TO DRIVE EPIC SIMULATION¹

Month	Day	EPIC ID#	Name	Weight	Grazing days
<i>kg/ha</i>					
Tillage Operation					
3	2	67	Graze	--	90
10	1	3	Drill plant ²	--	--
10	1	67	Graze	--	90
Fertilizer Applied					
3	5	63	34-0-0	150	--
9	20	63	34-0-0	100	--
9	20	63	11-52-0	75	--
Litter Applied					
3	1	21	Poultry-fresh broiler ³	3,750	--
6	15	21	Poultry-fresh broiler	3,750	--
¹ Operation schedule for first year, one-year rotation, 20-year simulation. Hartsells soil, EPIC Soil data ID no. 309, modified for North Alabama soils. Land slope = 2% and slope length was 30 meters.					
² First year of simulation.					
³ Fraction of broiler litter weight: mineral N = 0.012; NH ₃ = 0.99; organic N = 0.027; mineral P = 0.012; and organic P = 0.004.					

TABLE 12. COTTON MANAGEMENT INPUT USED TO DRIVE EPIC SIMULATION¹

Month	Day	EPIC ID#	Name	Weight
<i>kg/ha</i>				
Tillage Operation				
3	30	16	Disk bed	--
4	1	17	Row bed	--
4	15	2	Row plant cotton	--
4	30	19	Row cultivate	--
5	10	19	Row cultivate	--
6	1	19	Row cultivate	--
10	10	50	Harvest (95% eff.)	--
10	11	41	Kill	--
10	25	28	Mold board plow	--
Fertilizer Applied				
4	14	63	34-0-0	300
4	14	53	11-52-0	75
Litter Applied				
3	28	21	Poultry-fresh broiler ²	7,200
6	15	21	Poultry-fresh broiler	3,750
¹ Operation schedule for first year, one-year rotation, 20-year simulation. Decatur soil, EPIC Soil data ID no. 186, modified for Dewey soils in North Alabama. Land slope = 2% and slope length was 30 meters.				
² Fraction of broiler litter weight: mineral N = 0.012; NH ₃ = 0.99; organic N = 0.027; mineral P = 0.012; and organic P = 0.004.				

TABLE 13. SOIL TEST DATA FOR LITTERED AND NON-LITTERED SOILS IN NORTH ALABAMA USED TO EVALUATE THE ABILITY OF EPIC TO PREDICT THE FATE AND TRANSFORMATIONS OF P APPLIED AS LITTER

Soil	Soil pH		Soil test P		Soil test K		Soil test Mg		Soil test Ca	
	Litter	Non	Litter	Non	Litter	Non	Litter	Non	Litter	Non
			mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Decatur-Ap.....	7.1	5.0	120.0	13.0	204	122	93	58	1,985	397
Decatur-BA.....	7.0	5.4	126.0	5.5	153	68	82	56	2,024	512
Decatur-Btf.....	7.2	5.8	128.0	3.3	151	47	85	63	1,365	645
Decatur-Bt.....	7.0	5.3	2.5	0.9	118	22	72	108	529	512
Decatur-CB.....	5.3	4.9	1.3	0.8	38	24	56	123	425	387
Hartsells-Ap....	6.5	5.2	163.0	59.0	235	79	197	31	2,505	237
Hartsells-BA...	6.0	5.2	100.0	19.0	104	43	67	10	810	250
Hartsells-Btf....	5.8	5.0	66.0	5.3	84	42	56	8	559	273
Hartsells-Bt.....	4.8	4.8	1.3	0.8	65	44	48	13	344	113
Hartsells-CB....	4.6	4.8	0.8	0.8	56	34	35	12	254	80

of EPIC in planning BMPs for litter application. In addition, EPIC is an excellent tool to use in predicting soil loss by water erosion under many crops and management schedules.

Kingery et al. (40) reported P depth distributions determined by soil testing methods (Mehlich-1 extractable P). They sampled 11 paired fescue pastures on Hartsells soils in the poultry-producing region of North Alabama. Direct comparisons of total P cannot be made. However, Jones et al. (37) used soil test data to develop their active P pool concept. Soil test P depth distribution data were averaged for all pastures, and the same EPIC pasture management schedule used for the single site to predict total P after 10 and 20 years of litter application and conventional P fertilization was used for this averaged set. In this case active P was predicted with depth. The litter soil test and EPIC active P correspond well between simulated and measured (Figure 30). In this graph the weighted mean of the 0-15 cm layer predicted P was used since this is what was sampled by Kingery et al. (40). Only one EPIC-predicted point, 15-30 cm, under conventional fertilization does not follow the measured trend. There is a considerable amount of soil test P data available from many regions and there is considerable support for using soil test values as evidence of P accumulation in surface soil layers (67). EPIC offers a tool to predict P buildup to critical levels and the magnitude of soluble and sediment P in runoff when critical levels are reached. Figures 31 and 32 show 20-year EPIC simulations of P loss on sediment and as soluble P concentration in runoff from fescue pasture and cotton. Most notable is the high soluble P concentration predicted for runoff from pastures receiving litter. It is also notable that concentrations in runoff are not increasing appreciably. This shows that P losses are controlled, to a greater extent, by levels of annual applications rates and not by levels of P accumulation as fixed and tightly bound P.

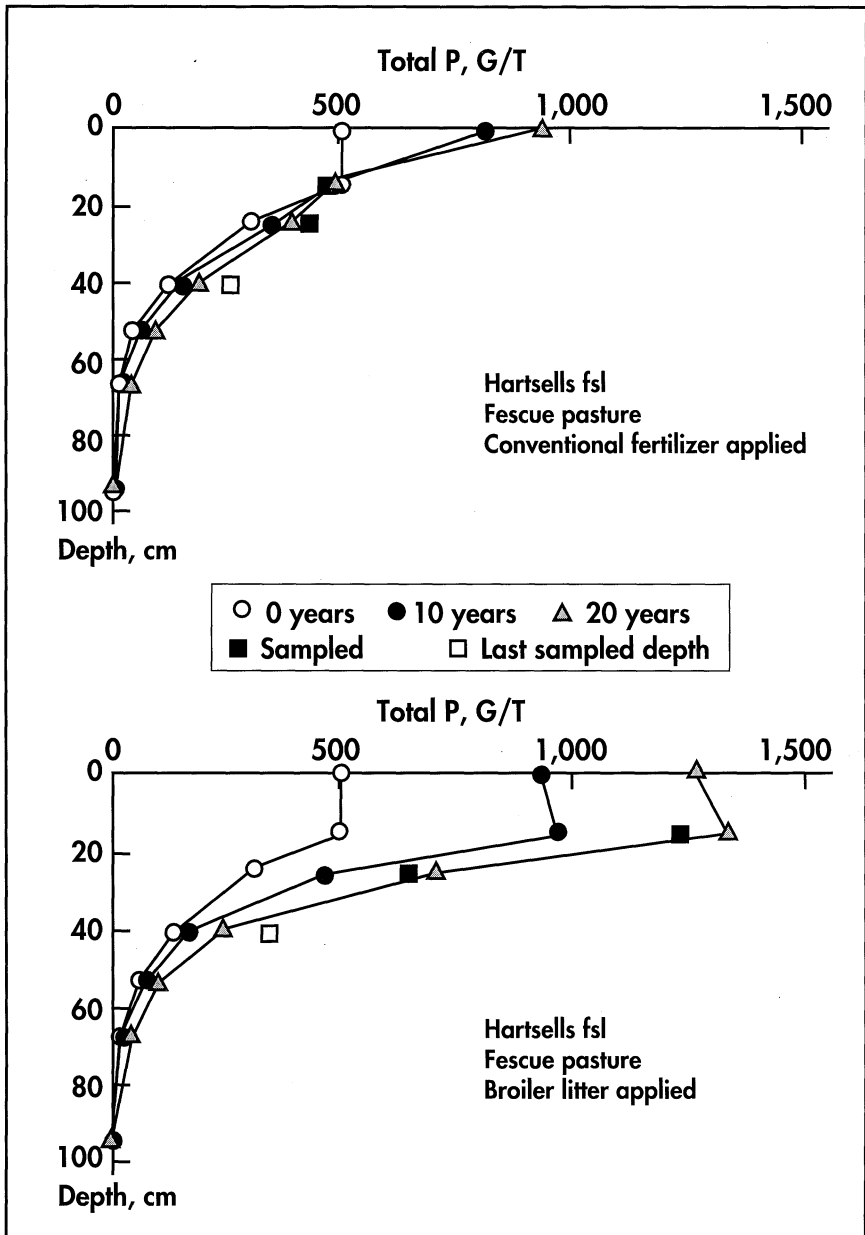


Figure 28. Sampled and EPIC-predicted P distribution with depth after 10 and 20 years of poultry litter and conventional mineral fertilizer P application on a fescue pasture.

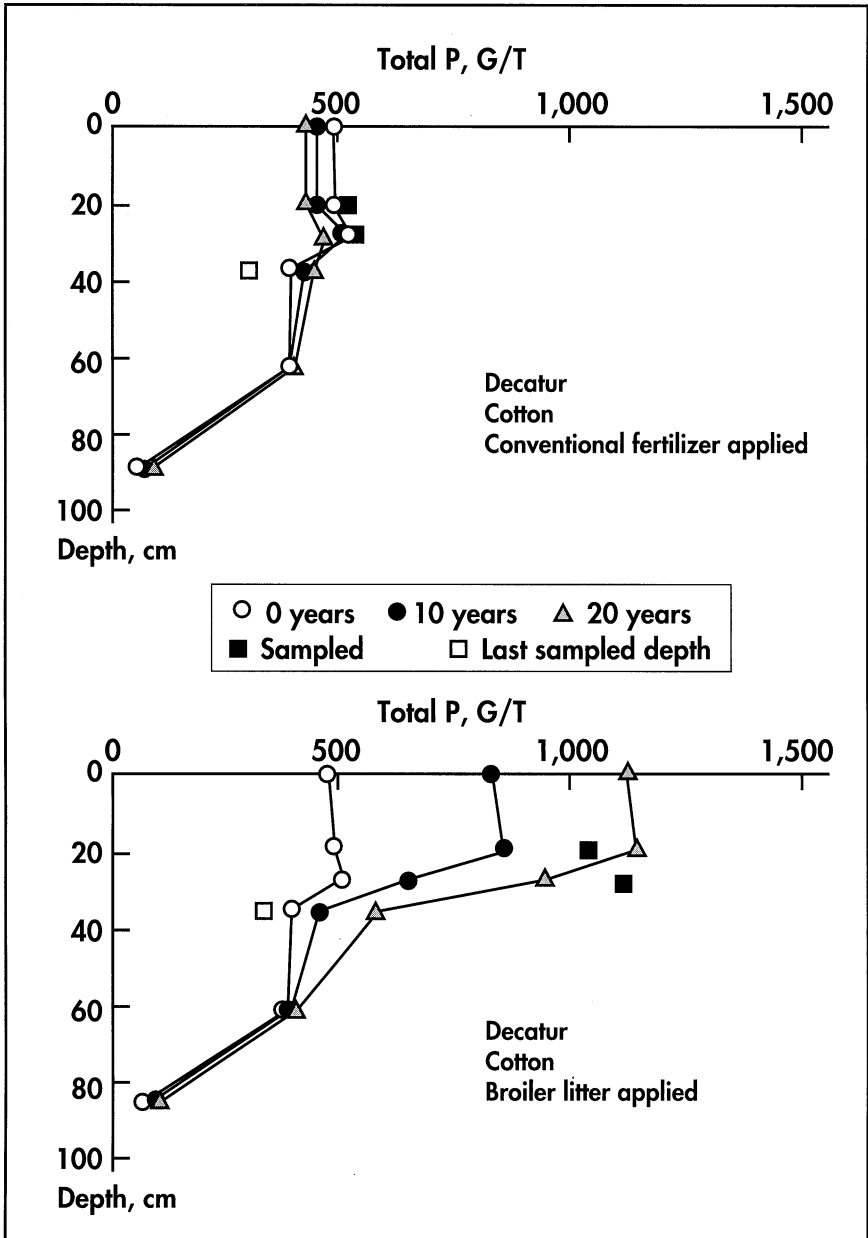


Figure 29. Sampled and EPIC-predicted P distribution with depth after 10 and 20 years of poultry litter and conventional mineral fertilizer P application on a cotton field.

TABLE 14. BACKGROUND INFORMATION FOR LITTERED AND NON-LITTERED SOILS IN NORTH ALABAMA USED TO EVALUATE THE ABILITY OF EPIC TO PREDICT THE FATE AND TRANSFORMATIONS OF P APPLIED AS LITTER

Soil & horizon	Total P	Organic P	Resin P	Soil test P	Ratio-STP	Ratio-ACT
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Littered						
Decatur-Ap.....	1,048	181	75.00	120.0	6.6	25.0
Decatur-BA.....	1,115	283	78.00	126.0	5.7	14.0
Decatur-Bt.....	338	53	1.27	2.5	121.0	138.0
Hartsells-Ap.....	1,231	416	68.00	163.0	4.0	6.9
Hartsells-BA.....	658	123	36.00	100.0	4.4	6.8
Hartsells-Bt.....	345	70	0.91	1.3	307.0	407.0
Non-littered						
Decatur-Ap.....	506 ¹	125	2.94 ¹	13.0 ²	28.0	37.0
Decatur-BA.....	510 ¹	104	1.41 ¹	5.5 ¹	74.0	110.0
Decatur-Bt.....	340	96	1.09	0.9 ³	828.0	1,351.0
Hartsells-Ap.....	473 ¹	269	7.62 ²	59.0 ¹	2.6	2.7
Hartsells-BA.....	433 ¹	117	4.42 ³	19.0	8.8	9.5
Hartsells-Bt.....	266	40	1.43	0.8	173.0	264.0

¹Indicates significant difference at the 0.01 level of probability.

²Indicates significant difference at the 0.05 level of probability.

³Indicates significant difference at the 0.10 level of probability.

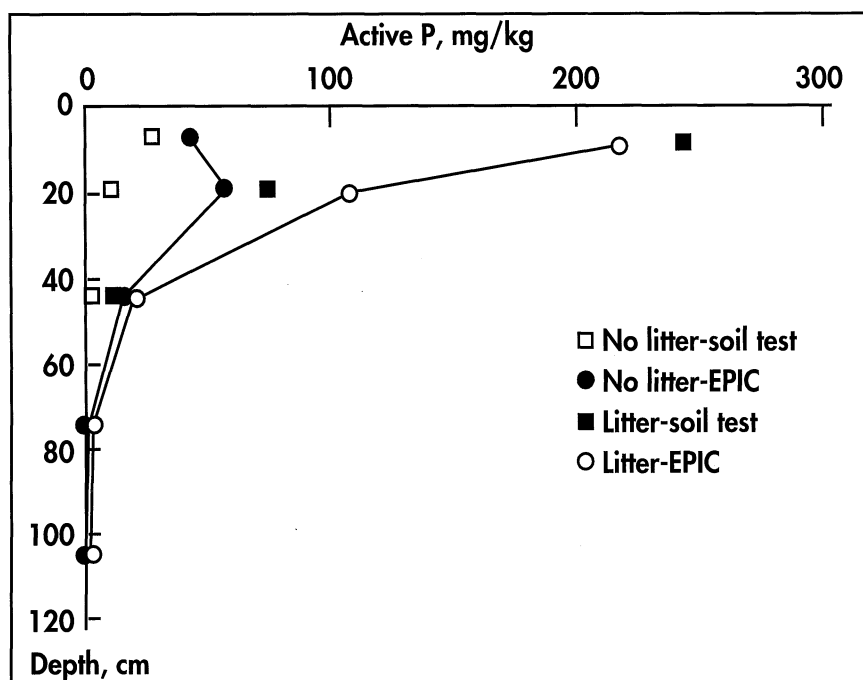


Figure 30. Soil test P and EPIC-predicted active P after 20 years of poultry litter application to fescue pastures on Hartsells soils in North Alabama.

RELATED PHOSPHORUS RESEARCH IN ALABAMA

Phosphorus Mobility Associated with Suspended Eroded Soil Material¹

Caldwell (12) conducted a study to characterize the mineralogy of water dispersible clays (WDC) in relation to soils and cropping practices. The objectives of this study were to identify the mineralogy of eroded soil material in runoff water from cropped and pasture land, half of which had received annual applications of poultry litter, and to suggest how the suspended material would behave with respect to P adsorption.

¹Caldwell, T. 1996. Mineralogical comparisons of surface soils and their water dispersible clay fractions with the suspended fractions in surface water of selected Alabama agricultural lands. M.S. Thesis, Auburn Univ. AL. 91p.

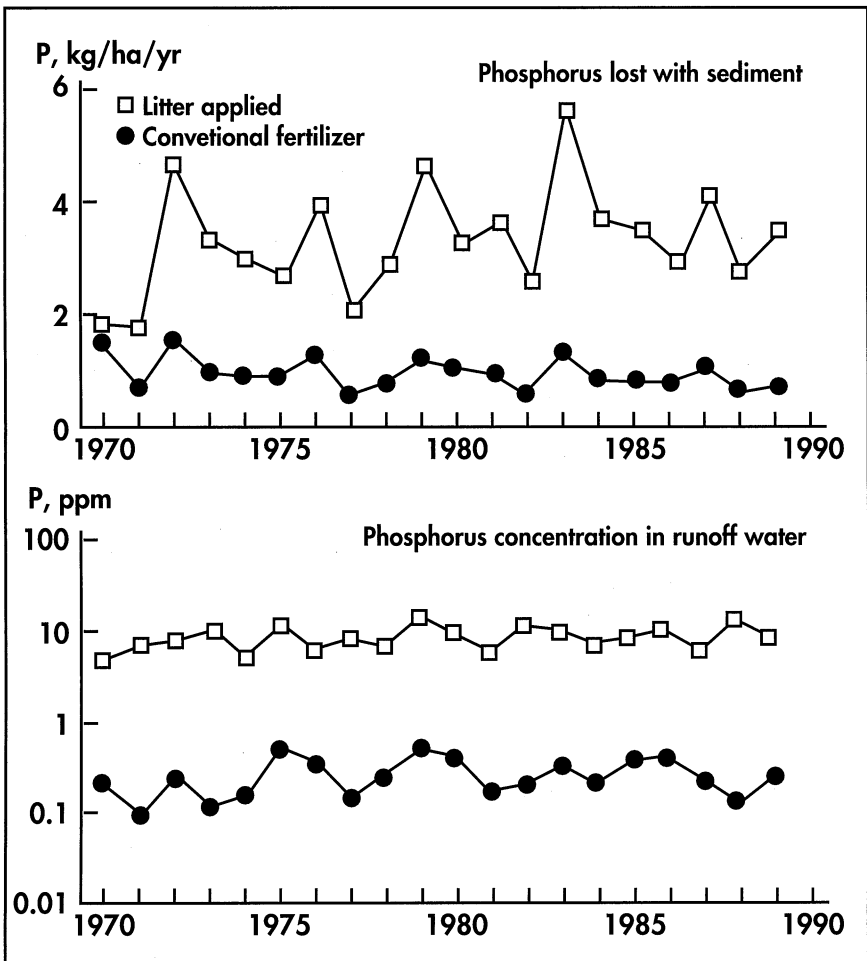


Figure 31. EPIC-predicted average annual P concentrations in runoff water from fescue pasture receiving poultry litter and under conventional fertilization for 20 years.

Gibbsite and goethite are noted for their phosphate adsorption capabilities (16, 76, 77, 81), but they comprise a small percentage of the mineralogy of the Hartsells and Dewey soils studied from Cullman and Cherokee counties. Kaolinite and hydroxy-interlayered-vermiculite (HIV) do not have the phosphate adsorbing capabilities of Fe and Al oxides, but they comprise the majority of the mineralogy of these soils. In general, the P adsorption capacities are as follows: amorphous hydrated oxides > goethite-gibbsite > kaolinite > 2:1 clays (16).

Phosphates bind to edge sites of HIV as well as to the sites located on the hydroxy interlayer. The Hartsells and Dewey soils also contained muscovite. Phosphate adsorption onto micas is minor and occurs only at the edge surfaces. Any reported significant phosphate adsorption onto mica surfaces is probably because of Fe oxide coatings (54).

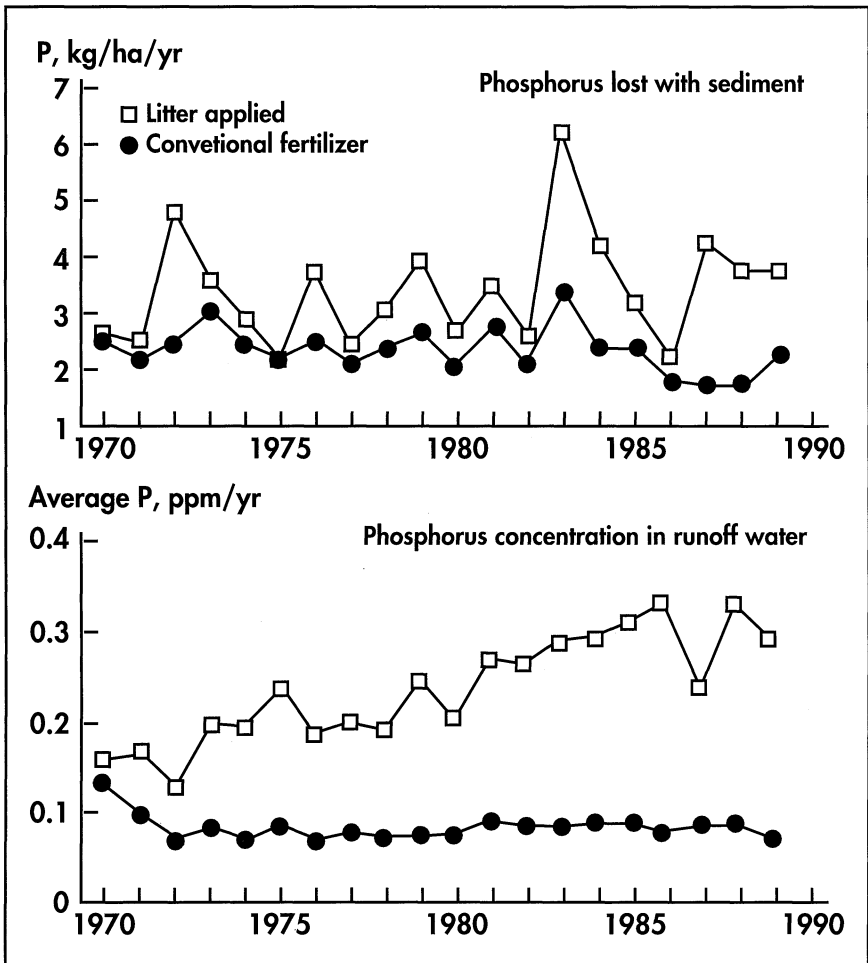


Figure 32. EPIC-predicted average annual P concentrations in runoff water from cotton fields receiving poultry litter and under conventional fertilization for 20 years.

The amount of phosphate desorbed is related to the amount of Bray P1-extractable P contained in the soil or eroded material (51, 77). Phosphate desorption is determined by: (1) P-desorption capacity of the soil or eroded material; (2) equilibrium chemical potential; and (3) rate of release (51). Oloya and Logan (51) observed that the soil material which contained low amounts of extractable P appeared to contain a pool of desorbable P that is greater than the amount desorbed. This pool of P was not depleted with sequential extraction. They suggested that this pool of P could be released over long periods of time. On the other hand, soil material that was high in extractable P contained a pool of easily desorbable P, which was depleted at about the fifth extraction. Riley and Syers suggested that the easily desorbed P is physically sorbed, while the more strongly held P is chemisorbed (55).

Large amounts of applied P can be eroded from cultivated land (21, 58). However, loss of applied P is generally less than 1% (64). Even at such low levels, the total and soluble P can exceed the critical values of 0.02 and 0.01 mg/L, above which biological growth can be stimulated (64). Particulate P levels ranging from 0.06-9.61 mg/L have been reported for runoff from cultivated land, pasture, and forest. Alberts and Moldenhauer (4) measured available P levels of 68-182 mg/L for the less than 0.05-mm fraction in runoff from a Sidell silt loam under various tillage treatments. The contribution of the water-dispersible clay (WDC) fraction to the particulate P content is difficult to assess. The primary clay, or WDC fraction, has been reported to be 5.2% or less of the total eroded soil material for a Miami silt loam (3), a Sidell silt loam (4), and Monona and Ida soils (3). The dissolved P concentrations from a recent study (0.170-3.408 mg/L for a Hartsells site in North Alabama and 0.0116-2.606 mg/L for an Orangeburg site in South Alabama) were within the ranges reported in the aforementioned studies (12).

Though most P in runoff water is lost in a particulate form (45, 63), loss of soluble P may increase as land-application rates of animal wastes increases. Annual animal waste applications to cultivated land and pasture in excess of crop requirements and P-adsorption capacity of soils can result in downward P movement (7, 23, 40, 53). If there is downward movement of P then it also can be desorbed into runoff water. Depending on the P-adsorption capacity of the suspended material and of the soil over which the runoff flows, the soluble P may be re-adsorbed (62) or remain in solution. Stream and river banks, which usually have high P-adsorption capacities, can reduce the P load entering waterways by adsorbing soluble P (78).

Concern over the pollution potential of P has led to an increased awareness of its transport from cultivated land, pasture, and aquacultural facilities. The Clean Water Act gave states the responsibility to develop strategies for controlling agricultural pollution. In Alabama, no laws exist which require monitoring of P movement. Currently, recommended limits set on the amount of broiler litter that can be applied to crop land and pasture are based on N content of the litter and crop N requirements.

Litter was observed to have no effect on suspended solid mineralogy. Pasture reduced the relative percentage of quartz in runoff water. Quartz was the dominant mineral in runoff from Hartsells and Orangeburg soils. Hydroxy-interlayered vermiculite and kaolinite, the major P adsorbing minerals in these soils, comprised over 50% of the suspended solid mineralogy in farm ponds and streams. Hydroxy-interlayered vermiculite was dominant in receiving waters in Hartsells watersheds, while kaolinite was dominant in Orangeburg watersheds. The water-dispersible clay of the Hartsells Ap horizon was a better indicator of suspended solid mineral distribution in receiving waters than was the water-dispersible clay of the Orangeburg Ap horizon. For the Orangeburg soil watersheds, subsoil mineralogy was the best indicator of suspended solid mineralogy in receiving waters because of contributions from exposed B and C horizons.

Watershed Study of Conventional- and Conservation-tillage Cotton Practices²

Soileau et. al. (72) conducted a watershed study in Colbert County, Ala., from 1984-89. Runoff sediment N and P were determined for both conventional and conservation tillage on cotton for a Decatur soil on 1-6% slopes. Surface runoff of P was markedly increased for storm events immediately after fertilizer P was surface applied to cotton under conservation tillage. In both tillage systems, most of the runoff losses of P were associated with the solution phase rather than the suspended solid phase. Under conservation tillage, average loss in the solution phase was 2.62 kg/ha per year; in the solid phase, 0.30 kg/ha per year. Under conventional tillage, average loss in the solution phase was 0.75 kg/ha per year; in the solid, 0.24 kg/ha per year. The study concluded that because of elevated losses of both N and P after surface application, it is important that NP applications be timely and at rates not exceeding crop needs. Total annual sediment losses for this watershed were much less than the tolerance limit of five tons per year and also less than predicted by the USLE equation.

Long-term Phosphorus Levels Determined by Soil Test Analysis³

Cope (14) conducted a study of the effects of 50 years of fertilization with P and K on soil test levels at six locations in Alabama. He found that on soils that received 14-18 kg/ha of P from 1929 through 1957, soil-test P increased from an average of 19 mg/kg in 1929 to 33 mg/kg by 1957. When applications were discontinued, the level dropped to that of untreated plots by 1973. Application of 27 kg/ha or more of P rapidly increased soil test P to "high" or "very high" levels, and these have been maintained by annual applications of 30 kg/ha during 20 years of high crop production. The highest rate, 54 kg/ha, raised average levels of soil-test P (Mehlich-1 extractable) from 43 kg/ha in 1929 to 217 kg/ha in 1957. This was one-ninth of the 1,566 kg/ha of P applied during this period.

² Soileau, J.M., J.T. Touchton, B.F. Hajek, and K.H. Yoo. 1994. Sediment, nitrogen and phosphorus runoff with conventional- and conservation-tillage cotton in a small watershed. *J. Soil and Water Cons.* 49 (1):82-89.(14)

³ Cope, J.T., Jr. 1981. Effects of 50 years of fertilization with phosphorus and potassium on soil test levels and yields at six locations. *Soil Sci. Soc. Am. J.* 45:342-347.

Soil Test Phosphorus Levels from Long-term Broiler Litter Application⁴

Kingery et. al. (40) conducted an investigation of the impacts of long-term land application of broiler litter on soil-chemical properties in the Sand Mountain region of North Alabama. The sampling sites were located in Cullman, Blount, Marshall, and Dekalb counties. From each county, three pairs of sites were chosen that consisted of long-term (15-25 years) litter and non-littered fescue pastures on matching soil series. The study showed P accumulation and downward movement to approximately 60 cm in littered pastures. Long-term land application of broiler litter increased soil test P (Mehlich-1 extractable) levels an average of 530% in the 0-60 cm depth, as compared to no-litter pastures. P concentrations measured in the 0-15 cm depth (greater than 250 mg/kg) in litter sites have a rating of "extremely high" (greater than 100 mg/kg), according to the Auburn University Soil Testing Laboratory. P concentrations of 25 mg/kg in the 0-15 cm depth are considered adequate for most crops on these soils.

P Accumulation and Runoff from Litter and Conventional Fertilizer Applications⁵

Hall (29) conducted a study during 1991-1993 to determine the impact of land-applied broiler litter on water quality, soil quality, and biomass production. The soil was a Decatur silt loam on 2% and 4% slopes on the Tennessee Valley Substation in Limestone County, Ala. Treatments on the two slopes included commercial fertilizer applied at soil test recommendation levels, and broiler litter at four and eight tons per acre. The cropping system was conventionally tilled corn and a winter cover of rye. The soil was sampled before, during, and after the study. Runoff water was collected with a Coshocton type runoff sampler. Soil percolate was collected with a wick lysimeter. The analysis of runoff water samples included total and dissolved P. The P content of the broiler litter was 14.8 g/kg in 1991 and 34 g/kg in 1992.

Total P concentrations in runoff waters from both slopes, and all P application rates exceeded the limit that will support algae growth in surface lakes and streams (0.002-0.1 mg/L) in the 1991-1992 crop year. The highest TP concentration was 2.66 mg/L from 4% slopes occurring in runoff in late December. In the 1992-1993 crop year, TP was significantly related to treatment. Total P concentrations reached a maximum of 8.1 mg/L in a November runoff event from plots receiving eight tons of litter per acre. The maximum concentration from 4% slopes this crop year was 6.6 mg/L.

Dissolved P concentrations in runoff during the 1991-1992 crop year from both slopes were not significant between treatments. Concentrations on all sampling occasions exceeded algae growth limits. The highest concentration,

⁴Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. *J. Env. Qual.* Vol 23, no. 1, pp. 139-147.

⁵Hall, B.M. 1994. Broiler litter effects on crop production, soil properties, and water quality. M.S. Thesis. Auburn University, Auburn, AL.

1.95 mg/L, occurred from a 2% slope in late September. During 1992-1993, dissolved P concentrations were highest on most runoff events where eight tons of litter were applied, reaching a maximum of 6.4 mg/L in a November runoff event.

Litter applications promoted greater concentrations of sediment P than fertilization. During the 1991-1992 crop year, the highest sediment P concentration occurred under four-ton application rates (0.8 mg/L), and all concentrations for all events exceeded algal limits for P effects on eutrophication. In the 1992-1993, sediment P concentrations were usually highest from the eight-ton treatment, reaching a peak of 3 mg/L in a November runoff event. This is three times the concentration observed in the preceding year. Mehlich-1 extractable P in the 0-15 cm and 15-30 cm layers at the end of the study was significantly affected by litter application on both slopes. Residual soil P concentrations were increased from about 25 mg/kg in commercial fertilizer treatments to 115 mg/kg at eight-ton-per-acre litter application rates. In the 0-5 cm layer, soil-test P had a rating of "extremely high," according to the Auburn University Soil Testing Laboratory.

The results of runoff water collection and P determinations indicated that all treatments, slope, two litter application levels, and commercial fertilizer application, have potential for degrading surface waters via losses of P. However, impacts of runoff losses of P are usually observed in receiving waters, such as rivers and lakes, rather than at the edge of the contributing field.

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