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Phosphorus Immobilization in Poultry Litter and Litter-amended soils with Aluminum, Calcium and Iron amendments

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Arkansas Water Resources Center

PHOSPHORUS IMMOBILIZATION IN POULTRY LITTER AND LITTER-AMENDED SOILS WITH ALUMINUM, CALCIUM AND IRON AMENDMENTS

Research Project Technical Completion Report

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Abstract

Arkansas produces approximately one billion broilers each year. Phosphorous (P) runoff from fields receiving poultry litter is believed to be one of the primary factors affecting water quality in Northwest Arkansas. Poultry litter contains approximately 20 g P kg⁻¹, of which about 2 g P kg⁻¹ is water soluble. Soils that have received repeated heavy applications of litter may have water soluble P contents of as high as 10 mg P Kg⁻¹ soil. The objective of this study was to determine if soluble P levels could be reduced in poultry litter and litter-amended soils with Al, Ca, and/or Fe amendments. Poultry litter was amended with alum, sodium aluminate, quick lime, slaked lime, calcitic limestone, dolomitic limestone, gypsum, ferrous chloride, ferric chloride, ferrous sulfate and ferric sulfate, and incubated in the dark at 25°C for one week. Three soils which had been excessively fertilized with poultry litter were amended with alum, ferrous sulfate, calcitic limestone, gypsum and slaked lime and incubated for 4 weeks at 25 °C. In the litter studies, the Ca treatments were tested with and without CaF₂ additions in an attempt to precipitate fluorapatite. At the end of the incubation period, the litter and soils were extracted with deionized water and soluble reactive P (SRP) was determined. SRP levels in the poultry litter were reduced from over 2,000 mg P kg⁻¹ litter to less than 1 mg P kg⁻¹ litter with the addition of alum, quick lime, slaked lime, ferrous chloride, ferric chloride, ferrous sulfate and ferric sulfate under favorable pH conditions. SRP levels in the soils were reduced from approximately 5 mg P Kg⁻¹ soil to less than 0.05 mg P Kg⁻¹ soil with the addition of alum and ferrous sulfate under favorable pH conditions. Gypsum and sodium aluminate reduced SRP levels in litter by 50 to 60 percent while calcitic and dolomitic limestone were even less effective. In soils, the Ca amendments were less effective than the Al and Fe amendments, although slaked lime was effective at high pH. The results of these studies suggest that treating litter and excessively fertilized soils with some of these compounds, particularly alum, could

significantly reduce the amount of SRP in runoff from littered pastures. Therefore, chemical additions to reduce SRP in litter and soil may be a best management practice in situations where eutrophication of adjacent water bodies due to P runoff has been identified. Preliminary calculations indicate that this practice may be economically feasible. However, more research is needed to determine any beneficial and/or detrimental aspects of this practice.

INTRODUCTION

Phosphorus is generally considered the limiting nutrient responsible for eutrophication in lakes and reservoirs, since certain algal species can obtain N from atmospheric sources. Tighter controls of point sources of P, such as municipal wastewater treatment plants, has resulted in decreased P loading from point sources into the aquatic environment in the last few decades. However, improvement of water quality has not always been observed when point source P loads were reduced. Therefore, attention is currently being focused on non-point sources of P, such as agricultural runoff. One of the major sources of P runoff from agricultural lands is animal waste.

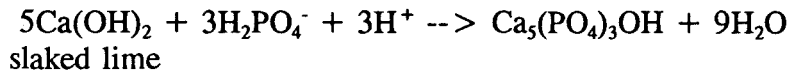
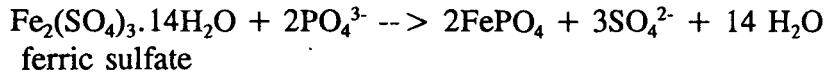
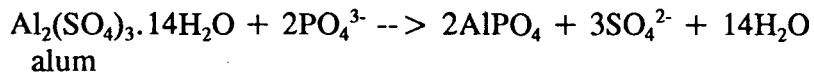
Several investigators have characterized P runoff from fields receiving poultry manure (Edwards and Daniel, 1993a, b; McLeod and Hegg, 1984; Westerman and Overcash, 1980; Westerman et al., 1983). These studies have all shown that P runoff increases as the manure or litter application rate increases and as rainfall intensity increases. Drying time has also been shown to be an important parameter with respect to P runoff, with longer periods between application and rainfall resulting in greatly reduced runoff of P (Westerman and Overcash, 1980; Westerman et al., 1983). Recent studies have shown high concentrations of P (14 - 76 mg P L⁻¹) in runoff from pastures receiving poultry litter, most of which is dissolved inorganic P ($\approx 85\%$), with only small amounts of particulate P (Edwards and Daniel, 1993a). Sonzogni et al. (1982) indicated that dissolved inorganic P is directly available to algae and concluded that best management practices used to decrease P runoff should consider the bioavailable-P load, rather than focusing on the total-P load.

Rapid and concentrated growth of poultry industry, fueled by the demand for low-fat meat, has caused concerns to be voiced in several states with respect to water quality. Arkansas is the number one poultry producing state in the U.S., with approximately one billion broilers

produced per year (Wooley, 1991). Each broiler produces approximately 1.5 kg of poultry litter over a 10-week growing cycle (Perkins et al., 1964). This litter contains 8-25.8 g P kg⁻¹, with soluble reactive P levels up to 4.9 g P kg⁻¹ (Edwards and Daniel, 1992). Runoff of P from fields receiving poultry litter has been speculated to be one of the primary factors affecting water quality in Northwest Arkansas. High bacterial counts and high biochemical oxygen demands have also been attributed to litter. Proposals to decrease the amount of litter applied to pastures have the greatest support at present. However, transporting materials greater distances and/or building litter storage facilities will increase the cost of disposal. An alternative solution to this problem may be chemical fixation (precipitation with metals and/or adsorption onto metal oxides or hydroxides). Compounds such as slaked lime (Ca(OH)₂ or alum (Al₂(SO₄)₃·14H₂O) could be added to the litter before field application, resulting in P fixation. To determine if P fixation using chemical amendments is feasible, information is needed to determine its potential impact on poultry production and the environment.

The best information on P fixation has been provided by researchers studying wastewater treatment. In a review of Swedish wastewater treatment plants, Ulmgren (1975) found that when alum was used to precipitate P, the pH had to be lower than 6.4 to result in P concentrations of 0.8 mg P L⁻¹, whereas the pH needed to reach this concentration with lime was 11.5. He indicated that at a pH of 6.0, AlPO₄ solubility reaches a minimum (0.01 mg P L⁻¹). The Al/P mole ratios generally found in the precipitates were 1.5 to 2.5. Of the plants studied in Sweden, 33 used alum, 9 used quicklime (CaO), and 1 used ferric chloride. Treatment with these substances not only reduced P content in effluent water, but also decreased suspended solids, BOD, heavy metals, worm eggs and parasites (Ulmgren, 1975).

Precipitation reactions for aluminum, calcium, and iron phosphates are:



(Ripley, 1974). Lime can be added as CaO or Ca(OH)₂. Similarly, ferric chloride or ferric sulfate appear to be equally effective. Sodium aluminate (Na₂Al₂O₄) has been used in the place of alum. Hsu (1976) indicated that the optimum pH for P removal with Al and Fe was dependent on the metal/P mole ratio. At metal/P ratios of two to five, the optimum pH range for P removal by Al was 5.5 to 8.0, whereas for Fe the optimum pH range was 4.7 to 7.1.

Very little work has been done on the chemical speciation of phosphorus in poultry litter. Sharpley et al. (1984) reported that 78% of the total P in cattle feedlot waste was inorganic, and that the major proportion of both organic and inorganic P was in labile forms. McCoy et al. (1986) concluded that the municipal sewage sludge composts they studied were very poor sources of plant available P because Fe and Al treatments were used to precipitate P in the sludge at the sewage treatment plant. These researchers also found that less than 5% of the P in these sludge composts was in an organic form. Similarly, Soon and Bates (1982) found that amending soils with Ca, Al or Fe-treated sludges increased the Al- and Fe-bound P fraction in the soils but had little effect on the content of organic P in the soils. Miller et al. (1993) found that air-drying increased the SRP level of a heavily littered Linker soil to values approaching 7.5 mg P Kg⁻¹ soil.

At pH values less than approximately 6, the most stable phosphate mineral in soils is AlPO₄•2H₂O (variscite), followed by FePO₄•2H₂O (strengite) (Lindsay and Vlek, 1977). In

soils with pH values greater than 6 the calcium phosphate minerals fluorapatite and hydroxyapatite are the most stable phosphate minerals. Pierzynski et al. (1990) reported that an amorphous analog of variscite with a $\log K_{so} = -27$ to -29 controlled aqueous phase P activities in soils excessively fertilized with fertilizers, sewage sludges or manures.

Poultry production provides an ideal setting for the use of chemical precipitants. At present, when broilers reach maturity and are removed from the houses, the litter (which is composed of a bedding material and manure) is collected and spread on adjacent pastures. This material has extremely high concentrations of water soluble P (>2000 mg P kg^{-1}). When the first heavy rainfall event occurs, P is transported with runoff water into nearby water bodies (Edwards and Daniel, 1993a). If alum or slaked lime were applied to the litter prior to removal from the houses, the water soluble P could be converted to an insoluble mineral form via precipitation or adsorption, making the P less susceptible to leaching or runoff. If conducted properly, P precipitation could result in the formation of minerals which are stable over geologic time periods, decreasing the threat of eutrophication of surface waters in poultry producing regions.

This research will determine the rates of chemical amendments such as alum and slaked lime that are needed to precipitate P in poultry litter and litter-amended (high soil test P) soils. Laboratory and field studies will be conducted which test how efficiently various Al, Ca, and Fe amendments immobilize P. The objectives are: 1) determine the variability in the content of water soluble phosphorus in poultry litter, 2) evaluate the effectiveness of various Al, Ca and Fe amendments in precipitating P in poultry litter and in soils excessively fertilized with poultry litter, 3) use rainfall simulators in small plot studies to determine if P runoff from pastures receiving chicken litter can be inhibited by alum and/or slaked lime additions, and 4) determine the stability of phosphate minerals formed when chicken litter is treated with various

amendments under a wide range of soil pH conditions. During the first year of this project the bulk of our effort has been directed at objective 2. Therefore, this report will focus on our accomplishments with regard to objective 2.

METHODS AND MATERIALS

Experiments with Poultry Litter

Twenty six grams of fresh poultry litter (20 grams dry weight equivalent) were weighed into glass bottles. The litter had been forced through a 10 mesh sieve to break up large clumps and mixed in a portable cement mixer for two hours to insure homogeneity. The bedding of this litter was rice hulls. The litter had not been stacked or composted. The initial pH (1:1) and electrical conductivity (1:10, litter:water extract) was 8.2 and 8970 $\mu\text{S cm}^{-1}$, respectively. Total N, P, and K were 42.8, 18.1, and 27.3 g kg^{-1} , respectively. Total Kjeldahl N was determined on the fresh poultry litter according to the method of Bremner and Mulvaney (1982). Total P and K were determined on fresh litter using the method of Huang and Schulte (1985).

The litter was amended with Al, Ca, and Fe compounds to reduce P solubility. Materials tested included alum, sodium aluminate, quick lime, slaked lime, calcitic limestone, dolomitic limestone, gypsum, ferrous chloride, ferric chloride, ferrous sulfate and ferric sulfate. All amendments were reagent grade materials. After the amendments had been added, the mixtures were stirred with a spatula for approximately one minute. The Ca treatments were tested with and without CaF_2 additions as a secondary amendment in an attempt to precipitate fluorapatite. Calcium carbonate was added as a secondary amendment in cases where the primary amendment was believed to be an acid forming compound. There were twenty different chemical treatments tested, with five rates of each treatment (total number of treatments equalled 100 plus control) and three replications (Table 1). The lowest rate of the Fe and Al amendments was equal to the

amount needed to achieve a 1:1 metal:P mole ratio, assuming the P content of the litter was 10 mg kg⁻¹. The lowest rate of the calcium amendments was based on a Ca:P ratio of 1.5:1. It should be noted that while the rates were based on the assumption that the P content of litter was 10 mg P kg⁻¹, the actual P content was found to be 18.1 mg P kg⁻¹ (therefore, the lowest rate of Al and Fe was equivalent to 1:1.8 mole ratio, etc.).

After amendments were added to the litter, deionized water was added to achieve a water content of 20% by volume. The amended litter was then incubated in the dark at 25°C for one week. A one week equilibration time was utilized for this study because this is usually the time scale between the removal of broilers from the houses after the final growout before litter removal and land application of the litter. At the end of this period, the litter was transferred to polycarbonate centrifuge tubes, shaken for two hours with 200 mL of deionized water, and centrifuged at 4066 g for 20 min. Unfiltered samples were collected for measurement of pH, alkalinity, and electrical conductivity (EC). Alkalinity was determined by titration, according to APHA method 2320 B (APHA, 1992). Filtered samples (0.45 um millipore filters) were collected for measurement of soluble reactive P (SRP), water soluble metals (Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Zn), soluble organic carbon (SOC), SO₄, and Cl. The metal and SRP samples were acidified to pH 2.0 with nitric acid to prevent precipitation. Chloride, SOC, and SO₄ samples were not acidified. Soluble reactive P was determined using an ascorbic acid technique, according to APHA method 424-G (APHA, 1992). Metals were analyzed using an inductively coupled argon plasma emission spectrometer (ICP), according to APHA method 3120 B (APHA, 1992). Soluble organic C was determined as the difference between total organic C and inorganic C as measured on a Rosemont DC-190 organic C Analyzer, using the combustion-infrared method according to APHA method 5310 B (APHA, 1992). Sulfate was determined using the turbidimetric method, according to APHA method 4500-SO₄²⁻ E (APHA, 1992).

Chloride was determined using the potentiometric method with a chloridometer, according to APHA method 4500-Cl⁻ D (APHA, 1992).

Experiments with Poultry Litter-Amended Soils

Soils were sampled from three fields located near the town of Lincoln in Washington County, Arkansas during the second week of June, 1993. Each of the fields had a history of heavy poultry litter applications. At the time of sampling all three fields were in fescue and were being used to graze steers. The soils were sampled to a depth of 4 cm using spades. Soil samples taken from approximately 20 locations throughout each field were composited to provide a single bulk sample from each field. These bulk samples were air-dried, ground, sieved (2 mm) and thoroughly mixed prior to use. The series names, taxonomic classifications and selected chemical properties of the soils are presented in Table 2. The pH was determined using a 1:2.5 soil:water ratio, organic matter (OM) content was determined by the Walkley-Black method, total P was determined by HNO₃ digestion at 120 °C followed by analysis of P in the diluted digest by inductively coupled argon plasma emission spectrophotometry (ICAPES), and soil test P (STP) was determined by extraction with Mehlich III solution (1:7 soil:solution ratio) followed by P analysis using ICAPES.

Fifty grams (oven dry equivalent) of soil were placed in 250 mL capacity, screw top, brown glass bottles. Amendments were added to the soil in the bottles in solid form at the rates given in Table 3. The five primary amendments used in this study were alum (Al₂(SO₄)₃•18H₂O), ferrous sulfate (FeSO₄•7H₂O), calcitic limestone (CaCO₃), slaked lime (Ca(OH)₂), and gypsum (CaSO₄•2H₂O). Rates of primary amendments were based on the total P content of the soil and on the metal:phosphate molar ratios in the compounds that were anticipated to form as a result of amendment additions, namely, AlPO₄, FePO₄, and Ca₅(PO₄)₃OH. The 1X rate of each of the primary amendments, then, corresponded to addition

of sufficient Al or Fe to provide a metal:total P molar ratio of 1:1 or to addition of sufficient Ca to provide a Ca:total P molar ratio of 5:3. The 0.1X rates corresponded to addition of one-tenth the amount of amendment as the 1X rate, and similarly for the other indicated rates.

Secondary amendments were added to some samples to adjust the pH to values which minimized the solubility of the anticipated reaction products. For AlPO_4 , FePO_4 , and $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ these minimum solubility pH values were taken as 6.0, 7.1, and 7.5, respectively. The actual rates at which the secondary amendments were added were determined by titrating soil/amendment mixtures with either HCl or NaOH and from these data calculating the number of milliequivalents of either alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$) or calcite (CaCO_3) required to maintain the pH of the soil:amendment mixtures at the desired values.

Following addition of primary and secondary amendments, sufficient water was added to the soil to achieve a gravimetric moisture content of 0.3 g g^{-1} . After thoroughly mixing the moistened soil:amendment mixtures, the bottles were capped and incubated in the dark at room temperature (20-22 °C) for four weeks. The bottles were opened and stirred once each week during the incubation. At the end of the incubation, sufficient deionized water was added directly to the soil in the bottles to achieve a soil:solution ratio of 1:2 (50 g soil:100 mL water). Bottles were then placed on an end-over-end shaker (30 rev min^{-1}) for 2 h and centrifuged at $4066 \times g$ for 20 min. Unfiltered samples were collected for measurement of pH and electrical conductivity (EC). The soluble reactive phosphate (SRP) contents of filtered ($0.45 \mu\text{m}$ millipore filters) samples were determined using an ascorbic acid technique according to APHA method 2320 B (APHA, 1992).

Each soil/treatment combination was run in triplicate, resulting in 138 bottles per soil and 414 bottles overall.

RESULTS

Experiments with Poultry Litter

Calcium Amendments

Calcium oxide decreased the water soluble P levels in the litter from > 2000 mg P/kg to < 1 mg P/kg when an equivalent of 43 g Ca was added per kg of litter (Fig. 1). It is not known whether this was due to precipitation or adsorption. Whatever the mechanism, the data suggest that soluble P runoff from fields receiving poultry litter could be decreased significantly if the litter were pretreated with CaO. The pH of the litter increased from 7.2 (control) to approximately 12 at the higher rates of CaO (Table 4). A reduction in pH of the litter treated with CaO would be expected with time, due to equilibration with atmospheric CO_2 . This gradual reduction in pH may result in increased P solubility, since the solubility of calcium phosphates is highly pH dependent. However, even if the pH drops to 8, the equilibrium concentration of the most soluble calcium phosphate minerals, such as brushite ($\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$), would be about 10^{-4} M or 3 mg P L^{-1} (Lindsay, 1979). This would still be roughly two orders of magnitude lower than soluble P levels determined for the litter used (200 mg P L^{-1}).

Recently, it has been determined that the majority of P runoff from land application of poultry manure occurs during the first runoff event (Edwards and Daniel, 1993a). If soluble P levels could be decreased for at least a few weeks following land application, then there would be time for precipitation and adsorption by soils to occur, as well as uptake by plants and microorganisms. Therefore, if the solubility of P was lowered for only a short period of time, it would be beneficial from both an environmental and an agronomic viewpoint.

Calcium hydroxide decreased P solubility in poultry litter in the same manner as CaO (Fig. 1). Since $\text{Ca}(\text{OH})_2$ is less caustic, this treatment would be preferable to CaO, which can cause severe burns upon skin contact.

Calcitic and dolomitic limestone had little effect on P solubility in poultry litter as shown by SRP concentrations (data not shown). There are several possible reasons why these amendments did not work. One possibility is that the experiment was not carried out for a sufficient period of time. Normally, it takes months for limestone to completely react and neutralize soil acidity. Our incubation period was one week, which may have been an insufficient time period for solubilization and precipitation reactions. Phosphorus adsorption by calcite should have occurred, since this is an extremely fast reaction. Kuo and Lotse (1972) found that 80% of the phosphate sorption from inorganic P solutions by CaCO_3 occurred within the first 10 seconds.

The pH of the unamended litter was initially 8.2, which decreased to 7.2 after one week. Both calcite and dolomite are relatively insoluble at this pH, which may have led to inadequate amounts of Ca^{2+} in solution to precipitate P. However, even if the Ca^{2+} concentrations in solution were low, P adsorption onto the calcite surface should have removed P from solution, as shown in previous research (Amer et al., 1985; Brown, 1980; Griffin and Jurinak, 1974; Stumm and Leckie, 1971). Phosphorus accumulation onto calcite surfaces was described by Stumm and Leckie (1971) as a three step process; (1) chemisorption of phosphate onto the surface causing the formation of amorphous calcium phosphate nuclei, (2) a slow transformation of these nuclei into crystalline apatite, and (3) crystal growth of apatite. In our study this process may have been inhibited by the high SOC levels in these treatments. High soluble C levels were measured in the extracts of samples which had relatively high pHs (Fig. 2). Innskeep and Silvertooth (1988) showed that apatite precipitation was inhibited by the presence of soluble organic compounds, such as fulvic and humic acids. Magnesium and pyrophosphate, both of which are present in poultry litter, also inhibit this reaction (Amer and Mostafa, 1981; Amer et al., 1985; El-Zahaby and Chen, 1982).

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) decreased SRP from over 2000 mg P kg^{-1} to approximately 700 mg P kg^{-1} at the 100 g kg^{-1} rate (Fig. 1). It should be noted that the lowest rate of gypsum used in this study was high enough to exceed the solubility product of gypsum (2.4 g L^{-1}). This helps to explain why increasing rates of this compound did not influence P (ie - water soluble Ca levels will not be expected to increase after the solubility has been exceeded). If the reduction in SRP noted with the gypsum treatment was due to the formation of calcium phosphate mineral(s), P removal could be enhanced with this amendment if the pH were increased to 8 or higher. If adsorption of P by gypsum was the dominant mechanism of P removal with this amendment, then concentrations of P should have decreased with increasing rates of gypsum. However, this was not observed.

The addition of CaF_2 ($K_{sp} = 3.4 \times 10^{-11}$) did not increase P removal in the Ca treatments, suggesting that fluorapatite formation did not occur (data not shown). This could have been due to the presence of organic acids, Mg, and HCO_3^- , all of which inhibit apatite formation (Brown, 1981; Innskeep and Silvertooth, 1988). Mineral equilibria studies often indicate that when calcium phosphates are forming the solubility is intermediate between octacalcium phosphate ($\text{Ca}_8\text{H}(\text{PO}_4)_3 \cdot 2.5\text{H}_2\text{O}$) and beta tricalcium phosphate ($\beta\text{-Ca}_3(\text{PO}_4)_2$) (Moore et al., 1991; Fixen et al., 1983).

Aluminum and Iron Amendments

Alum additions greatly decreased water soluble P (Fig. 3). Without CaCO_3 to buffer the pH, water soluble P increased at the highest alum rates. This was believed to be due to the acidity created by the alum, which may have caused: (1) dissolution of inorganic calcium phosphates, (2) acid hydrolysis of organic P, and/or (3) dissolution of $\text{Al}(\text{OH})_3$, which would result in P release if adsorption had been the primary mechanism of removal. The pH of the alum treated litter dropped to 3.5 at the highest rate (Table 4). Calcium phosphate minerals are

highly soluble at this pH and could release enough P to achieve the P concentrations noted at the higher rates (Lindsay, 1979). Dicalcium phosphate is added to poultry feed to help insure proper bone development, since most of the P in soybean and corn is phytate P (which is unavailable to chickens since they lack the phytase enzyme).

When CaCO_3 was added with the alum to buffer the pH, virtually 100% of the soluble P was removed from solution (figure 3). Hsu (1976) indicated that the optimum pH range for P removal by Al was 5.5 to 8.0, as stated earlier. Cooke et al. (1986) stated that alum removes phosphate from solutions by two different mechanisms, depending on the pH. Under acidic conditions ($\text{pH} < 6$) they indicated that AlPO_4 forms, whereas at pH 6 to 8, an $\text{Al}(\text{OH})_3$ floc forms, which removes P from solution by sorption of inorganic phosphate and entrapment of organic particles containing P.

Another benefit associated with treating litter with alum would be a decrease in soluble organic carbon (SOC) levels in runoff water from litter-amended fields. Soluble organic C levels were relatively low under acidic conditions, whereas they tended to be high in the controls and in treatments which increased the pH of the litter (Fig. 2). Decreases in SOC concentrations and associated reductions in biological oxygen demand of wastewaters are one of the primary functions of flocculents used in wastewater treatment (Ulmgren, 1975). Decreases in SOC runoff should also improve water quality in lakes and rivers receiving runoff from pastures amended with poultry litter treated with acid forming products by decreasing O_2 demand. Addition of metal flocculents also decreased the solubility of Cu and Zn, which occur in high concentrations in poultry litter (Edwards and Daniel, 1992). Minimum solubility of both of these metals occurred at approximately pH 6 (data not shown).

Sodium aluminate decreased SRP levels to around 600 mg P kg^{-1} litter at the lowest rate (Fig. 3). Increasing rates of sodium aluminate did not decrease water soluble P, which was

probably due to elevated pH at the higher rates. As mentioned earlier, the optimum pH range for P removal using Al is 5.5 to 8.0 (Hsu, 1976). Calcitic limestone as an additive to the sodium aluminate treatment did not decrease soluble P (data not shown).

Additions of ferric iron as $\text{Fe}_2(\text{SO}_4)_3 \cdot 2\text{H}_2\text{O}$ or FeCl_3 greatly decreased P solubility at the lower rates, but increased the solubility at the higher rates (Fig. 4). Increases in SRP at the higher rates may have been due to: (1) dissolution of calcium phosphates, (2) acid hydrolysis of organic P, and/or (3) a decrease in adsorption of P by Fe compounds due to dissolution of Fe oxides and hydroxides at low pH. The pH of these two treatments approached 2 at the higher rates (Table 4). These values are well below the optimum pH range (4.7 to 7.1) for P removal by Fe reported by Hsu (1976). Therefore, removal using these compounds would have been enhanced if the pH of the litter had been maintained at a higher value.

Hsu (1973, 1975) showed that the presence of sulfate extends the optimum range of acidity for P removal to lower pH levels for both Fe(III) and Al, with the effect being far more significant in the case of the Fe(III) system. Hsu (1976) stated that there is no need for acidity adjustment in an Fe(III) system with SO_4 present. He suggested that SO_4 induces coagulation of colloidal mixed salts such as $\text{Fe}(\text{OH})_3$ and FePO_4 by neutralizing the excess positive charges, but is unable to compete with PO_4 for Fe^{3+} . However, his studies were carried out with pure solutions, which did not contain condensed phosphates or organic-P compounds. The results from the present study indicate that pH adjustment is necessary even for Fe(III) systems which contain SO_4 , such as the $\text{Fe}_2(\text{SO}_4)_3 \cdot 2\text{H}_2\text{O}$ treatment, because when extremely acid conditions occur, water soluble P levels increase dramatically. It is well known that at low pH condensed phosphates and organic-P compounds hydrolyze, releasing orthophosphate (APHA, 1992).

Ferrous sulfate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) additions greatly decreased the solubility of P in poultry litter (Fig. 4). Water soluble P concentrations were not significantly different in the FeSO_4

treatment amended with CaCO_3 , indicating that P removal with this compound is less pH dependent than for some of the other Fe compounds. Additions of ferrous chloride greatly decreased P solubility (Fig. 4). Additions of calcitic limestone in conjunction with ferrous chloride resulted in more efficient P removal at lower rates than ferrous chloride alone (data not shown).

Experiments with Litter-Amended Soils

The General Linear Models (GLM) Procedure of SAS indicated that treatment was highly significant ($P > F 0.0001$) in explaining variation in SRP levels in each of the three soils. The least significant difference (LSD) between treatment means at the $\alpha=0.05$ level was 0.18 for all of the soils. For each soil, all 45 treatment means were significantly different from the control.

Calcium Amendments

Addition of calcium carbonate decreased the SRP contents of all three soils at all rates of addition (Figs. 5, 6 and 7). Little additional depression of the SRP was noted at rates of addition greater than 0.25X. At this and higher rates, the SRP contents of the soils were reduced by approximately 50%. Addition of calcium carbonate increased the pH of the soils (Table 5). At the highest (2X) rate of addition the pH values of the Fayetteville, Linker and Mountainburg soils were 7.36, 7.45 and 7.32, respectively, compared with control values of 6.07, 5.95 and 6.42. A parallel series of treatments in which alum was used as a secondary amendment were not used because the preliminary titrations of soil/amendment mixtures indicated that the desired pH (7.5 in the case of Ca amendments) could be maintained without the use of acidifying compounds.

Gypsum was considerably less effective in reducing soil SRP levels than calcium carbonate. Used alone, gypsum decreased SRP levels in the soils by 20 to 30 % when added

at rates greater than or equal to 0.5X (Figs. 8, 9 and 10). Addition of gypsum slightly decreased the pH values of the Fayetteville and Linker soils, while low rates increased the pH and high rates had no effect on the pH of the Mountainburg soil. When calcium carbonate was used as a secondary amendment the SRP contents of the soils were much lower than when gypsum was added alone. However, the extent of these reductions in SRP were similar in magnitude to those observed when calcium carbonate was added alone. The addition of calcium carbonate along with gypsum resulted in significant increases in pH in all three soils. In all soils the addition of gypsum + calcium carbonate was no more effective at reducing SRP levels than the addition of calcium carbonate alone.

Soluble reactive phosphate levels in all three soils were decreased by the addition of $\text{Ca}(\text{OH})_2$ (Figs. 11, 12 and 13). When added at equivalent rates, $\text{Ca}(\text{OH})_2$ was the most effective of the three Ca amendments used in this study at reducing soil levels of SRP. However, additions of $\text{Ca}(\text{OH})_2$ at rates of 0.5X or greater raised the pH of all soils to values approaching 8 (Table 5). When alum was added as a secondary amendment, soil pH values were lower than the $\text{Ca}(\text{OH})_2$ alone treatment but were still greater than or equal to 7 at $\text{Ca}(\text{OH})_2$ addition rates of 0.5X and greater. The addition of alum significantly reduced soil SRP levels relative to the $\text{Ca}(\text{OH})_2$ alone treatments.

Iron and Aluminum Amendments

Addition of alum at the 0.5X and 1X rates decreased SRP levels in all soils to values lower than those achieved with any of the Ca amendments (Figs. 14, 15 and 16). The lowest SRP level in each soil was associated with the 1X rate of alum. An increase in SRP at the 2X rate of alum was observed for all three soils and was most pronounced in the Linker soil. This increase may be due to the fact that 2X rates of alum lowered soil pH values into the 3.7 - 4 range (Table 5). The solubility of many aluminum minerals increases greatly at pH values lower

than 4. In all soils SRP was reduced to about 1 mg P Kg⁻¹ soil at the 0.5X rate and to less than 0.5 mg P Kg⁻¹ soil at the 1X rate. Addition of calcium carbonate as a secondary amendment increased soil pH (Table 5) and decreased SRP levels relative to the alum only treatments, particularly in the Linker soil. The lowest levels of SRP achieved with alum, 0.03, 0.01 and 0.02 mg P Kg⁻¹ soil for the Fayetteville, Linker and Mountainburg soils, respectively, were obtained using the 2X rate of alum plus CaCO₃.

Ferrous sulfate was the most effective amendment for reducing SRP levels in the soils (Figs. 17, 18 and 19). Soil levels of SRP at the 0.1X, 0.25X and 0.5 X rates of FeSO₄ were consistently lower than those observed for alum added at the same rate. Differences in SRP levels obtained with alum and ferrous sulfate at the 1X and 2X rates were not significant. Addition of CaCO₃ did not decrease SRP levels relative to the FeSO₄ only treatments at the 1X and 2X rates, but there was a decrease at lower rates. This was somewhat surprising, as the differences in pH between with and without CaCO₃ treatments was greater at the 1X and 2X addition rates (Table 5).

DISCUSSION

Recently, there has been increasing emphasis on decreasing runoff of bioavailable P, rather than particulate P, since it is more available for use by algae that are responsible for eutrophication (Sharpley et al., 1992; Sonzogni et al., 1982). Water soluble P is by far the most available form of P to algae and bacteria. Drastic reductions in soluble P levels running off agricultural lands receiving poultry litter should help improve the water quality of adjacent lakes and rivers.

It should be noted that alum and lime are relatively inexpensive and readily available. Calcium compounds, such as CaO or Ca(OH)₂, cost approximately \$55 per metric ton. Results from this study indicate that 50 kg of Ca(OH)₂ per metric ton of litter may be adequate to

immobilize most of the litter P. Since there are 20 metric tons of litter produced per house per growout (each house contains 15,000 to 20,000 birds), one ton of $\text{Ca}(\text{OH})_2$ (slaked lime) is needed per house per growout. Assuming five growouts per year, the annual cost of slaked lime for one house would be \$275. Gross incomes per house normally exceed \$25,000 per year. Therefore, the cost of slaked lime needed for P immobilization would be around 1% of the gross income, which should be economically feasible.

Our results also suggest that quantities of amendments required to immobilize P in excessively fertilized soils are low enough to be practical on a field scale. For example, the 1X rate of alum used in this study is equivalent to roughly 27 Mg ha^{-1} (12 t/6" acre-furrow-slice). However, it should not be necessary to treat the soil to a depth of 15 cm, because the runoff interacts with only the top few cm of the soil. If only the top 2.5 cm of the soil is to be treated, the 1X rate of alum is equivalent to roughly 4.5 Mg ha^{-1} (2 t/1" acre-furrow-slice). Similarly for the 1X rate of slaked lime, the required amount to treat a soil to a depth of 15 cm would be 9.7 Mg ha^{-1} (4.3 t/6" acre-furrow-slice) or 1.6 Mg ha^{-1} (0.7 t/1" acre-furrow-slice) to treat only the upper 2.5 cm of the soil. If slaked lime cost \$55 per metric ton, the cost of treating soil to a depth of 2.5 cm would be $\$55 \text{ Mg}^{-1} \times 1.6 \text{ Mg ha}^{-1} = \88 ha^{-1} (\$36 per acre). However, before valid economic analyses can be performed, on-farm experiments need to be conducted to determine if the soil and litter treatment levels examined in this study are adequate.

Although alum and ferrous sulfate are more expensive than $\text{Ca}(\text{OH})_2$, the benefits of using these compounds should far exceed that of the Ca compounds. Lowering the pH of the litter will decrease NH_3 volatilization. High levels of NH_3 in poultry houses increase the incidence of ascites in poultry (water belly) and other respiratory related maladies, such as New Castle Disease (Anderson et al., 1964) and airsacculitis (Ehrlich, 1963). Since the amount of NH_3 volatilization is a function of the ratio of NH_3/NH_4 in the litter, which is controlled by pH,

reducing the pH of the litter to around 6.0 will cause N losses via this mechanism to cease. This should result in increased weight gains in the birds, as well as decreased incidence of respiratory problems.

Currently, the number one complaint received by federal and state regulatory agencies concerning poultry production concerns odors arising from land application of litter. Ammonia is one of the primary agents responsible for the odor. Wolf et al. (1988) estimated that 37% of the N is lost from litter during the first 11 days of application. If these losses were combined with those that occur in the houses, the total loss by volatilization would probably exceed 50% of the total N. Therefore, volatilization losses not only result in air pollution, but in losses of valuable fertilizer N. Decreasing NH_3 volatilization will result in higher N/P ratios in poultry litter. Currently, the N/P ratio in litter is often as low as 2, whereas the the N/P ratio in the feed is near 8. The difference is mainly due to N loss via volatilization. Since application rates of litter are based on the N requirement of the crop, less litter could be applied per acre if the N content were higher.

Alum and ferrous sulfate were clearly more effective than any of the Ca amendments in immobilizing P in the excessively fertilized soils used in this study. Slaked lime was able to reduce SRP levels to quite low levels, but only at high rates and at pH values too high to permit normal crop growth. Alum and ferrous sulfate, on the other hand, reduced SRP to very low levels at relatively low rates of application and at soil pH values appropriate for crops. Which of these two equally effective amendments is "best" is not yet clear. Which costs less will certainly be a factor, but how these amendments perform in field trials will certainly be important. It should also be pointed out that the long-term effectiveness of these two amendments may differ dramatically due to differences in the stability of the P compounds that form following treatment. The mineral which we believe is forming following alum treatment

is variscite, AlPO_4 . This mineral is very insoluble in the pH range 5 - 7, but its solubility increases rapidly as the pH drops from 5 to 3.5. Therefore, P immobilized by treatment with alum will remain immobilized as long as the pH is not allowed to drop much below 5. The mineral that we believe is forming following ferrous sulfate treatment is strengite, FePO_4 . The solubility of this mineral is affected by pH in much the same way as the solubility of variscite. In addition, however, strengite becomes unstable under reducing conditions. Reducing conditions typically develop in a soil when it becomes waterlogged. If the soil stays waterlogged for several days, the ensuing reductive dissolution of strengite could result in the release of P to solution. Therefore, P immobilized by treatment with ferrous sulfate will remain immobilized as long as oxidizing conditions and pH values above 3 are maintained in the soil.

CONCLUSIONS

The results of this study showed that a reduction in soluble P levels in both poultry litter and high STP soils can be achieved using Al, Ca, and/or Fe amendments. Although P precipitation using chemical amendments has been used for over 30 years for wastewater treatment, there have been no reports in the literature of using this technology on animal manures or on excessively manured soils. More research is needed in this area to determine: (1) if these results can be verified by field studies, (2) if the P minerals formed by this process are stable in various geochemical environments, (3) if this is an economically feasible practice, and (4) if there are any other beneficial and/or detrimental side effects from this practice.

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Table 1. Rates of chemical amendments applied to poultry litter.

Treatment	rate of primary amendment	secondary
	-----g/kg litter -----	
1. CaO	30, 60, 90, 120, 150	0
2. CaO + CaF ₂	30, 60, 90, 120, 150	5
3. Ca(OH) ₂	40, 80, 120, 160, 200	0
4. Ca(OH) ₂ + CaF ₂	40, 80, 120, 160, 200	5
5. CaCO ₃	50, 100, 150, 200, 250	0
6. CaCO ₃ + CaF ₂	50, 100, 150, 200, 250	5
7. CaMg(CO ₃) ₂	100, 200, 300, 400, 500	0
8. CaMg(CO ₃) ₂ + CaF ₂	100, 200, 300, 400, 500	5
9. CaSO ₄ ·2H ₂ O	100, 200, 300, 400, 500	0
10. CaSO ₄ ·2H ₂ O + CaF ₂	100, 200, 300, 400, 500	5
11. Al ₂ (SO ₄) ₃ ·18H ₂ O	100, 200, 300, 400, 500	0
12. Al ₂ (SO ₄) ₃ ·18H ₂ O + CaCO ₃	100, 200, 300, 400, 500	100
13. Na ₂ Al ₂ O ₄	25, 50, 75, 100, 125	0
14. Na ₂ Al ₂ O ₄ + CaCO ₃	25, 50, 75, 100, 125	100
15. Fe ₂ (SO ₄) ₃ ·2H ₂ O	60, 120, 180, 240, 300	0
16. FeCl ₃	50, 100, 150, 200, 250	0
17. FeSO ₄ ·7H ₂ O	90, 180, 270, 360, 450	0
18. FeSO ₄ ·7H ₂ O + CaCO ₃	90, 180, 270, 360, 450	100
19. FeCl ₂ ·4H ₂ O	60, 120, 180, 240, 300	0
20. FeCl ₂ ·4H ₂ O + CaCO ₃	60, 120, 180, 240, 300	100

Table 2. Classification and properties of soils used in the studies.

Soil Series	Classification	pH	OM*	Total P	STP#
			%	-----mg kg ⁻¹ -----	
Fayetteville fine sandy loam	Fine-loamy, mixed, thermic Rhodultic Paleudalf	6.4	3.8	944	157
Linker loam	Fine-loamy, siliceous, thermic Typic Hapludult	6.1	2.4	1063	283
Mountainburg stony fine sandy loam	Loamy-skeletal, siliceous, thermic Lithic Hapludult	6.3	4.3	1291	237

*OM = organic matter

#STP = soil test phosphorus

Table 3. Rates of primary (1°) and secondary (2°) chemical amendments applied to the Fayetteville, Linker and Mountainburg soils.

Treatment [#]	Fayetteville		Linker		Mountainburg	
	1°	2°	1°	2°	1°	2°
	-----gkg ⁻¹ -----					
1. Control	0	0	0	0	0	0
2. 0.1X Al ₂ (SO ₄) ₃ •18H ₂ O	1.02	0	1.14	0	1.38	0
3. 0.1X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	1.02	0.12	1.14	0.10	1.38	0.12
4. 0.25X Al ₂ (SO ₄) ₃ •18H ₂ O	2.54	0	2.85	0	3.48	0
5. 0.25X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	2.54	0.42	2.85	0.54	3.48	0.30
6. 0.5X Al ₂ (SO ₄) ₃ •18H ₂ O	5.08	0	5.70	0	6.94	0
7. 0.5X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	5.08	1.00	5.70	1.36	6.94	0.98
8. 1X Al ₂ (SO ₄) ₃ •18H ₂ O	10.14	0	11.40	0	13.88	0
9. 1X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	10.14	2.74	11.40	3.42	13.88	2.78
10. 2X Al ₂ (SO ₄) ₃ •18H ₂ O	20.28	0	22.80	0	27.78	0
11. 2X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	20.28	7.10	22.80	7.32	27.78	7.68
12. 0.1X Ca(OH) ₂	0.38	0	0.42	0	0.52	0
13. 0.1X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	0.38	0.25	0.42	0.38	0.52	0.34
14. 0.25X Ca(OH) ₂	0.94	0	1.05	0	1.30	0
15. 0.25X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	0.94	0.28	1.05	1.38	1.30	0.84
16. 0.5X Ca(OH) ₂	1.88	0	2.12	0	2.60	0
17. 0.5X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	1.88	1.16	2.12	3.62	2.60	2.56
18. 1X Ca(OH) ₂	3.76	0	4.24	0	5.14	0
19. 1X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	3.76	3.84	4.24	6.44	5.14	6.72
20. 2X Ca(OH) ₂	7.52	0	8.48	0	10.30	0
21. 2X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	7.52	11.10	8.48	15.78	10.30	18.22
22. 0.1X FeSO ₄ •7H ₂ O	0.84	0	0.96	0	1.16	0
23. 0.1X FeSO ₄ •7H ₂ O + CaCO ₃	0.84	0.68	0.96	0.22	1.16	0.30
24. 0.25X FeSO ₄ •7H ₂ O	2.12	0	2.38	0	2.90	0
25. 0.25X FeSO ₄ •7H ₂ O + CaCO ₃	2.12	0.88	2.38	0.52	2.90	0.44
26. 0.5X FeSO ₄ •7H ₂ O	4.24	0	4.76	0	5.80	0
27. 0.5X FeSO ₄ •7H ₂ O + CaCO ₃	4.24	1.26	4.76	0.90	5.80	0.88
28. 1X FeSO ₄ •7H ₂ O	8.46	0	9.54	0	11.58	0
29. 1X FeSO ₄ •7H ₂ O + CaCO ₃	8.46	2.32	9.54	2.38	11.58	1.88
30. 2X FeSO ₄ •7H ₂ O	16.92	0	19.08	0	23.18	0
31. 2X FeSO ₄ •7H ₂ O + CaCO ₃	16.92	5.06	19.08	3.82	23.18	3.74
32. 0.1X CaCO ₃	0.50	0	0.58	0	0.70	0
33. 0.25X CaCO ₃	1.28	0	1.44	0	1.74	0
34. 0.5X CaCO ₃	2.54	0	2.86	0	3.48	0
35. 1X CaCO ₃	5.08	0	5.72	0	6.94	0
36. 2X CaCO ₃	10.16	0	11.44	0	13.90	0
37. 0.1X CaSO ₄ •2H ₂ O	0.88	0	0.98	0	1.20	0
38. 0.1X CaSO ₄ •2H ₂ O + CaCO ₃	0.88	0.52	0.98	5.72	1.20	6.94
39. 0.25X CaSO ₄ •2H ₂ O	2.18	0	2.46	0	3.00	0

Table 3. (Continued)

Treatment [#]	Fayetteville		Linker		Mountainburg	
	1°	2°	1°	2°	1°	2°
	-----gkg ⁻¹ -----					
40. 0.25X CaSO ₄ •2H ₂ O + CaCO ₃	2.18	0.58	2.46	5.72	3.00	6.94
41. 0.5X CaSO ₄ •2H ₂ O	4.38	0	4.92	0	6.00	0
42. 0.5X CaSO ₄ •2H ₂ O + CaCO ₃	4.38	0.76	4.92	5.72	6.00	6.94
43. 1X CaSO ₄ •2H ₂ O	8.74	0	9.84	0	12.00	0
44. 1X CaSO ₄ •2H ₂ O + CaCO ₃	8.74	0.88	9.84	5.72	12.00	6.94
45. 2X CaSO ₄ •2H ₂ O	17.48	0	19.70	0	24.00	0
46. 2X CaSO ₄ •2H ₂ O + CaCO ₃	17.48	0.92	19.70	5.72	24.00	6.94

[#]Primary amendments listed first followed by secondary amendments after the "+". See text for explanation of how rates were calculated.

Table 4. Effect of Al, Ca and Fe compounds on pH of poultry litter.

Amendment Level (see Table 1 for actual rates)

Treatment	1x	2x	3x	4x	5x
	----- pH units -----				
control	7.30				
CaO	9.82	11.76	12.29	12.41	12.44
CaO + CaF ₂	9.71	11.38	12.24	12.40	12.45
Ca(OH) ₂	9.12	11.06	12.23	12.32	12.33
Ca(OH) ₂ + CaF ₂	9.51	11.43	12.21	12.30	12.34
CaCO ₃	7.87	8.10	7.87	7.37	7.27
CaCO ₃ + CaF ₂	6.88	7.64	7.75	7.56	7.65
CaMg(CO ₃) ₂	7.69	7.35	7.84	8.24	7.98
CaMg(CO ₃) ₂ + CaF ₂	8.21	8.05	7.51	7.65	8.18
CaSO ₄ .2H ₂ O	7.41	7.57	7.36	7.68	7.32
CaSO ₄ .2H ₂ O + CaF ₂	7.36	7.14	7.43	7.61	7.32
Al ₂ (SO ₄) ₃ .18H ₂ O	5.73	4.26	3.81	3.59	3.50
Al ₂ (SO ₄) ₃ .18H ₂ O + CaCO ₃	7.56	6.75	6.46	5.37	4.18
Na ₂ Al ₂ O ₄	7.78	8.97	9.88	10.55	11.01
Na ₂ Al ₂ O ₄ + CaCO ₃	7.97	9.31	10.31	10.56	11.18
Fe ₂ (SO ₄) ₃ .2H ₂ O	7.21	4.86	2.77	2.45	2.33
FeCl ₃	5.33	3.52	2.21	1.97	1.88
FeSO ₄ .7H ₂ O	7.13	5.67	4.39	4.28	5.15
FeSO ₄ .7H ₂ O + CaCO ₃	6.73	6.17	6.03	6.14	5.21
FeCl ₂ .2H ₂ O	7.19	4.85	4.42	4.09	3.95
FeCl ₂ .2H ₂ O + CaCO ₃	7.32	6.23	6.05	5.83	5.34

(LSD_{0.05} = 0.30)

Table 5. Effect of Al, Fe, and Ca compounds on pH of aqueous extracts of Fayetteville, Linker and Mountainburg soils.

Treatment	Fayetteville	Linker	Mountainburg
	-----pH units-----		
1. Control	6.07	5.95	6.42
2. 0.1X Al ₂ (SO ₄) ₃ •18H ₂ O	5.80	5.45	6.25
3. 0.1X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	5.84	5.54	6.39
4. 0.25X Al ₂ (SO ₄) ₃ •18H ₂ O	5.38	5.07	6.23
5. 0.25X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	5.71	5.39	6.21
6. 0.5X Al ₂ (SO ₄) ₃ •18H ₂ O	4.81	4.61	5.87
7. 0.5X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	5.38	5.31	6.04
8. 1X Al ₂ (SO ₄) ₃ •18H ₂ O	4.35	4.16	5.07
9. 1X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	5.31	5.25	5.73
10. 2X Al ₂ (SO ₄) ₃ •18H ₂ O	3.80	3.71	4.00
11. 2X Al ₂ (SO ₄) ₃ •18H ₂ O + CaCO ₃	5.74	5.57	5.42
12. 0.1X Ca(OH) ₂	6.63	6.45	6.52
13. 0.1X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	6.48	6.19	6.53
14. 0.25X Ca(OH) ₂	6.79	7.00	6.93
15. 0.25X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	6.83	6.71	6.81
16. 0.5X Ca(OH) ₂	7.46	7.58	7.19
17. 0.5X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	7.31	7.00	7.13
18. 1X Ca(OH) ₂	7.68	7.86	7.49
19. 1X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	7.46	7.40	7.38
20. 2X Ca(OH) ₂	7.82	8.01	7.92
21. 2X Ca(OH) ₂ + Al ₂ (SO ₄) ₃ •18H ₂ O	7.61	7.65	7.55
22. 0.1X FeSO ₄ •7H ₂ O	5.97	5.80	6.82
23. 0.1X FeSO ₄ •7H ₂ O + CaCO ₃	6.44	5.88	6.77
24. 0.25X FeSO ₄ •7H ₂ O	5.61	5.31	6.49
25. 0.25X FeSO ₄ •7H ₂ O + CaCO ₃	6.20	5.66	6.57
26. 0.5X FeSO ₄ •7H ₂ O	5.15	4.86	6.21
27. 0.5X FeSO ₄ •7H ₂ O + CaCO ₃	5.91	5.21	6.42
28. 1X FeSO ₄ •7H ₂ O	4.56	4.40	5.64
29. 1X FeSO ₄ •7H ₂ O + CaCO ₃	5.45	5.24	6.18
30. 2X FeSO ₄ •7H ₂ O	3.72	3.41	4.72
31. 2X FeSO ₄ •7H ₂ O + CaCO ₃	5.13	4.50	5.45
32. 0.1X CaCO ₃	6.34	6.50	6.82
33. 0.25X CaCO ₃	6.84	7.11	7.12
34. 0.5X CaCO ₃	7.14	7.35	7.26
35. 1X CaCO ₃	7.24	7.47	7.30
36. 2X CaCO ₃	7.36	7.45	7.32
37. 0.1X CaSO ₄ •2H ₂ O	5.99	5.80	6.57
38. 0.1X CaSO ₄ •2H ₂ O + CaCO ₃	6.32	7.42	7.29
39. 0.25X CaSO ₄ •2H ₂ O	5.87	5.78	6.52

Table 5. (Continued)

Treatment	Fayetteville	Linker	Mountainburg
	-----pH units-----		
40. 0.25X CaSO ₄ •2H ₂ O + CaCO ₃	6.26	7.38	7.24
41. 0.5X CaSO ₄ •2H ₂ O	5.79	5.71	6.39
42. 0.5X CaSO ₄ •2H ₂ O + CaCO ₃	6.27	7.28	7.19
43. 1X CaSO ₄ •2H ₂ O	5.73	5.66	6.39
44. 1X CaSO ₄ •2H ₂ O + CaCO ₃	6.33	7.18	7.19
45. 2X CaSO ₄ •2H ₂ O	5.79	5.64	6.38
46. 2X CaSO ₄ •2H ₂ O + CaCO ₃	6.37	7.23	7.21
LSD (.05)	0.27	0.27	0.35

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Figure 1 - Effect of calcium amendments to poultry litter on water soluble reactive P.

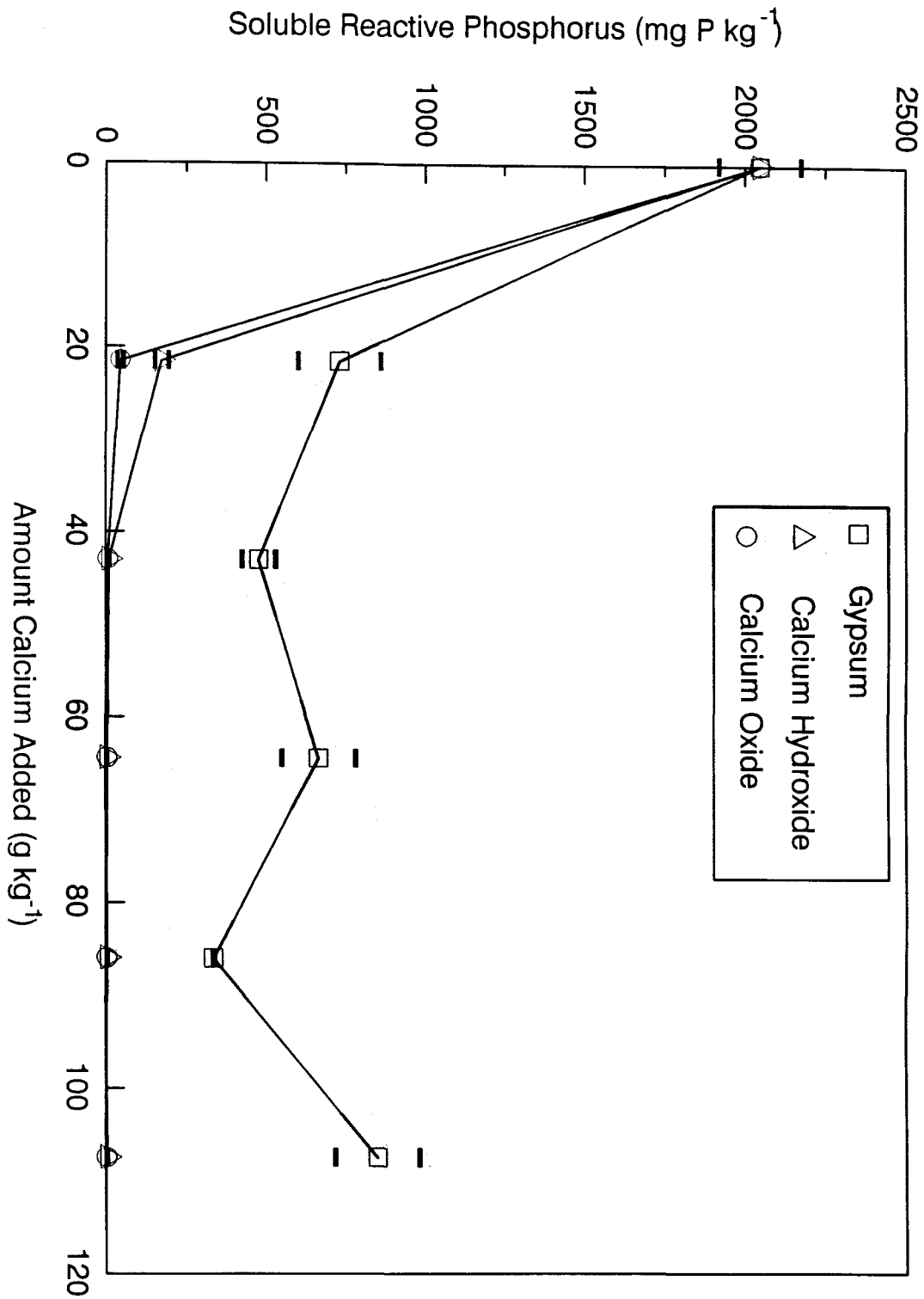


Figure 2 - Effect of poultry litter pH on soluble organic C.

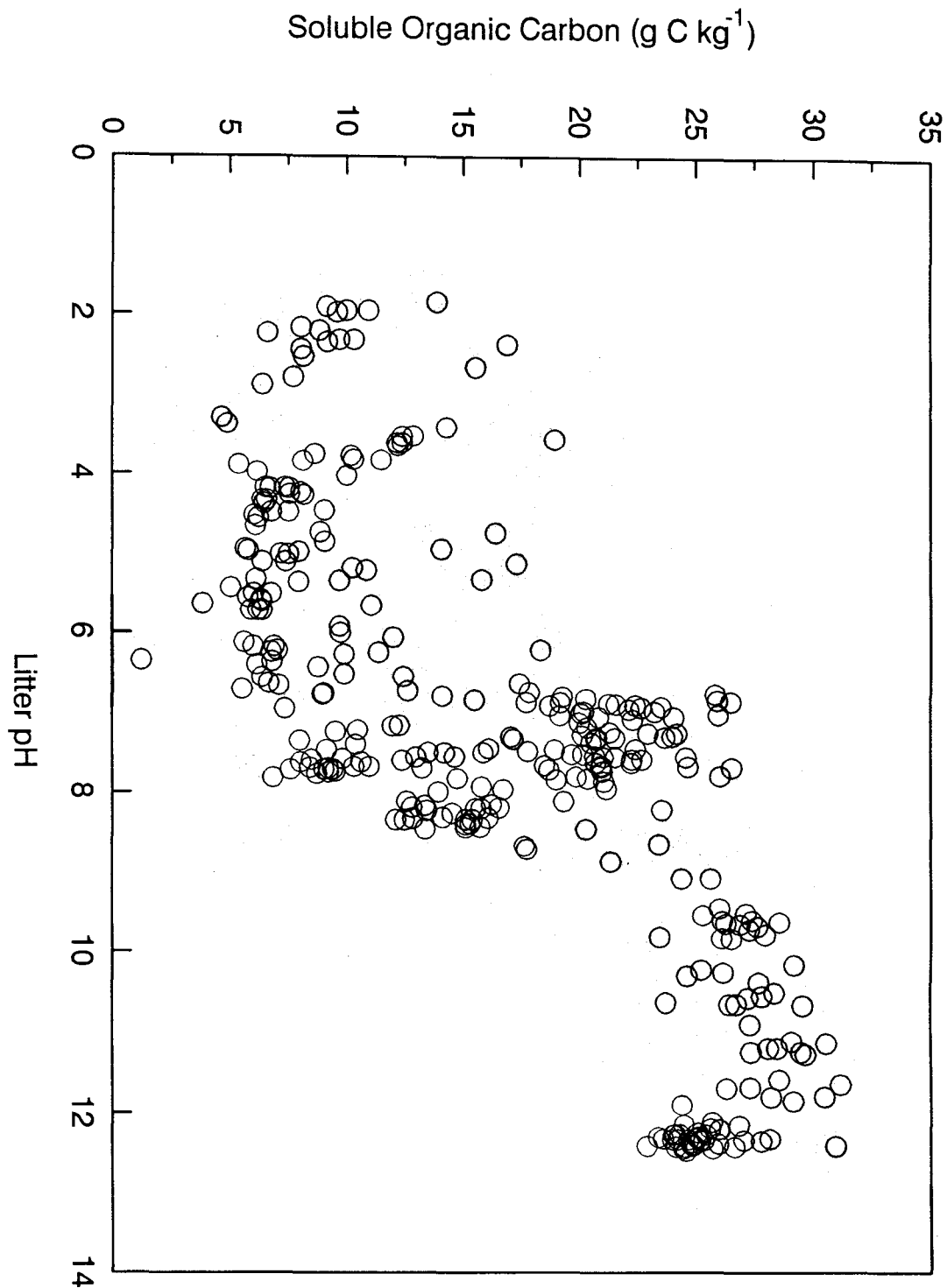


Figure 3 - Effect of aluminum amendments to poultry litter on water soluble reactive P.

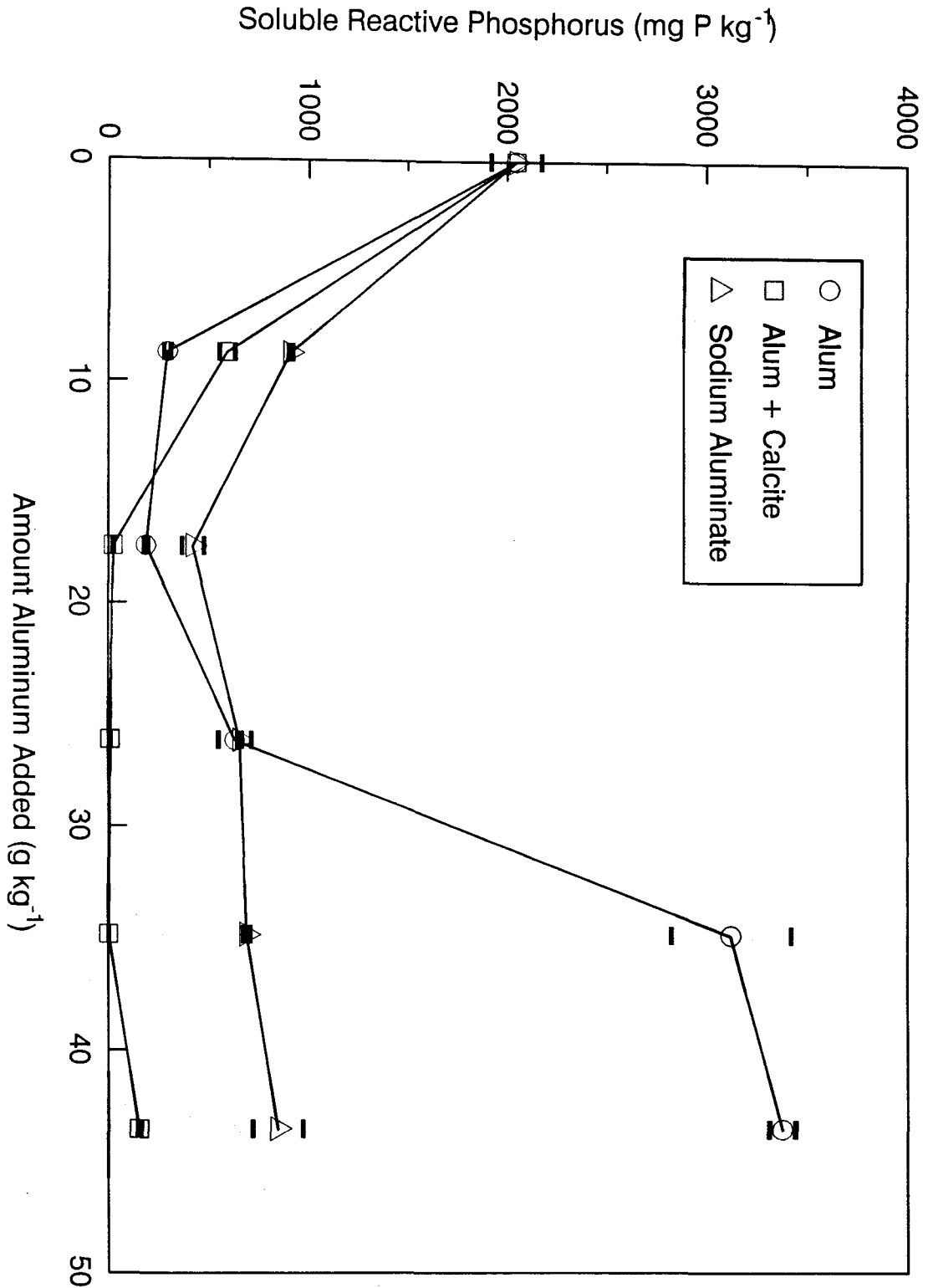


Figure 4 - Effect of iron amendments to poultry litter on water soluble reactive P.

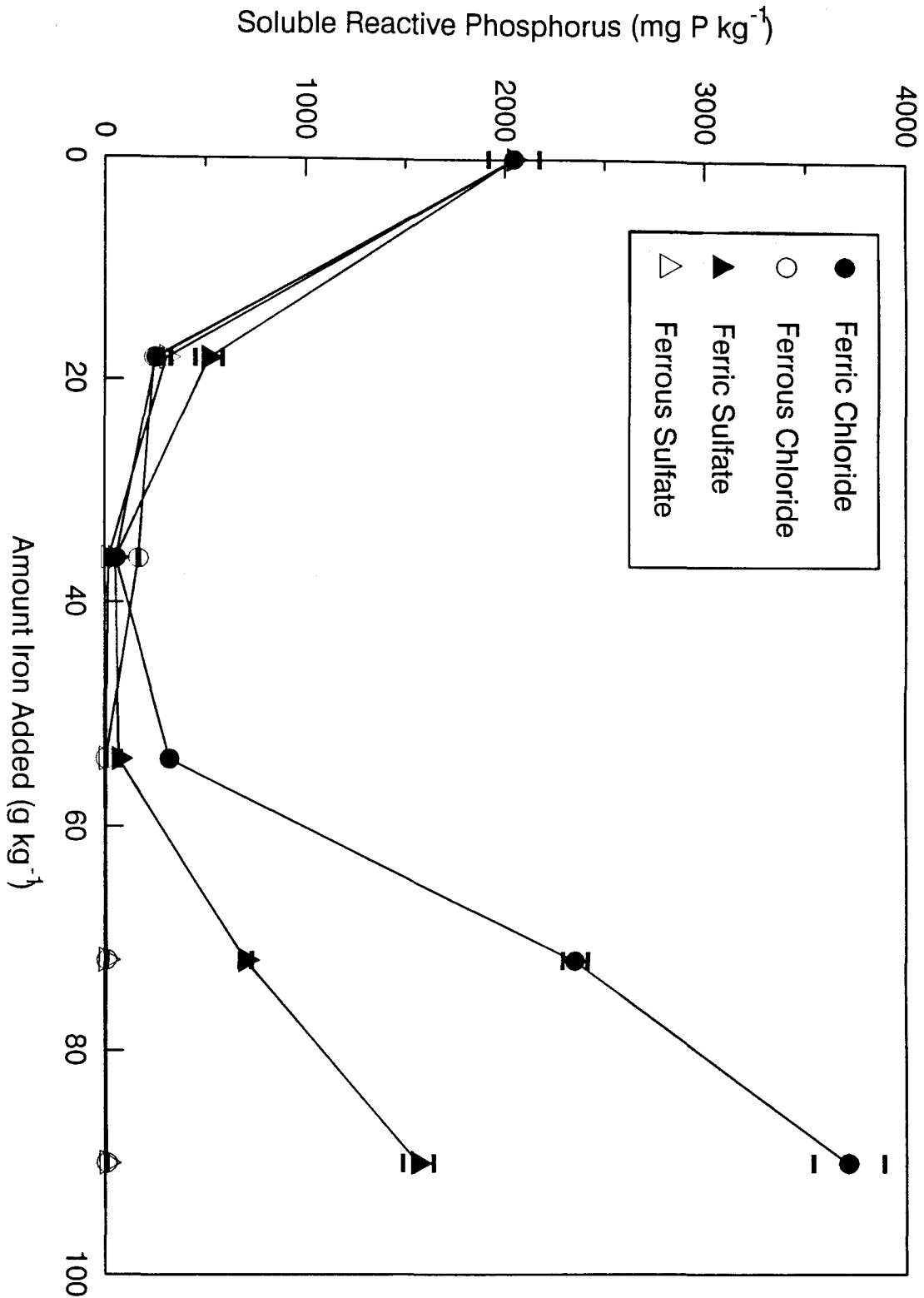


Figure 5 - Effect of calcium carbonate additions to Fayetteville soil on soluble reactive P.

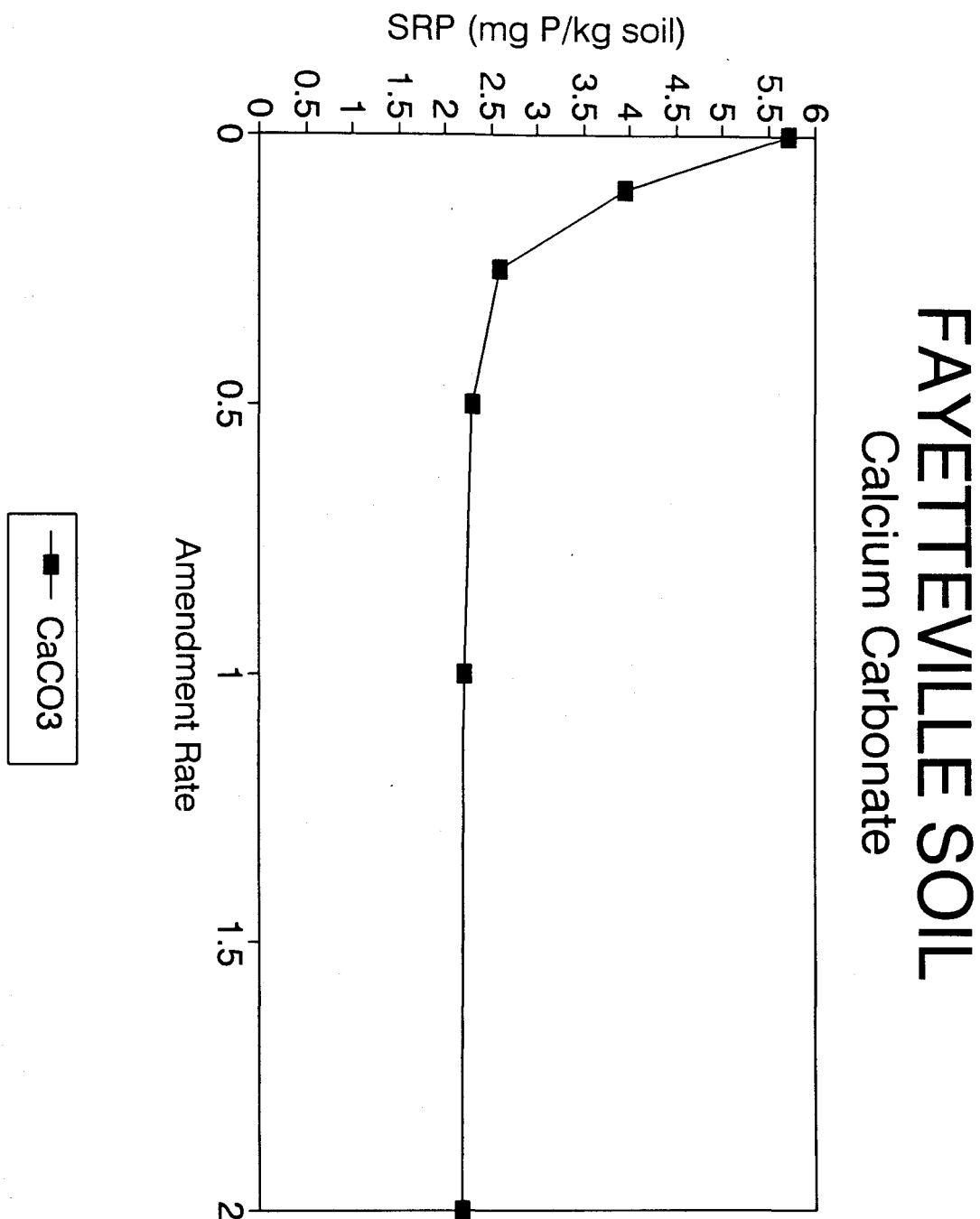


Figure 6 - Effect of calcium carbonate additions to Linker soil on soluble reactive P.

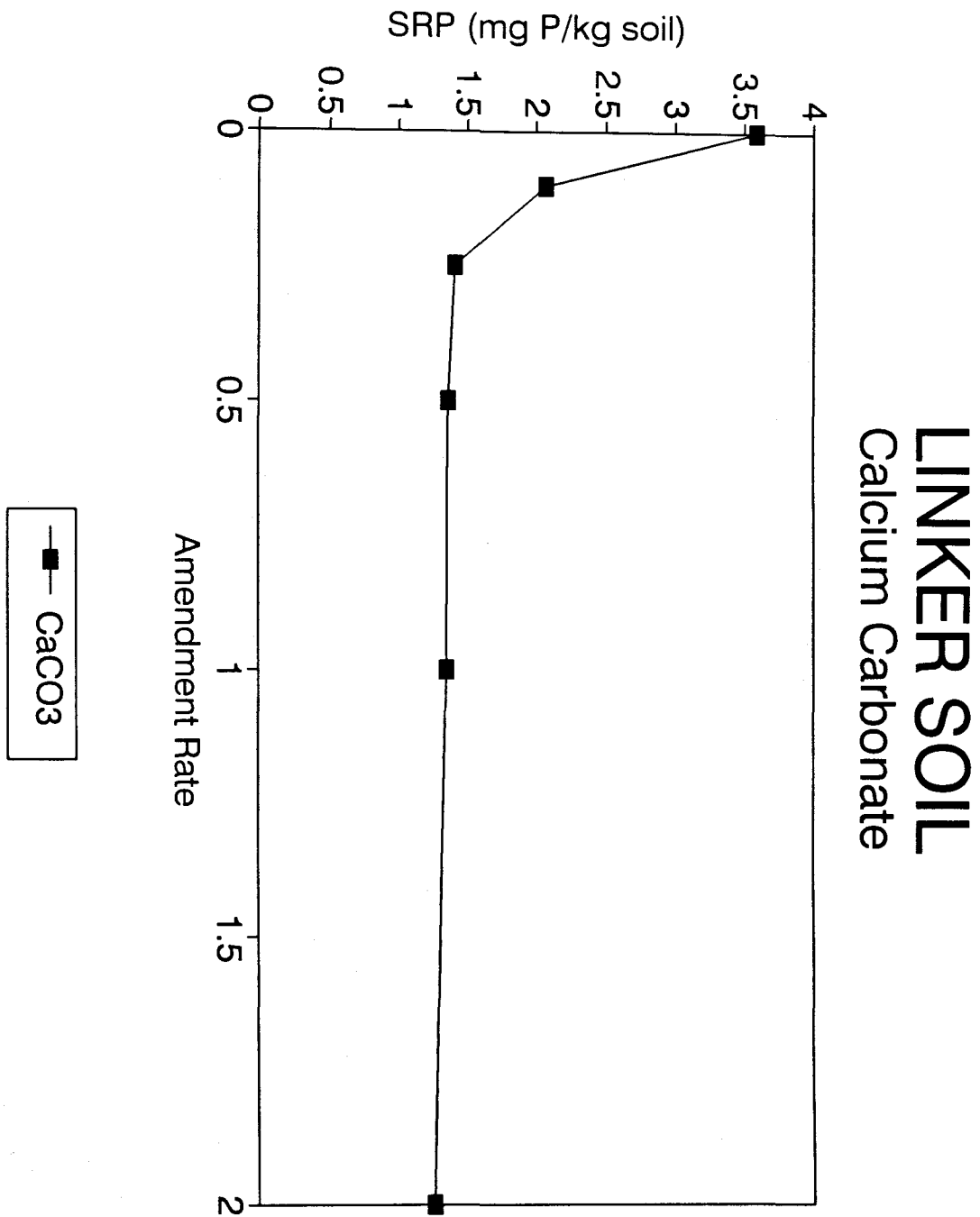


Figure 7 - Effect of calcium carbonate additions to Mountainburg soil on soluble reactive P.

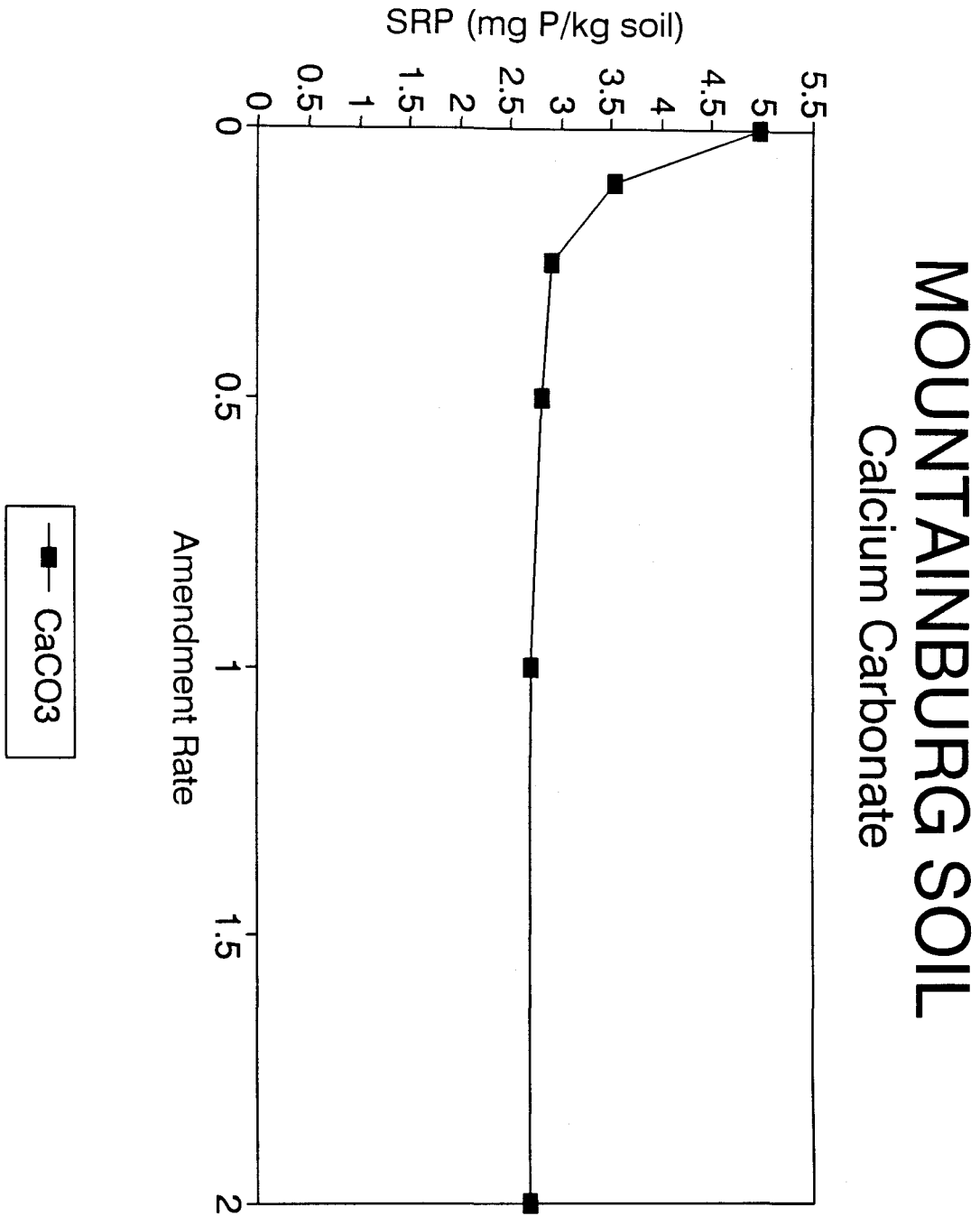


Figure 8 - Effect of gypsum additions to Fayetteville soil on soluble reactive P.

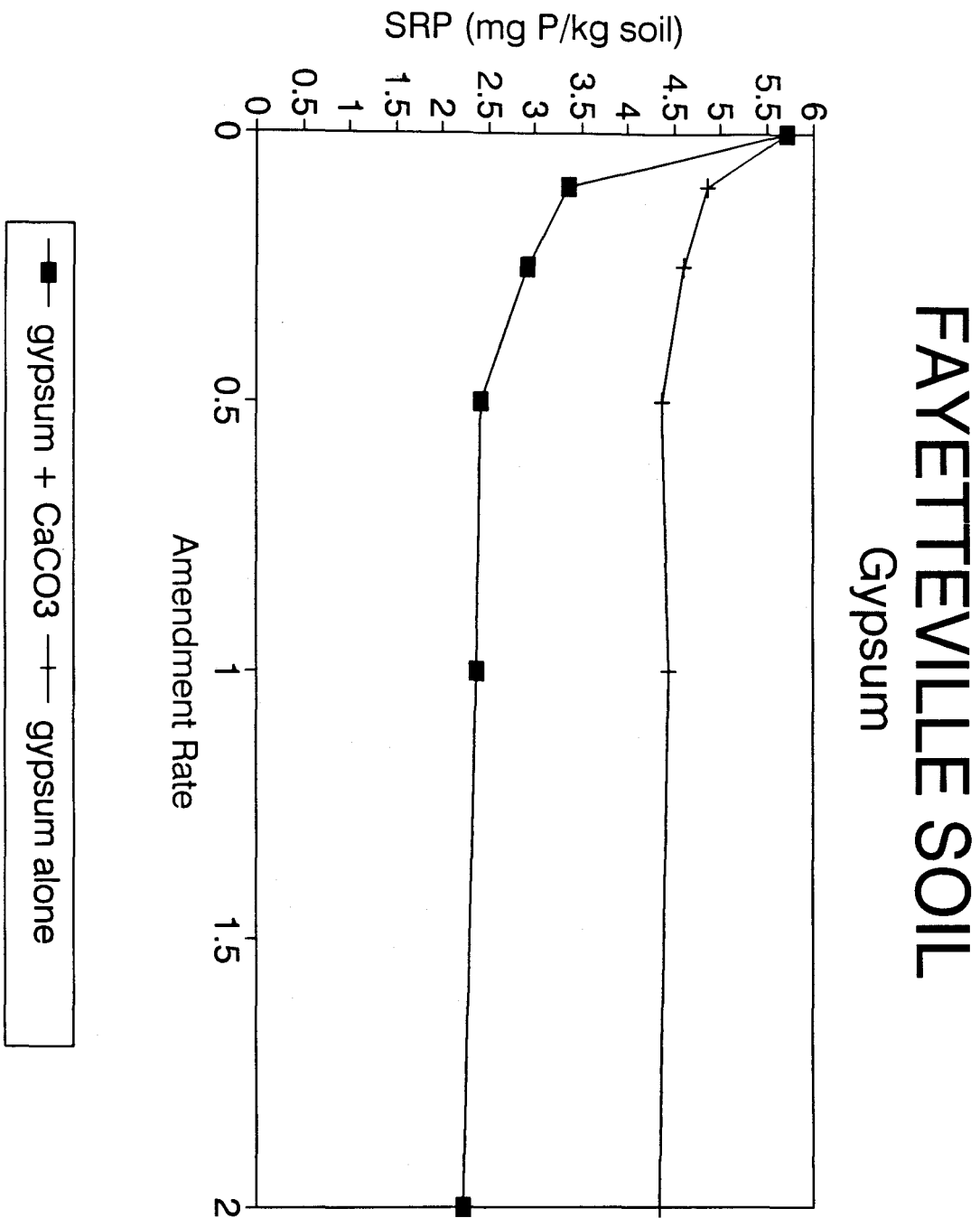


Figure 9 - Effect of gypsum additions to Linker soil on soluble reactive P.

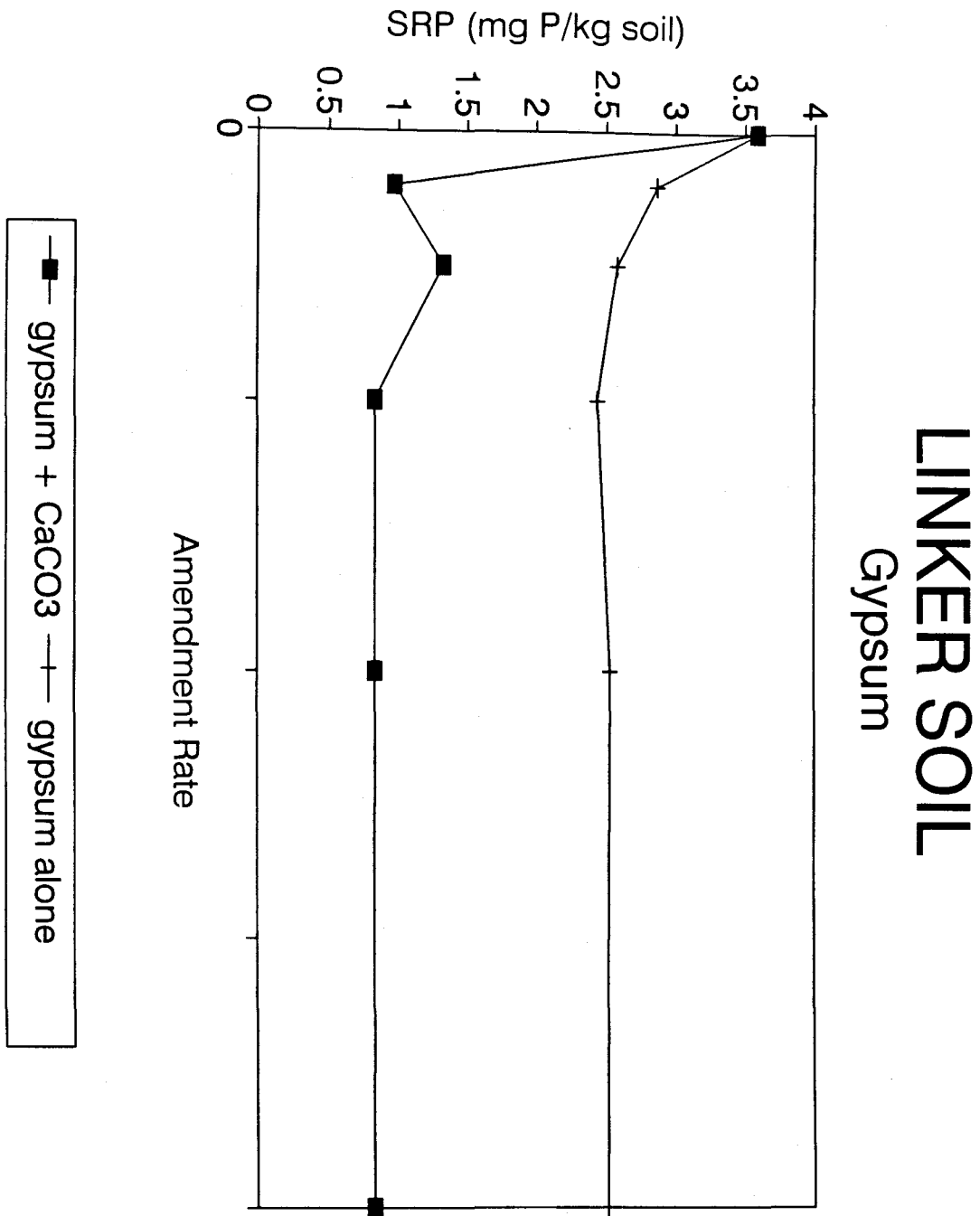


Figure 10 - Effect of gypsum additions to Mountainburg soil on soluble reactive P.

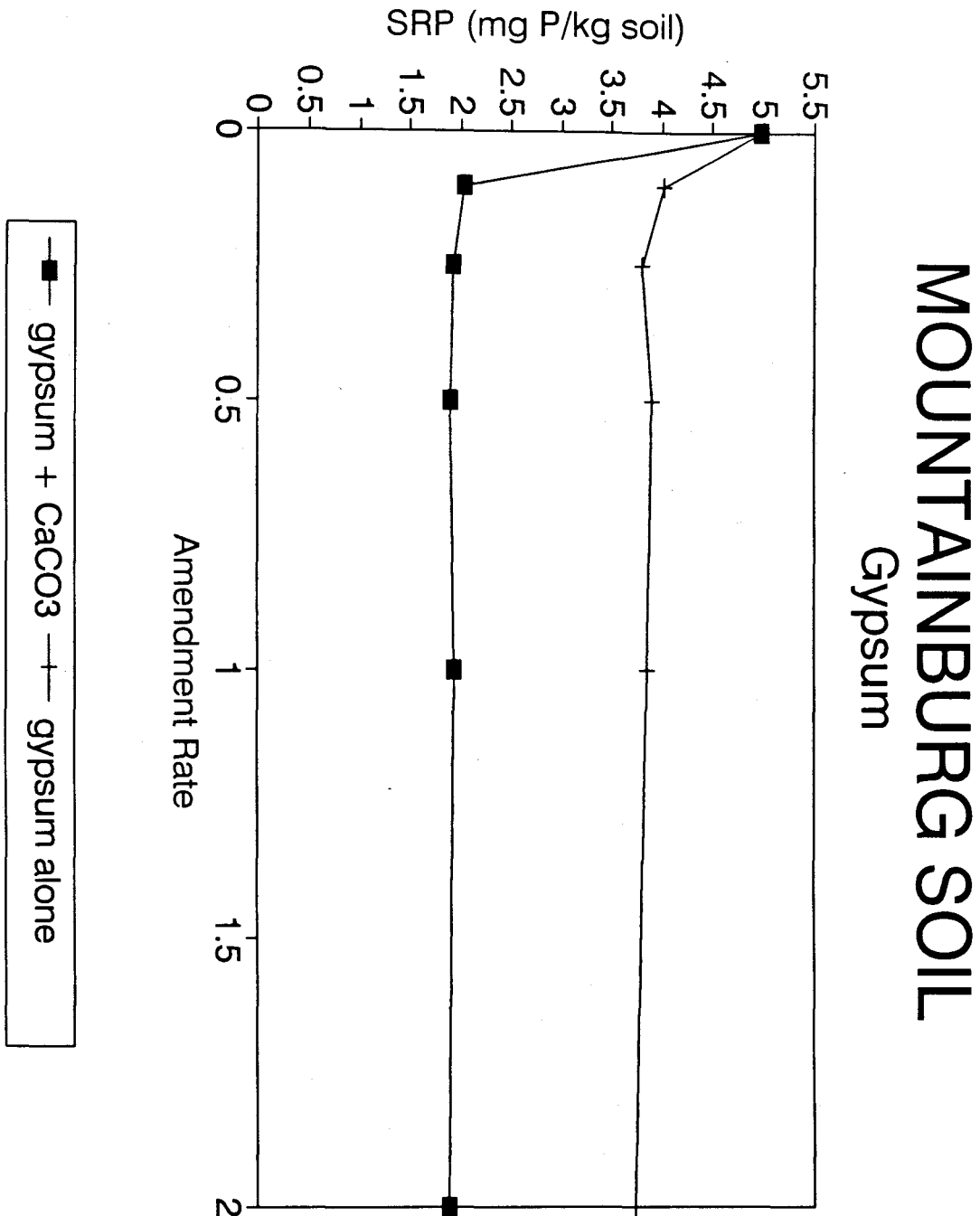


Figure 11 - Effect of slaked lime additions to Fayetteville soil on soluble reactive P.

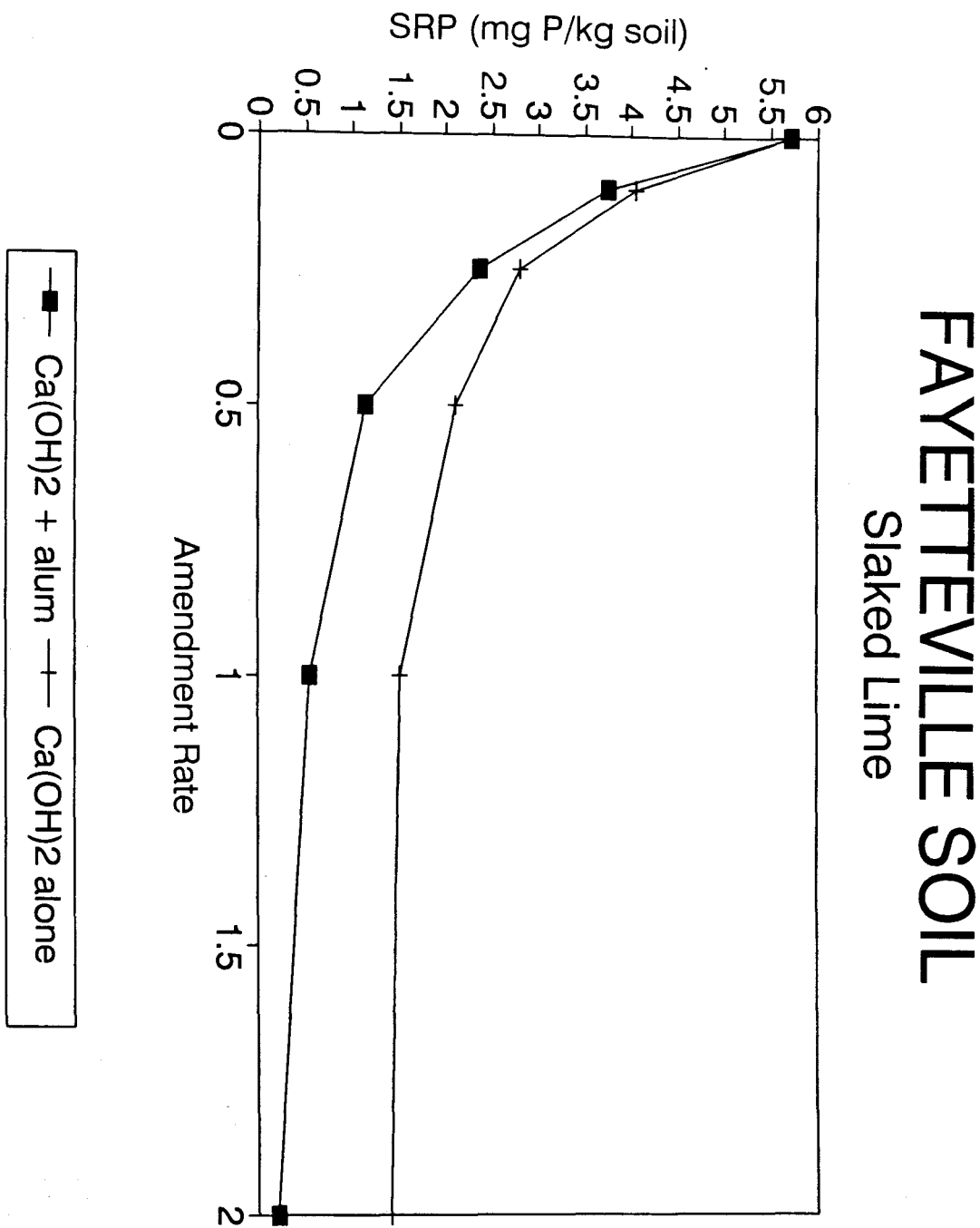


Figure 12 - Effect of slaked lime additions to Linker soil on soluble reactive P.

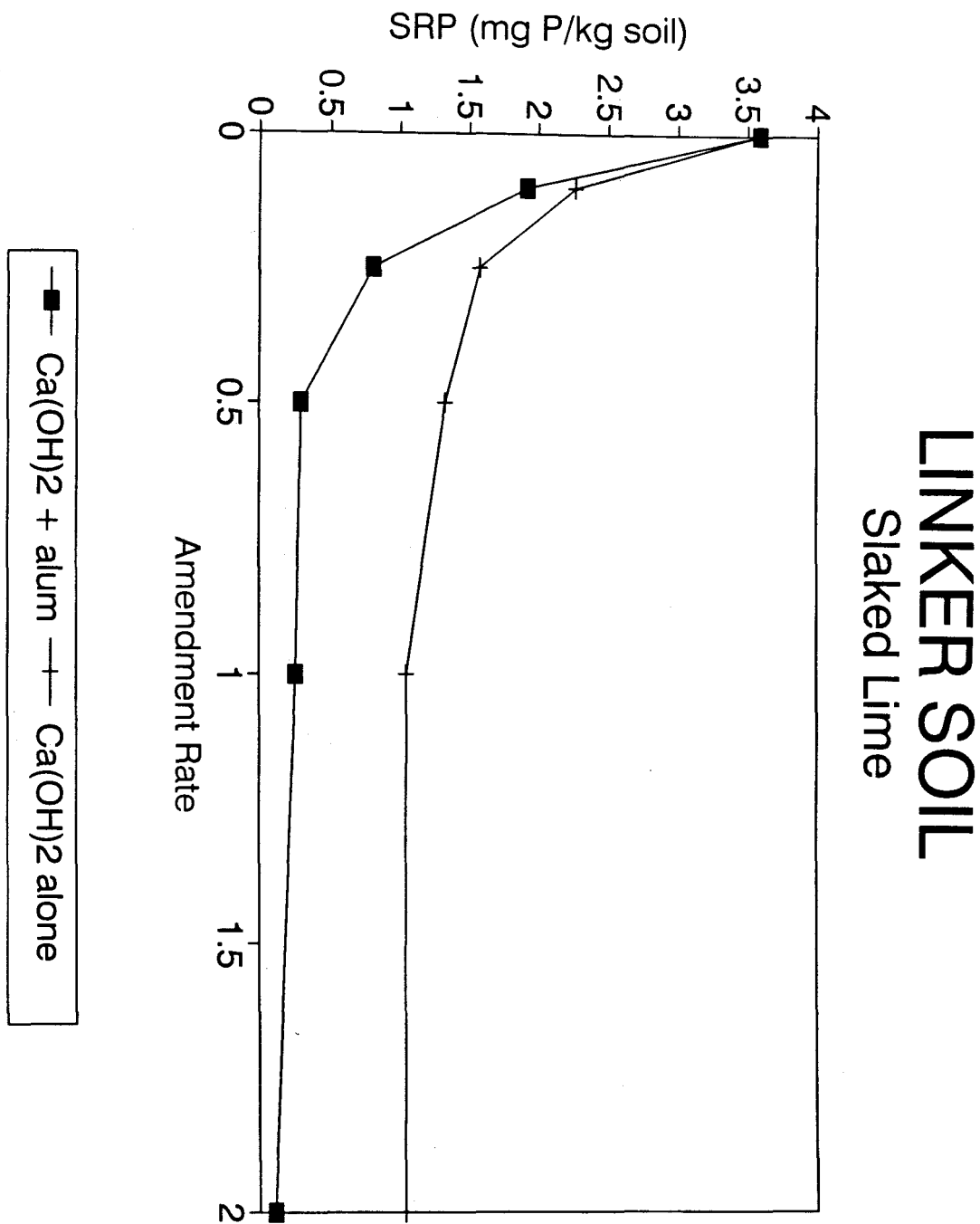


Figure 13 - Effect of slaked lime additions to Mountainburg soil on soluble reactive P.

MOUNTAINBURG SOIL

Slaked Lime

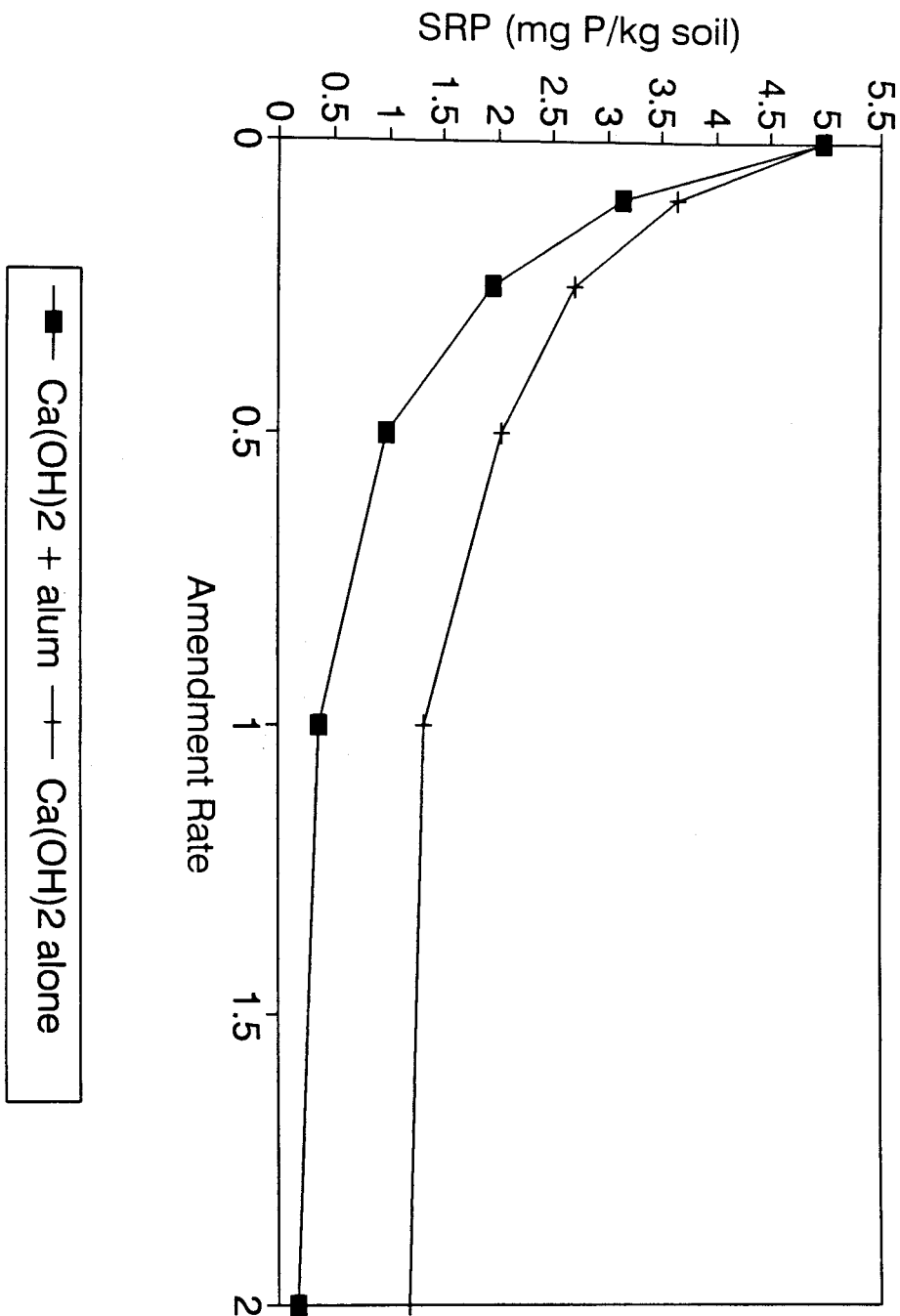


Figure 14 - Effect of alum additions to Fayetteville soil on soluble reactive P.

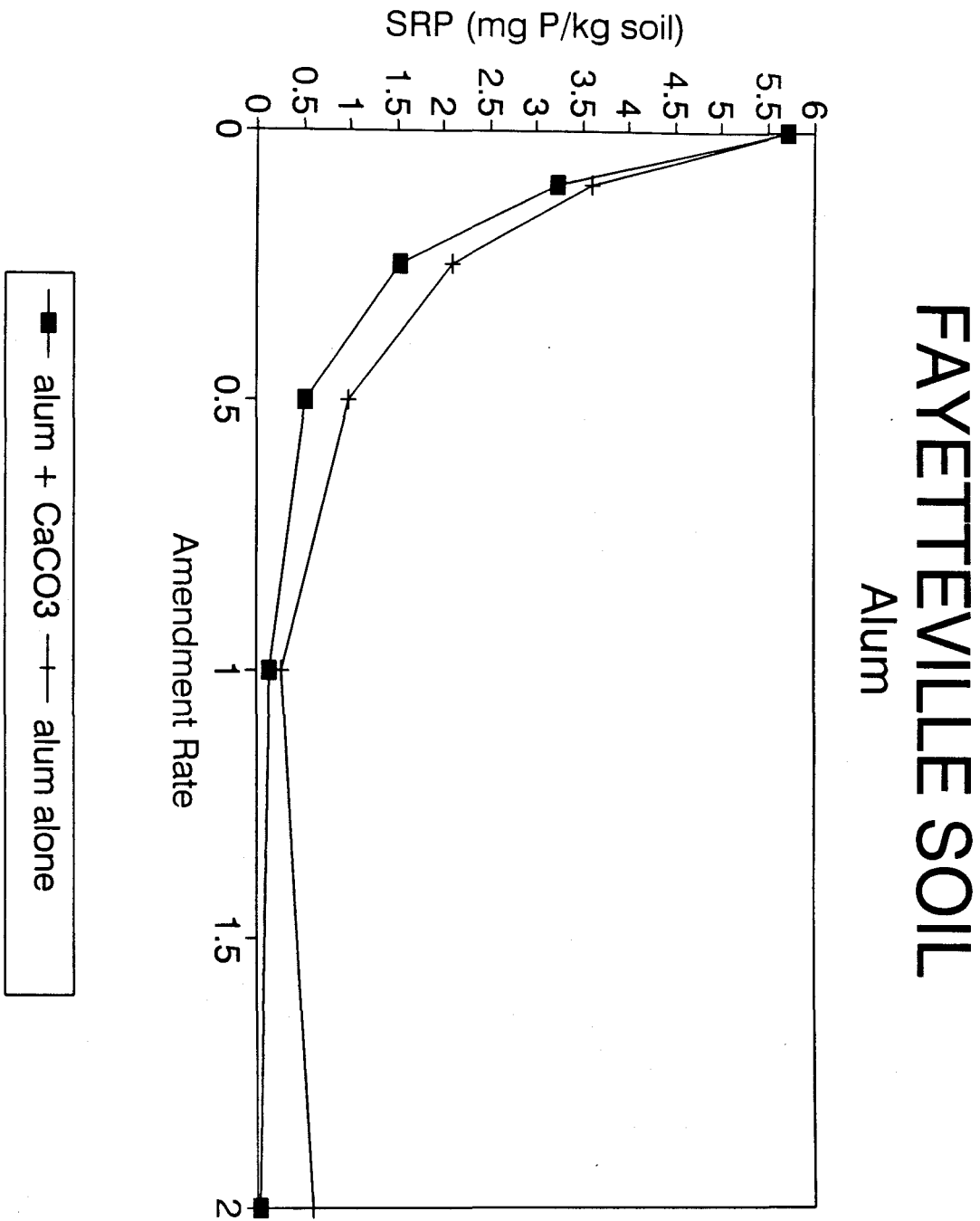


Figure 15 - Effect of alum additions to Linker soil on soluble reactive P.

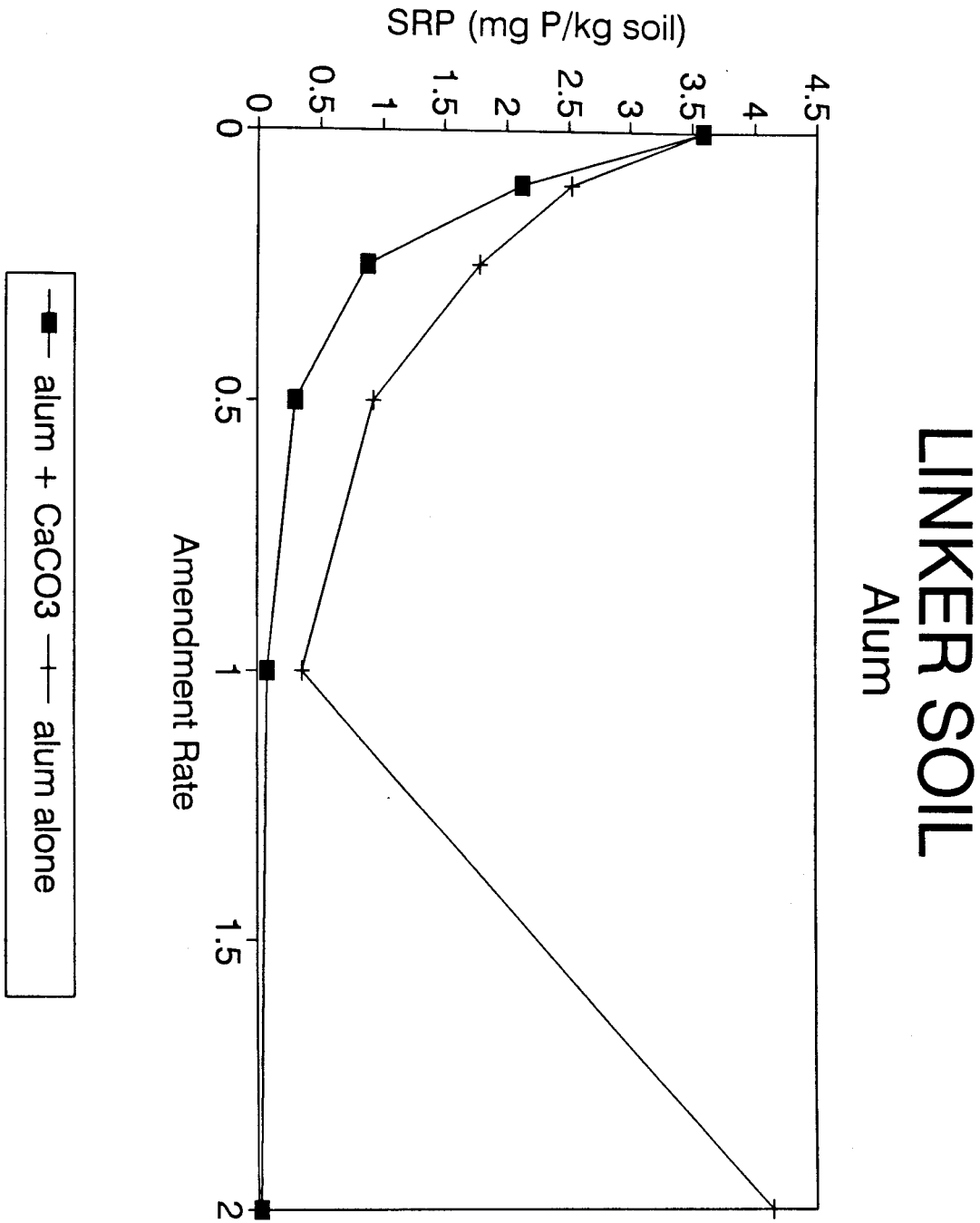


Figure 16 - Effect of alum additions to Mountainburg soil on soluble reactive P.

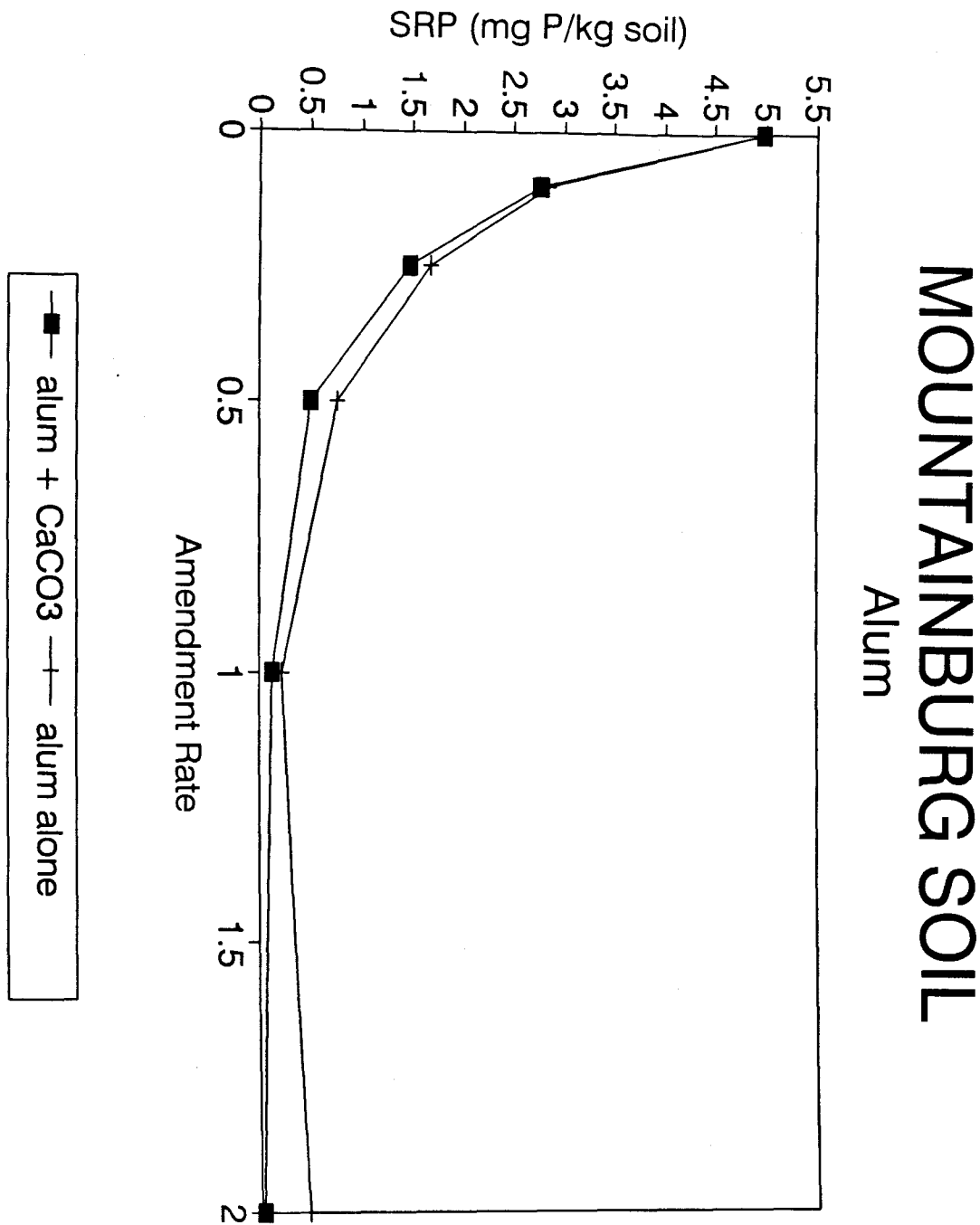


Figure 17 - Effect of ferrous sulfate additions to Fayetteville soil on soluble reactive P.

FAYETTEVILLE SOIL

Ferrous Sulfate

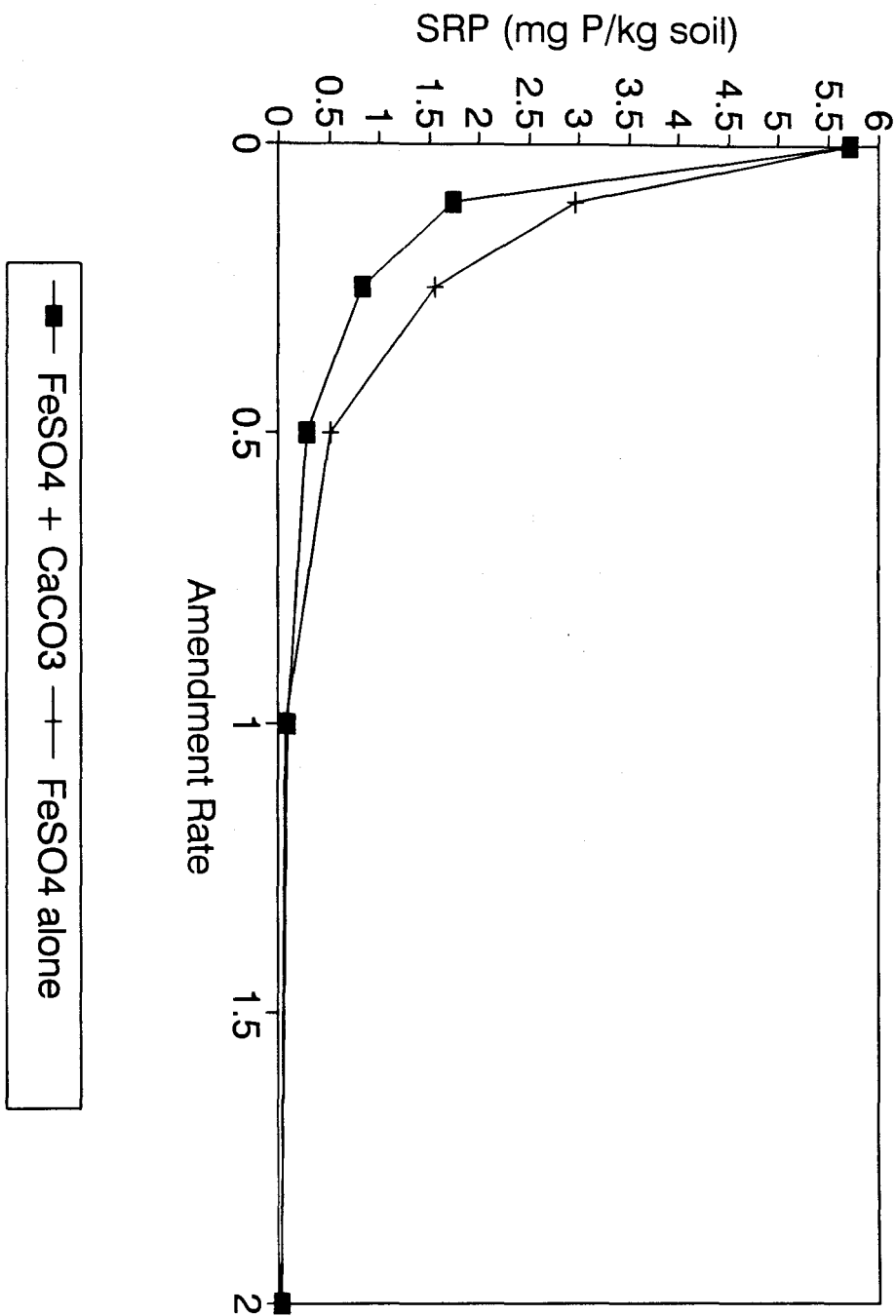


Figure 18 - Effect of ferrous sulfate additions to Linker soil on soluble reactive P.

LINKER SOIL

Ferrous Sulfate

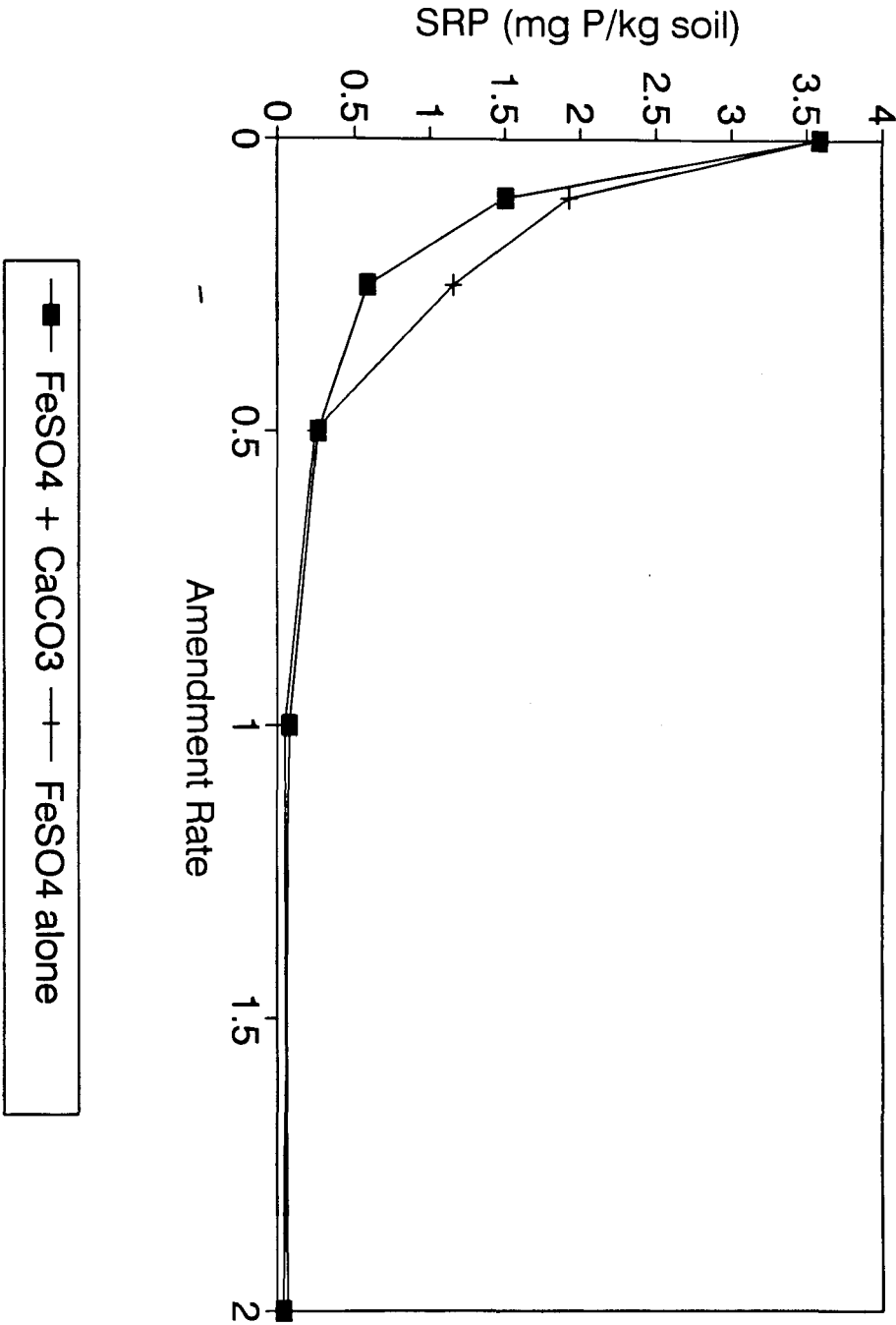


Figure 19 - Effect of ferrous sulfate additions to Mountainburg soil on soluble reactive P.

