

**Greenhouse and Laboratory Study for the  
Land Application of Water Treatment Residual**

by

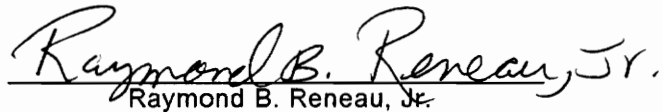
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Thesis submitted to the Faculty of the  
Virginia Polytechnic Institute and State University  
in partial fulfillment of the requirements for the degree of  
Master of Science  
in  
Environmental Engineering

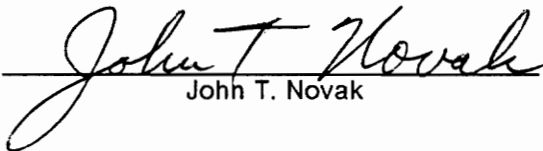
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July 1991

Blacksburg, Virginia

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(ABSTRACT)

The disposal of water treatment residual has received little attention due to a lack of regulation, funding, and concern about their environmental impacts. Many treatment plants discharge alum residual directly into nearby water courses or dewater them for landfilling. If suitable land is available, land application of residual is cost effective and has the potential for negligible effects on the environment and may prove to be a long-term solution to the disposal problem. This research project investigated the effects of land application of alum residual on crops or vegetation grown on fine loamy Slagle soil (*siliceous, thermic aquic hapludults*). Prior research identified the reduction in plant available P as a potential concern. During summer months, many water treatment plants also add powdered activated carbon (PAC) during the treatment process to prevent taste and odor problems. The PAC ultimately ends up in the residual and alters its chemical characteristics. The effects of land-applied PAC residual on plant growth was also investigated.

Fescue (*festuca arundinacae*) yields decreased with increased residual addition. Lime addition did not significantly effect fescue yield. Reductions in plant yield were attributed to a reduction in plant available phosphorus (P) in soils receiving higher residual loadings. Supplemental fertilization was able to overcome the P availability problem. The presence of manganese in the residual did not adversely affect plant yields. Likewise, incorporation of spent PAC into the residual did not reduce yields.

## **Acknowledgements**

Drs. Reneau, Novak, Dillaha, and Knocke provided the planning and foresight which led to the success of project. Their time and patience is greatly appreciated. The author would also like to thank the staff of the Virginia Tech Agricultural Engineering Water Quality Laboratory for their unending assistance with laboratory experiments and the growth studies. Chao Wen Lu of Statistical Consulting provided great assistance in analyzing the data. CH2M Hill Engineers and the City of Newport News funded this project.

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## Introduction

Currently, water treatment plant residual from many municipalities are discharged directly to nearby water courses. Recently, environmental criteria concerning the discharge of these residual have changed, and this practice is now often considered to be unacceptable. Land application of the residual is currently being considered as an option at many sites due to low costs, and the likelihood that this method will provide a long-term solution to the disposal problem. Considerable uncertainty exists as to the environmental consequences of land application of water treatment plant residual, however.

This research was undertaken to assess the possible environmental consequences of land application of water treatment plant residual on plant growth. The facilities studied were the Newport News, Virginia water treatment plants. The residual from these treatment plants was considered for application to nearby clear cut forest areas owned by the city.

The growth of fescue (*festuca arundinacae*) and loblolly pine seedlings (*pinus taeda*), the proposed vegetation in the land application areas, were studied to determine proper residual loadings and to evaluate potential harmful effects. Earlier experimentation by Dempsey and Elliott (1989) did not include plant studies but did indicate that land application of water treatment residual might limit plant growth by decreasing plant available phosphorus (P). Lime

addition to the land application site was also investigated because of regulations requiring the maintenance of a minimum soil pH at sites where residuals are applied to the land. The higher pH levels presumably minimize heavy metals mobility. Therefore, residuals loading, P addition, and lime addition were the variables in the first fescue study. The addition of powdered activated carbon (PAC) was included in these studies because of its use by water treatment plants to control taste and odor problems in the source water. The fescue was grown in individual pots in a greenhouse over a period of four months. A similar study was conducted with loblolly pines. The only differences in the pine seedling experiment was that there was no lime addition and reduced P addition. The experimental period was seven months.

After completion of growth cycles, the yield, plant tissue, and soils were analyzed to determine the effects of the soil amendments. The results of the first fescue study prompted a second study to pinpoint growth effects caused by the addition of P, Mn, and various PAC forms to the soil. Additional experiments were conducted on the soil after plant harvest to determine the fate of several elements of interest, primarily B, Fe, and Al.

The specific objectives of this study were:

1. Determine the effect of various residual and nutrient loadings on plant growth.
2. Find optimum residual and nutrient loading rates for minimal impacts on plant growth.
3. Determine the plant availability of various elements of concern in the residuals/soil mixtures.

# Literature Review

## **Introduction**

The disposal of water treatment residual was a simple task in the past. Most water treatment plants discharged residual to streams and rivers with limited regulatory control. However, with time, it became apparent that discharge of water treatment residual could create problems through the accumulation of residual along the bottom of slower moving channels. Benthic organisms and fish spawning areas can be covered with residual solids which may reduce their populations and productivity. The increased turbidity from the residual will also reduce photosynthesis and growth of submerged aquatic vegetation. High turbidity is a particularly acute problem in the Chesapeake Bay where residual from many areas may accumulate. Increased bacterial growth and oxygen demand due to increased solids are also potential problems.

During the summer months many treatment plants use PAC to remove tastes and odors from source water. The release of residual containing PAC into river channels may darken the water considerably and create an aesthetic problem. For many years, these problems were not addressed by regulatory agencies. However, in 1959, the state of Pennsylvania established limitations on the stream disposal of water treatment residual which included the removal of carbon (Crawford and Fischel, 1971). Recently, many water treatment authorities have considered land application of residual as a viable alternative to river disposal.

## **Water Treatment Processes and Regulation**

During the water treatment process, coagulants are added to the source water after primary settling. These coagulants promote the settling process by flocculating the finer particles and thus enhancing their removal. The most popular coagulants are alum ( $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ ) and ferric chloride ( $\text{FeCl}_3$ ). These chemicals, as well as the source water contaminants, are concentrated in the residual resulting from the coagulation process. The combined effects of these materials must be understood before proper land application can be initiated. Currently, there are over 3600 water treatment plants in the United States generating over one million tons of residual every year (Faust and Osman, 1983).

Funding for construction of residual processing facilities was allotted by the Water Pollution Control Act of 1965, PL 84-660. However, the projects which were funded were given a low priority. The projects proved to be ineffective due to inadequate management and operating conditions (JAWWA, 1978).

The Water Pollution Control Act Amendments of 1972, PL 92-500, dealt with residual disposal in a more serious manner. This new law classified residual as an industrial waste and required dischargers to obtain a National Pollutant Discharge Elimination System (NPDES) permit. However, funding needed to bring the treatment plants into compliance was not provided because the plants were considered an industry (JAWWA, 1978). Disposal of municipal wastewater sludges received a much higher priority which hindered research on disposal of water treatment residual (Gruninger, 1975). The enactment of PL 92-500 occurred over a period of years, and by July 1, 1977, all residual discharged to stream channels had to meet pH and total suspended solids (TSS) restrictions. The pH values had to fall between 6 and 10.5 depending on the process. The limit on TSS was also based on the type of process and was a function of mass loading, not concentration (JAWWA, 1978).

### **Residual Disposal Alternatives**

There are many alternatives to river disposal of residual such as sand drying beds, filter processing, and lagooning. These methods reduce residual volume, but an ultimate method of residuals solids disposal is still needed. Alum recovery, landfilling, and discharge to the sanitary sewer provide for solids disposal, but these still have their limitations. Alum recovery has been attempted, but the difficulty of removing organic color compounds from many source waters makes it unfeasible (Allen *et al.*, 1976). Bishop *et al.* (1987) discovered successful methods for alum recovery but the large quantities of sulfuric acid used in the process and its associated risks must be dealt with. Landfilling requires a high degree of dewatering which is expensive as current regulations prevent the landfilling of liquids (Hudson, 1981). Discharge to the sanitary sewer would simply shift the municipality's burden to the wastewater treatment

system. Reducing the amount of solids will make any disposal method easier. Solids reduction can be accomplished by the following methods (Bishop, 1978):

- improved coagulant mixing
- improved flow characteristics in clarifiers
- improved baffling during flocculation
- use of direct filtration to reduce coagulant use
- use of polymers to improve coagulation and decrease residual volume

With these processes the quantity of alum in the residual is reduced, but not the quantity of contaminants from the source water.

### **Physical Characteristics of Residual**

The residual volume is approximately 1% of the source water volume. Depending on the source water quality, the residual solids content ranges from 0.1 to 3.5%. If the source water is a lake or reservoir, the solids production is generally less than if the source water is a river due to differences in the concentration of TSS (JAWWA, 1978). Gruninger (1975) observed that the coagulation process generates 80 to 90% of the residual. The remaining residual are from the filter backwash.

Other types of water treatment processes generate residual that have been successfully land applied. Russell (1975) noted that the application of lime residual from water softening processes to agricultural fields was an excellent method of disposal and helps in soil acidity control. However, the benefits and problems associated with alum residual are not as clear. Volumes of information are available on the land application of wastewater residual, but data

on water treatment residual is scarce. This is reasonable considering potential risks and benefits of land applying wastewater residual (Dempsey and Elliott, 1989).

### **Chemical Characteristics of Residual**

In some respects, water treatment residual are more like fine textured soil than wastewater residual as shown in Table 1 on page 8.

During the coagulation process alum is converted to aluminum hydroxide which gives the soil a higher buffering capacity when land applied. The hydroxides form because the water pH is typically kept above 7 during treatment. Not only do the hydroxides act as a buffer, they also adsorb many types of reactive compounds. The adsorption can be beneficial or detrimental depending on the characteristics of the species (Dempsey and Elliott, 1989). The first concern with land applying the water treatment residual to soil is aluminum toxicity to plants. Fortunately, the soil's buffering capacity keeps Al relatively immobile. Even with a soil pH of 5,  $Al^{+3}$ , the most toxic species, is present in relatively low concentrations. However, this concentration depends on the type of minerals present. Elliott *et al.* (1989) claim that even continued land application of residual will not cause any negative effects from Al. For example, a 2% yearly loading (by mass) on Evesboro soil for 20 years will increase Al concentration only 20% above average soil levels. This increase is within normal soil fluctuations. Soils tend to have large variations in the concentration of the two primary Al forms, hydrous oxides and aluminosilicates (Elliott *et al.*, 1989). Bugbee and Frink (1985) stated that acid rain could be a potential threat, but a residual application rate of just 28 kg per hectare can neutralize a year of average rainfall with a pH of 4.

Dempsey and Elliott (1989) performed Microtox tests on various types of residual using *pseudomonas fluorescens* and concluded that only a few residual (those with high Cd concentration) were more toxic than soil. This toxicity can be neutralized by EDTA which proves that the toxicity is due to metals. Other studies done by Dempsey and Elliott (1989) suggest

**Table 1. Chemical Characteristics of Water Treatment Residual, Evesboro Soil, Wastewater Residual<sup>1</sup>**

Parameter	Water Treatment Residual	Evesboro Soil	Wastewater Residual
TOC, %	3	3	40
TKN, %	0.5	0.5	4
C/N Ratio	7	10	10
NH <sub>3</sub> -N, %	0.01	0.1	0.1
Total P, %	0.5	0.1	2.5
Al, %	2-20	4	0.5
Fe, %	1-15	7	1.5
pH	6-7	6-9	6.9-7.5
% solids	2	75	10
LOI, % <sup>2</sup>	33	5	70
Coliforms, #/100 mL	< 20	1000	10 <sup>6</sup>
Total Cd, mg/kg	< 2	0.4	15
Total Cu, mg/kg	200	12	800
Total Ni, mg/kg	100	25	80
Total Pb, mg/kg	220	15	500
Total Zn, mg/kg	550	40	1700

<sup>1</sup>Elliott, *et al.*, 1989

<sup>2</sup>Loss on ignition

residual have a high enough P binding capability to reduce plant growth. This reduction in plant available P is a function of:

- soil and residual types
- method and rate of application
- amount of time between application and planting

Residual bind both P in solution and labile P in the soil. Dempsey and Elliott (1989) claim that this trait makes water treatment residual suitable for application on soil with a high potential to release P to surface waters. However, soil P loss is mainly due to soil erosion. If the fixation of P by the residual results in low plant available P, then additional P fertilizer will be required to meet the needs of the plants which may ultimately increase total P losses in surface runoff. Another alternative is to grow crops that require less P in the application areas. Municipal wastewater residual, which contain high P levels, could also be land applied in combination with water treatment residual to furnish additional P (Elliott *et al.*, 1989).

### **Greenhouse Growth Studies**

Bugbee and Frink (1985) conducted studies with ryegrass (*lolium*) grown in a mixture of soil and water treatment residual which ranged from 0 to 100% residual in increments of 25%. The controls (0% loading) had a soil pH of 5.6. The residual additions increased soil pH with the 100% loading having a pH of 6.2. The increased residual loading reduced plant yield, but germination was unaffected. Further studies with lettuce (*lactuca sativa*) used varying amounts of soil, perlite, peat, and alum residual. Non-limiting nutrients were added to prevent them from becoming growth limiting factors. After two months of growth, the lettuce grown with residual exhibited a purple hue which indicated P deficiency. Yield and plant tissue analyses confirmed that residual addition resulted in a P deficiency. However, these tests were conducted at elevated levels of water treatment residuals application (up to 67%). A third

experiment with marigolds (*tagetes*) had residual loadings up to 67%, but this time the test had a variable which included doubling the addition of P required by standard soil tests. Unfortunately, they noted that P deficiency was not affected by the increased P addition. The marigolds absorbed higher amounts of Mn when grown in residual high in Mn. Ammonium, K, Cu, and Mg in the marigold tissue also increased with increased residual loading, but only slightly and well within normal growth requirements.

Lin (1988) conducted experiments with corn and soybeans grown in soil/residual mixtures of 0, 0.25, 1.0, and 2.0% residual in soil. The plant tissue had no statistically significant difference in the concentrations of Mg, Mn, Zn, Fe, Cu, Pb, and Ni as a function of water treatment residual loading. Oddly, the corn plots with 0.25 and 1% loadings had lower yields than the 0 and 2.0% loadings. The soybean yields were not affected by residual loading. Lin's results were tested by the F test and the least significant difference (LSD) method with a 90% confidence level. Elliott and Singer (1988) found that the addition of ferric chloride residual to soil reduced concentrations of Cd, Cu, Fe, Mn, Ni, and Zn in tomato plants grown in the mixture. This reduction in metals arose because of an increase in soil pH which lowered metal mobility. Studies by Heil and Barbarick (1989) with sorghum-sudangrass (*sorghum vulgare sudanense*) showed high levels of Cd in plant tissue with residual loadings of 2.0% and 2.5% applied to the soil. The Cd level was high enough to be toxic to cattle. They attributed this effect to reduced plant yield with subsequent concentration of Cd in the plant tissue.

### **Potential Soil and Groundwater Problems**

Elliott *et al.* (1989) studied potential contamination of groundwater with heavy metals due to residual application. A residual application rate of 10 kg/ha with a Cd content of 1.6 mg/kg would yield a concentration of 0.0018  $\mu\text{g/L}$  if 25% of the Cd was leached with 50 cm of percolating water. This concentration was well below the drinking water maximum contaminant level (MCL) of 10  $\mu\text{g/L}$ . Also, the adsorption of Cd by soil particles was not considered. Concentrations of Pb and Cr in water leached from the residual would also be below the drinking water MCLs. Toxic metals are present in the source water, as well as in the

coagulants, which leads to the levels reported in Table 1. In this respect, water treatment residual resemble wastewater sludges. When water treatment residual are land applied, a large amount of water becomes available due to their low solids content. A 2% application rate of residual with 1.5% solids will provide 30 cm of water to the soil. Precipitation and antecedent soil water could worsen this potential problem. Dewatering and the buffering capacity of the residual can reduce the possibility of groundwater contamination.

Many states have standards for all land applied wastes. Elliott *et al.* (1989) reported high levels of Ni in residual from ferric chloride processes which exceeded the standard for wastes applied to agricultural fields. The use of alum instead of ferric chloride will prevent this problem, or treatment plants can specify maximum Ni content in the coagulants they purchase. One source water tested by Dempsey and Elliott (1989) received acid mine drainage and had a very high metals concentration. The effluent water met the drinking water MCLs but the residual were unsuitable for land application.

The N content of water treatment residual has prompted some regulatory agencies to limit land application for fear of high nitrate concentrations in groundwater. The N forms in residual were analyzed by Elliott *et al.* (1989) in a nitrogen mineralization study. The authors discovered N to be present in stable organic forms and was not available after sixteen weeks. Heil and Barbarick (1989) noted that 16 to 192 mg/kg of N were present in alum, ferric, and organic polymer residual. However, most of this N is unavailable to plants because it is in a stable organic fraction and is not mineralized. In their growth study, N was added at twice the normal field recommendation to prevent it from becoming a growth limiting factor.

### **Comparison of Alum Residual and Ferric Chloride Residual**

Ferric chloride residual can be beneficial when land applied by providing Fe to soils that are Fe deficient such as calcareous soil. The residual do not contain  $\text{FeCl}_3$  in the salt form, but Fe is available as  $\text{Fe}(\text{OH})_3$  (s). Heil and Barbarick (1989) reported that Fe deficiencies could be corrected by 0.5 to 1.0% additions of ferric residual and 1.5 to 2.5% additions of alum res-

idual in their sorghum-sudangrass study. Ferric residual provided a liming effect when applied to Red Feather (Lithic Cryoboralt) soil which had a pH of 5.5. The sorghum-sudangrass had a higher yield with the 0.5 and 1.0% additions of both alum and ferric residual than with no additions. Although the plant tissue P was slightly reduced by the 0.5 and 1.0% loadings, they were not P deficient. Higher residual loading (2.5%) created severe P deficiencies in plant tissue which were overcome by adding P fertilizers. With an alum residual loading of 2.5%, doubling the P application increased yield by 29%. Doubling the P application with 2.5% ferric residual addition increased yields by 13%. These results conflict with Bugbee and Frink's conclusion that increasing P addition did not increase yields. However, Bugbee and Frink (1985) used very high residual loading rates in their study.

The relation between residual addition and P fixation can be described by the Langmuir isotherm:

$$C / (x/m) = 1/Kb + C/b \quad [1]$$

C = equilibrium P concentration (mg/L)

x/m = weight of P per unit weight of residual/soil mixture (mg/g)

K = P binding constant (L/mole)

b = P adsorption capacity (mg/g)

P sorption capacities are similar for both the ferric and alum residual. A study with organic polymer residual resulted in significantly higher plant tissue P levels than the other two types (Heil and Barbarick, 1989).

### **Forest Growth Studies**

While growth studies in controlled greenhouse environments can give precise yield and chemical analyses, they do not completely reproduce the natural state of a forest or field where land application will be attempted. Bugbee and Frink (1985) studied the effects of land applied residual by spraying them directly onto forested areas. Plots (11 m x 15 m) in deciduous and coniferous forests received a residual loading of 17,654 kg/ha (0.8% solids). Applications were made in the fall and the following spring. One year after the fall application,

the trees in the test plots showed little effect from the residual in growth or in the tissue analysis. Little visible evidence of the residual remained, but soil pH increased by 0.5 to 1.0 units in the top 10 cm of soil. The coniferous plots showed a slight decrease of P in plant tissue as a function of residual application. Manganese levels in plant tissue were reduced by the residual also. Overall, nutrient uptake by forest species was largely unaffected by water treatment residual application. The forest application study will take years to show final results, but it did demonstrate that residual could successfully be applied in liquid form to forest areas. During the study, residual with a 1.5% solids content were applied with a normal fire hose and tank truck (Bugbee and Frink, 1985).

### **Application Methods**

The EPA has many recommendations for the land application of wastewater residual in its publication, "Land Application of Municipal Sludge" (EPA, 1983). These methods could be adapted for water treatment residual. Spray irrigation application with a rotary sprayer can be used if the solids content is low enough (1%). Residual spreading with a tank truck is another alternative; however, this may not be the most economical method. Russell (1975) conducted experiments on water softening residual with various solids concentrations to find the best land application methods. If the residual are not dewatered, the high volume of water creates a significant transportation cost depending on the distance between the treatment plant and the application area. Lagooning can eliminate the need for mechanical dewatering and decrease the water content to about 50% solids. At this concentration, the residual can be handled as a "dry" material. Russell used a spreader originally designed for wastewater sludges and found it also to be effective for water softening residual. For even greater efficiency, the residual can be stockpiled with a dump truck at the application site which reduces travel time and operating costs for the spreader.

### **Conclusion of Literature Review**

The literature currently supports the land application of water treatment residual as a safe and economical disposal option. However, individual treatment plant operations and disposal site

conditions must be studied before a sound decision can be made on appropriate application rates and methods. Phosphorus binding is the largest drawback but can be overcome through proper crop selection or the addition of fertilizers. Other problems may arise from heavy metals depending on the source water and coagulants used. Increased buffering capacity is the primary benefit of land applying residual to soils. A practical application rate lies between 0.5 and 2.5%, with the lower rates being beneficial due to increased buffering capacity.

## **Experimental Methods**

## ***Fescue Studies***

### **First Fescue Study**

The experimental design for the first fescue (*festuca arundinacae*) greenhouse study was a randomized complete block with four replications. The treatment variables included:

- Five residual loading rates of 0, 1, 2, and 4%, and 2% residual plus 2.2% PAC.
- Two lime additions
- Two P additions

Applications levels are based on an oven dry weight (ODW) basis. The soil used in this study was taken from Slagle top soil in the proposed land application areas in Newport News, Virginia. Each pot contained 2 kg of soil mixture and had a capacity of 1.9 liters.

### ***Soil and Residual Mixture***

This study used a fine loamy Slagle soil (*siliceous, thermic aquic hapludults*) (SCS, 1983). The residual used was obtained during a period when PAC was not being used in the water treatment process and designated Residual 1 in this thesis. Consequently, the PAC treatment in this study was obtained by adding unused PAC to the soil. The PAC, Hydrodarco®, was derived from lignite coal and manufactured by the American Norit Corporation.

## ***Fertilizer Requirements***

When pot experiments are conducted to evaluate crop response to soil amendments, it is necessary that supplemental nutrients intended to be nonlimiting are supplied in adequate quantities for maximum response to the limiting nutrient. Required amounts of macronutrients will vary as a function of the amount of available nutrients already present in the soil. The soil used in this study was tested to determine the levels of plant available nutrients. For greenhouse studies, the nonlimiting nutrients are normally applied at rates four to eight times the rates commonly recommended in field application. Pot studies receive higher nutrient application than recommended for normal agricultural practices due to low soil volumes and high plant populations. If excess nutrients are not added, the use of soil test recommendations for application of nonlimiting nutrients may lead to crop response unrelated to the principal variables (Allen *et al.*, 1976). Previous greenhouse studies at Virginia Tech have indicated that twice the quantity recommended by the soil test analysis (using Virginia soil test recommendations) is adequate for nonlimiting nutrient application (Reneau, 1989). Consequently, this study used twice the recommended quantity of nonlimiting nutrients. Soil tests to determine fertilizer recommendations were conducted by the Virginia Tech Soil Testing Laboratory (Donohue and Gettier, 1988).

## ***pH Adjustment***

The limestone (dolomite) required to bring soil and residual mixtures to a pH value of 6.5 was determined using the Adams and Evans procedure for determining lime requirement (McLean, 1982).

This procedure is particularly well suited to the Slagle soil used in this study (SCS, 1983). A soil pH of 6.5 is required by the USEPA to decrease the solubility of heavy metals that may

**Table 2. Slagle Soil Lime Requirement After Residual Addition in the First Fescue Study**

Residual Loading Rate (%)	Lime (Mg/ha)*	Lime (g/2 kg pot)
0	4.72	4.20
1	4.51	4.02
2	3.62	3.22
4	3.26	2.90
2+PAC	3.62	3.22

\*assumes 2250 Mg of soil per hectare

be present in water treatment residual. This pH level will also increase availability of most macronutrients. Table 2 on page 18 lists the amount of lime added to each residuals level. The buffering capacity of the residual caused the lime requirement to decrease as the residual level was increased.

### ***Nutrient Addition***

The soil tests indicated that plant available P, K, Ca, Mg, and N were low as shown in Table 3 on page 20.

High target concentrations were desired to minimize deficiencies in nutrients not being investigated. A micronutrient mix would normally be applied to test pots in greenhouse studies. In this study, micronutrients were not applied since the addition of water treatment residual may create a micronutrient deficiency or toxicity. The potential for micronutrient deficiencies or toxicities were also an area of interest in this study.

Lime, P, and 50% of the N and K fertilizer were applied in a dry form as the pots were initially mixed. The remaining N, K, and  $MgSO_4$  were applied in solution form after the plants were well established. These nutrients were added as separate solutions.

### ***Pot Preparation***

Every greenhouse pot contained a total of 2 kg of soil plus residual on an oven dry weight (ODW) basis. The potting soil was prepared by placing the appropriate quantity of soil in a twin shell blender with the appropriate quantity of lime, P, N, S, and K. After mixing the lime and nutrients with the soil, the appropriate quantity of residual was added and the entire contents remixed. The final mixing received a minimum of 20 revolutions. The required

**Table 3. Nutrient Requirements of Potting Soil<sup>1</sup>**

Nutrient	Extractable Nutrient Level (mg/kg)	Required Conc. (mg/kg)	Target Conc. (mg/kg)	Nutrient Sources	Amounts Added (mg)
P	4	25	50	Ca(H <sub>2</sub> PO <sub>4</sub> ) <sub>2</sub>	406/812 <sup>2</sup>
K	36	30	60	KNO <sub>3</sub>	620
Ca	252	-	-	Ca(NO <sub>3</sub> ) <sub>2</sub> Ca(H <sub>2</sub> PO <sub>4</sub> ) <sub>2</sub> Lime	840 406/812 <sup>2</sup> see Table 2
Mg	35	-	-	MgSO <sub>4</sub> Lime	1434 see Table 2
N	-	50	100	KNO <sub>3</sub> Ca(NO <sub>3</sub> ) <sub>2</sub> NH <sub>4</sub> NO <sub>3</sub>	620 840 610

<sup>1</sup>Donohue and Hawkins, 1976

<sup>2</sup>All nutrients except P were nonlimiting and were added in excess to prevent deficiency effects. Phosphorus was added in two levels of 50 and 100 mg/kg.

quantities of soil were then removed from the blender, weighed and then added to the pots (Table 4 on page 22). Each greenhouse pot was double lined with plastic bags before the mixtures were placed into the pots to prevent water and nutrient loss.

### ***Watering***

To determine the field capacity of the soil, 100g (ODW) of soil was weighed into small sealable plastic bags (Whirlpak) and water was added to bring the soil moisture contents to 10, 12, 14, 16, 18, 20, and 22%. The closed bags were allowed to stand overnight at room temperature. Field capacity was estimated as the soil moisture content at which the entire soil volume was barely wetted which in this case proved to be 19%. Once field capacity was determined, the watering procedure to be followed during the experiment was established. Proper water content was determined by weighing each pot on a double beam balance and then adding water, on a daily basis, the amount of water required to bring the soil moisture content to 90% of field capacity. For example, if a pot had 2 kg of potting mixture and a field capacity of 19%, the required mass of water in the pot at 90% of field capacity would be:

$2000 \text{ g} \times 0.19 \times 0.90 = 342 \text{ g}$  or 342 mL of water. Therefore, the desired pot weight after watering would be the 2000 g + 342g plus the weight of the container. Therefore the difference in this sum and the weight of each pot on any given day would be the required water application in mL.

### ***Seeding***

Each pot received 0.25 g of 'Dixie Duet' fescue seed. Following germination and approximately 3.8 cm of growth, the fescue was thinned to 25 plants per pot.

**Table 4. Treatment Combinations in the First Fescue Study**

Residual Loading <sup>1</sup> Rate (%)	Lime	P Addition (mg/kg)
0	no	50
0	no	100
0	yes <sup>2</sup>	50
0	yes	100
1	no	50
1	no	100
1	yes	50
1	yes	100
2	no	50
2	no	100
2	yes	50
2	yes	100
4	no	50
4	no	100
4	yes	50
4	yes	100
2+2.2% PAC	no	50
2+2.2% PAC	no	100
2+2.2% PAC	yes	50
2+2.2% PAC	yes	100

<sup>1</sup>Residual 1 which contains no PAC

<sup>2</sup>Liming to soil pH of 6.5

### ***Pot Rotation***

All pots were rotated to a new position daily to prevent growth effects caused by varying temperatures and light conditions in the greenhouse.

### ***Clipping Procedures***

Due to accelerated growth in the greenhouse, the fescue had to be cut to 3.8 cm three times during the experiment. The plant material was placed in paper bags and dried in a 70° C forced air drying oven for two days. The multiple clippings were necessary to prevent the fescue plants from becoming too large and unmanageable.

## **Second Fescue Study**

Data from the first fescue study revealed new areas of interest in the land application of water treatment residual. The questions raised were as follows:

1. How will fescue respond to P additions other than 50 and 100 mg/kg?
2. Will increasing Mn in the soil (from application of water treatment residual) adversely affect the fescue?
3. Will the boron (B) associated with unused PAC be present in washed or spent PAC?

### ***Experimental Design***

The experimental design for the second fescue study was very similar to the first. Addition of nonlimiting nutrients was the same as in the first study as well as the mixing and clipping procedures. Each pot received 0.40 g of 'Dixie Duet' fescue seed. Following germination and growth of approximately 3.8 cm, the fescue was thinned to 40 plants per pot. A denser stand was used in the second study to more quickly produce a high plant yield for analysis. Other differences are described below.

### **Variables**

In the first study, increased P addition increased plant yield, however, increased residual loading *decreased* plant yield as predicted by Dempsey and Elliott (1989). The original fescue study had two soil P additions, 50 and 100 mg/kg. One purpose of the second fescue study was to determine the influences of varying rates of P application on yield and composition.

The second study had four P levels: 0, 50, 100, and 200 mg P/kg with a 2% residual loading rate.

Results from the first study also suggested that Mn levels in the plant tissue were elevated in some of the treatments with high residual loadings. The residual contained 6650 mg Mn/kg which might be available to the fescue, especially at a lower soil pH. While most of the residual loading effects in the first fescue study were thought to be due to P binding, Mn may have also inhibited growth. Therefore, studies with additional levels of Mn were applied to the potting soil. In addition to a 2% residual level, Mn was added to fescue pots in the form of MnO<sub>2</sub> (solid) to simulate Mn loading that would result from an additional 2% and 4% residual loading. P addition was held constant at 100 mg/kg for each Mn treatment.

Yields were low and B levels in plant tissue were very high when the potting soil contained 2.2% unused PAC in the first fescue study. Therefore, PAC was studied further. A recent change in water treatment procedures has reduced PAC use from 25 mg/L to 10 mg/L. Therefore, fescue growth was studied with a loading of 0.88% unused PAC in potting soil along with a 2.2% unused PAC addition. The 0.88% unused PAC addition corresponds to the expected new PAC loadings. Also, residual obtained during the summer that contained spent PAC (Residual 2) were studied at a 2.88% loading. A 2% residual loading with 0.88% *washed* PAC was studied to determine if the B effects could be reduced. The washed PAC was formed by rinsing each gram of PAC with 25 mL of deionized water.

In the first study, 3.22 grams of dolomitic lime was added to half the pots containing 2% residual. However, the soils analysis conducted after the growth cycle revealed lower pH values than expected. In the second study, 4.5 grams of lime was added to each pot.

Table 5 on page 26 summarizes the treatments and variables utilized in the second fescue study. All treatments were replicated four times.

**Table 5. Treatment Combinations in the Second Fescue Study**

P Addition (mg/kg)	Mn Addition (mg/kg)	Residual Loading Rate (%)	PAC Addition (%)
0	0	2	0
50	0	2	0
100	0	2	0
200	0	2	0
100	133 <sup>1</sup>	2	0
100	266 <sup>1</sup>	2	0
100	0	2.88 <sup>2</sup>	0
100	0	2	0.88% unused
100	0	2	2.2% unused
100	0	2	0.88% washed

<sup>1</sup>MnO<sub>2</sub> was added to simulate the Mn present in additional residual applications of 2% and 4%, respectively

<sup>2</sup>Residual containing spent PAC from Newport News water treatment plant (Residual 2)

## ***Pine Seedling Study***

The experimental design for the loblolly pine seedling (*pinus taeda*) greenhouse study was a randomized complete block with four replications. The treatment variables were five residual loading rates (0, 1, 2, 4%, and 2% + 2.2% PAC) and two P levels (Table 6 on page 28). The percentages were based on ODW of potting material. A total of 40 pots filled with 2 kg of potting material were used to conduct this experiment. The pot volume was 1.9 liters.

<sup>3</sup>Soil requirement

### ***Nutrient Addition***

The pots in the pine study received no lime, no added nutrients, and only one level of P addition. No soil amendments other than P addition were made because pines planted in residual disposal areas receive few, if any, soil amendments. The soil test indicated that plant available P, K, Ca, Mg, and N were low as shown in Table 3 on page 20. Monocalcium phosphate was the source of P in this study.

### ***Watering***

The plants were watered to 90% field capacity daily as described previously.

### ***Planting***

Loblolly pine seedlings were obtained from the Virginia Department of Forestry and kept refrigerated until planted. Three trees were placed in each pot after the roots were dipped in

**Table 6. Treatment Combinations for the Pine Seedling Study**

Residual Loading <sup>1</sup> Rate (%)	P Added (mg/kg)
0	0
0	50
1	0
1	50
2	0
2	50
4	0
4	50
2 + 2.2% PAC <sup>2</sup>	0
2 + 2.2% PAC <sup>2</sup>	50

<sup>1</sup>Residual used in this experiment do not contain PAC (Residual 1)

<sup>2</sup>Treatments with PAC were obtained by adding unused PAC to the soil

a fungicide solution. The soil/residual mixtures were then carefully added to prevent compaction and ensure proper tree spacing.

### ***Growth and Maintenance***

The trees were kept outside in a cold frame for three months and then placed in a greenhouse with an evaporative cooler to maintain an acceptable relative humidity. Each pot was thinned to one tree per pot as growth progressed. Pots that lost all three trees in the first four months of the study were replanted.

## ***Residual and Post-Harvest Analytical Methods***

### **Residual Analysis**

A 2 gram sample of water treatment residual was digested overnight at room temperature with 5 mL of nitric acid and 5 mL of perchloric acid (Clesceri, 1989). The solution was brought to a total volume of 50 mL and then allowed to settle. After filtering through 1  $\mu\text{m}$  glass fiber filter paper, the sample was analyzed with atomic adsorption using a graphite furnace for Pb, Se, and As. An inductively coupled plasma spectrometer (ICP) was used to determine P, K, Ca, Mg, Na, S, Zn, Mn, Cu, Fe, Al, B, Cd, Cr, Ag, and Ni.

### **Yield Analysis**

The fescue plants were clipped to 3.8 cm, then dried for two days at 70° C in a forced air drying oven. The plant tissue was weighed on an analytical balance and expressed as grams of dry biomass per pot. The yield from the pine seedlings was divided into several categories. The needles were pulled from the stems and separated into needle clusters and needle bases. The height and ground level diameter of the stems were measured and then separated from the roots. The needles, needle bases, stems, and roots were dried for two days at 70° C in a forced air drying oven and weighed on an analytical balance.

## **Initial Soil Analysis**

First, soil samples were air dried, crushed, and passed through a #10 sieve. Soil pH was determined by placing a 20 mL soil sample in 20 mL of deionized water. The sample was stirred, allowed to come to equilibrium, and the pH measured with a glass electrode pH meter. Soil chemical analyses were completed after extraction with the Mehlich 1 procedure which consists of a mixture of 0.05 N HCl and 0.025 N H<sub>2</sub>SO<sub>4</sub> (Donohue and Gettier, 1988). The extraction liquid was filtered through Whatman No. 1 filter paper and analyzed on the ICP for P, K, Ca, Mg, Mn, Zn, Fe, Cu, and Al.

## **Plant Tissue Analysis**

After drying, the plant tissue was ground, passed through a #16 sieve, and a 1.000 g sample was ashed at 475° C. The ash received 5 mL of concentrated hydrochloric acid and was allowed to stand for 30 minutes. Deionized water was added to bring the total volume to 50 mL (Donohue and Gettier, 1988). The solution was filtered through 1 μm glass fiber filter paper and analyzed on the ICP for P, K, Ca, Mg, Zn, Mn, Cu, Fe, B, and Al.

## ***Soil Studies***

In addition to the initial post-harvest soil analysis, additional experiments were conducted to investigate the effects of added residual, PAC, and P on soils and soil/residual mixtures.

### **Phosphorus Sorption**

The adsorption of P by soil/residual mixtures was analyzed in an incubation study. This experiment was conducted to determine the relationship between P in solution and P adsorption as reported by Field (1985). Seven residual mixtures and initial P concentrations of 0, 10, 20, 40, 80, and 160 mg/L were used for a total of 42 treatments as shown in Table 7 on page 33. Treatments were replicated four times. Three grams of sample was placed in a test tube and brought to a total volume of 25 mL with 0.01 M CaCl<sub>2</sub>. The sample was incubated for six days at room temperature and filtered through 1 μm glass fiber filter paper. A subsample was taken from each tube and added to a standard reagent color solution. The reagents consisted of ammonium paramolybdate, potassium antimony tartrate, sulfuric acid, and ascorbic acid. The color developed after 10 minutes and was tested on a spectrophotometer at a wavelength of 882 nm (Olsen and Sommers, 1982).

### **Boron Extraction**

The plant tissue analysis of the first fescue study showed very high levels of B in the plants that were grown with PAC. This experiment sought to find the B content of PAC, unused potting soil, and two potting soils taken from pots after final harvest. The two used potting

**Table 7. P Sorption Study Design**

Soil Loading (g)	Residual Loading (g)
3.00	0
2.97	0.03 <sup>1</sup>
2.94	0.06 <sup>1</sup>
2.88	0.12 <sup>1</sup>
2.97	0.03 <sup>2</sup>
2.94	0.06 <sup>2</sup>
2.88	0.12 <sup>2</sup>

<sup>1</sup>Residual 1, does not contain PAC

<sup>2</sup>Residual 2, obtained during the use of PAC

soils both contained 2% residual, no lime, and 50 mg P/kg, the only difference being no PAC and 2.2% PAC addition. To conduct the experiment, all glassware was soaked overnight in concentrated hydrochloric acid to remove any free B. Ten grams of sample was placed into a flask with 100 mL of 0.01 M  $\text{CaCl}_2$  solution. The solution was boiled for 5 minutes with a watch glass over the flask to help prevent evaporative losses. Any water lost was replaced with deionized water (Bingham, 1982). The solution was then filtered through 1  $\mu\text{m}$  glass fiber filter paper and analyzed on the ICP.

## **Ammonium Oxalate and Dithionite-Citrate-Bicarbonate Extractions**

These two experiments were undertaken to determine why plant available P was reduced by the addition of residual to the soil. Aluminum and Fe forms in soil will bind P according to Olsen and Sommers (1982). Consequently, Dempsey and Elliott (1989) report that the Fe and Al forms in water treatment residual can also bind P. Ammonium oxalate extraction in the dark removes mainly amorphous forms of metals and the dithionite-citrate-bicarbonate (DCB) extraction removes mainly crystalline forms of Fe. However, DCB is not effective for extracting Al. Aluminum and iron were extracted by the ammonium oxalate method as described below. A sample of 0.250 grams of soil were placed into a test tube with 50 mL of 0.2 M ammonium oxalate solution at pH 3. The test tubes were wrapped in aluminum foil to prevent interference from sun light and then shaken for two hours on a reciprocating shaker (Jackson *et al.*, 1986). The liquid sample was then centrifuged, and the supernatant was analyzed on the ICP for Al, Fe, and P. Iron was also extracted with the DCB method by placing four grams of soil into a test tube with 2 grams of  $\text{Na}_2\text{S}_2\text{O}_4$  and 25 grams of  $\text{Na}_3\text{C}_6\text{H}_5\text{O}_7 \cdot 5\text{H}_2\text{O}$ . The solution was brought to a volume of 118 mL with deionized water and shaken overnight. Five drops of Magnifloc® 579C flocculating agent were added and the solution was shaken vigorously for 15 seconds. The solution was transferred to a 250 mL volumetric flask and brought to volume with deionized water (Olson and Ellis, 1982). After settling, the samples were analyzed on the ICP

for Al, Fe, and P, but the DCB extraction method is primarily for Fe. Analysis for P was included in both experiments to determine their effectiveness for extracting P.

## ***Statistical Methods***

Yield, plant tissue, and soils analyses from all three studies were analyzed using Statistical Analysis System (SAS, 1990) procedures. The major statistical analyses employed were the Duncan's multiple range test (DMRT), general linear models (GLM), and regression. The only differences considered significant were those below the 5% level ( $P < 0.05$ ).

### **Duncan's Multiple Range Test**

SAS ranked the means from highest to lowest and grouped them into all possible pairs. The standard error of the difference between the means was computed and compared to the mean pairs. If the standard errors did not overlap, then the pair was considered to be statistically different (Gomez and Gomez, 1984). The treatments receive alphabetical letters. Those that receive the same letter are not considered to be statistically different.

### **General Linear Models**

For a closer look at significance of the means, the random variation of the data population (standard deviation) was compared to the means. If the means were calculated from widely scattered data, the GLM did not show any significant difference. (Ott and Mendenhall, 1985). GLM is a type of analysis of variance and was used in this study because of the differing number of pots for each treatment

## Regression Analysis

Many of the data sets have independent variables such as residual loading, P addition, and PAC addition. The resulting yields and plant composition are dependent variables which can be described with equations obtained with regression analysis. The method of least squares is the type of regression analysis used in this study with linear and non-linear variables. The correlation coefficient ( $r^2$ ) of the regression equation is an indicator of the quality of the equation. The closer  $r^2$  is to 1, the better the data fit the line (Ostle, 1954). For determining if linear or quadratic equations best represented the data, the coefficients of each equation were tested for significance. The coefficients of equations in this study have a significance of 0.95 or higher.

## Results and Discussion

## ***First Fescue Study***

### **Residual Addition**

While treatment effects can be compared to actual yields in larger field plots, values in this study may differ because both nutrients and toxins were not free to migrate. Therefore, the impacts of residual levels were magnified both positively and negatively.

Yield decreased with residual addition with the probability of error being 0.0001 (Figure 1 on page 40). The three highest yielding treatments had no residual addition. Four of the six lowest yielding treatments (excluding PAC) had a 4% residual addition. Yield results are presented in Table 8 on page 41. Average yield without residual application was 4.34 grams per pot. Yield was reduced by an average of 0.28 grams for each 1% increase in residual application.

Manganese levels in plant tissue increased with higher residual loading (Figure 2 on page 42). The probability of error is 0.0001. The maximum plant requirement of Mn in tissue is approximately 250-400 mg/kg (Donohue and Hawkins, 1979). This level was greatly exceeded with the 4% residual addition and no lime. Table 8 on page 41 shows the average values for tissue Mn and its relation to lime and residual addition. P addition had no effect on fescue tissue Mn.

Originally, Cu in the residual was thought to cause possible problems with plant growth. Copper sulfate is used to control algal problems in the reservoir which supplies the Newport News water treatment plant. The Cu might enter the residual and effect their suitability for land application. The Cu in plant tissue increased with higher residual loadings. However,

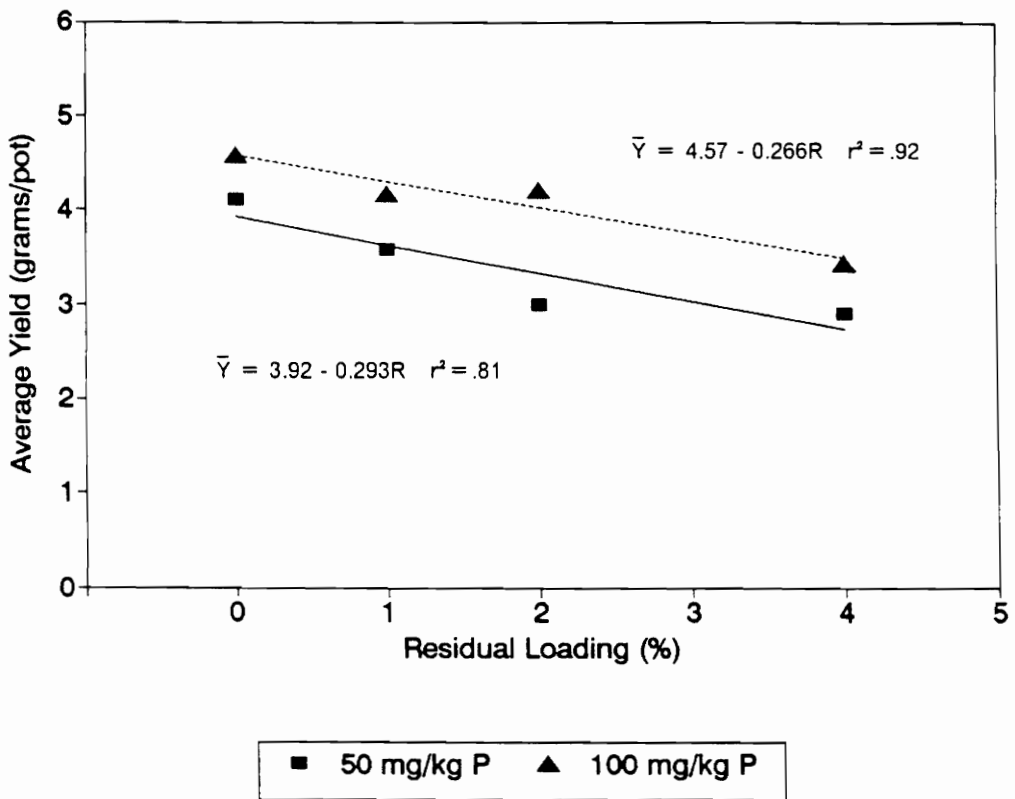


Figure 1. Average fescue yield ( $\bar{Y}$ ) versus residual application (R) for two P loading rates: Residual % is by weight in soil

**Table 8. Effects of Residuals, P, and Lime Addition on Average Fescue Yield and Mn and P Concentrations in Tissue**

Residual Loading Rate (%)	P Addition (mg/kg)	Lime	Avg. Fescue Yield (g)	Tissue Mn (mg/kg)	Tissue P (%)
0	50	no	3.83	560	0.287
0	100	no	4.87	480	0.318
0	50	yes	4.38	243	0.233
0	100	yes	4.28	238	0.298
1	50	no	3.56	810	0.240
1	100	no	4.06	816	0.293
1	50	yes	3.62	327	0.235
1	100	yes	4.27	287	0.275
2	50	no	3.31	1081	0.228
2	100	no	4.16	1101	0.260
2	50	yes	2.71	612	0.233
2	100	yes	4.27	465	0.268
4	50	no	2.86	1551	0.230
4	100	no	3.54	1459	0.248
4	50	yes	2.97	847	0.233
4	100	yes	3.35	824	0.268
2+PAC	50	no	1.69	333	0.205
2+PAC	100	no	1.89	320	0.237
2+PAC	50	yes	1.55	307	0.160
2+PAC	100	yes	2.03	350	0.273

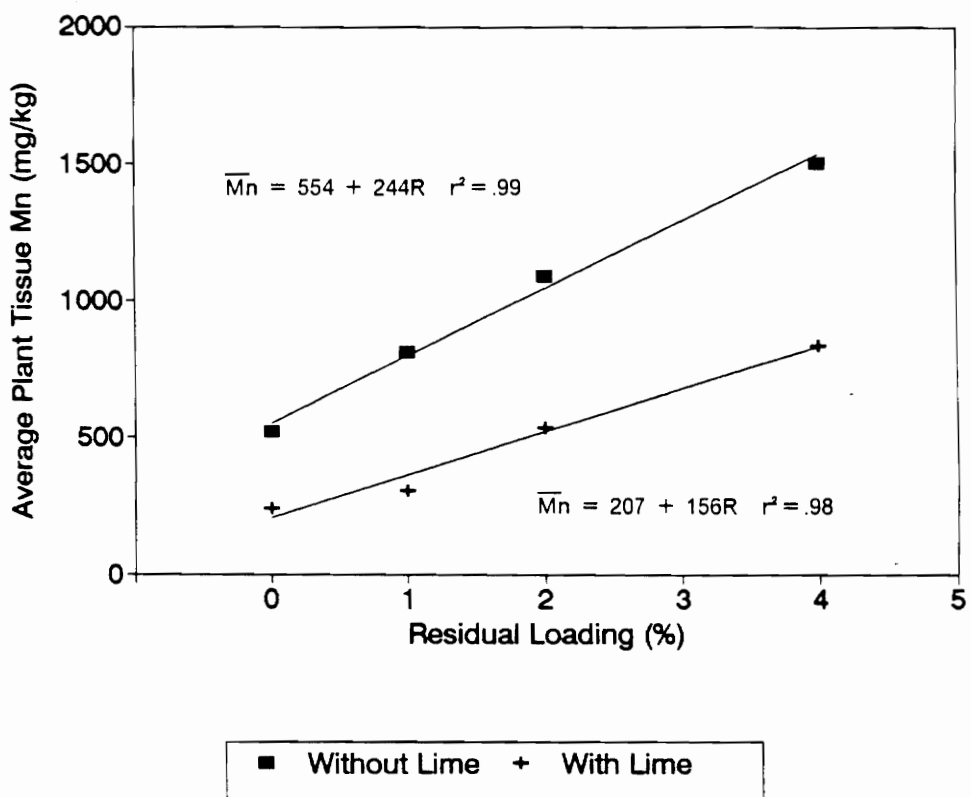


Figure 2. Average plant Mn tissue concentrations ( $\bar{Mn}$ ) versus residual addition (R) with and without lime addition: Residual % is by weight in soil

Figure 3 on page 44. shows that Cu levels in plant tissue were within normal ranges. No plant exceeded 22 mg/kg in the tissue, and normal levels are 6 to 20 mg/kg (Donohue and Hawkins, 1979). The addition of P and lime had no effect and plant tissue Cu.

The addition of residual to the soil reduced the amount of P in plant tissue with a 0.0001 probability of error (Table 8 on page 41). Figure 4 on page 45 shows this reduction; however, no regression was calculated due to the reversal of tissue P concentrations at the 1% residual loading rate. Normal fescue levels are 0.30 to 0.50 % (Donohue and Hawkins, 1979). Only one treatment reached this level - 0% residual, 100 mg P/kg, and no lime addition; however, lime addition had no significant effect on fescue tissue P.

## **Phosphorus Addition**

The addition of 100 mg P/kg to the soil increased plant growth and the amount of P in plant tissue with a 0.0001 probability of error in both cases. Six of the seven highest yielding treatments had 100 mg/kg P added to the soil. The four lowest yielding treatments (excluding PAC) had 50 mg/kg P added to the soil. Pots that received 50 mg/kg P yielded an average of 4.00 g of plant mass without residual application. Yields were reduced on the average by 0.28 g for each 1% increase in residual application. Pots that received 100 mg/kg P yielded an average of 4.53 g without residual application. Yields were reduced on the average by 0.27 g for each 1% increase in residual application. Figure 1 on page 40 shows the increase in yield as a function of increased P addition. Pots that received 100 mg P/kg averaged a 13% higher yield and 20% more P in plant tissue than pots with 50 mg P/kg. Nine of the ten treatments with the highest P in plant tissue had 100 mg/kg P added to the soil (Table 8 on page 41). The eight treatments with the lowest P in plant tissue had 50 mg/kg P added to the soil.

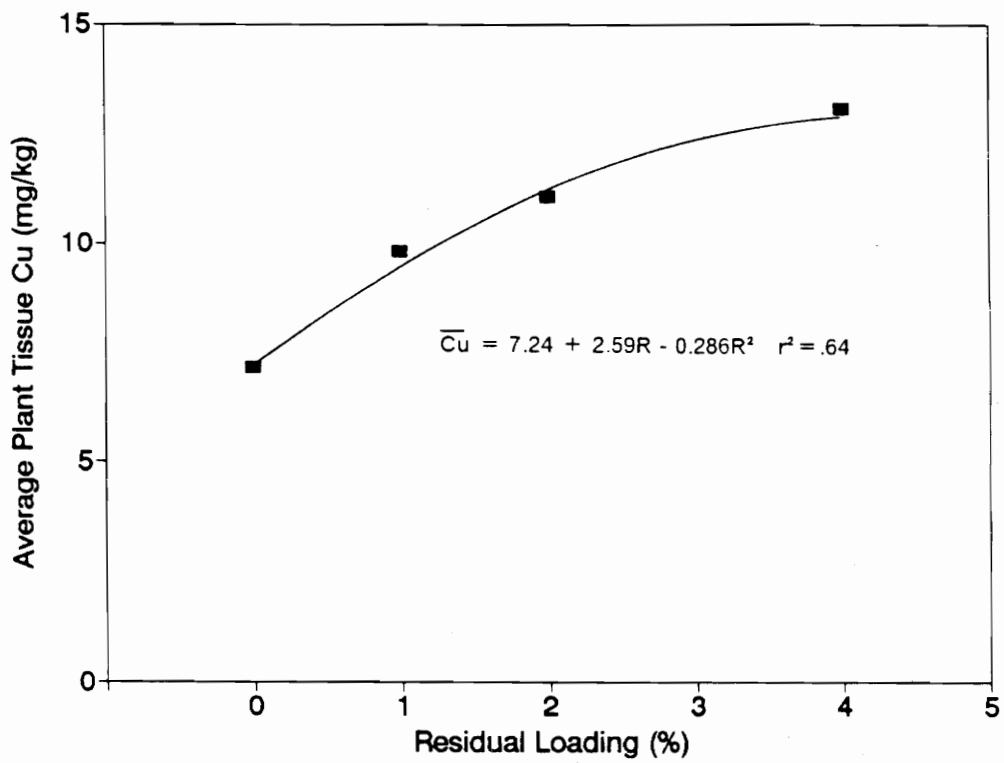


Figure 3. Average plant tissue Cu ( $\bar{Cu}$ ) versus residual loading (R) for all treatment combinations: Residual % is by weight in soil

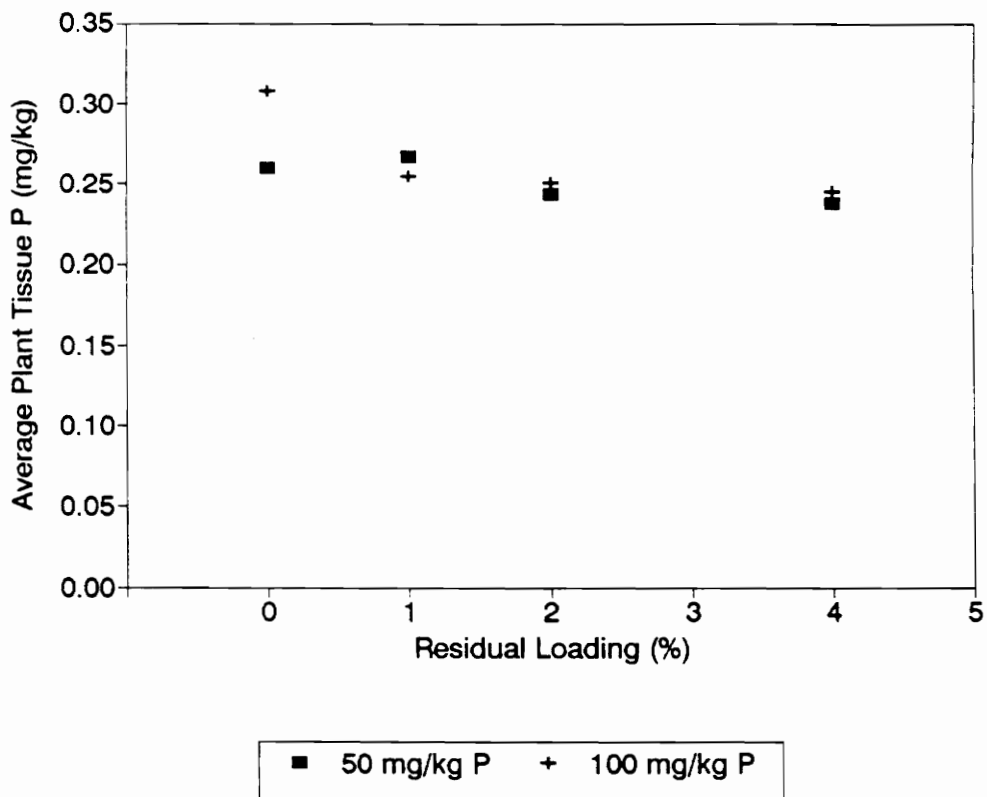


Figure 4. Average plant tissue P versus residual loading at two P addition levels: Residual % is by weight in soil

## Unused PAC Addition

The addition of unused PAC reduced yield and increased plant tissue boron levels (Table 9 on page 47). Pots that received 50 mg/kg P and 2% residual + 2.2% PAC had an average yield of 1.62 g - a 46% reduction in yield compared to pots with 50 mg/kg P, 2% residual, and no PAC.

Pots that received 100 mg/kg P and 2% residual + 2.2% PAC had an average yield of 1.96 g - a 54% yield reduction compared to pots with 100 mg/kg P, 2% residual, and no PAC.

Boron levels were extremely high in the plants grown with unused PAC. The maximum plant B requirement is approximately 20-30 mg/kg (Donohue and Hawkins, 1979). The average concentration of B in the plants with unused PAC in the soil was 435 mg/kg. The unused PAC contains approximately 409 mg B/kg.

## Lime Addition

The addition of lime to the soil had no effect on fescue yield with the probability of error being 0.79. However, Mn in the plant tissue tended to be lower when lime was added with a 0.0001 probability of error (Figure 2 on page 42). Plant yield with no lime addition averaged 3.38 grams per pot. When lime was added, average yield dropped slightly to 3.34 grams per pot. The target pH of 6.5 (where lime was added) was only reached in pots that contained unused PAC and lime (Table 20 on page 88). Soil pH increased with increased residual loading.

**Table 9. Effects of Unused PAC Additions on Yield and Tissue B Concentrations**

Residual Loading Rate (%)	P Addition (mg/kg)	Lime	Avg. Yield* (g)	Tissue B* (mg/kg)
2	50	no	3.31a	7.3a
2	100	no	4.16a	8.5b
2	50	yes	2.71b	8.7c
2	100	yes	4.27bc	6.5d
2 + PAC	50	no	1.69d	462.0e
2 + PAC	100	no	1.89d	426.7f
2 + PAC	50	yes	1.56cd	385.0g
2 + PAC	100	yes	2.03cd	467.3h

\*Treatments with the same letter are not significantly different below the 5% level.

## ***Second Fescue Study***

The objective of the second fescue study was to investigate the effects on plant growth of P, Mn, and residual combined with various forms of PAC. The specific treatments employed are presented in (Table 5 on page 26). Residual application rate was held constant at 2% (Residual 1) except for one treatment of 2.88% Residual 2 which was obtained from the Newport News water treatment plant during the use of PAC. After a growth period of two and a half months, the yield, soil, and plant tissue analyses produced the following results.

### **P Increment Study**

Fescue yields were increased by increased P addition as shown by Figure 5 on page 49. with a 0.0001 probability of error. The addition of P to the soil in excess of the quantity recommended by soil test requirements (50 mg/kg) increased plant growth. As mentioned in the literature review section and observed in the first fescue study, the binding of P by the land application of residual can result in reduction in plant growth if no P soil amendments are made.

According to the regression equation in Figure 5 on page 49, maximum plant yield with a 2% residuals loading will occur with 214 mg P/kg added to the soil. However, this value is beyond the range of the P additions tested and should be used with caution. The 200 mg P/kg addition is considered to be the maximum. In order to minimize excessive nutrient applications, 90% of maximum yield is often used as the yield goal (Reneau, 1991). To reach the 90% fescue yield levels, only 140 mg P/kg addition is required. Therefore, P application can be reduced by 30% with only a 10% reduction in yield. A reduced P application is important in areas where excess P can cause eutrophication in nearby water bodies.

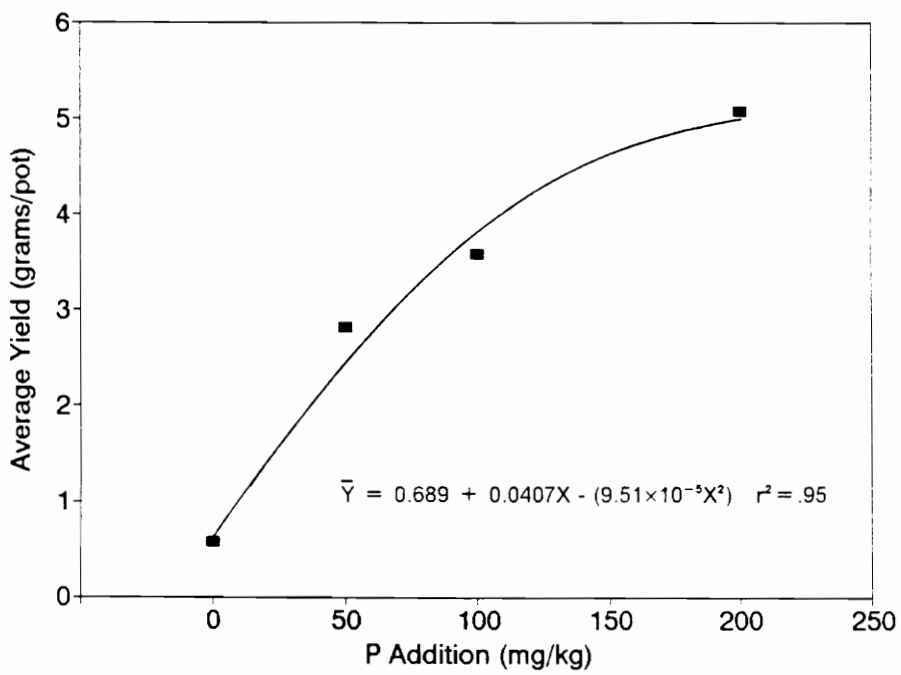


Figure 5. Average fescue yield (Y) versus P addition (X): P was added to the soil in the form of monocalcium phosphate

Phosphorus in plant tissue increased with P addition as seen in Figure 6 on page 51, with a 0.0001 probability of error. The plants grown with no P addition had the lowest P in plant tissue.

The optimum fescue P tissue level is 0.30 to 0.50 % which was not exceeded by the plants grown in this study (Donohue and Hawkins, 1979).

## **Mn Addition**

Manganese addition did not affect yield as indicated in Figure 7 on page 52. However, the Mn addition significantly increased the concentration of Mn in the plant tissue as shown in Figure 8 on page 53 with a 0.0007 probability of error.

According to Donohue and Hawkins (1979) the maximum plant Mn requirement is 250 to 400 mg/kg. This value was exceeded in all fescue tissue from pots with added Mn. However, this level was not phytotoxic as indicated by the stable fescue yield in Figure 7 on page 52. The levels of tissue Mn in these treatments were generally lower than in the first fescue study. This reduction may be attributable to the higher lime addition which resulted in a lower soil pH or because the residual contains forms of Mn other than MnO<sub>2</sub> (s).

## **PAC Addition**

### ***Effects of 0.88% PAC Additions***

#### **Yield**

The addition of 0.88% PAC in various forms - unused, washed, and Residuals 2 (containing

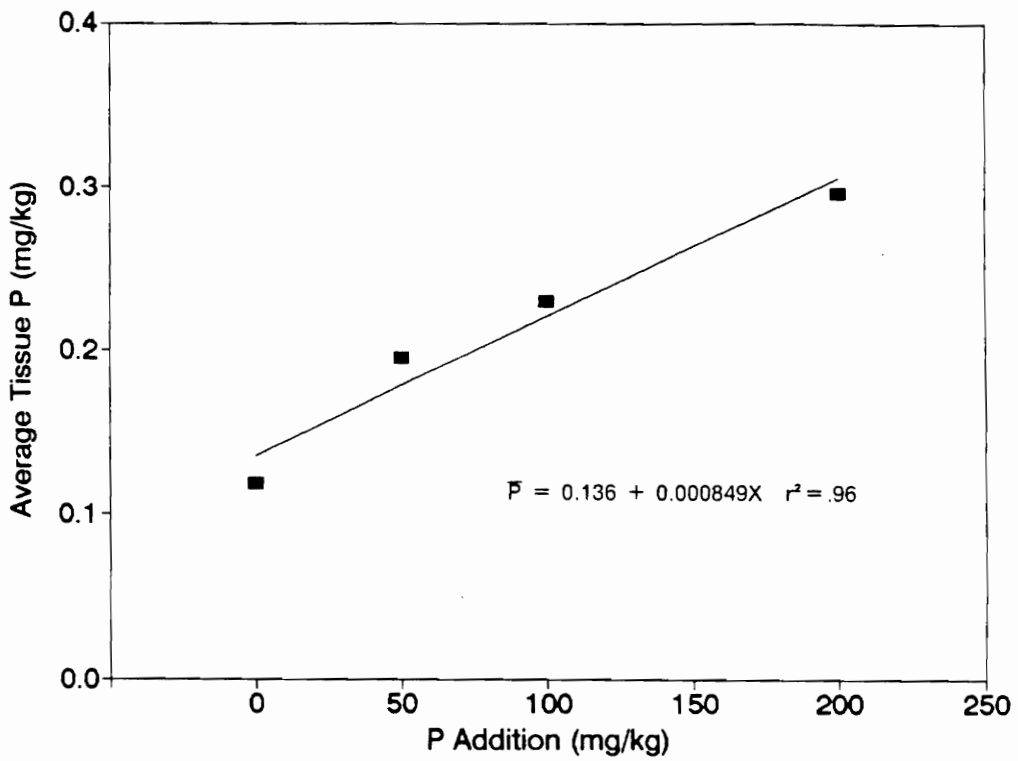
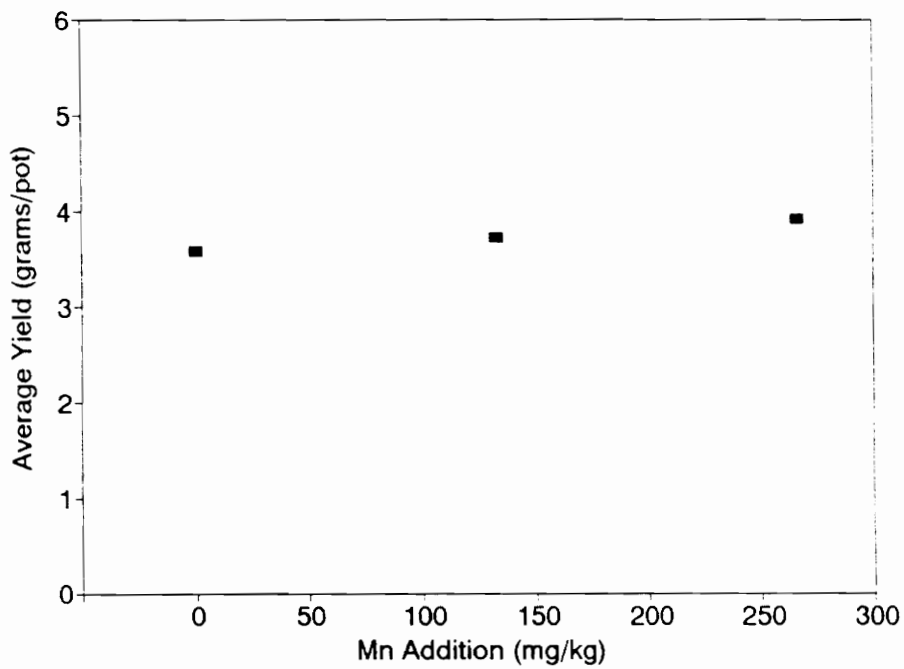


Figure 6. Average fescue tissue P ( $\bar{P}$ ) versus P addition (X): P was added to the soil in the form of monocalcium phosphate



**Figure 7. Average fescue yield versus Mn addition:**  $\text{MnO}_2$  was added to the soil to reproduce an extra 2% and 4% residual loading

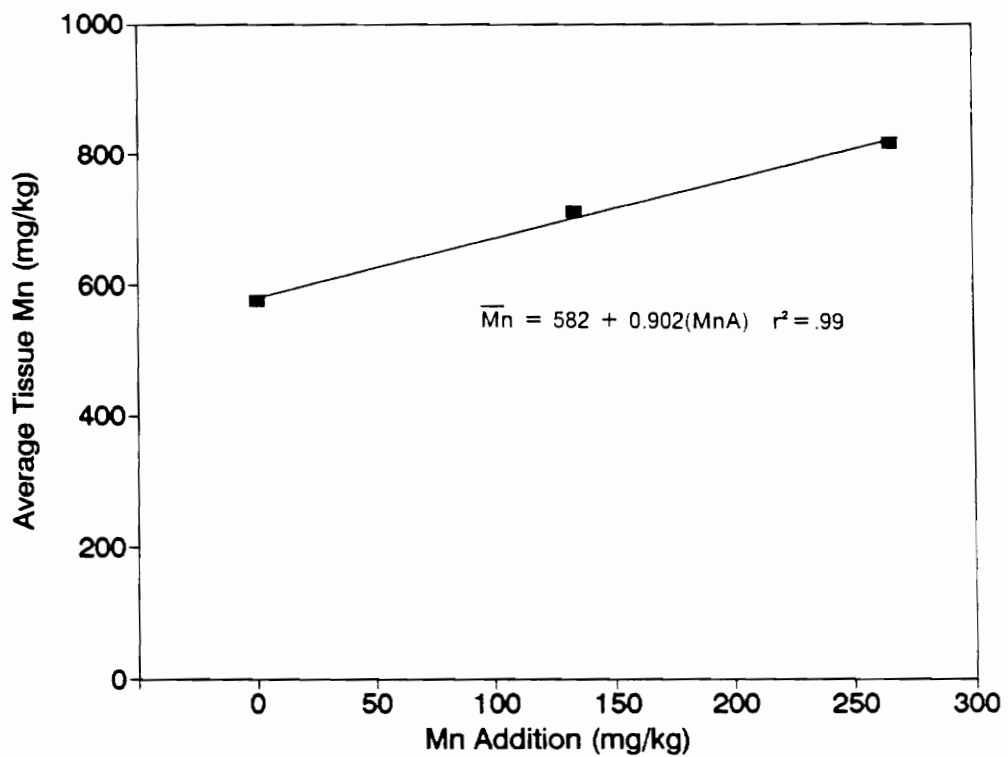


Figure 8. Mn in plant tissue ( $\bar{Mn}$ ) versus Mn addition (MnA):  $MnO_2$  was added to the soil to reproduce an extra 2% and 4% residual loading

spent PAC) - altered the plant growth and composition. The controls (no PAC), the 0.88% unused PAC, and 0.88% washed PAC additions were not significantly different with respect to yield (Table 10 on page 55). However, the addition of Residual 2 to the soil had a higher yield than any other treatment. Residual 2 contained almost three times as much P as Residual 1. This higher P level might account for the increased fescue growth since fescue yield increased with P addition as mentioned previously.

The land application of Residual 2 will not be a detriment to fescue growth. Treatments that employed unused and washed PAC produced lower yields than the treatment with Residual 2, but unused and washed PAC are not land applied.

#### **Plant Tissue Boron Content**

All 0.88% PAC treatments were different from each other with respect to plant tissue B (Table 10 on page 55). Washing the PAC removed some B; however, the addition of washed PAC to the soil still increased B in the plant tissue above the control level. The unwashed (unused) 0.88% PAC treatments had higher B levels than all other 0.88% PAC treatments. The levels of B in Residual 2 treatments and the controls were not different. Residual 2 was obtained during the use of PAC by the water treatment plant.

#### ***Effects of Unused PAC Additions***

Unused PAC was added at two loading rates of 0.88% and 2.2%. The addition of unused PAC lowered plant yield with a 0.0013 probability of error. The addition of unused PAC increased B in tissue with a 0.0001 probability of error. The yield decreased with the addition of unused PAC (Figure 9 on page 56).

**Table 10. Effects of PAC Addition on Fescue Yield and B Tissue Levels**

PAC Addition (%)	Avg. Yield <sup>1</sup> (g/pot)	Tissue B <sup>1</sup> (mg/kg)
No PAC	3.577a	8a
2.88 Residual 2 <sup>2</sup>	5.147b	8a
0.88 Washed	3.567a	31b
0.88 Unused	3.203a	86c
2.2 Unused	1.625c	195d

<sup>1</sup>Treatments with the same letter in the same column are not significantly different below the 5% level.

<sup>2</sup>Newport News residuals with spent PAC

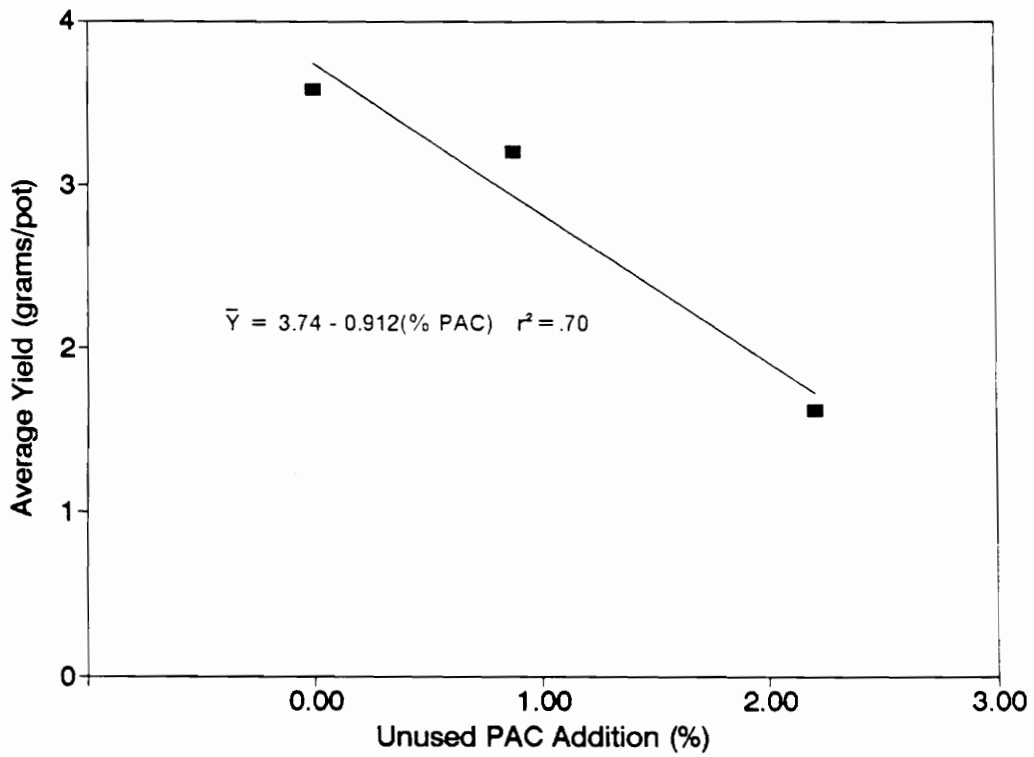


Figure 9. Average fescue yield ( $\bar{Y}$ ) versus unused PAC addition (UP): % PAC is by weight in the soil

The B content of plant tissue increased to 195 mg/kg as PAC addition increased. The normal B plant requirement of 10 to 30 mg/kg was exceeded by both unused PAC addition rates (Donohue and Hawkins, 1979). (Figure 10 on page 58).

High levels of B in plant tissue resulted in reduced plant growth as shown in (Figure 11 on page 59).

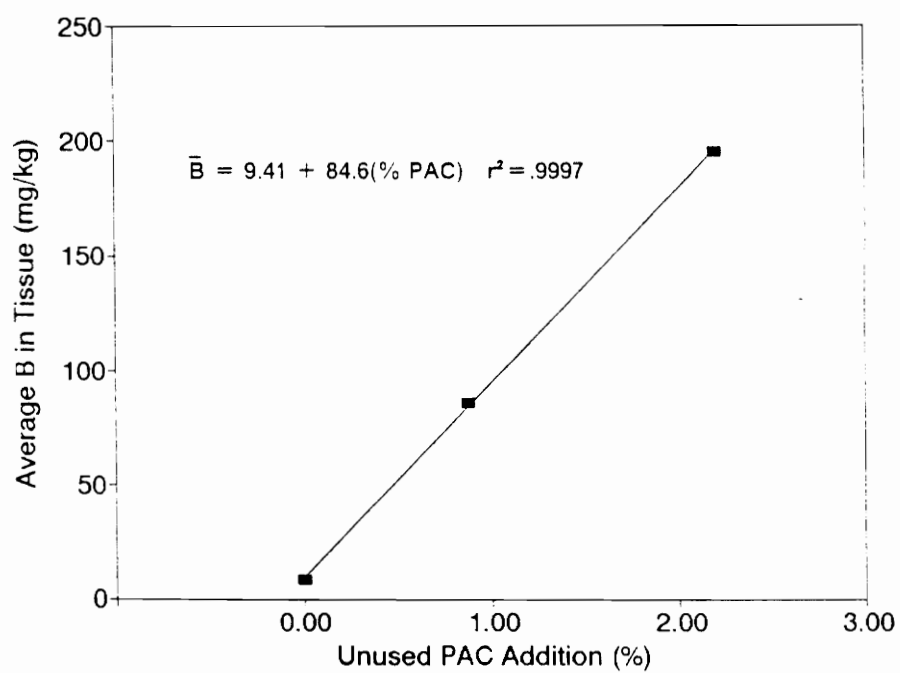


Figure 10. Average B in tissue ( $\bar{B}$ ) versus unused PAC addition (UP): % PAC is by weight in the soil

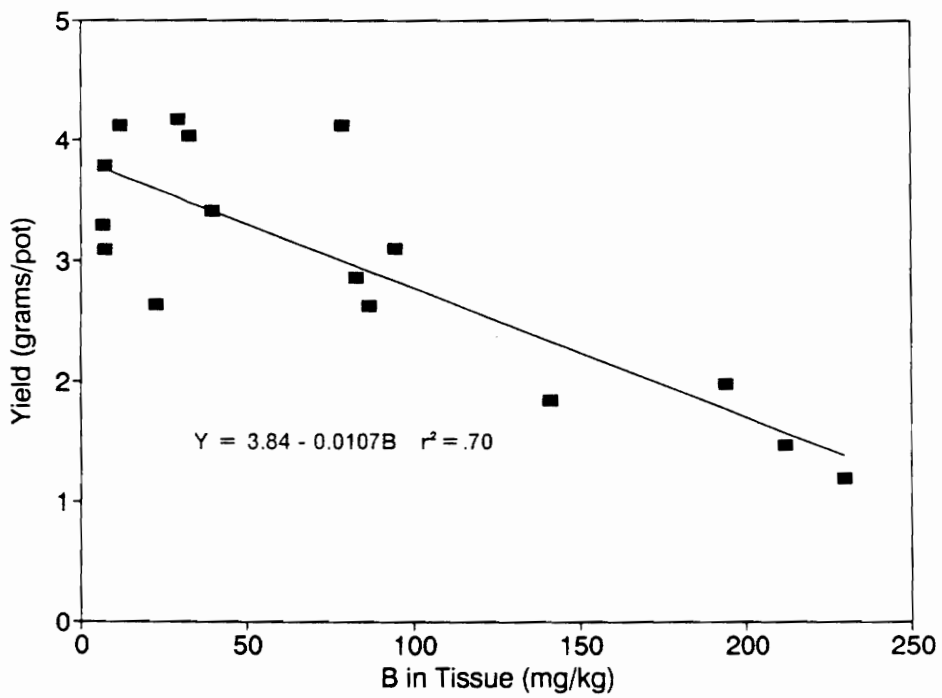


Figure 11. Fescue yield versus B in tissue

## ***Pine Seedling Study***

The high mortality of the pines made statistical analysis difficult. The yield data proved to be of little significance; however, the tissue analysis demonstrated some significant trends. No trees survived the treatment with 2.2% PAC and 50 mg/kg P.

### **Yield**

The base of each needle cluster was weighed separately from the needles themselves. New needle weight is the best indicator of yield because the trees are of slightly different sizes when planted. (Table 30 on page 100). lists the various parameters used to determine yield. However, yield did not appear to be a function of residuals loading as seen in Figure 12 on page 61 and Table 11 on page 62. Yield decreased slightly with residual loading, but the probability of error is 0.485. The trees grown with unused PAC and 0 mg P/kg had the lowest growth in nearly all parameters.

### **Phosphorus Addition**

Yield increased with P addition, but the probability of error is 0.160. Phosphorus in plant tissue was higher in plants with 50 mg/kg P addition than with no P addition with a 0.0001 probability of error. All treatments with P addition had more P in the plant tissue.

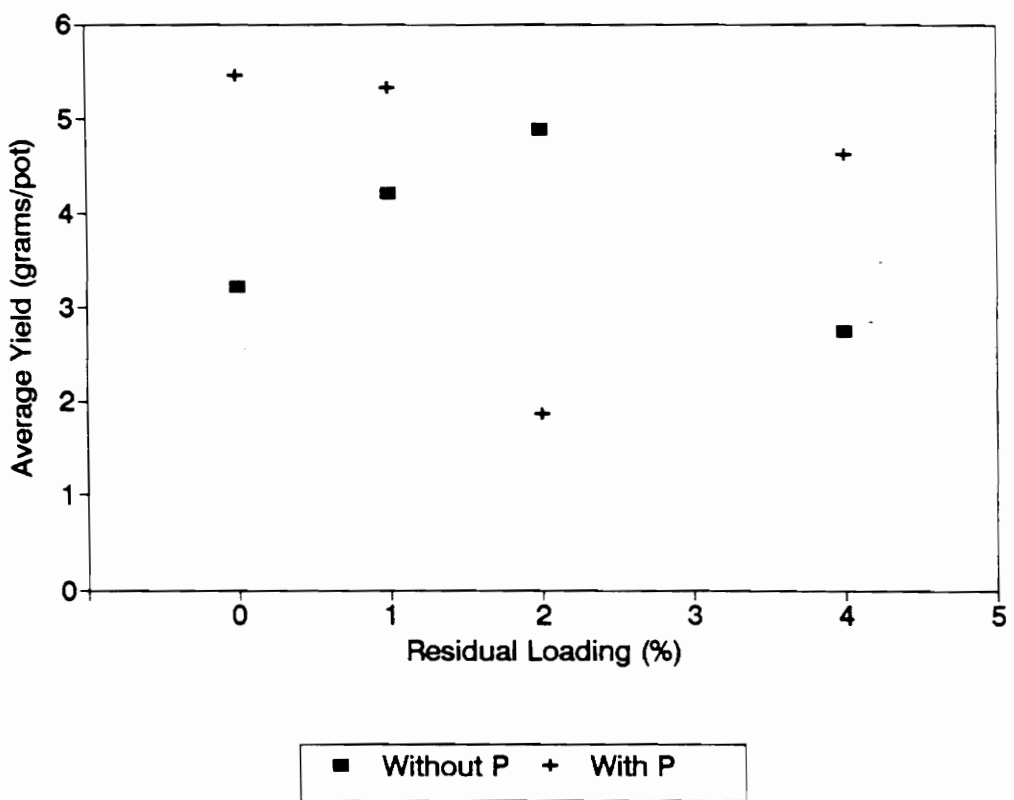


Figure 12. Average pine new needle growth versus residual loading rate with and without P addition: Residual % is by weight in soil

**Table 11. Treatment Effects on Pine New Needle Growth**

Residual Loading Rate (%)	P Added (mg/kg)	Avg. Yield* (g)	Tissue P* (mg/kg)
0	0	3.22abc	896bc
0	50	5.46a	1391ab
1	0	4.21ab	995abc
1	50	5.33a	1469a
2	0	4.88ab	780c
2	50	1.87c	1219abc
4	0	2.75bc	791c
4	50	4.62ab	1505a
2 + PAC	0	1.46c	1282abc

\*Treatments with the same letter are not significantly different below 5% level.

### ***Summary of Loblolly Seedling Growth***

The high mortality of the pines required two replants. The number of growth days for each tree is listed in (Table 30 on page 100). The replanted trees were analyzed for yield and tissue composition, but the results are compromised because of the differing number of growth days. Some pots showed strong growth and budding while others died even after multiple plantings.

## ***Soil Studies***

### **Phosphorus Sorption**

The residual loading rates in this experiment were the same as those used in the first fescue study - 0, 1, 2, and 4%. Identical loadings with Residual 2 were also studied. Residual 1 and 2 contain 1380 and 3870 mg P/kg, respectively. However, because of their established P binding capability, experimentation was initiated to determine the extent to which P would be adsorbed or desorbed from the soil/residual mixtures (Table 12 on page 65).

As in the first fescue study, increasing amounts of P were bound as the residual loading rate increased with the 0 mg/L initial P addition being the only exception. Phosphorus was extracted from the soil mixtures and put into solution at the 0 mg/L rate with all residual loadings.

In the second fescue study, plants grown with Residual 2 had higher yields and higher levels of P in the plant tissue than similarly loaded pots with Residual 1. However, the P sorption study found that P binding was very similar with both types of residuals. Figure 13 on page 67 and Figure 14 on page 68 show the Langmuir isotherm regression equations used to develop Table 13 on page 69. This table shows the equations and adsorption maximums of the different residual loadings. The data fit the regression equations well with the lowest  $r^2$  value being .95. However, the equations should be used with caution due to the apparent curve in the data. The Langmuir equations could be used to estimate soluble inorganic P which was available for plant uptake or lost in runoff as a function of residual addition and fertilization. These equations were developed for a mixture of Slagle soil and Newport News water treatment residuals. To further test the relationship between P binding and residual addition, Freundlich equations were developed from Figure 15 on page 70 and Figure 16 on page 71

**Table 12. P Sorption Study Results**

Soil (g)	Residual (g)	Initial P Concentration (mg/L)					
		0	10	20	40	80	160
		Average Final P Concentration (mg/L)					
3.00	0	.0439	.244	1.20	5.40	22.3	63.9
2.97	.03 Residual 1	.0136	.090	.248	3.11	13.2	61.2
2.94	.06 Residual 1	.0174	.079	.131	1.86	12.1	41.4
2.88	.12 Residual 1	.0159	.049	.038	.832	5.88	35.8
2.97	.03 Residual 2	.0120	.029	.165	2.64	8.38	52.2
2.94	.06 Residual 2	.0524	.030	.106	.975	5.23	37.1
2.88	.12 Residual 2	.0594	.015	.052	.606	5.16	20.6

Residual 1 does not contain PAC

Residual 2 was obtained during the use of PAC

The equations are listed in Table 14 on page 72. Residual 2 had slightly higher adsorption maximums than Residual 1.

## **Extractable Boron**

The hot calcium chloride extraction removed an average of 409 mg B/kg from the unused PAC. The unused soil yielded an average of only 0.45 mg B/kg, representing a 900 fold reduction (Table 15 on page 73). Soil taken from pots that had 2% residual, no lime, 50 mg P/kg, and unused 2.2% PAC had an average of 12.3 mg B/kg. Similar pots without PAC averaged only 1.1 mg B/kg, an eleven fold reduction. Table 19 presents the results of the extraction. This experiment confirms that large amounts of B can be extracted from PAC and PAC amended soils even after a four month growth cycle. The greenhouse studies proved that this B is plant available.

## **Ammonium Oxalate and Dithionite-Citrate-Bicarbonate Extractions**

As residual loading increased, both extractable Al and Fe increased with both extraction methods (Table 17 on page 85). This increase in Al and Fe and the decrease of P in plant tissue with residual addition support Dempsey and Elliott's (1989) theory that the metals in alum residual are responsible for P binding. On average, the ammonium oxalate extraction yielded lower levels of Fe than the DCB extraction due to the amorphous and crystalline forms of the Fe present (Figure 17 on page 74 and Figure 18 on page 75).

The Al forms tended to be amorphous while the Fe forms tended to be crystalline. Figure 19 on page 76 demonstrates how an increase in amorphous Al can increase the P adsorption maximum.

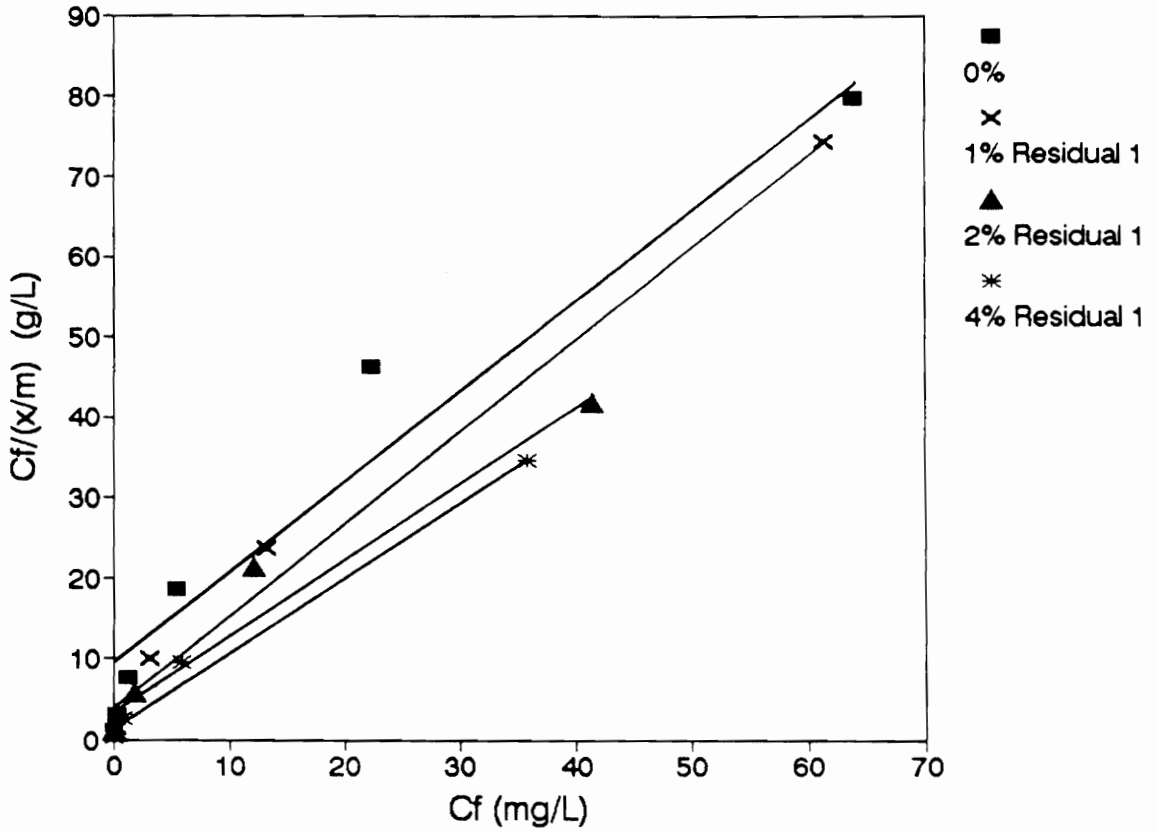


Figure 13. Residual 1 Langmuir Plots: Residual without spent PAC was added to soil at 0, 1, 2, and 4% loading rates.

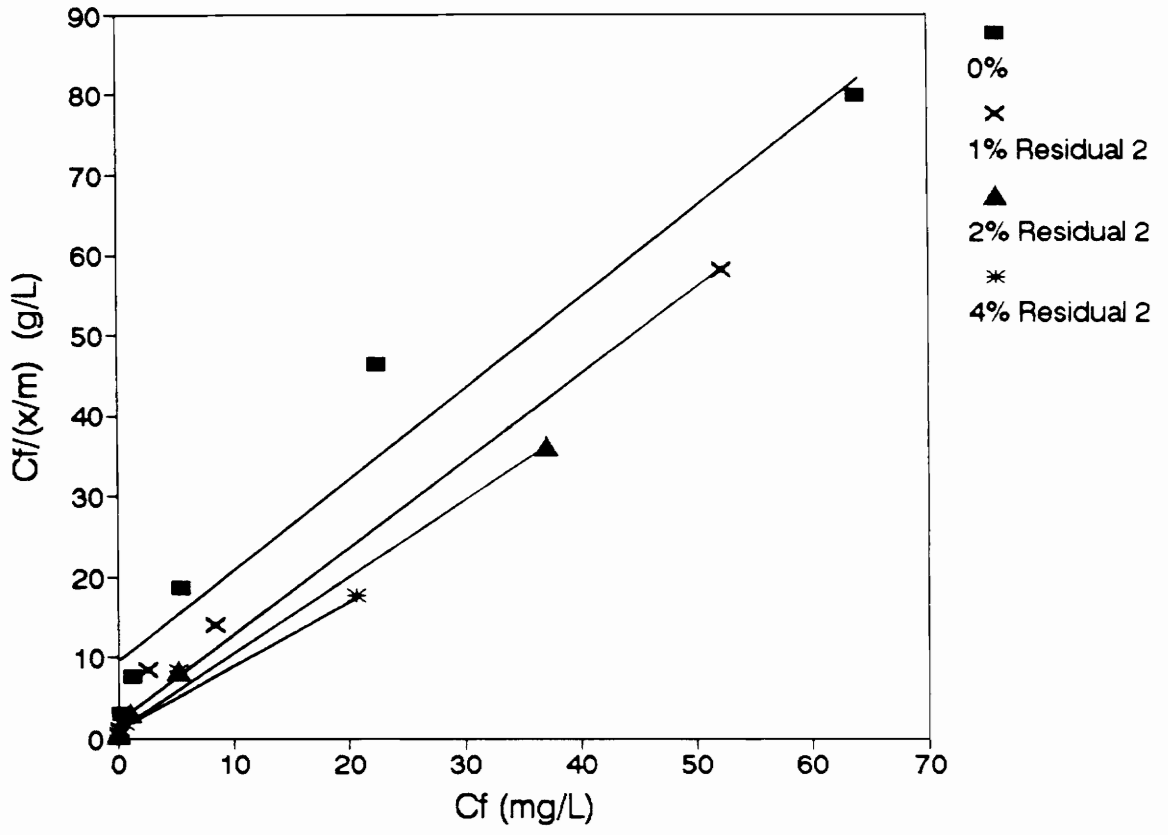


Figure 14. Residual 2 Langmuir Plots: Residual with spent PAC was added to soil at 0, 1, 2, and 4% loading rates.

**Table 13. P Sorption Study Langmuir Equations**

Residual	Equation	r <sup>2</sup>	Adsorption Maximum (b) in mg/g
0%	$P/(x/m) = 9.47 + 1.16P$	.95	0.855
1%, Residual 1	$P/(x/m) = 4.00 + 1.17P$	.99	0.855
2%, Residual 1	$P/(x/m) = 3.33 + .977P$	.95	1.024
4%, Residual 1	$P/(x/m) = 1.53 + .935P$	.99	1.070
1%, Residual 2	$P/(x/m) = 2.85 + 1.07P$	.99	0.935
2%, Residual 2	$P/(x/m) = 1.54 + .942P$	.99	1.062
4%, Residual 2	$P/(x/m) = 1.27 + .832P$	.96	1.202

where P is the concentration of phosphorus in mg/L and x/m is the adsorbate/adsorbent ratio

Residual 1 does not contain PAC

Residual 2 was obtained during the use of PAC

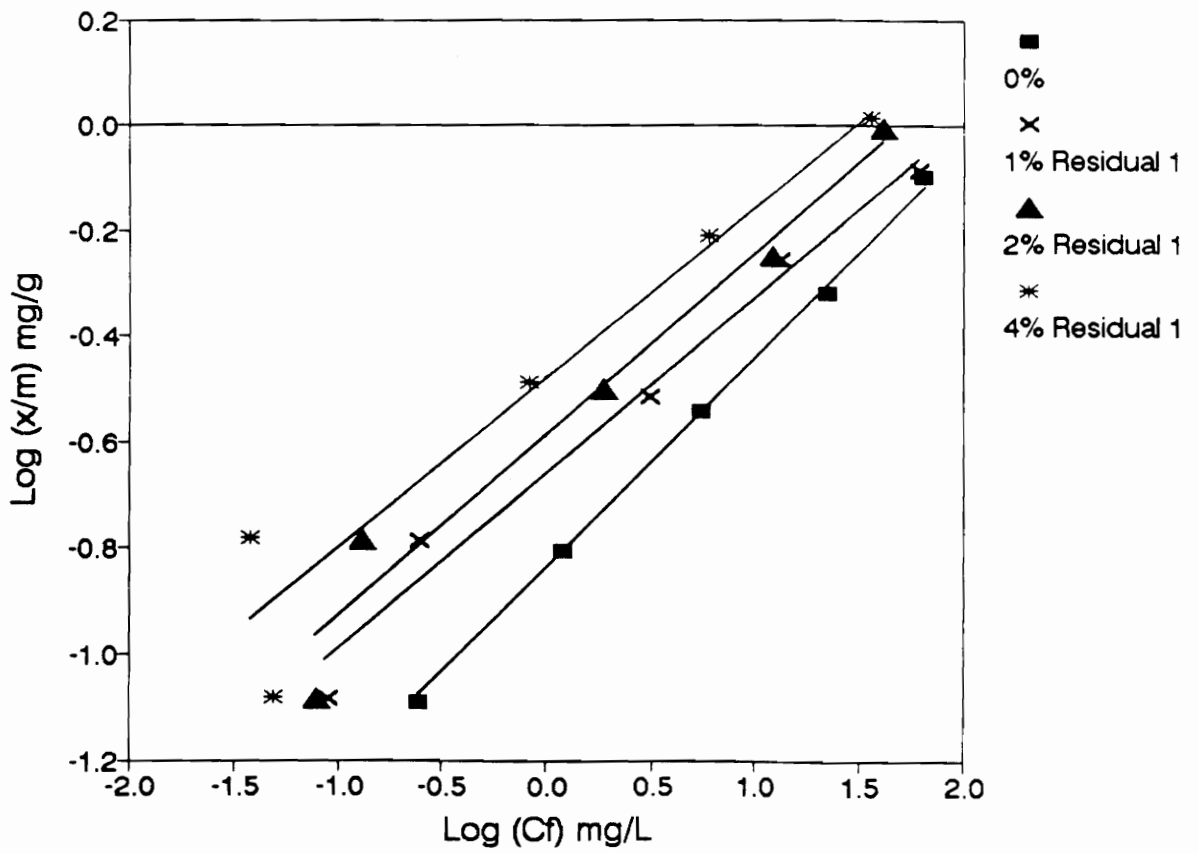


Figure 15. Residual 1 Freundlich Plots: Residual without spent PAC was added to soil at 0, 1, 2, and 4% loading rates.

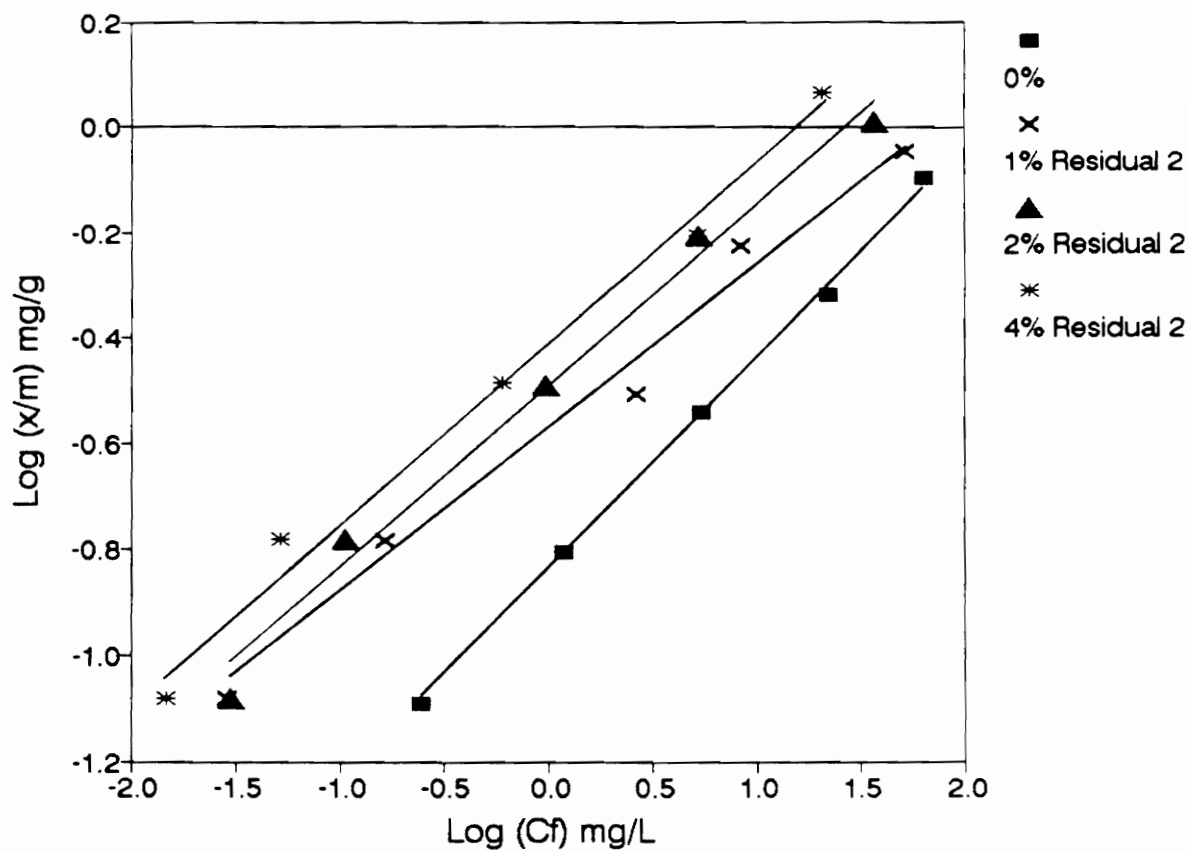


Figure 16. Residual 2 Freundlich Plots: Residual with spent PAC was added to soil at 0, 1, 2, and 4% loading rates.

**Table 14. P Sorption Study Freundlich Equations**

Residual Loading	Equation
0%	$x/m = 2.69Cf^{2.47}$
1%, Residual 1	$x/m = 2.14Cf^{2.97}$
2%, Residual 1	$x/m = 1.78Cf^{2.85}$
4%, Residual 1	$x/m = 1.41Cf^{3.08}$
1%, Residual 2	$x/m = 1.51Cf^{3.16}$
2%, Residual 2	$x/m = 1.41Cf^{2.87}$
4%, Residual 2	$x/m = 1.12Cf^{2.92}$

where  $C_f$  is the final solution concentration in mg/L and  $x/m$  is the adsorbate/adsorbent ratio in mg/g

Residual 1 does not contain PAC

Residual 2 was obtained during the use of PAC

**Table 15. Boron Extraction from Soil, PAC, and Soil/Residual Mixtures**

	Boron Levels (mg/kg)			
	Virgin Soil	PAC	Used Soil without PAC	Used Soil with PAC
Replication #1	.404	415	1.800	12.0
Replication #2	.424	417	.809	12.8
Replication #3	.525	395	.728	12.1
Average	.451	409	1.110	12.3

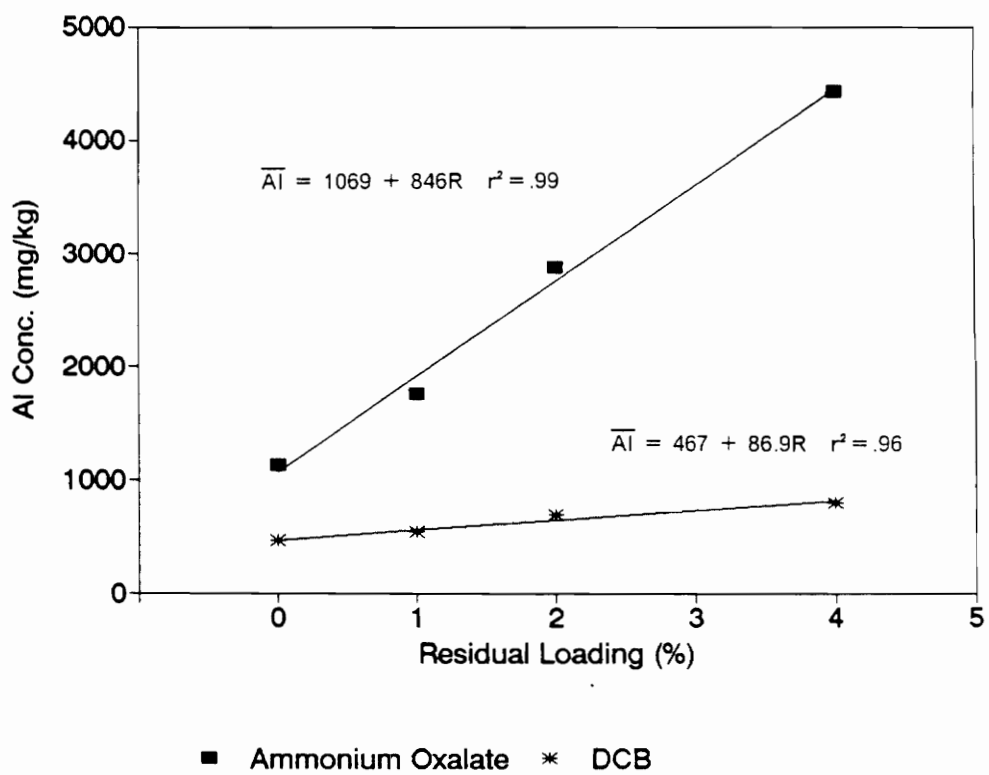


Figure 17. Relationship between residual loading (R) and Ammonium Oxalate and DCB extractable Al (AI)

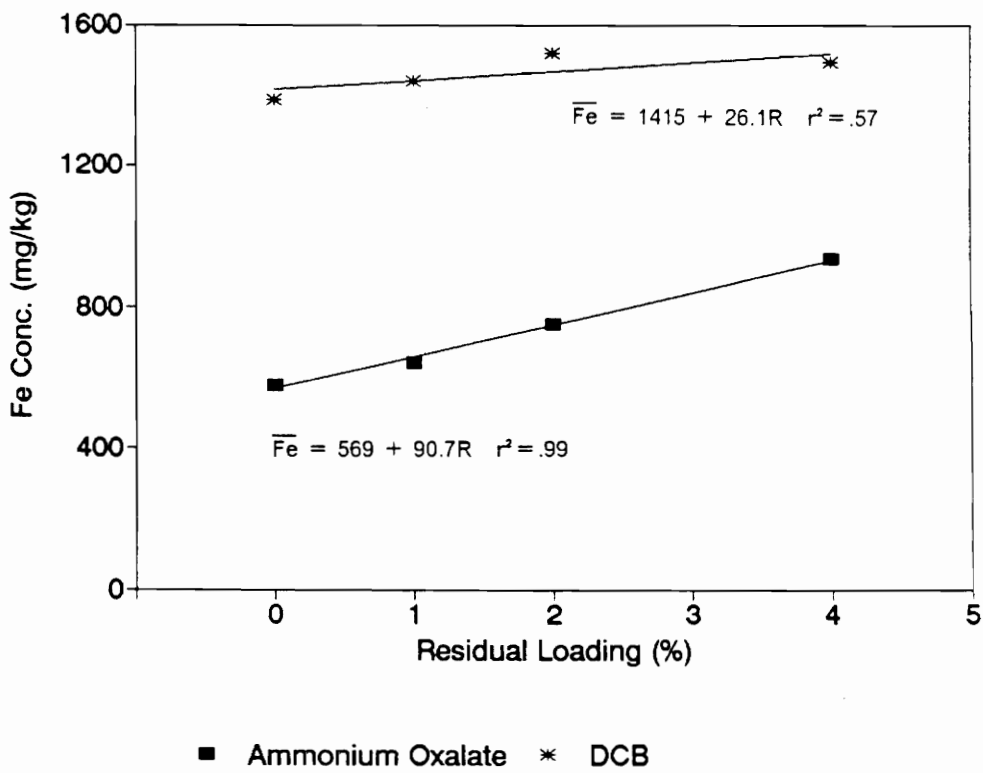


Figure 18. Relationship between residual loading (R) and Ammonium Oxalate and DCB extractable Fe ( $\bar{Fe}$ )

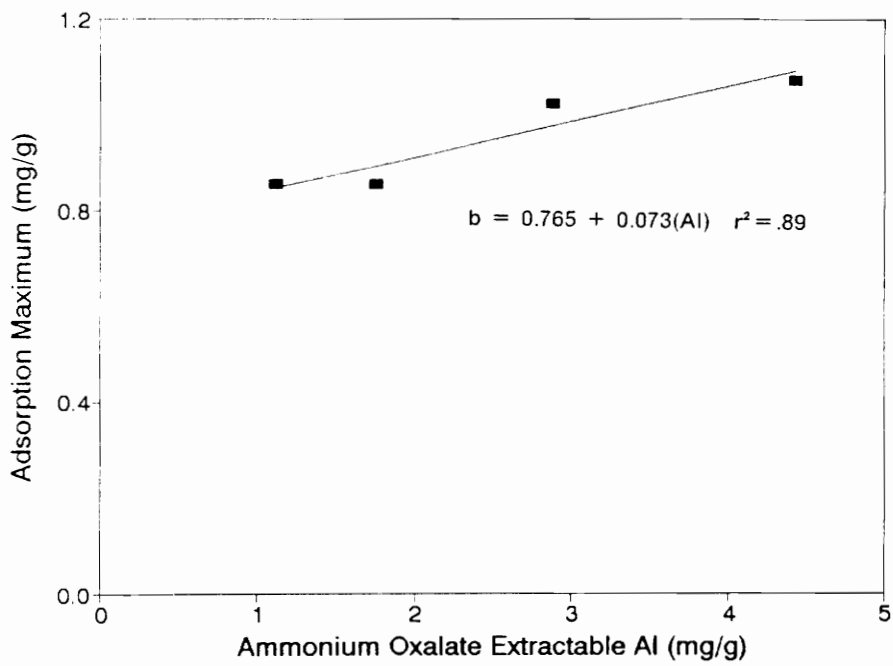


Figure 19. Langmuir adsorption maximum (b) versus extractable aluminum (AI)

The soil/residuals ratios were identical in the P sorption, Ammonium Oxalate, and DCB experiments. The residual contain large amounts of Al and Fe as shown in Table 17 on page 85. The soils contained higher levels of amorphous Al and Fe with higher residual loading after the four month growth cycle (Table 16 on page 78). The higher Al and Fe levels increased the P adsorption maximum of the soil and thus decreased plant available P. This reduction in plant available P was the primary cause for growth reduction in the greenhouse studies.

**Table 16. Ammonium Oxalate and DCB Extraction Means in mg/kg**

Residual Loading Rate (%)	Ammonium Oxalate		Dithionite-Citrate-Bicarbonate	
	Al	Fe	Al	Fe
0	1127 a	580 a	461 a	1387 a
1	1760 b	642 b	535 b	1442 a
2	2880 c	753 c	683 c	1522 b
4	4434 d	934 c	799 d	1492 c

Treatments with the same letter are not significantly different below the 5% level.

## Summary and Conclusions

1. The first fescue study proved the addition of Residual 1 to soil can reduce plant growth. Residual 1 does not contain PAC. The residual loading also appeared to increase Mn levels in the plant tissue. Doubling the P application rate increased fescue yields by approximately 13%, suggesting that the decreased yield is due to P adsorption by the residual. Plants with the unused PAC treatment had very high levels of B in the tissue, excess tissue B symptoms, and the lowest plant yields. Liming had no significant effect on yield.
2. In the second fescue study, all treatments received 2% residual loading rate. The addition of P to the soil increased plant yield; plants with the 200 mg P/kg addition had 80% higher yields than plants that which received 50 mg P/kg. The effects of adding MnO<sub>2</sub> to the soil were minimal indicating that growth reductions caused by the addition of water treatment residual to the soil were not due to MnO<sub>2</sub> in the residual. Plants grown with Residual 2 had higher yields than any other PAC treatment. Residual 2 was obtained during the use of PAC by the water treatment plant. The increased growth might be the result of higher P content of Residual 2. The addition of unused PAC to the soil reduced plant growth as in the first fescue study, presumably due to its growth inhibiting concentrations of B.

3. The high mortality of the pines made statistical analysis difficult, and the results of this portion of the study are of limited value. On average, plant yields decreased slightly with residual addition. However, the decrease in growth was not significant.
4. P was sorbed from solution by mixtures of soil and Residual 1 and Residual 2 (with and without spent PAC). Regressed Langmuir isotherm equations from the data show that adsorption of P increased with increased addition of both types of residual.
5. Large amounts of B were extracted from PAC compared to the very small amounts extracted from the Slagle soil used in this study. Soils amended with unused PAC contained much higher quantities of B than unamended soils. However, the second fescue study demonstrated that residual that contains spent PAC is not a detriment to plant growth. Because of its solubility, B is most likely leached from the PAC during the treatment process.
6. The Ammonium Oxalate and Dithionite-Citrate-Bicarbonate extraction methods both yielded higher levels of Al and Fe as residual loading increased. Aluminum forms in the amended soils were predominantly amorphous while Fe forms were crystalline. The amorphous Al forms are likely to cause a reduction in plant available P when land applied. Reduced levels of plant available P were associated with decreased plant yield.

The greenhouse study and related experiments showed that the water treatment residual used in this study can be land applied at rates of 1 to 4% on Slagle and similar soils with minimal impact on fescue growth. The growth inhibiting effects caused by the reduction of available P can be overcome through proper fertilization. The data indicate that routine soil test procedures can probably be used to make recommendations for water treatment residual application to soils in the eastern United States. However, since greenhouse data cannot be directly translated to the field, studies should be conducted under field conditions to confirm greenhouse studies.

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# Appendix A. Experimental Data

**Table 17. Residual Analysis**

All elements are in mg/kg except Se and As which are in  $\mu\text{g}/\text{kg}$

Parameter	Residual 1	Residual 2
TKN	163	252
P	1,380	3,870
K	1,400	592
Ca	6,530	6350
Mg	882	499
Na	419	296
S	6,440	6,310
Zn	164	38
Mn	6,650	3,470
Cu	842	1,510
Fe	19,670	11,800
Al	154,000	150,000
B	82	161
Cd	*	*
Cr	147	26
Ag	*	*
Ni	*	*
Pb	61.4	38.0
Se	2.380	890
As	21.4	1250

\* none detected

Note: All elements were tested on the ICP except for Pb, Se, and As which were tested on an atomic adsorption graphite furnace.

**Table 18. First Fescue Study Variables**

Treatment #	Pot #	Residual (%)	Lime	P (mg/kg)
1	01-04	0	no	50
2	05-08	0	no	100
3	09-12	0	yes	50
4	13-16	0	yes	100
5	17-20	1	no	50
6	21-24	1	no	100
7	25-28	1	yes	50
8	29-32	1	yes	100
9	33-36	2	no	50
10	37-40	2	no	100
11	41-44	2	yes	50
12	45-48	2	yes	100
13	49-52	4	no	50
14	53-56	4	no	100
15	57-60	4	yes	50
16	61-64	4	yes	100
17	65-68	2 + 2.2% PAC	no	50
18	69-72	2 + 2.2% PAC	no	100
19	73-76	2 + 2.2% PAC	yes	50
20	77-80	2 + 2.2% PAC	yes	100

Table 19. First Fescue Study Yield Data

Pot #	Mass (g)	Pot #	Mass (g)	Pot #	Mass (g)
<i>0% LOADING</i>		<i>2% LOADING</i>		<i>2% + PAC LOADING</i>	
<b>No Lime, 50 mg/kg P</b>		<b>No Lime, 50 mg/kg P</b>		<b>No Lime, 50 mg/kg P</b>	
1	3.94	33	3.05	65	1.93
2	5.23	34	3.82	66	1.90
3	3.09	35	3.21	67	1.23
4	3.06	36	3.16	68	*
<b>No Lime, 100 mg/kg P</b>		<b>No Lime, 100 mg/kg P</b>		<b>No Lime, 100 mg/kg P</b>	
5	5.76	37	4.95	69	1.76
6	5.13	38	4.32	70	2.75
7	4.15	39	3.68	71	1.70
8	4.41	40	3.68	72	1.34
<b>Lime, 50 mg/kg P</b>		<b>Lime, 50 mg/kg P</b>		<b>Lime, 50 mg/kg P</b>	
9	4.79	41	2.70	73	1.45
10	4.95	42	*	74	1.91
11	3.40	43	2.44	75	1.31
12	*	44	2.97	76	*
<b>Lime, 100 mg/kg P</b>		<b>Lime, 100 mg/kg P</b>		<b>Lime, 100 mg/kg P</b>	
13	4.85	45	4.06	77	2.01
14	4.30	46	4.79	78	1.74
15	3.65	47	4.07	79	1.89
16	4.31	48	4.16	80	2.48
<i>1% LOADING</i>		<i>4% LOADING</i>			
<b>No Lime, 50 mg/kg P</b>		<b>No Lime, 50 mg/kg P</b>			
17	3.65	49	3.12		
18	3.91	50	3.36		
19	3.66	51	2.25		
20	3.02	52	2.72		
<b>No Lime, 100 mg/kg P</b>		<b>No Lime, 100 mg/kg P</b>			
21	3.42	53	3.95		
22	4.19	54	3.29		
23	5.01	55	3.24		
24	3.60	56	3.70		
<b>Lime, 50 mg/kg P</b>		<b>Lime, 50 mg/kg P</b>			
25	4.30	57	3.24		
26	4.02	58	4.39		
27	2.64	59	2.14		
28	3.51	60	2.09		
<b>Lime, 100 mg/kg P</b>		<b>Lime, 100 mg/kg P</b>			
29	4.87	61	3.65		
30	4.35	62	3.95		
31	3.97	63	2.90		
32	3.89	64	2.88		

\*pots fell from greenhouse table which limited plant growth

**Table 20. First Fescue Study Soils Analysis**

concentrations are mg/kg in soil

Pot #	P	K	Ca	Mg	Mn	Zn	Fe	Cu	Al	pH
<b>0% Residual, No Lime, 50 mg/kg P</b>										
01	17.0	30.5	366	74.6	17.0	1.67	21.6	.639	283	5.0
02	14.9	24.1	336	69.6	14.2	1.62	19.7	.511	273	5.0
03	19.4	44.0	398	82.7	17.7	1.92	18.9	.741	300	4.7
04	22.0	52.0	412	83.2	17.2	1.96	18.1	.677	288	4.6
<b>0% Residual, No Lime, 100 mg/kg P</b>										
05	38.5	19.2	392	65.7	12.7	1.76	18.0	.626	291	5.0
06	31.3	22.1	390	72.0	13.5	1.73	18.2	.626	284	4.9
07	33.6	31.8	407	76.5	15.9	1.82	17.7	.600	280	4.8
08	45.8	26.0	406	70.4	15.6	1.78	17.8	.703	284	4.9
<b>0% Residual, Lime, 50 mg/kg P</b>										
09	16.1	27.7	503	137	8.61	2.70	14.8	.600	260	5.4
10	19.2	24.1	514	151	8.27	2.68	14.2	.575	251	5.6
11	20.8	44.3	526	168	12.9	2.81	17.4	.652	273	5.4
12	19.0	23.7	547	171	10.3	2.36	14.5	.754	266	5.7
<b>0% Residual, Lime, 100 mg/kg P</b>										
13	44.5	25.2	536	156	9.27	3.21	14.9	.664	285	5.6
14	44.6	29.3	552	158	9.16	2.83	14.4	.549	275	5.5
15	43.0	30.2	542	169	9.37	3.24	14.1	.716	268	5.5
16	41.4	26.9	526	157	9.46	2.91	15.0	.562	277	5.5
<b>1% Residual, No Lime, 50 mg/kg P</b>										
17	21.2	36.8	383	76.3	26.3	1.39	17.2	1.32	338	5.1
18	19.9	35.3	388	78.3	26.0	1.36	17.4	1.44	335	5.0
19	18.3	30.6	401	75.6	23.9	1.24	16.9	1.37	308	5.1
20	20.9	44.5	402	80.7	38.7	1.42	23.5	1.48	338	4.9
<b>1% Residual, No Lime, 100 mg/kg P</b>										
21	45.8	33.8	438	69.8	27.0	1.40	19.0	1.75	363	5.0
22	40.7	25.6	351	71.3	20.8	1.56	19.0	2.04	353	5.1
23	38.8	25.9	401	65.5	24.4	1.50	16.9	1.28	307	5.1
24	52.0	36.2	445	72.5	26.3	1.46	17.5	1.38	337	5.0
<b>1% Residual, Lime, 50 mg/kg P</b>										
25	22.8	26.3	448	136	14.7	2.25	14.1	1.23	281	5.7
26	19.8	33.5	530	155	14.8	2.52	14.1	1.19	302	5.6
27	19.7	57.2	528	164	15.2	2.29	14.3	1.43	314	5.5
28	20.6	38.3	534	162	14.7	2.47	14.1	1.48	326	5.7
<b>1% Residual, Lime, 100 mg/kg P</b>										
29	44.7	23.5	568	152	13.6	2.55	14.6	1.34	296	5.7
30	41.8	27.1	516	155	13.5	2.26	15.8	1.21	276	5.7
31	45.2	28.0	546	153	13.4	2.50	14.6	1.33	287	5.7
32	42.6	27.6	522	146	13.6	2.57	15.5	1.44	287	5.6
<b>2% Residual, No Lime, 50 mg/kg P</b>										
33	20.7	44.8	378	71.8	28.1	.992	19.7	2.66	412	5.2
34	21.6	33.2	389	70.7	32.8	1.03	19.0	2.54	405	5.3
35	21.4	66.6	425	74.6	33.7	1.03	19.3	2.57	411	5.1
36	20.3	44.7	391	75.4	36.9	1.16	18.4	2.47	384	5.2
<b>2% Residual, No Lime, 100 mg/kg P</b>										
37	36.1	25.1	412	57.7	23.0	1.17	17.6	2.21	351	5.4
38	39.4	28.4	404	68.6	26.0	1.15	17.9	2.38	355	5.3
39	38.7	33.7	438	72.9	30.0	1.23	18.4	2.44	375	5.2
40	41.6	33.5	412	70.8	30.0	1.16	18.0	2.42	376	5.2

(continued on next page)

Continuation of Table 4

Pot #	P	K	Ca	Mg	Mn	Zn	Fe	Cu	Al	pH
<b>2% Residual, Lime, 50 mg/kg P</b>										
41	19.8	44.6	510	137	20.0	3.57	14.9	2.13	329	5.5
42	22.2	75.6	484	138	25.9	2.47	15.9	1.75	307	5.3
43	19.6	46.9	478	134	20.9	2.16	14.7	2.01	305	5.5
44	18.6	43.4	500	135	20.6	2.43	14.8	1.93	306	5.5
<b>2% Residual, Lime, 100 mg/kg P</b>										
45	42.2	31.6	515	129	20.0	2.12	14.8	1.83	306	5.6
46	38.7	29.7	507	133	19.3	2.11	14.9	1.78	298	5.7
47	39.8	25.5	526	124	17.9	2.16	15.5	2.15	306	5.7
48	38.8	29.5	526	134	21.1	2.06	14.9	1.85	313	5.7
<b>4% Residual, No Lime, 50 mg/kg P</b>										
49	18.9	40.4	418	71.2	55.0	.938	18.3	3.48	417	5.4
50	19.5	45.8	435	71.1	57.1	1.13	19.4	3.91	450	5.4
51	22.7	57.4	446	75.7	66.2	0.99	21.0	3.94	458	5.3
52	19.7	45.4	412	73.0	55.2	1.00	19.9	3.83	456	5.4
<b>4% Residual, No Lime, 100 mg/kg P</b>										
53	38.1	33.6	455	72.1	45.8	1.03	19.0	3.63	434	5.4
54	38.4	41.6	460	75.4	53.0	1.05	18.0	3.22	385	5.4
55	44.1	34.6	440	73.6	51.6	1.02	19.3	3.54	427	5.5
56	36.0	28.0	460	66.5	52.2	0.92	17.0	2.97	342	5.4
<b>4% Residual, Lime, 50 mg/kg P</b>										
57	20.5	74.5	546	137	56.8	1.71	18.6	2.83	350	5.6
58	43.4	31.0	567	124	43.2	2.00	17.1	2.85	363	5.8
59	21.0	54.4	540	122	46.2	2.19	15.7	2.82	356	5.5
60	21.7	66.1	566	138	45.7	2.99	16.3	3.54	408	5.6
<b>4% Residual, Lime, 100 mg/kg P</b>										
61	40.0	34.4	574	136	40.0	2.19	14.3	3.02	337	5.7
62	38.5	32.0	548	126	40.2	1.91	15.5	3.28	373	5.8
63	38.2	47.4	599	141	48.0	2.07	22.7	3.28	375	5.6
64	44.2	55.0	697	141	55.6	2.08	23.0	3.69	426	5.6
<b>2% Residual + PAC, No Lime, 50 mg/kg P</b>										
65	29.5	105.	1320	231	51.6	1.50	42.6	1.46	478	6.1
66	23.3	74.0	1190	211	58.8	1.57	43.2	1.29	408	6.2
67	22.0	87.9	1070	204	48.6	1.37	53.5	1.64	441	6.2
68	20.3	87.0	992	200	42.0	1.40	43.7	1.50	406	6.2
<b>2% Residual + PAC, No Lime, 100 mg/kg P</b>										
69	45.0	75.8	1139	209	45.6	1.46	44.3	1.34	442	6.3
70	42.1	39.6	1083	188	43.9	1.31	44.4	1.29	409	6.4
71	42.6	66.0	1091	197	42.4	1.42	46.5	1.54	438	6.2
72	41.6	76.9	1333	230	51.1	1.48	62.2	1.32	480	6.5
<b>2% Residual + PAC, Lime, 50 mg/kg P</b>										
73	21.3	72.8	1200	238	41.9	2.32	42.9	1.28	391	6.5
74	22.3	66.5	1190	241	46.1	2.35	45.8	1.32	419	6.6
75	22.0	74.2	892.	206	47.9	2.45	43.4	1.48	397	6.6
76	20.8	95.9	1240	258	53.4	2.81	62.4	2.00	461	6.5
<b>2% Residual + PAC, Lime, 100 mg/kg P</b>										
77	46.8	100.	1210	243	47.5	2.86	44.9	1.54	449	6.6
78	43.8	70.6	1140	236	46.5	2.31	46.4	1.42	444	6.6
79	41.9	67.7	1141	225	46.5	2.84	44.1	1.02	383	6.6
80	42.9	48.2	1180	235	45.7	2.33	46.1	1.06	389	6.6

**Table 21. First Fescue Study Plant Tissue Analysis**

Note - N, P, K, Ca, and Mg are in % and Zn, Mn, Cu, Fe, B, and Al are mg/kg in plant tissue

Pot#	N	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Al
<b>0% Residual, No Lime, 50 mg/kg P</b>											
1	4.55	0.26	5.05	0.82	0.63	49	563.	9	89	11	43
2	4.37	0.25	4.99	0.79	0.60	40	515.	7	95	9	47
3	4.77	0.28	5.15	0.66	0.59	38	530.	6	91	8	41
4	4.62	0.32	5.64	0.86	0.71	43	588.	8	92	9	36
<b>0% Residual, No Lime, 100 mg/kg P</b>											
5	4.38	0.30	4.90	0.80	0.66	45	511.	8	91	8	40
6	4.52	0.31	4.94	0.79	0.69	42	469.	8	90	10	37
7	4.59	0.35	5.44	0.80	0.63	42	532.	8	97	9	54
8	4.62	0.31	5.36	0.66	0.56	44	407.	7	80	6	37
<b>0% Residual, Lime, 50 mg/kg P</b>											
9	4.48	0.22	4.87	0.74	0.71	46	288.	8	110	8	48
10	4.36	0.22	4.92	0.72	0.72	46	216.	7	82	8	31
11	4.82	0.24	5.11	0.75	0.75	52	251.	7	88	8	41
12	4.91	0.25	5.10	0.68	0.68	55	215.	7	81	9	36
<b>0% Residual, Lime, 100 mg/kg P</b>											
13	4.70	0.29	5.07	0.72	0.70	58	265.	6	86	6	37
14	4.77	0.31	5.32	0.81	0.74	58	232.	6	106	7	71
15	4.75	0.31	5.66	0.79	0.74	54	216.	6	91	7	37
16	4.53	0.28	5.02	0.70	0.70	53	239.	6	83	7	34
<b>1% Residual, No Lime, 50 mg/kg P</b>											
17	4.66	0.23	5.14	0.73	0.56	35	754.	9	79	7	55
18	4.37	0.23	4.97	0.67	0.53	35	692.	10	98	7	80
19	4.44	0.24	5.13	0.71	0.56	36	820.	9	90	7	49
20	4.68	0.26	5.56	0.82	0.55	42	974.	10	103	8	57
<b>1% Residual, No Lime, 100 mg/kg P</b>											
21	4.86	0.29	5.09	0.89	0.52	40	777.	9	93	8	50
22	4.78	0.30	5.62	0.84	0.63	45	798.	10	93	7	88
23	4.41	0.31	5.30	0.83	0.63	41	813.	10	92	9	42
24	4.54	0.27	5.51	0.87	0.64	43	876.	9	92	7	55
<b>1% Residual, Lime, 50 mg/kg P</b>											
25	4.56	0.22	5.09	0.70	0.73	45	370.	11	87	7	34
26	4.56	0.22	5.32	0.74	0.70	41	347.	9	88	6	53
27	4.78	0.25	5.56	0.68	0.73	38	330.	10	84	6	34
28	4.88	0.25	5.24	0.67	0.70	39	261.	11	105	7	39
<b>1% Residual, Lime, 100 mg/kg P</b>											
29	4.37	0.26	5.07	0.74	0.71	44	272.	9	91	7	40
30	4.56	0.29	5.54	0.68	0.74	48	248.	10	90	6	40
31	4.72	0.28	5.45	0.82	0.76	48	293.	10	93	7	49
32	4.76	0.27	5.39	0.87	0.70	51	335.	11	174	6	210
<b>2% Residual, No Lime, 50 mg/kg P</b>											
33	4.52	0.21	5.14	0.76	0.62	31	991.	10	93	7	56
34	4.45	0.21	5.07	0.78	0.65	32	1120	11	86	7	37
35	4.58	0.24	5.56	0.63	0.53	32	900.	10	95	6	86
36	4.64	0.25	5.59	0.94	0.66	34	1320	11	101	9	78
<b>2% Residual, No Lime, 100 mg/kg P</b>											
37	4.69	0.25	5.39	0.89	0.70	40	1060	12	100	9	48
38	4.37	0.24	5.17	0.82	0.66	37	988.	11	94	8	53
39	4.61	0.27	5.71	0.96	0.72	42	1140	12	96	8	47
40	4.50	0.28	5.70	1.01	0.72	43	1210	12	104	9	53

(continued on next page)

Continuation of Table 5

Pot #	N	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Al
<b>2% Residual, Lime, 50 mg/kg P</b>											
41	4.64	0.22	5.10	0.80	0.79	41	515.	11	89	8	46
42	4.78	0.19	5.33	0.75	0.61	16	505.	9	95	9	60
43	4.83	0.23	5.31	0.79	0.76	36	593.	10	102	8	70
44	4.64	0.25	5.80	0.94	0.85	49	729.	12	104	10	47
<b>2% Residual, Lime, 100 mg/kg P</b>											
45	4.62	0.29	6.06	0.83	0.72	50	512.	11	93	7	47
46	4.50	0.24	4.90	0.75	0.64	43	425.	9	126	6	33
47	4.70	0.27	5.63	0.88	0.74	51	485.	13	96	7	37
48	4.68	0.27	5.19	0.80	0.67	47	439.	11	102	6	68
<b>4% Residual, No Lime, 50 mg/kg P</b>											
49	4.54	0.24	6.05	0.94	0.67	33	1540	13	102	8	46
50	4.37	0.21	4.92	0.73	0.62	33	1310	12	143	7	62
51	4.61	0.23	5.35	0.80	0.67	34	1580	11	103	7	119
52	4.37	0.24	5.69	0.94	0.67	35	1770	12	115	10	68
<b>4% Residual, No Lime, 100 mg/kg P</b>											
53	4.43	0.26	5.95	1.02	0.74	40	1500	13	103	8	50
54	4.37	0.25	5.48	1.00	0.74	34	1470	12	98	9	47
55	4.34	0.25	5.60	0.83	0.61	34	1260	11	90	7	39
56	4.55	0.23	5.50	0.96	0.69	36	1610	22	105	9	199
<b>4% Residual, Lime, 50 mg/kg P</b>											
57	4.51	0.23	5.67	0.84	0.75	37	846.	16	93	8	44
58	4.75	0.26	5.75	0.96	0.81	44	813.	15	211	7	85
59	4.88	0.20	4.85	0.81	0.65	37	963.	12	86	6	35
60	4.68	0.20	4.72	0.76	0.66	35	766.	11	94	7	100
<b>4% Residual, Lime, 100 mg/kg P</b>											
61	4.29	0.28	6.03	1.11	0.88	50	914.	13	116	9	80
62	4.72	0.25	5.43	0.79	0.66	36	636.	11	89	7	37
63	4.42	0.28	5.90	1.03	0.76	42	879.	13	104	7	64
64	4.60	0.26	5.98	1.00	0.77	47	868.	12	103	7	58
<b>2% Residual + PAC, No Lime, 50 mg/kg P</b>											
65	4.70	0.20	5.92	0.76	0.57	19	372.	7	94	525	48
66	4.81	0.21	5.38	0.64	0.49	19	293.	6	83	399	33
67	4.45	0.20	5.86	0.60	0.50	5	320.	6	92	475	39
68	4.79	0.22	6.10	0.79	0.62	1	318.	6	95	457	247
<b>2% Residual + PAC, No Lime, 100 mg/kg P</b>											
69	4.66	0.23	5.46	0.59	0.52	19	319.	7	84	377	38
70	4.19	0.24	5.76	0.60	0.56	18	294.	8	88	436	34
71	4.72	0.24	5.81	0.70	0.62	20	346.	7	92	467	28
72	4.63	0.20	5.86	0.58	0.50	0	346.	7	83	484	28
<b>2% Residual + PAC, Lime, 50 mg/kg P</b>											
73	4.57	0.17	5.64	0.64	0.53	3	384.	7	85	435	38
74	4.74	0.16	5.06	0.65	0.51	20	307.	7	78	385	42
75	4.76	0.17	5.48	0.56	0.54	0	291.	5	79	411	144
76	4.71	*	*	*	*	*	*	*	*	*	*
<b>2% Residual + PAC, Lime, 100 mg/kg P</b>											
77	4.72	0.21	5.54	0.59	0.50	19	299.	6	81	378	25
78	0.00	0.37	9.29	1.05	0.94	36	482.	10	127	570	56
79	4.71	0.26	6.40	0.65	0.60	23	325.	7	91	493	37
80	4.68	0.25	6.08	0.70	0.61	23	292.	7	92	428	38

\*plant mass too low for analysis

**Table 22. First Fescue Study Calcium Chloride Extraction**

concentrations are mg/kg in soil or PAC

Material	Zn	Fe	B	P	Cu	Mn
Virgin Soil	.929	4.49	.404	<.060	.123	26.2
Virgin Soil	.400	4.67	.424	<.060	.105	26.3
Virgin Soil	.371	4.67	.525	<.060	.123	26.6
Unused PAC	<.004	<.005	415	1.37	.052	.125
Unused PAC	<.004	<.005	417	1.46	.052	.055
Unused PAC	<.004	<.005	395	1.57	.105	.055
<b>2% Residual, No Lime, 50 mg/kg P, no PAC</b>						
Pot # 33	<.004	2.82	1.800	.607	.264	43.5
Pot # 34	<.004	3.15	0.809	<.060	.264	45.3
Pot # 35	<.004	3.58	0.728	<.060	.264	51.5
<b>2% Residual, No Lime, 50 mg/kg P, 2.2% PAC</b>						
Pot # 65	<.004	<.005	12.0	<.060	.088	8.90
Pot # 66	<.004	<.005	12.8	<.060	.088	11.5
Pot # 67	<.004	<.005	12.1	.648	.088	10.1

**Table 23. First Fescue Study Ammonium Oxalate Extraction**

concentrations are mg/kg in soil

Pot #	Al	Fe	P
<b>0% Residual, No Lime, 50 mg/kg P</b>			
1	1110	606	117
2	1120	570	120
3	1130	561	123
<b>0% Residual, No Lime, 100 mg/kg P</b>			
5	1150	576	155
6	1110	552	158
7	1140	613	166
<b>1% Residual, No Lime, 50 mg/kg P</b>			
17	1630	637	139
18	1740	599	126
19	1660	684	144
<b>1% Residual, No Lime, 100 mg/kg P</b>			
21	2120	690	192
22	1720	582	169
23	1690	662	179
<b>2% Residual, No Lime, 50 mg/kg P</b>			
33	2960	764	165
34	3070	770	163
35	2810	727	148
<b>2% Residual, No Lime, 100 mg/kg P</b>			
37	2510	726	189
38	2870	763	214
39	3060	770	210
<b>4% Residual, No Lime, 50 mg/kg P</b>			
49	4040	896	172
50	3390	800	155
51	6330	1200	237
<b>4% Residual, No Lime, 100 mg/kg P</b>			
53	4540	937	233
54	4240	887	226
55	4060	886	229

**Table 24. First Fescue Study DCB Extraction**

concentrations are mg/kg in soil

Pot #	Al	Fe	P
<b>0% Residual, No Lime, 50 mg/kg P</b>			
1	431	1320	70.4
2	453	1380	69.9
3	457	1387	75.4
<b>0% Residual, No Lime, 100 mg/kg P</b>			
5	470	1400	99.5
6	466	1400	98.6
7	487	1436	105.8
<b>1% Residual, No Lime, 50 mg/kg P</b>			
17	539	1454	79.8
18	520	1400	74.2
19	509	1390	71.2
<b>1% Residual, No Lime, 100 mg/kg P</b>			
21	571	1450	99.8
22	543	1460	99.8
23	530	1500	100.6
<b>2% Residual, No Lime, 50 mg/kg P</b>			
33	735	1530	84.6
34	676	1470	78.9
35	709	1560	83.1
<b>2% Residual, No Lime, 100 mg/kg P</b>			
37	656	1520	102.5
38	673	1520	105.0
39	649	1530	105.2
<b>4% Residual, No Lime, 50 mg/kg P</b>			
49	803	1520	84.2
50	813	1430	77.4
51	792	1480	101.9
<b>4% Residual, No Lime, 100 mg/kg P</b>			
53	807	1490	84.4
54	813	1520	101.7
55	767	1510	103.8

**Table 25. Second Fescue Study Variables**

Pot #	P (mg/kg)	Mn Equiv	Residual and PAC
121-124	0	0	2% Residual 1
125-128*	50	0	2% Residual 1
129-132*	100	0	2% Residual 1
133-136	200	0	2% Residual 1
137-140	100	+2%	2% Residual 1
141-144	100	+4%	2% Residual 1
145-148	100	0	2.88% Residual 2
149-152	100	0	2% Residual 1 + 0.88% Virgin PAC
153-156*	100	0	2% Residual 1 + 2.2% Virgin PAC
157-160	100	0	2% Residual 1 + 0.88% Washed PAC

\*denotes repeat of variables from first fescue study

**Table 26. Second Fescue Study Yield Data**

all weights are in grams

Pot #	1st Yield	2nd Yield	3rd Yield	Combined
<b>2% Residual, 0 mg/kg P</b>				
121	0.211	0.148	0.134	0.493
122	0.402	0.276	0.171	0.849
123	0.184	0.180	0.115	0.479
124	0.192	0.176	0.117	0.485
<b>2% Residual, 50 mg/kg P</b>				
125	1.011	1.430	0.750	3.191
126	0.928	1.297	0.464	2.689
127	0.896	1.000	0.442	2.338
128	1.169	1.463	0.441	3.073
<b>2% Residual, 100 mg/kg P</b>				
129	1.355	1.681	0.752	3.788
130	1.216	1.428	0.654	3.298
131	0.963	1.511	0.621	3.095
132	1.601	1.891	0.635	4.127
<b>2% Residual, 200 mg/kg P</b>				
133	2.496	2.166	0.620	5.282
134	1.851	2.322	0.822	4.995
135	2.305	2.239	0.650	5.194
136	1.963	2.215	0.676	4.854
<b>2% Residual + 2% Mn Equivalent, 100 mg/kg P</b>				
137	1.323	1.333	0.592	3.248
138	1.706	1.953	0.746	4.405
139	1.738	1.735	0.713	4.186
140	1.156	1.290	0.581	3.027
<b>2% Residual + 4% Mn Equivalent, 100 mg/kg P</b>				
141	1.936	2.172	0.797	4.905
142	0.184	0.108	0.136	0.428
143	1.560	1.806	0.766	4.132
144	0.781	1.331	0.612	2.724
<b>2.88% PAC Residual, 100 mg/kg P</b>				
145	1.914	2.109	0.679	4.702
146	3.026	2.510	0.753	6.289
147	2.096	2.042	0.678	4.816
148	1.939	2.193	0.649	4.781
<b>2% Residual, 0.88% Unused PAC, 100 mg/kg P</b>				
149	0.995	1.181	0.451	2.627
150	1.172	1.322	0.609	3.103
151	1.777	1.844	0.595	4.216
152	1.169	1.258	0.440	2.867
<b>2% Residual, 2.2% Unused PAC, 100 mg/kg P</b>				
153	0.344	0.529	0.323	1.196
154	0.712	0.772	0.361	1.845
155	0.437	0.670	0.366	1.473
156	0.686	0.886	0.432	1.984
<b>2% Residual, 0.88% Washed PAC, 100 mg/kg P</b>				
157	1.640	1.788	0.750	4.178
158	1.000	1.160	0.482	2.642
159	1.334	1.506	0.574	3.414
160	1.582	1.779	0.672	4.033

**Table 27. Second Fescue Study Soils Analysis**

concentrations are mg/kg in soil

Pot #	Ca	Mg	P	K	Mn	Zn	Fe	Al	Cu	B	pH
<b>2% Residual, 0 mg/kg P</b>											
121	606	160	5.3	86	16.2	5.68	15.9	638	3.85	0.22	5.7
122	532	118	5.3	92	31.0	3.60	16.6	592	3.72	0.22	5.3
123	527	136	5.4	103	18.4	6.60	16.4	629	3.88	0.22	5.6
124	562	158	5.7	111	21.4	6.30	15.6	633	4.23	0.22	5.6
<b>2% Residual, 50 mg/kg P</b>											
125	582	168	21.2	64	19.9	2.73	15.1	592	3.65	0.22	5.4
126	568	111	20.6	48	20.3	2.10	16.3	652	3.65	0.20	5.7
127	661	194	21.2	67	18.7	2.53	15.6	662	4.18	0.21	5.5
128	615	169	24.2	74	25.7	2.55	16.4	694	4.15	0.22	5.3
<b>2% Residual, 100 mg/kg P</b>											
129	676	154	51.4	48	19.9	2.98	14.7	530	3.23	0.21	5.3
130	636	148	45.6	58	33.1	3.23	22.1	683	3.78	0.22	5.3
131	611	123	42.3	59	32.8	2.62	17.1	745	4.42	0.22	5.4
132	566	105	36.1	33	21.6	2.35	16.2	666	3.97	0.22	5.6
<b>2% Residual, 200 mg/kg P</b>											
133	615	111	69.6	34	18.0	2.85	15.6	616	3.68	0.22	5.7
134	628	150	74.3	26	18.1	2.73	15.5	632	3.98	0.20	5.7
135	592	112	74.4	37	19.5	2.72	15.4	621	3.90	0.20	5.6
136	563	99	80.5	30	20.6	2.86	15.5	640	4.29	0.20	5.9
<b>2% Residual + 2% Mn Equivalent, 100 mg/kg P</b>											
137	563	116	43.7	56	33.7	3.18	16.3	554	3.62	0.21	5.4
138	559	114	39.2	34	31.0	7.14	16.3	552	3.54	0.20	5.6
139	571	129	35.0	30	31.9	2.05	16.0	549	4.12	0.21	5.5
140	530	106	39.0	47	25.2	3.14	16.0	583	4.04	0.21	5.7
<b>2% Residual + 4% Mn Equivalent, 100 mg/kg P</b>											
141	550	118	39.6	30	34.0	5.55	14.9	512	3.43	0.22	5.5
142	579	216	6.5	165	73.3	2.69	15.3	553	3.90	0.22	5.2
143	618	135	40.3	31	58.8	2.65	15.7	579	3.95	0.22	5.4
144	547	114	43.7	81	62.9	2.36	16.3	527	3.48	0.22	5.3
<b>2.88% PAC Residual, 100 mg/kg P</b>											
145	518	119	44.8	24	8.3	3.02	13.3	352	1.42	0.19	5.9
146	560	117	46.3	22	8.7	3.15	13.1	317	0.81	0.20	5.8
147	556	143	45.4	21	7.8	3.01	13.3	321	0.86	0.22	5.5
148	598	151	48.6	25	9.0	4.50	13.1	314	0.79	0.22	5.3
<b>2% Residual, 0.88% Unused PAC, 100 mg/kg P</b>											
149	755	149	40.1	57	30.7	2.53	20.9	536	2.64	1.53	5.8
150	819	156	41.2	61	36.0	3.01	20.8	530	2.92	1.57	5.7
151	854	158	78.7	45	30.3	2.88	21.8	560	2.65	1.75	5.8
152	746	135	42.5	52	33.3	2.52	22.3	594	3.14	1.68	6.0
<b>2% Residual, 2.2% Unused PAC, 100 mg/kg P</b>											
153	1089	199	41.4	92	49.7	2.91	38.8	599	2.31	4.97	6.2
154	1025	211	41.9	76	29.7	3.71	34.1	583	2.27	5.28	6.2
155	1140	273	41.7	103	36.5	4.73	36.1	591	2.27	5.57	6.2
156	1123	207	42.4	93	48.2	3.26	45.4	544	1.99	5.45	6.3
<b>2% Residual, 0.88% Washed PAC, 100 mg/kg P</b>											
157	798	147	45.6	50	39.9	2.79	27.8	568	3.16	1.55	6.3
158	765	161	36.4	55	31.5	2.65	21.6	622	3.35	1.06	6.0
159	765	153	41.4	58	34.0	2.91	26.6	557	2.81	1.26	5.9
160	712	148	39.7	29	28.2	2.59	20.1	562	3.13	0.96	6.0

**Table 28. Second Fescue Study Plant Tissue Analysis**

Note - N,P,K,Ca, and Mg are in % and Zn,Mn,Fe,Al,Cu, and B are mg/kg in plant tissue

Pot #	N	P	K	Ca	Mg	Zn	Mn	Fe	Al	Cu	B
<b>2% Residual, 0 mg/kg P</b>											
121	*	0.143	4.42	0.681	0.692	37.9	824	103.8	83.6	18.5	22.3
122	17.1	0.128	4.40	0.730	0.580	39.8	872	111.8	123.7	17.8	30.2
123	*	0.114	3.50	0.566	0.584	30.9	616	84.3	54.1	13.7	17.7
124	*	0.091	2.74	0.475	0.544	27.7	491	76.7	63.8	13.4	11.6
<b>2% Residual, 50 mg/kg P</b>											
125	13.3	0.190	5.18	0.708	0.577	37.9	560	86.6	43.9	14.4	8.7
126	22.2	0.190	4.99	0.776	0.540	36.6	563	79.4	38.3	13.5	8.0
127	21.7	0.193	5.19	0.689	0.575	37.1	584	81.3	42.7	14.0	7.4
128	19.6	0.208	5.18	0.652	0.617	35.0	613	88.6	38.0	15.4	14.6
<b>2% Residual, 100 mg/kg P</b>											
129	*	0.250	5.22	0.651	0.594	40.4	553	83.7	42.8	23.3	7.3
130	18.9	0.218	4.46	0.576	0.555	32.6	563	71.9	43.3	17.9	6.5
131	18.1	0.205	5.08	0.667	0.550	35.1	548	85.3	40.5	13.5	7.4
132	16.7	0.245	5.00	0.726	0.602	38.9	643	87.7	50.4	17.6	11.8
<b>2% Residual, 200 mg/kg P</b>											
133	13.3	0.274	4.55	0.730	0.662	35.3	539	77.2	36.3	13.6	6.7
134	18.1	0.260	4.52	0.771	0.663	35.7	537	85.8	39.1	15.7	8.4
135	23.8	0.297	4.83	0.773	0.657	38.8	584	89.3	40.7	16.3	7.6
136	4.2	0.355	5.38	0.834	0.733	44.1	572	96.8	40.9	16.8	7.2
<b>2% Residual + 2% Mn Equivalent, 100 mg/kg P</b>											
137	20.8	0.227	4.88	0.670	0.577	37.1	745	82.0	36.4	12.7	6.9
138	19.5	0.200	4.97	0.720	0.554	44.1	734	81.2	36.4	15.9	6.8
139	14.1	0.196	4.51	0.577	0.532	36.9	725	73.1	30.0	14.2	12.0
140	21.3	0.257	5.56	0.726	0.648	43.2	646	87.1	40.9	19.1	7.8
<b>2% Residual + 4% Mn Equivalent, 100 mg/kg P</b>											
141	19.0	0.234	5.20	0.719	0.654	44.2	804	85.6	41.8	17.7	7.8
142	*	0.079	2.28	0.343	0.301	19.5	513	44.2	30.9	11.4	6.2
143	3.3	0.202	4.40	0.734	0.640	40.6	762	82.2	46.0	14.4	11.1
144	15.1	0.255	5.20	0.653	0.572	38.0	887	78.9	32.1	13.5	7.5
<b>2.88% PAC Residual, 100 mg/kg P</b>											
145	4.1	0.313	5.19	0.701	0.635	47.4	281	85.6	43.1	13.8	11.1
146	17.2	0.201	4.10	0.547	0.523	70.5	174	68.0	42.3	10.4	6.9
147	18.4	0.231	4.31	0.542	0.538	37.1	223	72.3	40.5	12.0	6.9
148	16.9	0.310	4.85	0.767	0.610	43.9	285	84.9	47.5	15.3	7.4
<b>2% Residual, 0.88% Unused PAC, 100 mg/kg P</b>											
149	17.5	0.203	5.05	0.551	0.494	31.6	354	89.1	35.2	13.5	86.8
150	20.4	0.191	5.15	0.633	0.500	31.2	382	83.5	42.1	13.2	94.3
151	21.7	0.252	4.92	0.632	0.552	31.4	356	85.7	47.8	14.0	78.8
152	5.2	0.199	4.82	0.579	0.528	28.3	442	77.4	36.6	16.9	82.8
<b>2% Residual, 2.2% Unused PAC, 100 mg/kg P</b>											
153	5.3	0.187	5.22	0.563	0.449	27.3	325	89.8	45.5	14.4	230.
154	0.8	0.125	4.37	0.390	0.341	19.3	277	61.5	30.7	11.9	141.
155	0.9	0.201	5.38	0.592	0.480	29.4	393	85.3	46.7	15.7	212.
156	8.0	0.176	5.03	0.550	0.460	25.7	352	75.9	32.5	12.5	194.
<b>2% Residual, 0.88% Washed PAC, 100 mg/kg P</b>											
157	1.7	0.188	4.18	0.529	0.475	34.8	288	84.8	110.9	21.9	29.4
158	1.7	0.177	4.61	0.437	0.506	31.5	258	78.8	43.2	14.9	22.6
159	*	0.223	4.75	0.647	0.547	30.9	289	81.3	46.0	15.5	39.7
160	16.9	0.221	5.33	0.690	0.591	38.0	341	80.0	37.3	16.6	33.0

\*Plant mass too low for analysis.

**Table 29. Pine Seedling Variables**

Treatment #	Pot #	Residual (%)	P (mg/kg)
1	81-84	0	0
2	85-88	0	50
3	89-92	1	0
4	93-96	1	50
5	97-100	2	0
6	101-104	2	50
7	105-108	4	0
8	109-112	4	50
9	113-116	2 + 2.2% PAC	0
10	117-120	2 + 2.2% PAC	50

**Table 30. Pine Seedling Yield Data**

Pot #	Needle Wt. gm	Needle Base Wt. gm	Stem Wt. gm	Stem Ht. cm	Root Wt. gm	Ground Level Diameter cm	Growth Days
<b>0% Residual, 0 mg/kg P</b>							
81	4.087	0.809	2.422	26.1	3.976	0.69	220
83	2.788	0.656	3.177	30.8	2.551	0.64	180
84	1.075	0.246	2.567	26.1	1.793	0.57	220
<b>0% Residual, 50 mg/kg P</b>							
85	4.173	0.684	5.553	35.6	3.479	0.75	220
86	4.633	0.734	4.695	26.7	5.003	0.90	220
88	4.837	1.332	5.293	35.4	4.427	0.73	220
<b>1% Residual, 0 mg/kg P</b>							
90	2.965	0.658	4.110	24.7	3.757	0.62	220
91	5.396	1.172	7.512	30.5	6.451	0.78	220
92	1.914	0.515	3.772	34.4	1.490	0.60	220
<b>1% Residual, 50 mg/kg P</b>							
95	4.559	0.909	6.447	28.0	4.632	0.79	220
96	4.554	0.641	6.303	32.0	6.204	0.74	220
<b>2% Residual, 0 mg/kg P</b>							
98	3.981	0.963	3.485	30.2	5.087	0.67	220
99	3.787	1.026	7.172	37.6	5.361	0.95	220
<b>2% Residual, 50 mg/kg P</b>							
102	1.437	0.271	3.624	22.0	1.675	0.66	220
104	1.738	0.294	1.992	21.0	1.989	0.47	118
<b>4% Residual, 0 mg/kg P</b>							
105	3.433	0.879	5.630	32.1	4.138	0.74	220
107	2.146	0.420	3.971	24.8	3.285	0.75	220
108	1.026	0.335	1.482	24.4	1.012	0.50	220
<b>4% Residual, 50 mg/kg P</b>							
110	3.741	0.653	5.153	30.9	5.988	0.87	220
111	4.403	0.934	6.415	29.3	4.695	0.78	220
112	3.410	0.723	4.657	33.8	4.461	0.74	220
<b>2% Residual + PAC, 0 mg/kg P</b>							
115	2.104	0.412	2.652	26.7	1.439	0.60	220
116	0.349	0.050	3.001	18.0	1.023	0.50	118

**Table 31. Pine Seedling Soils Analysis**

Pot #	P	K	Ca	Mg	Zn	Mn	Fe	Al	Cu	B	pH
<b>0% Residual, 0 mg/kg P</b>											
81	2.95	62.8	337	40.6	1.90	7.47	16.0	230	0.47	0.16	5.2
83	2.96	53.2	314	35.7	1.82	9.06	15.9	237	0.45	0.16	5.1
84	3.85	91.3	335	41.1	2.11	11.13	16.1	243	0.47	0.16	4.6
<b>0% Residual, 50 mg/kg P</b>											
85	16.6	55.6	339	34.6	1.94	7.88	16.6	245	0.45	0.15	5.3
86	14.8	56.0	350	38.4	1.47	7.20	15.6	234	0.42	0.15	5.4
88	15.5	61.2	346	37.0	1.46	7.96	15.6	233	0.45	0.15	5.3
<b>1% Residual, 0 mg/kg P</b>											
90	3.97	62.1	380	43.8	1.16	11.74	16.3	330	1.70	0.19	5.0
91	3.52	58.9	320	35.8	1.06	18.99	24.9	355	1.80	0.16	5.3
92	3.67	72.8	364	42.2	1.29	12.56	16.4	319	1.77	0.16	4.9
<b>1% Residual, 50 mg/kg P</b>											
95	17.3	56.8	365	38.1	0.93	9.91	16.7	342	1.88	0.15	5.5
96	16.9	48.0	343	32.9	0.99	13.46	18.3	364	2.00	0.15	5.7
<b>2% Residual, 0 mg/kg P</b>											
98	3.39	50.5	362	36.3	0.80	13.95	17.1	383	2.50	0.16	5.3
99	3.77	50.4	372	36.0	0.90	15.09	17.6	428	2.70	0.16	5.5
<b>2% Residual, 50 mg/kg P</b>											
102	20.4	79.4	438	45.3	1.03	16.69	15.7	398	2.68	0.18	5.1
104	25.5	80.6	413	41.4	1.16	19.44	16.6	366	2.55	0.16	5.1
<b>4% Residual, 0 mg/kg P</b>											
105	4.28	53.8	407	37.3	0.77	27.50	17.1	452	3.43	0.19	5.4
107	3.80	61.3	403	37.1	0.83	23.97	16.9	424	3.43	0.16	5.4
108	5.19	107.	453	47.5	0.97	39.24	17.9	469	3.80	0.16	5.2
<b>4% Residual, 50 mg/kg P</b>											
110	15.7	52.7	430	35.4	0.89	20.07	15.7	431	3.45	0.15	5.7
111	16.1	55.4	438	35.9	0.86	25.03	15.7	432	3.43	0.16	5.7
112	15.0	51.9	416	36.9	0.78	23.91	16.2	395	3.28	0.16	5.5
<b>2% Residual + PAC, 0 mg/kg P</b>											
115	3.14	72.5	834	103.	1.32	30.30	21.6	346	1.28	4.22	6.4
116	4.01	109.	911	131.	1.23	29.52	22.9	357	1.25	5.36	6.2

**Table 32. Pine Tissue Analysis**

Note - N,P,K,Ca, and Mg are in % and Zn,Mn,Cu,Fe,B, and Al are mg/kg in plant tissue

Pot#	N	P	K	Ca	Mg	Zn	Mn	Fe	Al	Cu	B
<b>0% Residual, 0 mg/kg P</b>											
81	*	0.083	1.12	0.342	0.125	82.8	659	108.	149	12.2	24
83	5.6	0.114	0.91	0.350	0.105	66.7	668	74.0	156	10.5	24
84	6.0	0.072	1.16	0.347	0.118	58.4	729	59.6	157	9.7	16
<b>0% Residual, 50 mg/kg P</b>											
85	2.3	0.126	0.78	0.238	0.080	46.3	469	76.2	174	8.1	19
86	1.4	0.143	0.72	0.313	0.092	74.8	538	67.1	96	10.2	16
88	4.7	0.148	0.93	0.294	0.087	77.7	626	71.8	99	11.1	13
<b>1% Residual, 0 mg/kg P</b>											
90	6.7	0.073	1.23	0.277	0.110	56.9	492	55.2	91	9.4	12
91	3.0	0.126	0.74	0.259	0.092	31.2	387	88.4	156	9.2	12
92	3.1	0.100	1.19	0.369	0.114	72.2	793	73.3	168	12.5	16
<b>1% Residual, 50 mg/kg P</b>											
95	1.6	0.134	0.87	0.298	0.108	36.4	400	70.1	130	8.7	13
96	1.7	0.160	0.84	0.342	0.139	53.1	603	114.	150	16.9	19
<b>2% Residual, 0 mg/kg P</b>											
98	3.3	0.080	1.29	0.335	0.119	57.9	683	76.6	105	9.2	14
99	2.7	0.076	1.00	0.271	0.120	31.3	494	58.1	92	9.6	9
<b>2% Residual, 50 mg/kg P</b>											
102	5.6	0.124	1.35	0.345	0.121	46.4	511	50.1	75	10.4	18
104	2.0	0.120	1.46	0.302	0.094	39.2	371	52.5	58	11.4	13
<b>4% Residual, 0 mg/kg P</b>											
105	2.0	0.086	1.54	0.296	0.167	37.0	788.5	61.5	108	11.6	20
107	2.7	0.097	1.47	0.506	0.158	34.4	1016.	56.8	90	11.2	11
108	*	0.054	0.48	0.374	0.128	36.4	919.0	84.3	197	8.6	7
<b>4% Residual, 50 mg/kg P</b>											
110	5.4	0.144	0.75	0.294	0.084	54.3	715.1	57.8	102	9.3	15
111	4.1	0.156	0.99	0.380	0.125	44.8	892.0	59.0	100	11.7	17
112	5.4	0.151	0.93	0.418	0.110	45.5	1001.	85.6	110	11.8	12
<b>2% Residual + PAC, 0 mg/kg P</b>											
115	*	0.085	0.94	0.268	0.175	35.0	142	52.4	68	9.6	336
116	*	0.171	0.77	0.311	0.212	34.0	213	42.0	120	10.9	105

\*Plant mass too low for analysis.

**Table 33. P Sorption Study - Langmuir Data**

m = 3 grams, Cf = final solution concentration

Residual Loading and Type	Initial P (mg/L)	Cf (mg/L)	x/m (mg/g)	Cf/(x/m) (g/L)
0%	10	.2445	.0813	3.01
0%	20	1.198	.157	7.65
0%	40	5.400	.288	18.7
0%	80	22.3	.481	46.4
0%	160	63.9	.801	79.8
1%, Type 1	10	.0900	.0826	1.09
1%, Type 1	20	.248	.166	1.51
1%, Type 1	40	3.11	.307	10.1
1%, Type 1	80	13.3	.556	23.8
1%, Type 1	160	61.2	.823	74.4
2%, Type 1	10	.0789	.0827	.954
2%, Type 1	20	.131	.166	.788
2%, Type 1	40	1.86	.318	5.85
2%, Type 1	80	12.1	.566	21.5
2%, Type 1	160	41.5	.988	41.9
4%, Type 1	10	.0486	.0829	.586
4%, Type 1	20	.038	.166	.228
4%, Type 1	40	.83	.326	2.54
4%, Type 1	80	5.88	.618	9.52
4%, Type 1	160	35.8	1.03	34.6
1%, Type 2	10	.0286	.0831	.344
1%, Type 2	20	.165	.165	.998
1%, Type 2	40	2.64	.311	8.48
1%, Type 2	80	8.38	.600	14.0
1%, Type 2	160	52.2	.899	58.0
2%, Type 2	10	.0300	.0831	.361
2%, Type 2	20	.106	.166	.639
2%, Type 2	40	.98	.325	3.01
2%, Type 2	80	5.24	.623	8.40
2%, Type 2	160	37.1	1.02	36.2
4%, Type 2	10	.0148	.0832	.178
4%, Type 2	20	.0520	.166	.313
4%, Type 2	40	.606	.328	1.84
4%, Type 2	80	5.18	.623	8.31
4%, Type 2	160	20.6	1.16	17.7

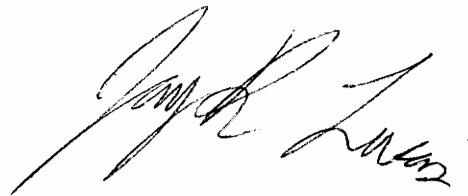
## Appendix B. Greenhouse Study Chronology

Sept 89	Soil from Newport News was dried and sieved
Oct 89	Residual received and analysis started
Nov 89	Performed Adams and Evans procedure to determine lime loading requirement (McLean, 1982) Experimental design developed for greenhouse study Soil tested for field capacity
Dec 89	Experimental pots prepared
03 Jan 90	Seeded fescue pots
14 Jan 90	Planted pines for first time
31 Jan 90	Planted pines for second time
02 Feb 90	Added the magnesium sulfate and remaining potassium nitrate to the fescue in solution form
08 Feb 90	Added the remaining calcium nitrate to the fescue in solution form
15 Feb 90	Added the remaining ammonium nitrate to the fescue in solution form
28 Feb 90	Cut fescue for the first time
06 Mar 90	Planted pines for the third time
07 Mar 90	Site visit by representatives of CH2MHill and Newport News
13 Mar 90	Moved trees outside to cold frame
24 Mar 90	Cut fescue for the second time
13 Apr 90	Submitted first report to CH2MHill
19 Apr 90	Cut fescue for the third and final time
01 May 90	Sieved soil from fescue pots
03 May 90	Analysis of sieved soils initiated
09 May 90	Fescue tissue samples from the first and second clippings prepared and analysis begun

15 Jun 90	Moved pine trees into greenhouse with evaporative cooler
18 Jun 90	Extracted Zn, Fe, B, P, Cu, and Mn from PAC and soil samples with hot calcium chloride (Bingham, 1982)
02 Jul 90	Extracted Al, Fe, and P from fescue potting soil with ammonium oxalate (Jackson <i>et al.</i> , 1986)
26 Jul 90	Extracted Al, Fe, and P from fescue potting soil with DCB procedure (Olson and Ellis, 1982)
27 Jul 90	Initiated dewatering of residual containing PAC Planned experimental design of second fescue study
22 Aug 90	Prepared pots for second fescue study
04 Sep 90	Seeded pots for second fescue study with Kentucky 31 study
13 Sep 90	Reseeded with Dixie Duet
12 Oct 90	Pulled needles and needle bases from pines Measured stem height of pines
16 Oct 90	Added the magnesium sulfate to the fescue in solution form
17 Oct 90	Added the remaining potassium nitrate to the fescue in solution form
19 Oct 90	Measured diameter of pine stems
23 Oct 90	Added the remaining calcium nitrate to the fescue in solution form
28 Oct 90	Cut second fescue study plants for the first time Weighed pine stems and roots
31 Oct 90	Added the remaining ammonium nitrate to the fescue in solution form
02 Nov 90	Sprayed fescue with malathion to eliminate aphids
05 Nov 90	Photographed different fescue variables
18 Nov 90	Performed HCl extraction on pine tissue (Donohue and Gettier, 1988)
19 Nov 90	Performed nitric-perchloric acid digestion on PAC residual (McLean, 1982)
20 Nov 90	Clipped second study fescue plants for the second time
30 Nov 90	Clipped second study fescue plants for the third and final time
03 Dec 90	Prepared soil samples from second fescue pots for analysis
06 Dec 90	Prepared second fescue plant tissue for analysis

## Vita

Jay Lucas was born in Eden, North Carolina on December 13, 1962 where he lived for several years until he moved to Richmond, Virginia. After graduation from Douglas Freeman High School in 1981, he entered the Virginia Military Institute. He graduated in 1985 and received a Bachelor of Science in Civil Engineering and a commission in the U. S. Air Force. He served for four years as an environmental and design engineer in the United States and abroad. In August of 1989 he entered graduate school at Virginia Tech to pursue a Master of Science in Environmental Engineering.

A handwritten signature in black ink, appearing to read "Jay Lucas". The signature is written in a cursive style with a large initial "J" and "L".