BENEFICIAL UTILIZATION OF DRINKING WATER TREATMENT RESIDUALS AS A SOIL SUBSTITUTE IN LAND RECLAMATION

By

ROBERT JOHN ZUPANCIC

Bachelor of Science

Berea College

Berea, Kentucky

1996

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 1999

OKLAHOMA STATE UNIVERSITY

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Thesis Approved:

Nicholas T. Basta
Thesis Adviser

Gordon Johnson

Larry A. Redmon

Wayne B. Powell
Dean of the Graduate College

ACKNOWLEDGMENTS

I want to especially acknowledge the patience and guidance provided by my advisor, Dr. Nick Basta, and him allowing me the opportunity to work with water treatment residuals. I greatly appreciate the help and guidance provided by my committee advisors, Dr. Gordon Johnson and Dr. Larry Redmon.

Without the assistance of my fellow graduate students I would not have been able to complete this project. I would like to thank Steve McGowen for helping me improve my knowlege of computers, and his patience while I learned how to operate the ICP. I would like to thank Jack Schroder for his expert analytical skills and knowledge of biological systems, and allowing me the opportunity to scrape cotton rat bones. Also, my deepest appreciation goes to Lori Gallimore for her many hours of helping me with my project by collecting WTR materials, performing laboratory analysis, harvesting, and sampling plots. Lastily, I appreciate Micah DeLeon for allowing me the opportunity to work with spectral based plant nutrient determinations.

Most important, I would like to thank my wife, Karmen Shawn Zupancic for all her support, patience, and help as I have completed the requirements for a Master's in Plant and Soil Science.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

Forward

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BENEFICIAL UTILIZATION OF DRINKING WATER TREATMENT RESIDUALS AS A SOIL SUBSTITUTE IN LAND RECLAMATION

ABSTRACT

Soil substitutes are in great demand for land reclamation due to large areas of abandoned mine lands and urban development in Oklahoma. Dewatered drinking water treatment residuals (WTR) have properties and characteristics similar to fine-textured soils and may be useful as a soil substitute. However, past studies have shown that vegetation grown on WTR amended soil exhibit P deficiencies. The objectives of this experiment were to determine if i) WTR can support vegetative growth, ii) P fertilizer additions can over come vegetative P deficiencies, and iii) soil tests used to make P fertilizer recommendations can be used to predict WTR utilization as a soil substitute and predict vegetative response to P fertilizer additions.

In this study, three alum WTR ranging in P adsorption capacity, were evaluated and compared with a Grant silt loam soil. Bermudagrass (*Cynodon dactylon*) was grown with P fertilizer additions of 0, 50, 100, and 200 mg P kg^{-1}, with four replications per treatment. Tissue concentrations of P, K, Ca, Mg, Mn, Al, Cu, Fe, and Zn were determined for each vegetation harvest. Phosphorus adsorption isotherms, water soluble-P (H_2O-P), Mehlich-3 P (M3-P), and resin extractable P (UNIBEST-P) were measured for the untreated and P amended WTR and soil.

Plant response to unamended and P amended materials were evaluated by the total accumulative plant yield and the tissue-P concentration at the last harvest. A bermudagrass sufficient tissue-P concentration was determined to be 2,500 mg P kg^{-1} based upon other research and the results of this experiment. Bermudagrass grown on Grant soil yields (15, 20, 27 g pot^{-1}, respectively) responded to P addition on the first

three P rates (0, 50, 100 mg P kg^{-1}) and tissue-P concentrations (1360, 2230, 2550, 3880 mg P kg^{-1}, respectively) responded across all treatments. However, bermudagrass grown in the WTR did not respond to P fertilizer additions. When P was not added, bermudagrass yields followed the trend of Mohawk > Grant soil > Wister > ABJ (27.0, 15.1, 7.0, 0.9 g pot^{-1}, respectively). Bermudagrass tissue-P concentrations were Grant soil > Mohawk > Wister > ABJ (3000, 2360, 1320, 578 mg kg^{-1}, respectively). Overall, yields of the bermudagrass grown on the soil increased with P fertilizer additions, but did not show increased responses to P fertilization when grown on WTR.

Phosphorus adsorption capacity followed the trend Grant soil < Wister < Mohawk < ABJ, but did not describe the growth potential where Grant soil, Mohawk > Wister > ABJ. The Grant soil, ABJ, and Wister exhibited a linear increase in M3-P with P addition; however, only the Grant soil responded with increased bermudagrass yields with P additions. Poor relationships between WTR M3-P and bermudagrass yield, tissue-P concentrations, and P-uptake were found. H_2O-P increased linearly for P additions on the Grant soil, while H_2O-P was deficient at all P additions. The UNIBEST method was able to extract increasing amounts of P with time from the Grant soil, ABJ, and Wister (I = 14.2, 12.1, 4.42 μg resin^{-1}, respectively), but was not able to accurately predict the P requirements for adequate vegetative growth.

Based on forage yield and tissue-P concentration data, the Mohawk and Wister WTR can be used as a soil substitute. ABJ is not suitable as a soil media due to growth inhibition and severe P deficiency of this material. Phosphorus adsorption isotherms, M3-P, and resin-P were not accurate predictors of vegetative growth on WTR with P addition. M3-P was a good predictor of which WTR materials would adequately support vegetative growth. H_2O-P was related to plant growth, but test results were variable and difficult to duplicate. Soil P tests were unable to accurately predict fertilizer P required to correct P deficiencies of the WTR.

INTRODUCTION

As potable water consumption continues to increase (7.5×10^6 gallon increase between 1980 -1990) drinking water treatment facility operators are increasingly concerned with the disposal of water treatment residuals (WTR) (USBC, 1996). Prior to the early 1980s, WTR were discharged into nearby surface waters, but presently disposal systems primarily include landfilling or on-site storage (USEPA, 1996). Increased landfill charges, federal limits on the amounts of WTR allowed into surface waters, and limited on-site storage have encouraged water treatment facilities to seek alternative disposal options (Elliott et al., 1990; Butkus et al., 1998). Proposed beneficial land application methods are the reduction of runoff P in areas with high soil P (Coale et al., 1994; Peters and Basta, 1996), co-application with biosolids to reduce P availability (USEPA, 1996), and as a soil substitute in land reclamation (USEPA, 1996).

WTR are a by-product of surface water flocculation and clarification. The primary constituents include sediments and organic materials flocculated out of source water and Al or Fe added during the flocculating process. All of these substances are naturally found in large concentrations in the lithosphere and are not considered hazardous by the U.S. Environmental Protection Agency (Butkus et al., 1998). Dewatered WTR (> 20% solids) display physical and chemical characteristics similar to fine-textured soils (DeWolfe, 1993; USEPA, 1996).

Surface mining and urban construction result in land disturbances which cause environmental concerns and may create the need for additional topsoil (Sutton, 1979). Over 1.8 million hectares of land were permitted for surface mining in 1997 with 15,000 ha in Oklahoma (OSM, 1997). The Office of Surface Mining reported 16,000 ha of abandoned mine land (AML) were reclaimed in the U.S. during 1997 (OSM, 1997). Furthermore, there is more than 10,000 ha of AML needing reclaimed in Oklahoma (OSM, 1998). Urban construction develops 400,000 ha of land yearly (Sorensen et al., 1997; USDA, 1997). The result is a need for 150 billion Mg of topsoil or soil substitute, assuming 25% of the disturbed areas require an additional 0.15 m of soil.

Trace metal concentrations of WTR are typical of natural soils with the plant available fraction generally less than 6% of the total content (Elliott et al., 1990). Low availability of metals in WTR is due to the neutral to basic characteristics of these materials (pH 6.5 - 9.5) (Elliott et al., 1990; Geertsema et al., 1994). Evaluation of WTR using the Toxicity Characteristic Leaching Procedure (TCLP) (USEPA, 1986) indicated that WTR did not exceed the allowable limits for metals on the list (Cornwell and Westerhoff, 1981). Elliott et al. (1990) performed a five-step sequential fractionation procedure on 8 different WTR, and reported that total concentrations and exchangeable fractions of Cd, Cr, Cu, Ni, Pb, and Zn were similar to concentrations found in soil. Geertsema et al. (1994) reported that there was no movement of metals through the soil profile or to shallow groundwater during a 30 month field study after 6 Mg ha^{-1} WTR was applied. In general, the environmental risk of metal toxicity is very low in WTR due to the nonacidic pH.

The primary concerns with land application of WTR are the potential for induced P deficiencies. Several potting studies have shown that WTR can reduce plant available P and cause P deficiencies. Rengasamy et al. (1980) and Bugbee and Frink (1985) have shown that soil and potting media amended with WTR (0.2 - 66% v v^{-1}) increased soil structure and water holding capacity, but induced P deficiencies in marigolds (*Tagetes* cv. lemondrop), lettuce (*Lactuca sativa*, cv. iceberg), and corn (*Zea mays*). A subsequent study that included twice the recommended P fertilizer did not reverse the P deficiency symptoms in marigolds (Bugbee and Frink, 1985). Elliott and Singer (1988) have shown that additions (20 - 100 g WTR kg^{-1}) of a ferric WTR to an Elkton silt loam induced a P deficiency in tomato plants (*Lycopersicon esculentum*). Heil and Barbarick (1989) reported that increasing WTR additions (5 - 25 g WTR kg^{-1}) on both a calcareous (pH = 7.5) and acidic (pH = 5.2) soil significantly reduced P tissue concentrations in sorghum-sudangrass (*Sorghum bicolor* L. Monench 'NB280S'-*S. sudanense* Stapf). Cox et al. (1997) demonstrated that surface application (4.5 - 17.8 g dry WTR kg^{-1}) of WTR slurry (2% solids) to an acidic soil (pH = 4.4) reduced dry matter yields, tissue-P concentrations, and P-uptake of wheat (*Triticum aestivum* cv. Atlas 66). Phosphorus fertilizer additions up to 75 mg P kg^{-1} have been reported to increase the yield of sorghum-sudan and wheat grown on WTR, but did not completely eliminate the P deficiency caused by the WTR amendments (Heil and Barbarick, 1989; Cox et al., 1997). In all the above mentioned studies, WTR application > 10 g WTR kg^{-1} (20 Mg ha^{-1}) resulted in reductions in tissue-P concentrations while no other WTR induced nutrient deficiencies or toxicities were observed or reported.

WTR have been surface applied to forest soils without causing negative environmental effects (Grabarek and Krug, 1987; Geertsema et al., 1994). Grabarek and Krug (1987) reported that a broadcast application (17.5 Mg dry WTR ha^{-1}) of WTR slurry (1.5% solids) to a mature forest in Connecticut did not affect tree growth or nutrient content after one year. Geertsema et al. (1994) reported on an intensive study designed to assess the environmental effects of alum WTR land application (36, 52 Mg dry WTR ha^{-1}) on groundwater quality and loblolly pine seedling growth over a 30 month period. General soil characteristics, groundwater characteristics, and pine growth analyses showed no statistically significant differences between unamended compared to WTR amended sites (Geertsema et al., 1994). Although land disposal of WTR did not have undesirable environmental effects, disposal did not benefit soil properties or landowner profits, and therefore other beneficial alternatives should be investigated.

WTR are primarily soil particles, which do not inhibit seed germination (Bugbee and Frink, 1985; Rengasamy et al. 1980). Furthermore, WTR contain similar levels of macro and micro plant nutrients as compared to soil (Elliott and Dempsey, 1991). Due to the soil-like characteristics of WTR and the demand for soil, it is proposed that WTR could be used in the place of soil in circumstances requiring minimal or non-optimal vegetative growth, such as abandoned mine land reclamation, road corridor revegetation, and urban construction. However, the high P fixing capacity of WTR is similar to that of andisols which also contain large quantities of amorphous Al and Fe oxides due to their volcanic origin (McFarlane and Walmsley, 1977; Molina et al., 1991; Buol et al., 1997).

Determining the quantity and P fertilizer application strategy for high P fixing soils is difficult due to the inability of soil tests to accurately predict P additions required for optimal plant growth (Sanchez and Salinas, 1981; Sanchez and Uehara, 1981; Cajuste et al., 1992). Soil P extractants commonly used in the U.S., such as Bray I (Bray and Kurtz, 1945), Mehlich I (Mehlich, 1953), and Olsen bicarbonate (Olsen, 1954), often overestimate the amount of P available to plants grown on andisols and soils with high amorphous oxide concentrations (Sanchez and Salinas, 1981; Gardiner and Christensen, 1991). When P applications are banded, the interpretation of soil test becomes even more difficult due to residual effects of the band application (Sanchez and Salinas, 1981). The ability of phosphorus soil tests to predict the adequacy of WTR to support vegetative growth has not been studied.

The objectives of this experiment were to determine if i) WTR can support vegetative growth, ii) P fertilizer additions can overcome any vegetative P deficiencies, and iii) soil tests used to make P fertilizer recommendations can be used to predict WTR utilization as a soil substitute and predict vegetative response to P fertilizer additions.

MATERIALS AND METHODS

Three WTR were collected from AB Jewell (ABJ), Mohawk, and Poteau Valley Improvement Authority (Wister) water treatment facilities in eastern Oklahoma.

Treatment processes, surface water source, and primary coagulants of the WTR are described in Table 1. For comparison, a Grant silt loam (fine, silty mixed thermic Udic Argiustoll) was collected from an unfertilized area at the Lahoma Agriculture Experiment Station at Lahoma, OK. The WTR and soil were air-dried and passed through a 6.0 mm sieve and 3.0 kg of the dry materials were potted into 0.25 m diameter plastic pots. Bulk densities of the potted material were determined from four randomly selected pots per WTR or soil following the last bermudagrass harvest (Table 2).

Growth chamber studies were conducted to determine if bermudagrass would respond to P fertilization of WTR. The experimental design was a complete randomized design with three P treatments and four replications per treatment. Fertilizer P additions were based upon a laboratory P adsorption study to achieve water soluble-P (H_2O-P) levels of 0.05 mg L^{-1}. The highest P fertilizer treatment of 200 mg P kg^{-1} is equivalent to the application of 2,500 kg ha^{-1} of diammonium phosphate fertilizer. Fertilizer P was thoroughly incorporated into the 3.0 kg of WTR or soil by applying a KH_2PO_4 solution with a garden sprayer. Potassium chloride was added (up to 250 mg K kg^{-1}) to the above P solution to match K added from the KH_2PO_4. Nitrogen was applied as NH_4NO_3 before establishment of vegetation (25 mg N kg^{-1}) and after each harvest to ensure adequate N (25 mg N kg^{-1} harvest $^{-1}$). Phosphorus applications were incorporated into each material at 0, 50, 100, and 200 mg P kg^{-1}.

Bermudagrass Establishment and Analysis

Bermudagrass (*Cynodon dactylon,* variety Greenfield) was grown in the pots containing WTR or soil for 4 months. Before establishing the bermudagrass in the pots, it was sprigged (5 g pot $^{-1}$) into 500 g of deionized (DI) H_2O washed sand, and fertilized with a P deficient Hoagland's solution (Jones, 1997) for three weeks. After three weeks of growth in the sand, the bottoms of the containers were removed and the plants were transferred to the top of the pots containing WTR or soil (Stanford and DeMent, 1957). Bermudagrass was grown in controlled environment growth chambers with 16-h of daylight, 22° C. Before vegetation establishment, field capacity was determined gravimetrically by saturating the soil or WTR in the pot, allowing to drain for 24 hrs, and weighing (Peters, 1965). Moisture was maintained in the materials by watering as needed and adjusting the materials to field capacity weekly.

The bermudagrass was harvested at 36, 70, 110, and 140 DAE and oven dried at 60° C for 24 hours. Harvested tissue was digested by wet digestion using the nitric and perchloric acid method (Jones and Case, 1990) and was analyzed for P, K, Ca, Mg, Al, Cu, Fe, and Zn using inductively coupled argon plasma atomic emission spectroscopy (ICP).

Soil and WTR Analysis

WTR and soil were extracted by 1:5 soil:DI H_2O (Kuo, 1990) and 1:10 soil:M3 extractant (Mehlich, 1984) for P determination before establishment and after the final harvest of each vegetation. Phosphorus concentrations in the H_2O extracts were determined by the modified abscorbic acid method (Kuo, 1996) while P, K, Ca, Mg extracted by M3 were analyzed by ICP. Readily available N in WTR or soil (NO_3-N and NH_4-N) was determined by 2M KCl extraction and analyzed by automated flow injection analysis (Lachat, 1989, 1990). The pH, EC, Mn, and Al were determined in 1:2 soil:DI H_2O extracts. Total C and N of WTR and soil were determined using a Carlo-Erba NA 1500 dry combustion analyzer (Schepers et al., 1989). Plant available SO_4 was extracted with a 500 mg P L^{-1} solution as $Ca(H_2PO_4)_2$ (Fox et al., 1964) and analyzed by ICP. Plant available Fe and Zn were extracted with DTPA-TEA (Lindsay and Norvell, 1978) and analyzed by ICP. The CEC was determined by sodium saturation (Rhoades, 1982). The acid ammonium oxalic method (pH 3.0) was used to estimate the concentration of noncrystalline and poorly crystalline Al forms (Al-Ox) in the soil or WTR (Ross and Wang, 1993).

Phosphorus sorption curves were determined by a modification of the Fox and Kamprath method (1970). Fox (1981) proposed that a faster equilibration could be accomplished by constantly shaking the soil/P solution horizontally for 18 hours instead of static equilibration for 6 days. Also the soil:P was changed to a 1:25 ratio from the 1:10 ratio used by Fox and Kamprath (1970). Adsorption methods were performed on unamended soil and WTR using 6 g soil or WTR and 150 mL P solution (0, 4, 8, 16, and 32 mg P L^{-1}).

Resin extractable P was determined by creating saturated pastes of approximately 50 g of soil or WTR and transferring to 120 mL plastic containers as described by the UNIBEST method (Yang et al., 1991). A resin ball containing anion and cation exchange resins (UNIBEST, Bozeman, MT) was inserted into the center of the paste and the container was tightly sealed. The containers were incubated at 30° C for 1, 2, 4, 7, and 14 days. Resin extractions were performed in duplicate. Resin balls were removed from the soil or WTR, rinsed thoroughly with DI H_2O to remove all soil particles and frozen. Cations and anions were extracted from the resin balls by equilibrating with 20 mL of 2M HCl for 15 minutes, rinsing again with 25 mL of 2M HCl, filtering through a 0.45 μm membrane filter, combining filtrate and diluting up to 50 mL with DI H_2O. All HCl extracts were analyzed by ICP and reported on a μg $resin^{-1}$ basis. This method is used to quantify both intensity (I) and quantity (Q) factors for P. The I is expressed as the resin concentration at Day 1, while Q is the slope of the line between Day 1 and Day 4 (Yang et al., 1991).

Statistical Methods

Mean separation was performed using SAS (SAS Institute, 1985) and regression analyses were performed using SigmaPlot (SSPS Inc., 1997). Differences in the mean values reported at $p < 0.05$ in Table 3, 4; and Fig. 2, 4 were calculated using PROC GLM and LSMEANS (Swallow, 1984; Steele et al., 1997).

RESULTS AND DISCUSSION

Composition of WTR and Grant soil

Past studies have shown that WTR contain similar concentrations of nutrients as soil and that P is the only plant limiting factor (Elliott et al., 1990; Elliott and Dempsey, 1991). The WTR studied contain adequate N for bermudagrass growth under reclamation conditions (Bradshaw and Chadwick, 1980; Zhang et al., 1998). Furthermore, 240 - 320 mg N kg^{-1} was mineralized during a 23 day incubation study due to the very high microbial content of these WTR (Table 2). The M3-P values of the WTR materials are above the level required for 50% sufficiency for forages (5 mg P kg^{-1}), however only Mohawk (30 mg P kg^{-1}) has a M3-P value near the 100% sufficiency level for forages (30 mg P kg^{-1}). Although, below detectable levels (BDL) of H_2O-P in ABJ and Wister, and the low level (0.01 mg P L^{-1}) in Mohawk are indicative of plant P deficiencies (White, 1980; Fox, 1981). The plant available indicies of K, Ca, Mg, SO_4, Fe, and Zn in WTR are all ≥ the 50% sufficiency levels for forage grasses (Zhang et al., 1998). However, the moderately low level of K in Wister was not a factor in the potting study due to the addition of K (250 mg K kg^{-1}). The pH and EC of WTR are similar to nonsaline agricultural soil and should not impede plant growth (Table 2).

The WTR have much higher P sorption capacities than the Grant soil (Fig. 4) and are similar to the very high P adsorptive capacity of andisols (Fox and Kang, 1978; Fox, 1981; Gardiner and Christensen, 1991; Leal et al., 1994; Buol et al., 1997). The Al-Ox contents of the WTR (12 - 57 g Al-Ox kg^{-1}) are much higher than the Grant soil (Table 2), and are within the range (5.1 - 60.7 g Al-Ox kg^{-1}) reported for andisols in Costa Rica and Panama (Molina et al., 1991). In the three WTR studied, P solubility strongly correlated with the Al-Ox fraction (Basta et al., 1999). The high amorphous oxide could cause vegetation P deficiencies reported by Rengasamy et al. (1980), Bugbee and Frink (1985), Heil and Barbarick (1989), and Cox et al. (1997).

Andisols can be agriculturally productive, but special care must be taken in the management of P to ensure adequate plant nutrition (Sanchez and Uehara, 1981). One management technique for high P fixing soils is utilizing the low soil P required by some agricultural crops such as upland rice and sweet potatoes (0.003 mg P L^{-1}). Fox (1981) reported that cassava (*Manihot esculenta*) required low levels of P (0.005 mg P L^{-1}) in solution for 95% maximum growth, whereas soybeans (*Glycine max*), tomatoes (*Lycopersicon esculentum*), and head lettuce (*Lactuca sativa*) required > 0.02 mg P L^{-1}. However, large variations in required P have been reported due to environmental factors, yield potentials associated with different climatic conditions, and other soil factors that reduce the maximum yield goal potential (Jones and Benson, 1975; Gardner and Jones, 1973; Fox, 1979).

Two primary management strategies have emerged to adequately meet crop P requirements on high P fixing soils; the first consists of an initial heavy application of P fertilizer followed by substantial residual effects for several years, and the second is a low input option traditionally based on band application of P (Sanchez and Uehara, 1981). The heavy application of P requires 0.5 - 1.0 Mg P ha^{-1} to achieve residual effects longer than 4 years (Sanchez and Uehara, 1981). Banding P has been shown to be more beneficial than the high initial P application in certain high-fixing soils (Kamprath, 1967; Barber, 1995).

The water extractable Al and Mn levels in the WTR were elevated compared to the Grant soil, but should not inhibit root or shoot growth at these concentrations (Bohn et al., 1985) (Table 2). Inhibition of root growth is not expected considering Al and Mn toxicities occur primarily on acid soils, generally pH < 5 (Fales and Ohki, 1982; Duncan et al., 1983; Bohn et al., 1985) (Table 2). Measured cation exchange capacities of ABJ and Mohawk (54.7 and 29.7 cmol kg^{-1}) were considerably higher than the values of the Grant soil and Wister. The total C, total N, C:N ratio, NH_4-N, and pH values (Table 2) are similar to other published values for alum WTR (Heil and Barbarick, 1989; DeWolfe, 1993; Geeretsema et al., 1994). Chemical analysis of the WTR and Grant soil indicated ample nutrition for all nutrients, except P, and no toxic or growth inhibiting constituents for bermudagrass.

Bermudagrass Yield and Response to P Fertilizer

Analysis of variance showed that bermudagrass yield between materials (mean in parenthesis) were Grant soil (20.6 g pot^{-1}), Mohawk (23.6 g pot^{-1}) > Wister (9.59 g pot^{-1}) > ABJ (1.11 g pot^{-1}) at $p < 0.05$ (Fig. 1). Wister yields were similar to that of the Grant soil without P additions ($p < 0.05$), while bermudagrass grown on ABJ exhibited very little growth for all P treatments (Fig. 1). Only bermudagrass grown on the Grant soil exhibited a yield or tissue-P response to fertilizer additions ($R^2 = 0.98$, tissue-P). For bermudagrass grown on Grant soil, the tissue-P concentrations at the last harvest (140 DAE, 30 days of growth) were deficient at the 0 and 50 mg P kg^{-1} treatments (Kelling and Matocha, 1990). Tissue-P concentrations of the WTR ranged from borderline (2335 mg P kg^{-1} Mohawk) to very deficient (339 mg P kg^{-1} ABJ) (Fig. 1). Bermudagrass yield increased as the tissue-P concentrations increased except for the excessive tissue-P concentrations of the Grant soil that depressed plant yields (Fig. 2). In general this shows that ABJ material has minimal yield potential, Wister has 50% of the maximum yield potential, and that Mohawk is equal to the maximum yield potential of the Grant soil. Bermudagrass P-uptake on the 100 mg P kg^{-1} addition followed the same trend as the tissue-P concentrations, with the Grant soil > Mohawk > Wister > ABJ (Fig. 3).

Bermudagrass Nutrient Concentrations

The bermudagrass nutrient contents were evaluated at the last harvest (140 DAE) on materials that did not receive P additions (Table 3). These comparisons were made to demonstrate the ability of WTR to supply vegetation with adequate amounts of P, K, Ca, Mg, Cu, Fe, and Zn and to illustrate that P is the primary nutrient limiting plant growth. Bermudagrass tissue concentrations were compared to adequate values reported by Kelling and Matocha (1990). Bermudagrass tissue-P and Mg concentrations were below adequate (2400 and 3000 mg kg^{-1}, respectively) for all materials when no P was added (Table 3). Bermudagrass K tissue concentrations were above adequate (15 g kg^{-1}) for the Grant soil and Wister, but below adequate for ABJ and Mohawk (7.3 and 11.8 g kg^{-1}, respectively). Calcium tissue concentrations were at adequate levels (5,500 mg kg^{-1}) for Mohawk and Wister, while the Grant soil and ABJ were borderline adequate (4950, 5420 mg kg^{-1}, respectively). Copper, Fe, Zn, and Mn tissue concentrations were above adequate levels for all materials. Deficient tissue concentrations of P, K, Ca, and Mg in bermudagrass grown on ABJ were most likely the result of the stunted growth caused by the low H_20-P in ABJ. Mohawk contained high levels of plant available Ca which could have reduced the bermudagrass uptake of K and Mg (Tisdale et al., 1993). The Ca and Mg deficiencies exhibited in bermudagrass grown on the Grant soil are not easily explained considering that Ca is rarely a limiting nutrient in Oklahoma soils (Zhang et al., 1998). Furthermore, soil test Mg was almost three times what is required for 100% sufficiency (Zhang et al., 1998).

Bermudagrass Metal Accumulation

Vegetation accumulation of Al, Zn, Fe, Cu, and Mn were evaluated at the last harvest on materials that did not receive P additions (Table 3, 4) because some research has shown that vegetation tissue concentrations of Mn and Cu increase as WTR loading increases. Bermudagrass tissue concentrations of Al, Cu, Fe, Mn, and Zn were all below the ranges reported to be toxic to livestock by NRC (1980) (Table 3). The tissue Mg concentration of Mohawk and ABJ could cause grass tetany in cattle or sheep if additional Mg was not supplemented in their diet (Ball et al., 1996) (Table 3). Bermudagrass metal accumulation for WTR was not significantly higher than plants grown on the Grant soil (Table 4). This is consistent with research that has shown no increased uptake of Al, Cd, Cu, Fe, or Zn in tomatoes, loblolly pine, sorghum-sudan, and wheat grown on mixtures of WTR and soil up to 600 g WTR kg^{-1} soil (Bugbee and Frink, 1985; Elliott and Singer, 1988; Heil and Barbarick, 1989; Geertsema et al., 1994; Cox et al., 1997). However, Cox et al. (1997) and Lucas et al. (1994) have shown increases in Mn concentration of 300 - 800 mg kg^{-1} when increasing WTR application from 0 - 40 g WTR kg^{-1} soil. Tilchin et al. (1990) reported increased concentrations of Mn (150 - 250 mg kg^{-1}) and Cu (1.5 mg kg^{-1}) in fescue with every 1% increase in WTR applied to soil (36 - 56 Mg WTR ha^{-1}).

P Soil Test Methods

The ability of P adsorption curves, M3-P, H_2O-P, and resin extraction (UNIBEST-P) methods to predict vegetative response to P fertilizer additions and to determine the ability of the WTR to support vegetative growth were evaluated. Fox and Kamprath (1970) stated, "Predicting requirements for P fertilizers on highly weathered soils by the use of phosphate sorption isotherms takes into account both intensity and capacity factors. This approach provides a method for studying reaction of P fertilizers which is more closely related to plant needs than some of the classical studies on solubility of P reaction products". P sorption isotherms for ABJ, Mohawk, and Wister exhibit similar P sorption characters as andisols (MacFaralane and Walmsley, 1977; Gardiner and Christensen, 1991; Jones et al., 1979). P sorption isotherms for a group of andisols from Guatemala are shown in Fig. 4B for comparison (Leal et al., 1994). Both the WTR and andisols show H-type P adsorption (Fig. 4) (Sposito, 1989).

Fox (1981) proposed that the P fertilizer required for the maximum yield of corn can be estimated from P sorption isotherms by adding the amount of P adsorbed at the 0.05 mg P L^{-1} solution concentration (Fig. 4A). The amount of P adsorbed to achieve 0.05 mg P L^{-1} is approximately 10 and 250 mg P kg^{-1} for Wister and Mohawk respectively, while ABJ requires much more than 800 mg P kg^{-1} (Fig. 4A). The adsorption capacity trend for these materials is ABJ > Mohawk > Wister. However, the yield and P-uptake of bermudagrass grown on Mohawk was greater than Wister and does not correspond to the P availability predicted by the adsorption isotherms. The prediction of vegetation requiring greater than 800 mg P kg^{-1} amendment on ABJ was representative of the minimal bermudagrass yields observed on this material. Although this method has worked on a wide range of tropical soils, research has shown that it can be difficult to establish critical levels of a few parts per billion that often correspond to the critical range in high P fixing soils (Sanchez and Salinas, 1981).

M3-P is a widely used soil test to measure plant available P, K, and Mg (Hanlon and Johnson, 1984; Fixen and Grove, 1990; Sharply et al., 1994). In Oklahoma, the M3-P 100% sufficiency level for bermudagrass is 32 mg P kg^{-1}, and the 50% sufficiency level ranged from 0 - 5 mg P kg^{-1} (Zhang et al., 1998). The relationship between fertilizer P added and M3-P values following the final bermudagrass harvest (210 days after P addition) are shown in Fig. 5. The Grant soil, ABJ, and Wister exhibited a significant ($p < 0.01$) linear increase in M3-P with P additions, although only bermudagrass grown on the Grant soil responded to P additions (Fig 1). All materials had M3-P values $\geq$ than 30 mg P kg^{-1} for additions $\geq$ 50 mg P kg^{-1}. Poor relationship between M3-P and bermudagrass yield, tissue-P concentrations (harvest 4), and P-uptake for WTR were found (Fig. 6). Only the tissue-P concentration on the Grant soil was related to M3-P ($r^2 = 0.99$) (Fig. 6). Perhaps the strong acidity (pH $\approx$ 2.4) and fluoride concentration (0.015 M F^-) of the M3 solution dissolves excessive amounts of P associated with amorphous Al and Fe oxides that is not plant available. Similarly, acid extractable P is generally poorly correlated to plant response on high P fixing soils (Cajuste et al., 1992; Baravalle et al., 1993; Leal et al., 1994). However, the M3-P of the unamended WTR followed the same trend as the bermudagrass yield on the WTR, Mohawk > Wister > ABJ ($p < 0.01$).

Water extractable P is well related to a wide range of plant P nutritional adequacy levels for soils and estimates immediately available plant P (Bingham, 1949; Fixen and Grove, 1990; Kuo, 1996). The P concentrations considered to be critical for plant response to P vary widely (0.05 - 0.30 mg L^{-1}) depending on the plant species and the P buffering capacity of the soil (Fox and Kamprath, 1970; White, 1980; Fox, 1981). Research by Fox (1981) has shown that a H_2O-P value of 0.01 mg L^{-1} correlates to 75% of a maximum yield for corn and grain sorghum (*Sorghum bicolor*), while 0.05 mg L^{-1} indicates 100% of maximum yield. Therefore, an adequate H_2O-P level for bermudagrass growth in the WTR materials would correspond to 0.02 mg L^{-1} based on the bermudagrass data presented in Fig. 1, and the requirements for corn and sorghum reported by Fox (1981). Table 5 indicates that as P is added to the Grant soil, H_20-P increases from 0.035 to 1.41 mg L^{-1} and is sufficient at all levels of P additions. All WTR exhibited deficient H_20-P at all levels of P additions, while Mohawk displayed borderline adequate amounts at the 50 and 200 mg kg^{-1} additions (0.014 and 0.020 mg P L^{-1}, respectively) (Table 5). ABJ did not contain measurable $H_2$0-P at any P addition level, while $H_2$0-P in Wister was only detectable at the 200 mg kg^{-1} addition (0.014 mg P L^{-1}). These low levels of $H_2$0-P are most likely the result of the high amount of amorphous Al in these WTR materials. Peters and Basta (1996) have shown that even small additions of WTR (30 g WTR kg^{-1} soil) to a high M3-P soil (550 mg P kg^{-1}) caused approximately 11 mg L^{-1} reduction in H_2O-P. Although H_2O-P is related to plant available P in WTR, its reproducibility is poor as indicated by the large standard deviations (Table 5).

Resin-extractable P measured by the UNIBEST method simulates the P sink of plant roots and simultaneously extracts both cations and anions (Yang et al., 1991; Skogley, 1992). UNIBEST method was used on the unfertilized Grant soil and WTR to determine the I and Q parameters (Fig. 7). Data for the Grant soil and ABJ exhibited a linear response over the 14 day extraction period with I = 14.2 and 12.1 μg P $resin^{-1}$, and Q = 2.71 and 4.27 μg P $resin^{-1}$ day^{-1}, respectively. Wister resin data fit a quadratic curve, with I = 4.42 μg P $resin^{-1}$ and Q = 4.19 μg P $resin^{-1}$ day^{-1}. Mohawk displayed no trend in resin P with time, I = 52.9 μg P $resin^{-1}$. Although this method was able to extract P from the Grant soil, ABJ, and Wister, it was not able to accurately predict the P requirements for adequate plant growth considering these three materials exhibited similar resin extraction trends, but very dissimilar plant growth.

CONCLUSIONS

Vegetation yields and tissue data indicated that Mohawk and Wister could potentially be used as soil substitutes in land reclamation. However, the reduced bermudagrass yield and deficient tissue-P concentrations on Wister would require special management to increase the P availability of this material. The ABJ material is not suitable for vegetative growth due to the low P availability. However, the high P sorption characteristics of ABJ may serve as a P sink in soils with excessive levels of P. Beneficial utilization of WTR as a soil substitute in land reclamation would ultimately benefit the general public through lower municipal costs and help protect the environment by converting unproductive land into healthy ecosystems capable of supporting both plant and animal communities.

Phosphorus additions up to 200 mg P kg^{-1} did not increase the plant availability of P on the WTR materials, although P additions did increase the yield and tissue-P concentrations of bermudagrass grown on the Grant soil. This high P requirement exhibited by WTR are similar to P requirements noted by other researchers when working with andisols. Volcanic ash based allophanic soils may require $\geq$ 1000 Mg P ha^{-1} to increase yields of tomatoes, potatoes, and corn to optimal production levels. Band application of P on WTR should be researched to determine the ability of this management practice to increase P fertilizer availability.

Soil test P values were not closely related to vegetative growth or response to P fertilizer additions on the WTR materials evaluated. Phosphorus adsorption isotherms demonstrated the large P sorption capacity of WTR, but failed to accurately predict the amount of P fertilizer additions needed for bermudagrass growth on the Mohawk and Wister. M3-P may have overestimated plant availability of P in WTR, which is most likely due to the over extraction of amorphous aluminum bound P that is not readily plant available. H_2O-P appears to predict the ability of bermudagrass to adequately grow on WTR if the H_2O-P level is above 0.01 - 0.02 mg P L^{-1}.

WTR materials vary in their chemical characteristics and ability to grow plants due to the different treatment processes and qualities of source water at individual water treatment facilities. The most beneficial utilization of WTR with deficient levels of nutrients is land reclamation where minimal management and sub-optimal yields are required.

REFERENCES

Ball, D.M., C.S. Hoveland, and G.D. Lacefield. 1996. Southern Forages, 2nd ed. Potash and Phosphate Institute; Foundation for Agronomic Research, Norcross, GA.

Baravalle, R.A., R.A. Rosell, and A.E. Glave. 1993. Phosphorus in the Pampean semi-arid region of Argentina. I. Bray and anionic exchange resin extractable phosphorus. Commun. Soil Sci. Plant Anal. 24(13/14):1567-1576.

Barber, S.A. 1995. Soil nutrient bioavailability: A mechanistic approach. John Wiley and Sons, New York, NY.

Basta, N.T., L. Gallimore, and E. Dayton. 1999. Nutrient adsorption capacity of water treatment residuals. WEF/AWWA Joint Residuals and Biosolids Management Conference. Charolette, NC. Jan. 27-29. WEF, Alexander, VA.

Bingham, F.T. 1949. Soil test for phosphate. California Agriculture 3:11-12.

Bohn, H.L., B.L. McNeal, and G.A. O'Connor. 1985. Soil Chemistry, 2nd ed. John Wiley & Sons, New York, NY.

Bradshaw, A.D., and M.J. Chadwick. 1980. The restoration of land: The ecology and reclamation of derelict and degraded land. Blackwell Publishing, Los Angeles, CA.

Bray, R.H., and L.T. Kurtz. 1945. Determination of total, organic and abailable forms of phosphorus in soils. Soil Sci. 59:39-45.

Bugbee, G.J., and C.R. Frink. 1985. Alum sludge as a soil amendment: Effects on soil properties and plant growth. Conn. Agric. Exp. Stn. Bull. 827, New Haven, CT.

Buol, S.W., F.D. Hole, R.J. McCracken, and R.J. Southard. 1997. Soil genesis and classificataion. 4th ed. Iowa St. Univ. Press, Ames, Al.

Butkus, M.A., D. Grasso, C.P. Schulthess, and H. Wijnja. 1998. Surface complexation modeling of phosphate adsorption by water treatment residuals. J. Environ. Qual. 27:1055-1063.

Cambell, C.A., Y.W. Jame, O.O. Akinremi, and H.J. Beckie. 1994. Evaluating potential nitrogen mineralization for predicting fertilizer nitrogen requirements of long-term field experiments. p. 81-100. *In* J.L. Havlin and J.S. Jacobsen (eds.) Soil testing: Prospects for improving nutrient recommendations. ASA SSSA, Madison, WI.

Cajuste, L.J., V.H. Alvarez, and R.J. Laird. 1992. Evaluation of chemical extractants for assessing phosphate availability in volcanic ash soils. Commun. Soil Sci. Plant Anal. 23(17/20), 2189-2206.

Coale, F.J., P.S. Porter, and W. Davis. 1994. Soil amendments for reducing phosphorus concentrations of drainage water from histosols. Soil Sci. Soc. Am. J. 58:1470-1475.

Cornwell, D.A., and G.P. Westerhoff. 1981. Management of water treatment plant sludges. P. 31-62. *In* J.A. Borchardt et al. (ed.) Sludge and its ultimate disposal. Ann Arbor Science Publ., Ann Arbor, MI.

Cox, A.E., J.J. Camberato, and B.R. Smith. 1997. Phosphate availability and inorganic transformation in an alum sludge-affected soil. J. Environ. Qual. 26:1393-1398.

DeWolfe, J.R. 1993. Analyses, bioavailability and mineralization of nutrients on soils receiving WTR. AWWA/WEF Joint Residuals Management Conference. Phoenix, AZ. Dec. 5-8, 1993. AWWA, Denver, CO.

Duncan, R.R., R.B. Clark, and P.R. Furlani. 1983. Laboratory and field evaluations of sorghum for response to aluminum and acid soil. Agron. J. 75:1023-1026.

Elliott, H.A., and B.A. Dempsey. 1991. Agronomic effects of land application of water treatment sludges. J. AWWA. 84(3):126-131.

Elliott, H.A., B.A. Dempsey, and P.J. Maille. 1990. Content and fractionation of heavy metals in water treatment sludges. J. Environ. Qual. 19:330-334.

Elliott, H.A., and L.M. Singer. 1988. Effect of water treatment sludge on growth and elemental composition of tomato (lycopersicon esculentum) shoots. Commun. Soil Sci. Plant Anal. 19(3):345-354.

Fales, S.L., and K. Ohki. 1982. Manganese deficiency and toxicity in wheat: Influence on growth and forage quality of herbage. Agron. J. 74:1070-1073.

Fixen, P.E., and J.H. Grove. 1990. Testing soils for phosphorus. p. 141-180. *In* R. L. Westerman (ed.) Soil Testing and Plant Analysis. 3rd ed. SSSA Book Ser. 3. SSSA, Madison, WI.

Fox, R.L. 1979. Comparative responses of field grown crops to phosphate concentrations in soil solutions. p. 81-106. *In* H.W. Mussell and R.C. Staples (eds.) Stress physiology in crop plants. Wiley-Interscience New York, NY.

Fox, R.L. 1981. External phosphorus requirements of crops. p. 223-239 *In* M. Stelly et al. (ed.) Chemistry in the soil environment. ASA Spec. Publ. 40. ASA and SSSA, Madison, WI.

Fox, R.L., and E.J. Kamprath. 1970. Phosphate sorption isotherms for evaluating the phosphate requirements of soils. Soil Sci. Soc. Amer. Proc. 34:902-906.

Fox, R.L., and B.T. Kang. 1978. Influence of phosphorus fertilizer placement and fertilizer rate on maize nutrition. Soil Sci. 125:34-40.

Fox, R.L., R.A. Olson, and H.F. Rhoades. 1964. Evaluating the sulfur status of soils by plants and soil tests. Soil Sci. Soc. Am. Proc. 28:243-246.

Gardner, B.R., and J.P. Jones. 1973. Effects of temperature on phosphate sorption isotherms and phosphate desorption. Comm. Soil Sci. Plant Anal. 4:83-93.

Gardiner, D.T., and N.W. Christensen. 1991. Pear seedling response to phosphorus in a phosphorus-fixing soil. Commun. Soil Sci. Plant Anal. 22(15/16):1597-1603.

Geertesema, W.S., W.R. Knocke, J.T. Novak, and D. Dove. 1994. Long-term effects of sludge application to land. J. AWWA. 86(11):64-74.

Grabarek, R.J., and E.C. Krug. 1987. Silviculture application of alum sludge. J. AWWA. 79(6):84-88.

Hanlon, E.A., and G.V. Johnson. 1984. Mehlich III, Bray/Kurtz, ammonium bicarbonate, DTPA, ammonium acetate, soil extractants, phosphorus, potassium, magnesium, soil testing. Commun. Soil Sci. Plant Anal. 15(3):277-294

Heil, D.M., and K.A. Barbarick. 1989. Water treatment sludge influence on the growth of sorghum-sudangrass. J. Environ. Qual. 18:292-298.

Jones, J.B., Jr. 1997. Hydroponics: A practical guide for the soilless grower. St. Lucie Press, Boca Raton, FL.

Jones, J.B. Jr., and V.W. Case. 1990. Sampling, handling, and analyzing plant tissue samples. p. 389-427. *In* R.L. Westerman (ed.) Soil testing and plant analysis. 3rd ed. SSSA Book Ser. 3. SSSA, Madison, WI.

Jones, J.P., and J.A. Benson. 1975. Phosphate sorption isotherms for ferilizer P needs of sweet corn (<u>zea</u> <u>mays</u>) grown on a high phosphorus fixing soil. Commun. Soil Sci. Plant Anal. 6(5):465-477.

Jones, J.P., B.B. Singh, M.A. Fosberg, and A.L. Falen. 1979. Physical, chemical, and mineralogical characteristics of soils from volcanic ash in northern Idaho: II. Phosphorus sorption. Soil Sci. Soc. Am. J. 43:547-552.

Kamprath, E.J. 1967. Residual effects of large application of phosphorus on high fixing soils. Agron. J. 59:25-27.

Kelling, K.A., and J.E. Matocha. 1990. Plant analysis as an aid in fertilizing forage crops. p. 603-643. *In* R. L. Westerman (ed.) Soil Testing and Plant Analysis. 3rd ed. SSSA Book Ser. 3. SSSA, Madison, WI.

Kuo, S. 1996. Phosphorus. p. 869-919. *In* D.L. Spark et al. (ed.) Methods of soil analysis. Part 3. Chemical Methods. SSSA Book Ser. 5. SSSA and ASA, Madison, WI.

Lachat Instruments. 1989. Quickchem method 12-107-04-1-B. Lachat Instr., Milwaukee, WI.

Lachat Instruments. 1990. Quickchem method 12-107-06-1-B. Lachat Instr., Milwaukee, WI.

Leal, J.E., M.E. Summer, and L.T. West. 1994. Evaluation of available P with different extractants on Guatemalan soils. Commun. Soil Sci. Plant Anal. 25(9/10):1161-1196.

Lindsay, W.L., and W.A. Norvell. 1978. Development of a DTPA micronutrient soil test. p. 84. Agronomy abstracts. ASA, Madison, WI.

Lucas, J.B., T.A. Dillah, R.B. Reneau, J.T. Novak, and W.R. Knocke. 1994. Alum sludge land application and its effect on plant growth. J. AWWA. 86(11)75-83.

MacFarlane, M., and D. Walmsley. 1977. Effect of soil solution phosphorus in volcanic ash soils on the response of tomato (*Lycopersicum esculentum*) to added phosphate. Plant and Soil. 47:547-558.

Marschner, H. 1995. Mineral Nutrition of Higher Plants, 2nd ed. Academic Press, New York, NY.

Mehlich, A. 1953. Determination of P, Ca, Mg, K, Na and NH4. North Carolina Soil Testing Div. Mimeo, Raliegh.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15(12):1409-1416.

Molina, E., I. Bornemisza, F. Sancho, and D.L. Kass. 1991. Soil aluminum and iron fractions and their relationships with P immobilization and other soil properties in andisols of Costa Rica and Panama. Commun. Soil Sci. Plant Anal. 22(13/14):1459-1476.

NRC. 1980. Mineral tolerance of domestic animals. National Research Council. National Academy Press, Washington, DC.

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. 939. U.S. Gov. Print. Office, Washington, DC.

Office of Surface Mining (OSM). 1997. Office of surface mining annual report, 1997. USDI-OSM. U.S. Gov. Print. Office, Washington, DC.

Office of Surface Mining (OSM). 1998. Abandoned mine land inventory system. OSM-Reclamation and Enforcement, Washington, DC.

Peters, D.B. 1965. Water availability. p. 279-285. *In* C.A. Black (ed.) Methods of soil analysis Part 1. Physical and mineralogical properties. SSSA, Madison, WI.

Peters, J.M., and N.T. Basta. 1996. Reduction of excessive bioavailable phosphorus in soils by using municipal and industrial wastes. J. Environ. Qual. 25:1236-1241.

Rengasamy, P., J.M. Oades, and T.W. Hancock. 1980. Improvement of soil structure and plant growth by addition of alum sludge. Commun. Soil Sci. Plant Anal. 11(6):533-545.

Rhoades, J.D. 1982. Cation exchange capacity. p. 149-157. *In* A.L. Page, R.H. Miller, and D.R. Keeney (eds.) Methods of soil analysis, Part 2, Chemical and microbiological properties, 2nd ed. Soil Sci. Soc. Am., Madison, WI.

Ross, G.J., and C. Wang. 1993. Acid ammonium oxalate method. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Canadian Soc. of Soil Sci., Lewis Publ., Ann Arbor, MI.

Sanchez, P.A., and J.G. Salinas. 1981. Low-input technology for managing oxisols and ultisols in Tropical America. Adv. Agron. 34:279-406.

Sanchez, P.A., and G. Uehara. 1981. Management considerations for acid soils with high phosphorus fixation capacity. p. 471-514. *In* F.E. Khasawneh (ed.) The role of phosphorus in agriculture. ASA Madison, WI.

SAS Institute, Inc. 1988. SAS/STAT User's Guide, Release 6.0 edition. SAS Institute, Inc., Cary, NC.

Schepers, J.S., D.D. Francis, and M.T. Thompson. 1989. Simultaneous determination of total C, total N, and ^{15}N on soil and plant material. Commun. Soil Sci. Plant Anal. 20(9/10):949-959.

Schepers, J.S., and J.J. Meisinger. 1994. Field indicators of nitrogen mineralization. p. 31-47. *In* J.L. Havlin and J.S. Jacobsen (eds.) Soil testing: Prospects for improving nutrient recommendations. ASA SSSA, Madison, WI.

Skogley, E. O. 1992. The universal bioavailability environment/soil test UNIBEST. Commun. Soil Sci. Plant Anal. 23(17-20):2225-2246.

Smethurst, G. 1988. Basic water treatment: For application world-wide. Thomas Telford, London.

Sposito, G. 1989. The Chemistry of Soils. Oxford University Press, New York, NY.

SPSS Inc. 1997. SigmaPlot User's Guide, 4.0 for Windows 95, NT & 3.1. SPSS Inc., Chicago, IL.

Sorensen, A.A., R.P. Greene, and K. Russ. 1997. Farming on the edge. American Farmland Trust. Northern Illinois University, DeKalb, IL.

Stanford, G., and J.D. DeMent. 1957. A method for measuring short-term nutrient adsorption by plants: I. Phosphorus. Soil Sci. Soc. Proc. 21:612-617.

Steele, R.G., J.H. Torrie, and D.A. Dickey. 1997. Principles and procedures of statistics. 3rd ed. McGraw-Hill, New York, NY.

Sutton, P. 1979. Reclamation alternatives for disturbed lands and their application in humid regions. *In* Planning the uses and management of land. M.T. Beatty et al. (eds.). Agron. Monogr. 21. ASA, CSSA, SSSA, Madison, WI.

Swallow, W.H. 1984. Those overworked and oft-misused mean separation procedures – Duncan's, LSD, etc. Plant Disease 68(10):919-921.

Tilchin, M., B. Ramaley, E. Leininger, T. Dillaha, D. Manning, and B. Peterson. 1990. Land application of alum residuals. ASAE Paper No. 902541. 1990 International Winter Meeting. Chicago, IL. ASAE, St. Joseph, MI.

Tisdale, S.L., W.L. Nelson, J.D. Beaton, and J.L. Havlin. 1993. Soil fertility and fertilizers. 5th ed. Macmillan Pub. Co., New York, NY.

U.S. Bereau of the Census (USBC). 1996. Statistical abstract of the Unites States: 1996 116th ed. Washington DC.

U.S. Department of Agriculture (USDA). 1997. Agriculture resources and environmental indicators, 1996-97. USDA Agric. Handb. 712. U.S. Gov. Print. Office, Washington, DC.

USEPA. 1986. Test methods for evaluating solid wastes. SW-846, 3rd ed. U.S. Environmental Protection Agency. Washington, DC.

USEPA. 1996. Management of water treatment plant residuals: Technology transfer handbook. U.S. Environmental Protection Agency, American Society of Civil Engineers. American Water Works Association. USEPA Office of Research and Developement, Washington, DC

White, R.E. 1980. Retention and release of phosphate by soil and soil constituents. p. 71-114. In P.B. Tinker (ed.) Soils and agriculture. John Wley and Sons, New York.

Yang, J.E., E.O. Skogley, SJ. Georgitis, B.E. Schaff, and A.H. Ferguson. 1991. Phytoavailability Soil Test: Development and verification of theory. Soil Sci. Soc. Am. J. 55:1358-1365.

Zhang, H., G.V. Johnson, W.R. Raun, N.T. Basta, and J.A. Hattey. 1998. OSU soil test interpretions. OSU Extension Fact no. 2225. Cooperative Extension Service, Stillwater, OK.

Table 1. Treatment plant location, water source, primary flocculating chemicals, and dewatering mechanism of WTR used in this study.

WTR	Location	Water Source	Primary chemicals added to water	Dewatering process
ABJ	AB Jewell Water Treatment Plant Tulsa, OK	Lake Oologah	$Al_2(SO_4)_3$ Ionic polymers	Belt press
Mohawk	Mohawk Water Treatment Plant Tulsa, OK	Lake Spavinaw	$Al_2(SO_4)_3$ Lime Ionic polymers	Belt press
Wister	Poteau Valley Improvement Authority Water Treatment Plant Poteau, OK	Lake Wister	$Al_2(SO_4)_3$	Sand beds

Table 2. Properties and nutrient status of the unfertilized WTR and soil materials.

		Material				Adequate
	unit	Soil	ABJ	Mohawk	Wister	range
Properties						
D_b †	g cm^{-3}	1.10	0.61	0.60	0.93	
pH		6.10	7.90	7.70	6.30	5.7-8.0 ‡
EC	dS m^{-1}	0.08	0.62	0.54	0.44	< 4.00 ‡
CEC	cmol kg^{-1}	13.5	54.7	29.7	16.4	
C	g kg^{-1}	5.8	77.9	155.0	22.2	
N	g kg^{-1}	0.7	10.6	14.6	2.8	
C:N	ratio	8.6	7.4	11.0	7.8	< 20 ‡
N §	mg kg^{-1}	18.0	320.0	243.0	----	
Al-Ox	g kg^{-1}	2.5	57	26	12	
Al	mg L^{-1}	0.00	0.24	0.13	0.16	< 1.00 ††
Mn	mg L^{-1}	0.54	7.11	1.83	5.75	< 80 ††
Nutrient						
NO_3-N	mg kg^{-1}	18	19	140	14	> 60 ‡‡
NH_4-N	mg kg^{-1}	19	70	130	26	
M3-P	mg kg^{-1}	12.0	6.0	30.0	21.0	> 30 §§
H_2O-P	mg L^{-1}	0.04	BDL ##	0.01	BDL	
K	mg kg^{-1}	208	214	197	73.7	> 200 §§
Ca	mg kg^{-1}	1100	4640	45,800	1250	
Mg	mg kg^{-1}	285	73.5	121	143	> 100 §§
SO_4	mg kg^{-1}	13.0	12.5	122	165	> 3.0 §§
Fe	mg kg^{-1}	16.7	7.6	58.8	89.8	> 2.0 §§
Zn	mg kg^{-1}	2.10	0.55	1.30	4.00	> 0.3 §§

† Bulk density

‡ Tisdale et al., 1993

§ N mineralized after 23 days of incubation at 23° C and at field capacity.

†† Bohn et al., 1985

‡‡ N required for 5 Mg ha^{-1} bermudagrass yield goal (Zhang et al., 1998)

§§ Nutrient level requirements for 95% sufficient level for bermudagrass (Zhang et al., 1998)

Below detectable levels (< 0.02 mg P L^{-1})

Table 3. Bermudagrass tissue nutrient composition of the final harvest grown in the control pots (0 mg P kg^{-1}).

		Bermudagrass†				Adequate range for grasses	Toxicity range for livestock
		Grant soil	ABJ	Mohawk	Wister		
Yield‡	g pot^{-1}	**2.19**	**0.19**	**3.59**	**2.65**		
		1.77-2.51	0.00-0.31	2.15-4.73	1.59-4.55		
P	mg kg^{-1}	**1360a§**	**324b**	**2120c**	**1330a**	**2400 - 2800#**	----
		969-1550	298-368	1890-2530	970-1510		
K	g kg^{-1}	**22.1a**	**7.3b**	**11.8c**	**23.5a**	**15 - 18#**	----
		20.9-23.5	7.0-7.6	7.5-15.8	17.6-26.4		
Ca	mg kg^{-1}	**4950a**	**5420a**	**9360b**	**5990a**	**5000 - 30,000#**	----
		4020-5710	4480-6410	8160-10300	4350-7540		
Mg	mg kg^{-1}	**2060ab**	**750c**	**1350a**	**2240b**	**3000 - 10,000#**	**< 2000 ††**
		1820-2210	690-840	1100-1550	1530-3490		
Al	mg kg^{-1}	**37.7a**	**240b**	**16.5a**	**21.9a**	----	**200 - 1000‡‡**
		24.0-58.9	197-302	8.84-25.7	8.00-48.2		
Cu	mg kg^{-1}	**11.1a**	**4.75b**	**12.1a**	**10.4a**	**5 - 20§§**	**100 - 800‡‡**
		7.03-13.46	4.50-5.02	9.68-13.57	7.00-12.94		
Fe	mg kg^{-1}	**167a**	**423b**	**165a**	**119a**	**50 - 300§§**	**500 - 1000‡‡**
		149-182	280-566	149-173	98-138		
Mn	mg kg^{-1}	**142a**	**727b**	**180a**	**347c**	**10 - 50§§**	**400 - 1000‡‡**
		83.0-217	553-949	150-216	275-445		
Zn	mg kg^{-1}	**47.0a**	**29.2a**	**33.9a**	**40.7a**	**15 - 30§§**	**300 - 500‡‡**
		39.1-51.3	22.3-40.0	22.0-58.4	22.1-59.5		

† 4th bermudagrass harvest, 4 weeks of growth, 140 DAE

‡ Dry matter yield

§ Values with a similar letter across a nutrient are not significantly different ($p < 0.05$).

\# Kelling and Matocha (1990)

†† Ball et al. (1996)

‡‡ NRC (1980)

§§ Marschner et al. (1995) and Zhang et al. (1998)

Table 4. Metal uptake for bermudagrass on WTR and soil with zero P additions. All measurements are expressed as ug pot^{-1}.

	Material†			
Metal	**Soil**	**ABJ**	**Mohawk**	**Wister**
Al	740 a	67 b	600 a	110 b
Zn	585 a	25 b	413 ac	307 c
Fe	6930 a	251 b	8810 a	2170c
Cu	227 a	6 b	604 a	56 b
Mn	2340 ab	483 c	3780 a	1400 bc

† Means with the same letter within a metal (horizontally) are not significantlly different ($p < 0.05$).

Table 5. Grant soil and WTR H_2O-P (1:5) following the final bermudagrass harvest. All means are reported in mg P L^{-1}.

P addition	Material			
	Grant soil	ABJ	Mohawk	Wister
0	0.04 ± 0.04 †	0.00	0.01 ± 0.01	0.00
50	0.10 ± 0.08	0.00	0.02 ± 0.01	0.00
100	0.37 ± 0.16	0.00	0.01 ± 0.01	0.00
200	1.41 ± 0.60	0.00	0.02 ± 0.001	0.01 ± 0.005

† mean ± 1 SD

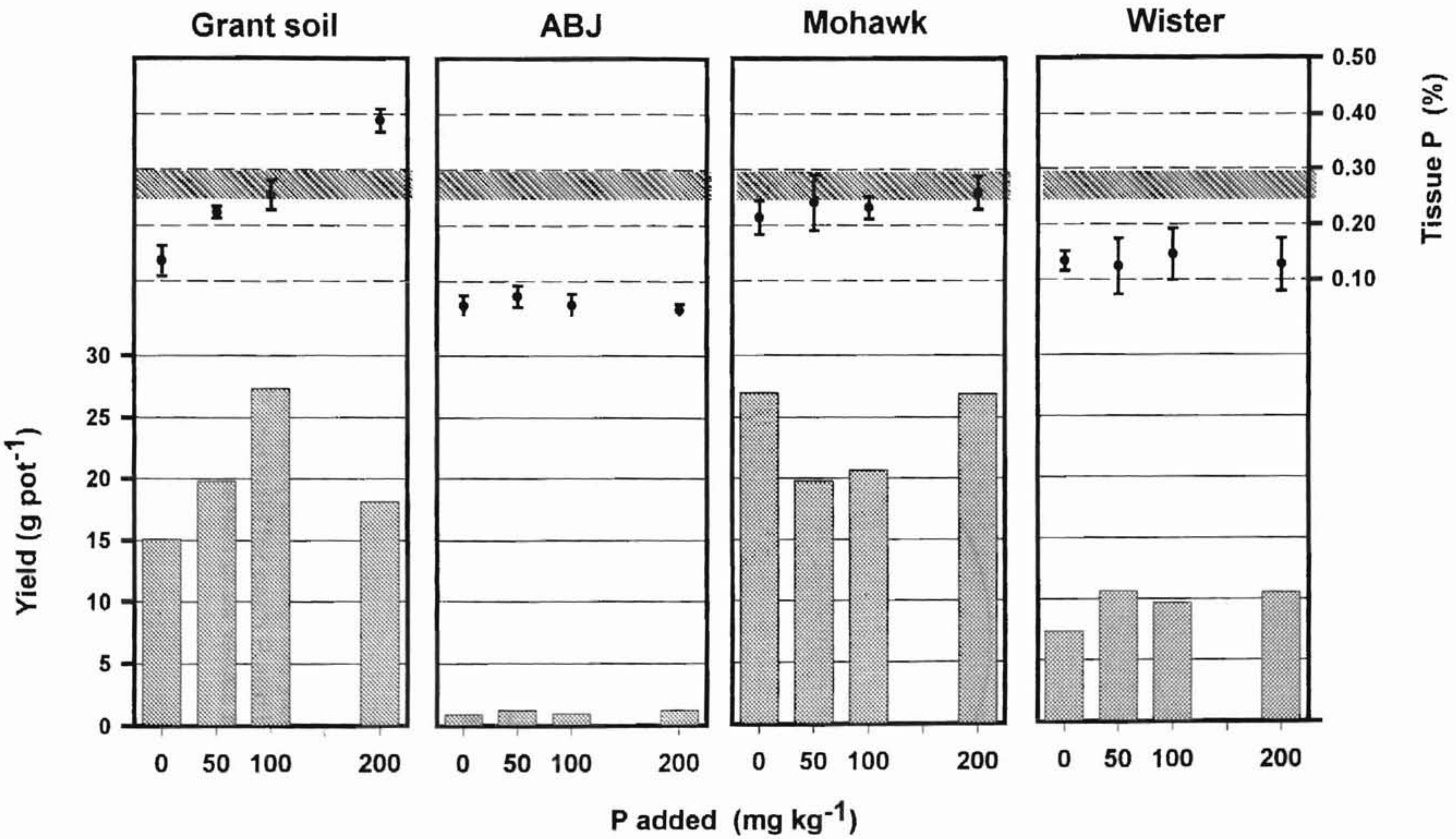

Fig. 1. Bermudagrass cumulative yield (136 DAE) and tissue-P concentration at the last harvest (28 days of growth). Adequate P tissue range is higlighted. Error bars indicate ± 1 standard deviation (SD).

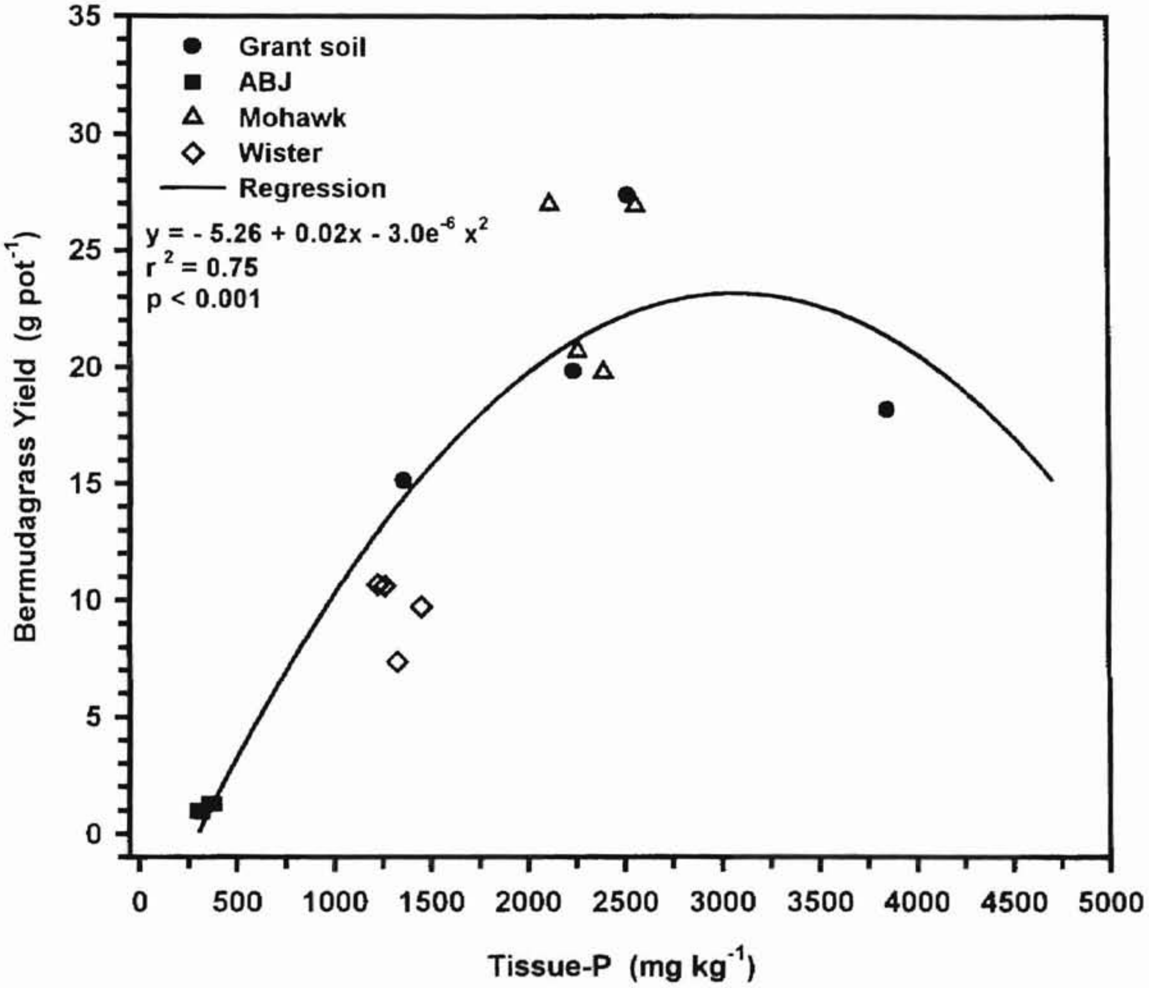

Fig. 2. Relationship between bermudagrass tissue-P at the final harvest (4 weeks of growth) and cumulative bermudagrass yield. Data points represent the mean tissue-P and yield for each P addition per material. Quadratic line represents the regression of all values for materials and P additions (n=64).

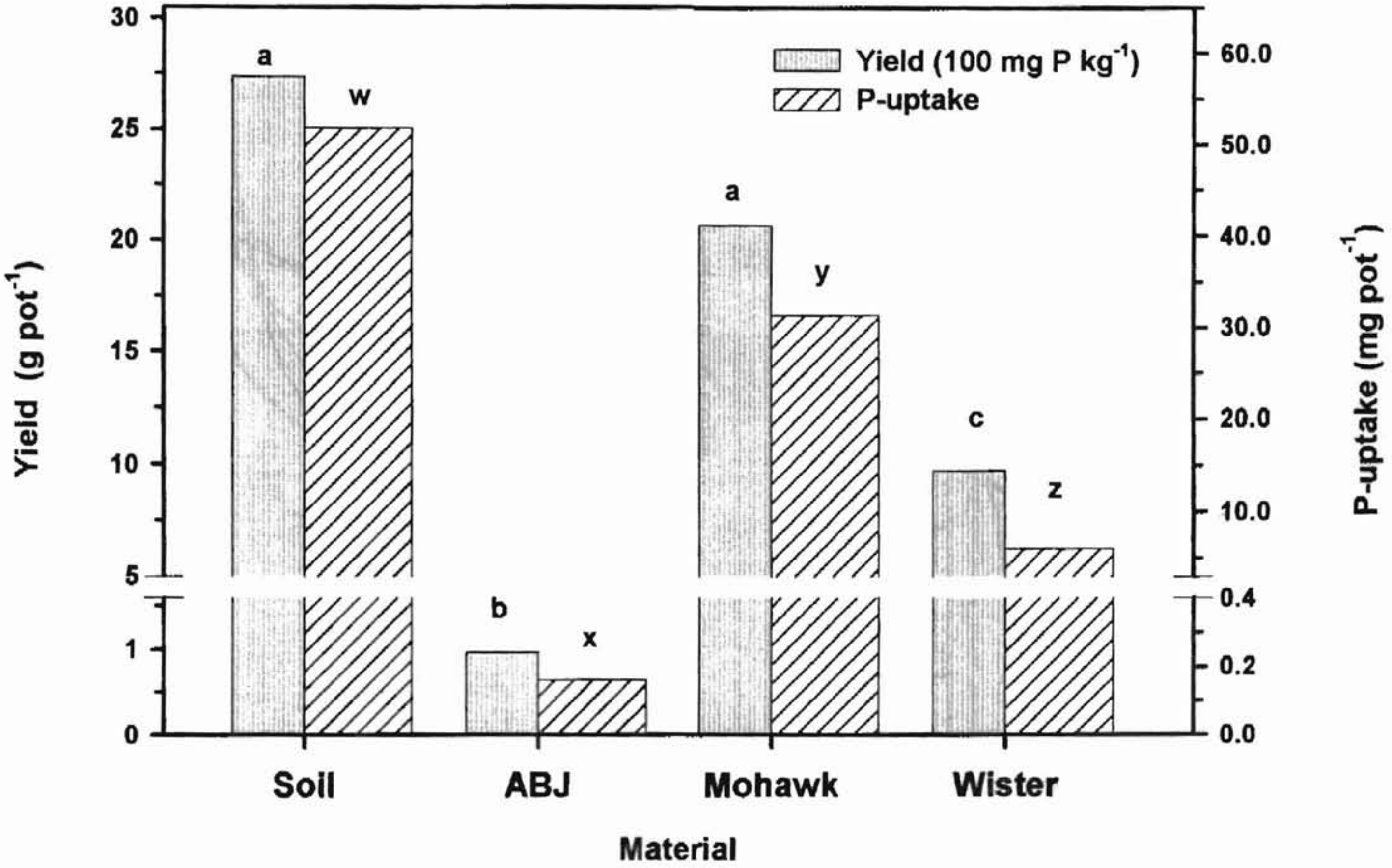

Fig. 3. Cumulative bermudagrass yield and P-uptake for the 100 mg P kg^{-1} treatment. Values with same letter are not statistically different ($p < 0.05$).

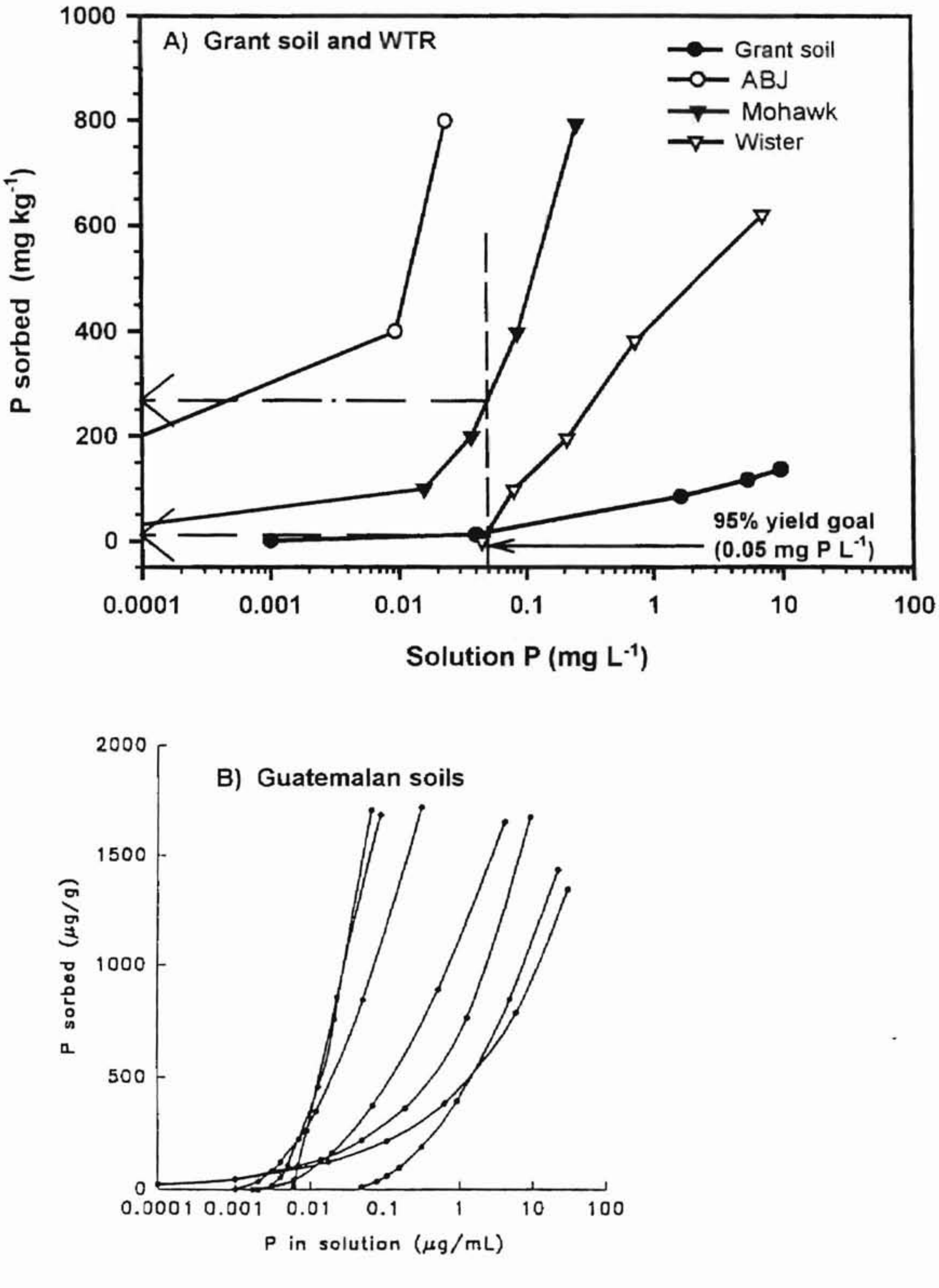

Fig. 4. A) P adsorption curves for the WTR materials before fertilizer P addition with P fertilizer needed to achieve 95 % maximum yield proposed by Fox (1981) and B) P adsorption curves of Guatemalan andisols, adopted from Leal et al. (1994).

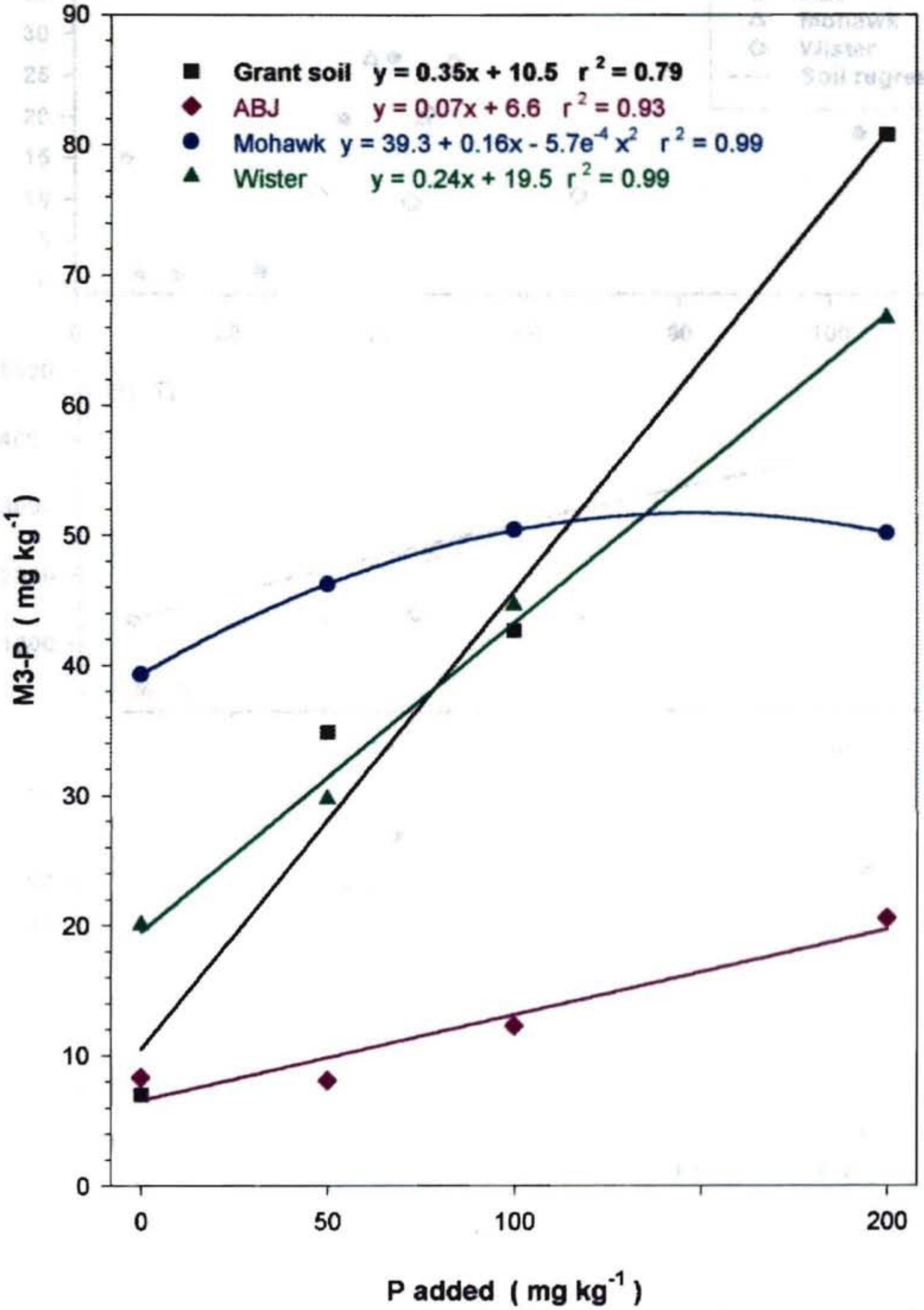

Fig. 5. M3-P values for pots following the last bermudagrass harvest (210 days after fertilization)

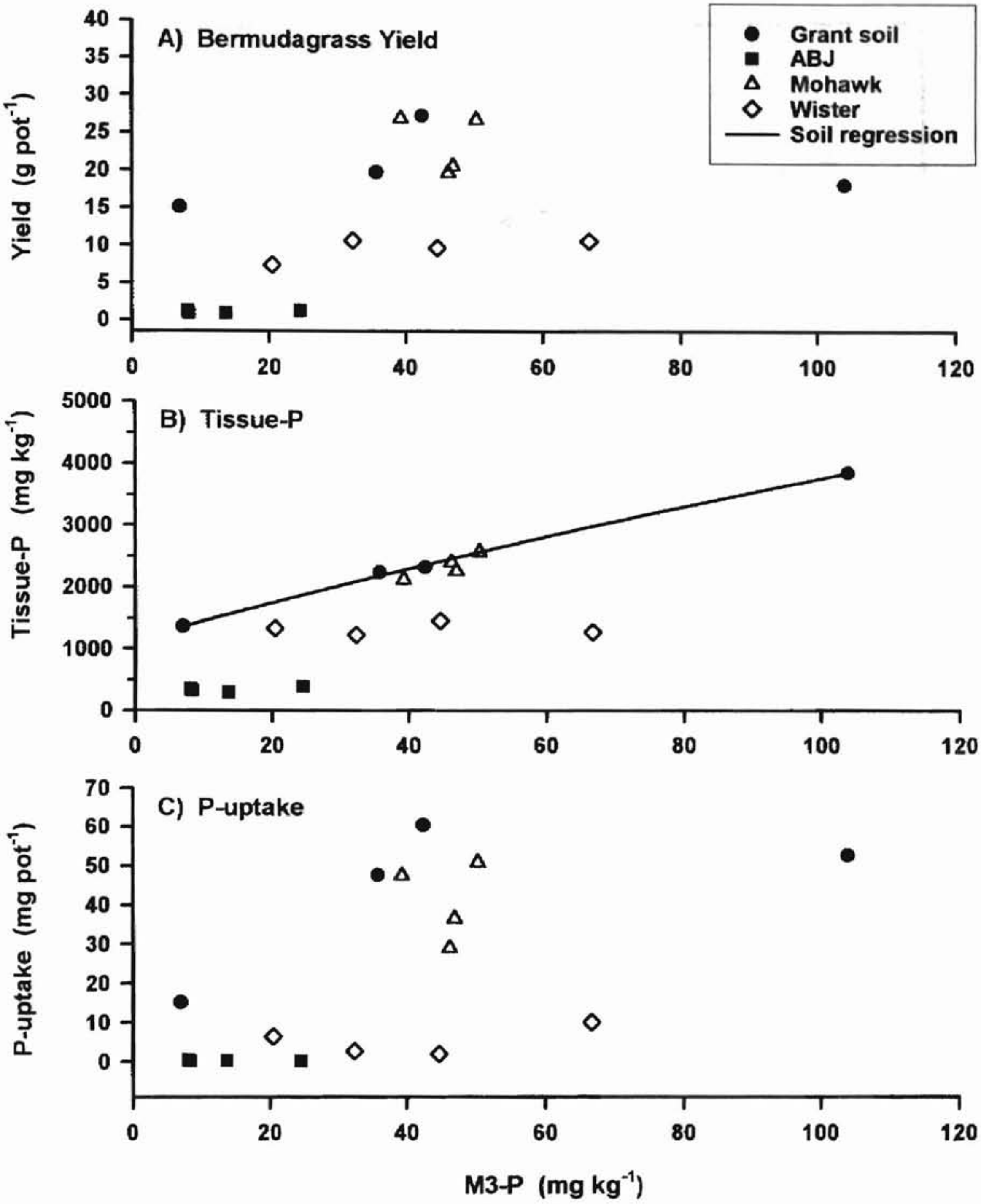

Fig. 6. Relationship between M3-P and A) cumulative bermudagrass yield, B) tissue-P (harvest 4, 4 weeks of growth), and C) cumulative P-uptake. The only significant relationship was between Grant soil M3-P and tissue-P concentration ($y = 1160 + 30x - 0.04x^2$, $r^2 = 0.99$, $p<0.01$). The graph symbols represent the mean value for each variable for each P addition (0, 50, 100, 200 mg P kg^{-1}).

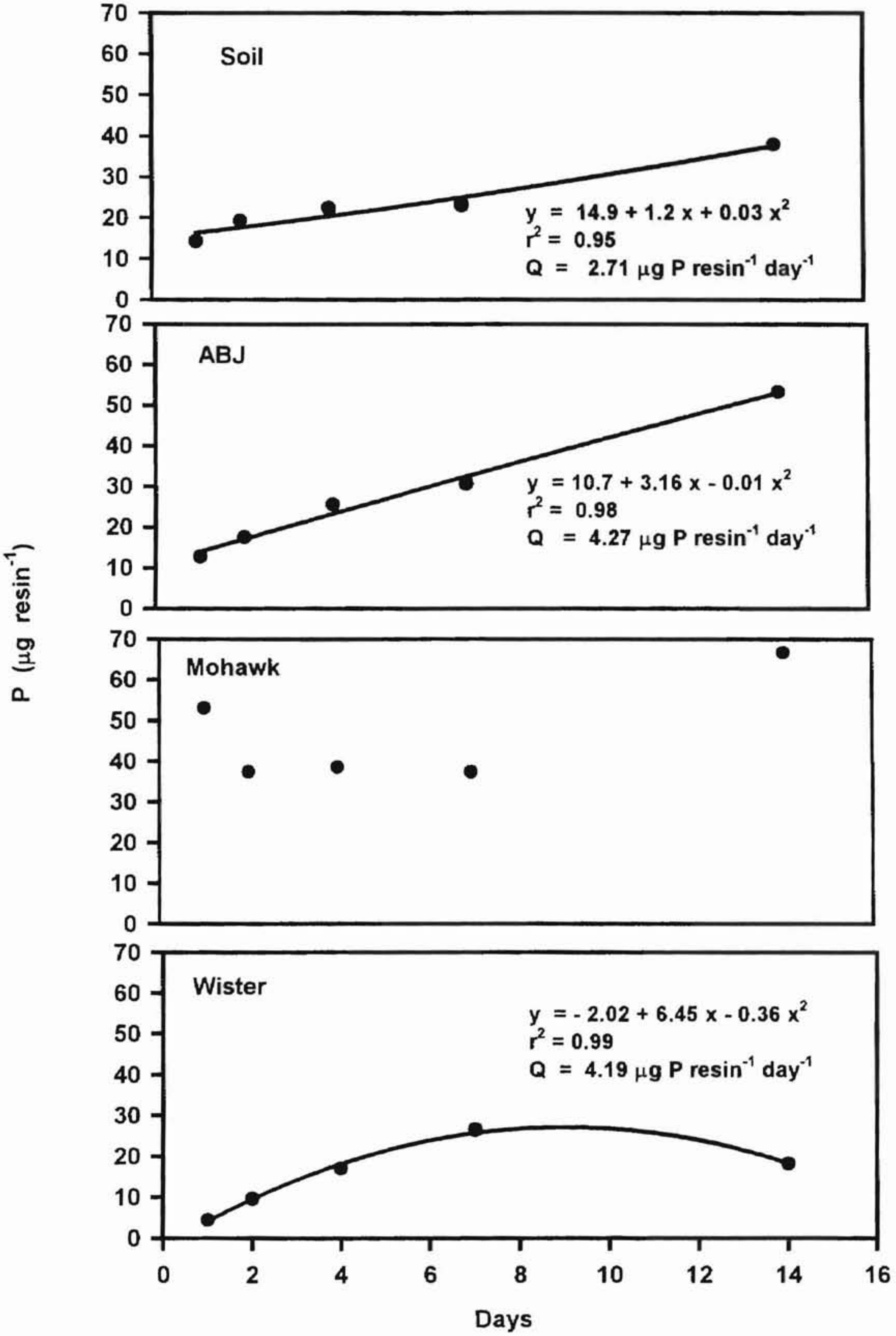

Fig. 7. Unibest extractable P for the unfertilized Grant soil and WTR.

Appendix I

Additional Bermudagrass Data

Table I-1 (continued). Bermudagrass data for Yield, P-tissue concentration, P-uptake, M3-P, and H_2O-P.

Pot #	Mat.	TRT	Dry Yield (g pot^{-1})					Tissue Concentration (mg kg^{-1})				P uptake (mg pot^{-1})				After harvest 4	
		(mg P kg^{-1})	1^a	2	3	4	sum	1	2	3	4	2	3	4	Sum	M3-P	H_2O-P
																mg kg^{-1}	mg L^{-1}
2	M	0	0.818	5.197	21.474	3.825	31.31	973	2309	1587	1915	11.998	34.073	7.325	53.396	40.95	0.020
6	M	0	0.511	2.991	11.429	3.640	18.57	1989	1662	1476	1886	4.972	16.869	6.866	28.707	38.05	0.000
7	M	0	1.356	8.227	21.303	2.153	33.04	1243	1664	1654	2149	13.686	35.239	4.628	53.552	39.74	0.000
17	M	0	0.408	3.203	16.660	4.732	25.00	1424	2977	1976	2533	9.535	32.919	11.986	54.440	38.55	0.020
221	M	50	0.433	2.369	8.373	3.066	14.24	549	.	955	1840	.	7.995	5.642	13.637	51.52	0.020
220	M	50	0.674	.	25.999	2.591	29.26	461	.	1527	2770	.	39.695	7.177	46.872		0.025
218	M	50	0.367	1.132	8.260	4.252	14.01	1066	2051	1933	2849	2.322	15.964	12.112	30.399	43.60	0.020
219	M	50	0.647	.	17.853	3.050	21.55	664	.	1049	2121	.	18.731	6.470	25.201	43.56	0.000
1	M	100	0.317	2.816	15.241	4.945	23.32	1467	2730	1571	.	7.687	23.938	.	31.625	49.78	0.000
8	M	100	0.677	1.944	16.736	2.814	22.17	1032	2246	1660	2477	4.367	27.789	6.969	39.125	49.16	0.000
11	M	100	0.497	3.737	10.921	2.742	17.90	1437	2552	1789	2032	9.538	19.536	5.573	34.647	51.69	0.022
15	M	100	1.457	2.562	11.475	3.840	19.33	1127	2550	2238	2278	6.533	25.687	8.747	40.967	36.59	0.000
9	M	200	1.732	3.716	16.909	2.501	24.86	1700	806	1409	2415	2.995	23.823	6.041	32.859	52.56	0.025
10	M	200	0.569	3.323	17.557	3.691	25.14	1672	3314	1823	2227	11.012	32.002	8.219	51.233	53.94	.
12	M	200	1.132	6.174	9.106	5.363	21.78	1714	2669	2211	2845	16.480	20.130	15.255	51.866	39.64	0.024
14	M	200	1.953	7.315	23.044	3.524	35.84	2049	2519	1723	2772	18.426	39.710	9.768	67.904	54.63	.
26	W	0	1.483	.	2.204	1.593	5.28	1940	.	779	.	.	1.717	.	1.717	21.72	0.000
30	W	0	0.903	0.722	2.031	2.439	6.10	626	445	1204	970	0.321	2.445	2.365	5.131	19.63	0.000
33	W	0	0.709	0.916	4.658	4.555	10.84	865	553	930	1505	0.507	4.333	6.856	11.696	19.94	0.000
37	W	0	0.696	.	4.494	2.006	7.20	505	.	939	1508	.	4.220	3.026	7.246	20.57	0.000
38	W	50	0.652	0.900	3.417	0.431	5.40	867	526	812	714	0.474	2.775	0.308	3.557	32.45	0.000
139	W	50	0.733	1.783	5.512	1.484	9.51	633	1357	816	912	2.420	4.495	1.354	8.269	30.92	0.000
140	W	50	0.58	2.683	9.801	3.094	16.16	1450	1122	1039	1795	3.011	10.183	5.554	18.748		0.000
141	W	50	0.675	1.908	6.552	2.438	11.57	838	1142	409	1489	2.178	2.680	3.631	8.489	33.86	0.000
23	W	100	0.68	3.624	8.997	1.824	15.13	1219	1058	644	1391	3.833	5.793	2.537	12.163	41.44	0.000
25	W	100	0.858	1.807	5.256	1.478	9.40	1533	664	928	1937	1.201	4.877	2.863	8.941	44.62	0.000
27	W	100	1.193	2.426	3.666	0.693	7.98	1085	609	538	835	1.476	1.974	0.578	4.029	47.64	0.000
28	W	100	0.382	0.833	3.910	1.265	6.39	1520	764	1124	1642	0.636	4.393	2.078	7.107	44.86	0.000
22	W	200	0.827	2.868	6.767	1.540	12.00	2277	1266	944	1013	3.631	6.390	1.560	11.580	66.66	0.000
24	W	200	0.351	2.036	5.109	1.548	9.04	729	667	755	727	1.356	3.858	1.126	6.340	66.52	0.000
32	W	200	0.836	1.652	4.241	1.840	8.57	1152	835	768	1747	1.379	3.257	3.214	7.851	66.98	0.029
35	W	200	0.407	1.058	8.450	2.839	12.75	2575	1314	982	1572	1.390	8.299	4.464	14.153		0.027

a. Harvest number

Table I-1. Bermudagrass data for Yield, P-tissue concentration, P-uptake, M3-P, and H_2O-P.

Pot #	Mat.	TRT	Dry Yield (g pot^{-1})					Tissue Concentration (mg kg^{-1})				P uptake (mg pot^{-1})				After harvest 4	
		(mg P kg^{-1})	1[a]	2	3	4	sum	1	2	3	4	2	3	4	Sum	M3-P	H_2O-P
																mg kg^{-1}	mg L^{-1}
42	A	0	0.384	0.445	.	0.249	1.078	1151	474	.	369	0.211	.	0.092	0.303	7.20	0.000
43	A	0	0.775	0.250	.	0.310	1.335	601	495	.	304	0.124	.	0.094	0.218	9.94	0.000
49	A	0	0.458	0.120	.	0.193	0.771	732	825	.	298	0.099	.	0.058	0.157	8.65	0.000
48	A	0	0.288	0.230	.	0.000	0.518	1054	410	.	.	0.094	.	.	0.094	7.40	0.000
158	A	50	0.568	0.373	.	0.348	1.289	614	637	.	576	0.238	.	0.201	0.438	7.91	0.000
159	A	50	0.586	0.762	.	0.394	1.742	845	1016	.	328	0.774	.	0.129	0.904	5.28	0.000
160	A	50	0.269	0.759	.	0.448	1.476	932	637	.	145	0.483	.	0.065	0.548	9.90	0.000
161	A	50	0.385	0.120	.	0.133	0.638	862	600	.	371	0.072	.	0.049	0.121	9.26	0.000
44	A	100	0.285	0.663	.	0.505	1.453	695	540	.	345	0.358	.	0.174	0.532	12.27	0.000
45	A	100	0.378	0.100	.	0.154	0.632	689	845	.	270	0.084	.	0.042	0.126	12.29	0.000
50	A	100	0.475	0.175	.	0.189	0.839	.	517	.	264	0.090	.	0.050	0.140		0.000
57	A	100	0.405	0.346	.	0.194	0.945	925	358	.	296	0.124	.	0.057	0.181	16.57	0.000
52	A	200	0.626	0.253	.	0.220	1.099	823	626	.	625	0.158	.	0.137	0.296	22.64	0.000
51	A	200	0.67	0.605	.	0.159	1.434	556	359	.	240	0.217	.	0.038	0.255	41.31	0.000
53	A	200	0.725	0.329	.	0.134	1.188	761	471	.	287	0.155	.	0.038	0.194	17.69	0.000
55	A	200	1.001	0.345	.	0.000	1.346	506	436	.	.	0.150	.	.	0.150	21.35	0.000
102	L	0	1.466	2.942	9.232	2.037	15.68	1717	821	807	1549	2.416	7.452	3.155	13.022	8.09	0.000
103	L	0	1.477	5.649	11.727	1.770	20.62	1028	1403	792	1517	7.924	9.292	2.685	19.901	6.58	0.000
104	L	0	2.585	1.890	.	2.430	6.91	2210	1293	.	969	2.444	.	2.355	4.799	.	0.105
105	L	0	1.002	4.544	9.212	2.510	17.27	1474	2514	887	1414	11.422	8.174	3.548	23.145	6.27	0.234
113	L	50	.	5.043	14.036	4.703	23.78	.	1664	2090	2172	8.389	29.331	10.217	47.937	29.71	0.041
114	L	50	.	4.300	11.418	3.966	19.68	.	3735	2166	2305	16.062	24.736	9.141	49.939	34.26	0.195
115	L	50	.	2.724	11.486	1.743	15.95	.	3291	2422	4703	8.964	27.819	8.197	44.980	40.51	0.064
101	L	100	0.841	8.805	13.064	5.424	28.13	4141	3291	2165	2261	28.980	28.278	12.265	69.523	8.16	0.000
106	L	100	1.892	9.598	10.086	5.379	26.96	4157	2235	2370	2517	21.452	23.900	13.537	58.888	42.00	0.271
107	L	100	1.17	7.624	11.765	3.215	23.77	4145	2950	2423	2782	22.491	28.501	8.945	59.937	45.96	0.588
108	L	100	2.844	7.579	16.525	3.622	30.57	4466	3197	1757	.	24.233	29.037	.	53.270	39.27	0.371
110	L	200	2.701	2.804	12.666	4.297	22.47	4397	3229	3033	3653	9.054	38.413	15.697	63.165	92.51	1.339
111	L	200	0.829	2.034	8.541	1.610	13.01	.	.	3485	4066	.	29.761	6.547	36.308	150.90	2.051
112	L	200	0.452	3.175	12.846	2.568	19.04	3446	2672	3141	3839	8.484	40.352	9.859	58.695	68.99	0.847

[a] Harvest number

Table I-2. Cadmium, molybdum, nickle, and selenium concentration of bermudagrass tissue, wheat grain, and NIST plant SRM.

			Metal concentration		
		Cd	Mo	Ni	Se
			(mg kg^{-1})		
Toxic to Plants [a]			> 1,000	> 50	> 10-100
Material	**P addition**				
	mg P kg^{-1}		**Bermudagrass**		
Grant soil	0	0.71 0.64-0.88	BDL [b]	4.6 3.2-4.6	BDL [c]
	200	0.90 0.78-1.02	0.17 BDL-0.29	4 3.9-4.0	BDL
Mohawk	0	0.14 0.14-0.15	0.17 BDL-0.24	2.7 1.8-3.7	BDL
	200	0.14 0.12-0.17	0.13 BDL-0.26	2.6 1.6-4.6	BDL
Wister	0	0.43 0.29-0.55	0.14 BDL-0.29	1.8 1.2-3.2	BDL
	200	0.65 0.62-0.67	0.4 0.22-0.54	3.2 1.0-5.8	BDL
			Wheat		
Mohawk	400	0.11 0.09-0.14	0.05 BDL-0.20	0.9 0.5-1.8	BDL
			NIST #1573a	**Tomato leaves**	
Tissue concentration		1.59	0.46	1.8	BDL
% recovery (3 reps)		104	101	110	---

a. Marshner, 1995

b. Below Detectable Levels (<0.1 mg Mo kg^{-1})

c. BDL (< 0.5 mg Se kg^{-1})

Appendix II

Preliminary Wheat Study

Table II-1. Wheat study experimental design and harvest dates.

Parameter	Quantity
Material (WTR and soil)	3.0 kg pot^{-1}
P rates	0, 100, 200, 400 mg P kg^{-1}
Replication	4 reps per treatment
N rate	25 mg N kg^{-1}
K rate	250 mg K kg^{-1}
Wheat variety	Tonkawa
Wheat seeding rate	20 seeds pot^{-1}
Harvest 1	30 days after establishment (DAE)
Harvest 2	100 DAE

Table II-2. Wheat yield and tissue nutrient composition collected from the final harvest.

		Wheat†			
		Grant soil	**ABJ§**	**Mohawk**	**Wister**
Yield#	g pot^{-1}	**0.49** 0.07-0.92	**0.33** 0.33	**1.45** 0.80-2.20	**0.33** 0.10-0.60
P	mg kg^{-1}	**1580a††** 1490-1660	**907b††** 907	**2810c** 1910-3240	**1060b††** 692-1460
K	%	**4.05a** 3.1-4.7	**3.00a‡‡** 3.0	**4.60a** 2.7-5.9	**3.91a** 3.3-4.4
Ca	mg kg^{-1}	**5990a** 4340-8920	**7710a** 7710	**6010a** 2750-8950	**7400a** 3890-11200
Mg	mg kg^{-1}	**2390a** 1810-3250	**1170b††** 1170	**1160b††** 731-1350	**2490a** 1940-3340
Cu	mg kg^{-1}	**7.69ab** 6.5-8.8	**5.40a** 5.4	**9.47b** 8.6-9.9	**9.08b** 5.8-11.1
Fe	mg kg^{-1}	**110a** 58.6-174	**104ab** 104	**94.0a** 74.4-133	**246b** 98.8-328
Zn	mg kg^{-1}	**30.5ab** 24.8-37.8	**12.1ab** 12.1	**22.2a** 16.2-37.7	**59.0b** 22.4-86.9
Mn	mg kg^{-1}	**243a** 169-380	**573b** 573	**169a** 87.3-224	**448b** 233-581

Values with a similar letter are not significantly different ($p<0.05$).

† 2cd wheat harvest, 10 weeks of growth, 100 DAE

§ Only one pot

\# Dry matter yield

†† Deficient based upon levels reported by Westfall et al. (1990)

‡‡ Border line deficient, within 10% of adequate

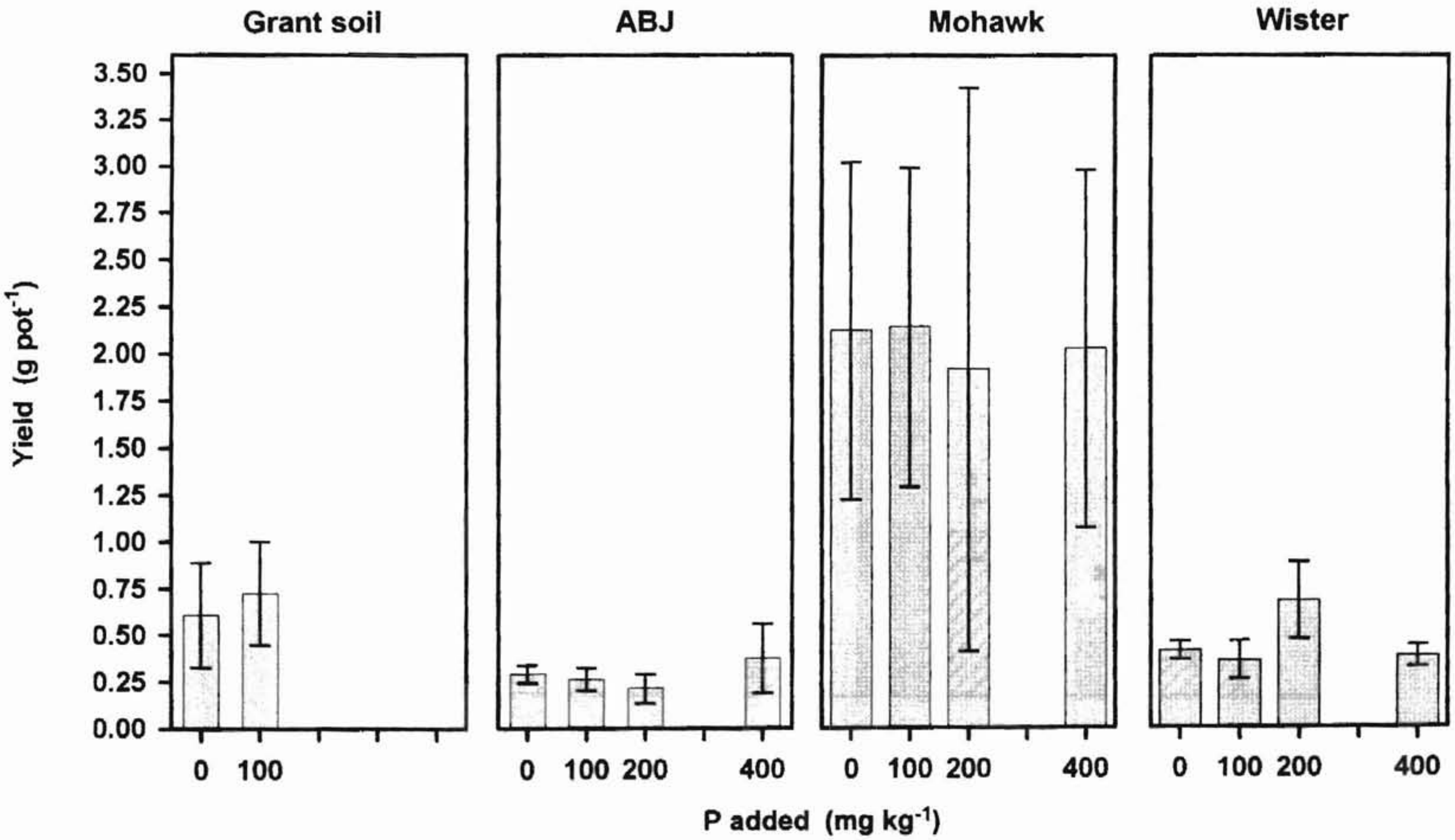

Fig. II-1. Cumulative wheat yield, 100 DAE. Error bars indicate ± 1 SD.

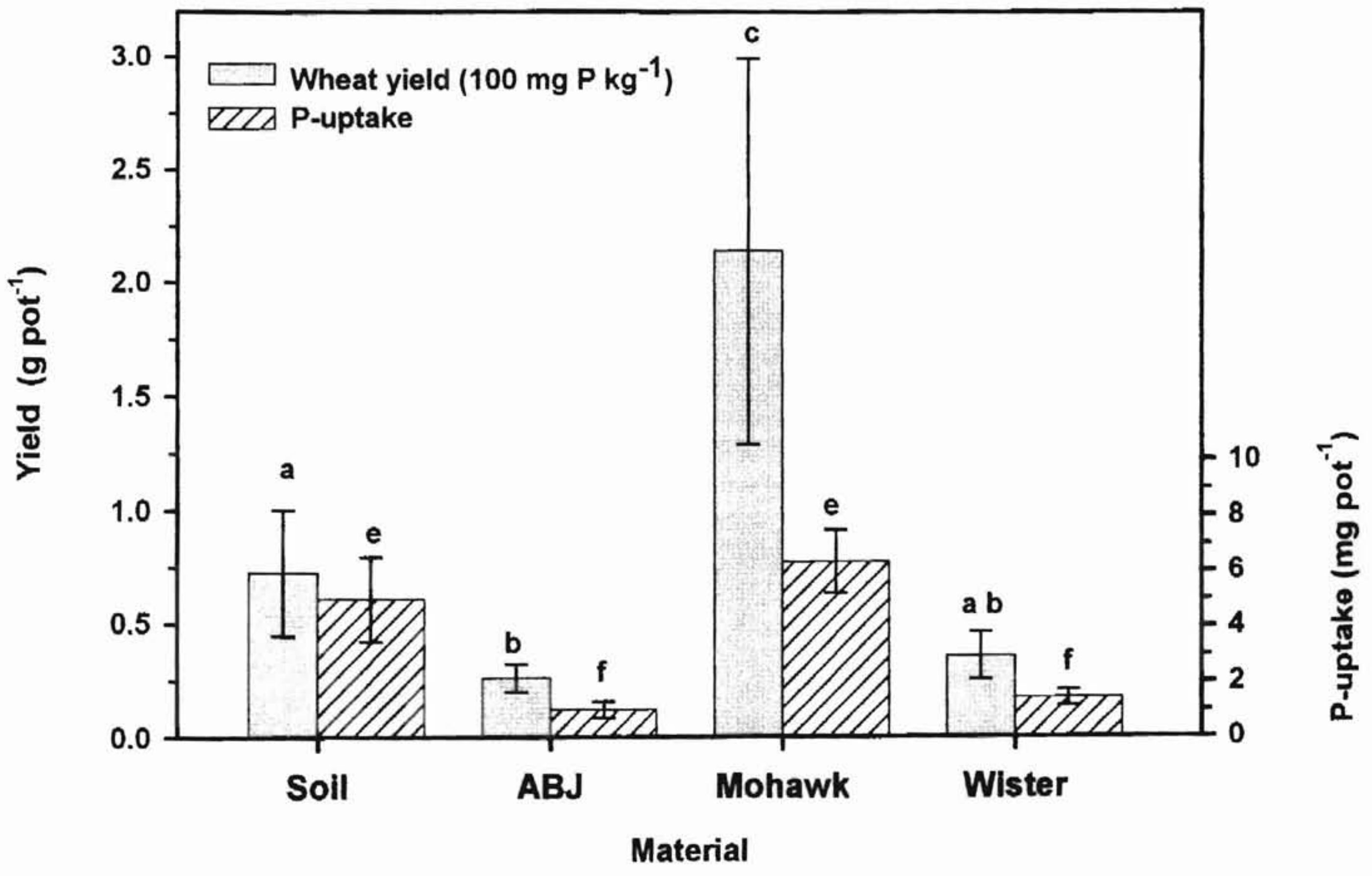

Figure II-2. Cumulative wheat yield and P-uptake for the 100 mg P kg^{-1} fertilizer addition. Values with same letter are not statistically different ($p < 0.05$). Error bars indicate ± 1 SD.

Appendix III

UNIBEST Method Data

Table III-1. UNIBEST extraction of Al from unfertilized Grant soil and WTR

Sample	Days	Solution Al (mg/L)	Al[a] ug resin^{-1}	AVG	Sample	Days	Solution Al (mg/L)	ug resin^{-1}	AVG
GS-1	1	0.2194	10.97	**10.29**	A-21	1	26.32	1316.00	**1169.75**
GS-2	1	0.192	9.60		A-22	1	20.47	1023.50	
GS-3	2	0.3383	16.92	**15.79**	A-23	2	20.15	1007.50	**1238.75**
GS-4	2	0.2934	14.67		A-24	2	29.4	1470.00	
GS-5	4	0.2763	13.82	**15.00**	A-25	4	17.94	897.00	**1092.75**
GS-6	4	0.3237	16.19		A-26	4	25.77	1288.50	
GS-7	7	0.4873	24.37	**27.00**	A-27	7	24.12	1206.00	**1312.75**
GS-8	7	0.5925	29.63		A-28	7	28.39	1419.50	
GS-9	14	1.454	50.89	**53.55**	A-29	14	56.04	2802.00	**2367.25**
GS-10	14	1.124	56.20		A-30	14	38.65	1932.50	
W-11	1	1.183	59.15	**63.25**	M-31	1	10.13	506.50	**481.20**
W-12	1	1.347	67.35		M-32	1	9.118	455.90	
W-13	2	2.723	136.15	**115.10**	M-33	2	3.519	175.95	**231.55**
W-14	2	1.881	94.05		M-34	2	5.743	287.15	
W-15	4	4.634	231.70	**194.15**	M-35	4	6.057	302.85	**257.28**
W-16	4	3.132	156.60		M-36	4	4.234	211.70	
W-17	7	8.836	441.80	**379.53**	M-37	7	3.474	173.70	**253.80**
W-18	7	6.345	317.25		M-38	7	6.678	333.90	
W-19	14	4.123	206.15	**251.00**	M-39	14	12.2	610.00	**673.00**
W-20	14	5.917	295.85		M-40	14	14.72	736.00	

a. Al (ug resin^{-1}) = Solution Al * 50

Table III-2. UNIBEST extraction of Ca from unfertilized Grant soil and WTR

Sample	Day	Solution Ca (mg/L)	Ca [a] ug resin^{-1}	AVG	Sample	Day	Solution Ca (mg/L)	Ca ug resin^{-1}	AVG
GS-1	1	6.132	306.6	**278**	A-21	1	42.93	2146.5	**2156**
GS-2	1	4.979	248.95		A-22	1	43.3	2165	
GS-3	2	7.714	385.7	**367**	A-23	2	55.86	2793	**3126**
GS-4	2	6.965	348.25		A-24	2	69.17	3458.5	
GS-5	4	10.84	542	**532**	A-25	4	59.09	2954.5	**2498**
GS-6	4	10.42	521		A-26	4	40.83	2041.5	
GS-7	7	17.24	862	**885**	A-27	7	49.79	2489.5	**4417**
GS-8	7	18.17	908.5		A-28	7	126.9	6345	
GS-9	14	38.94	1362.9	**1358**	A-29	14	168.3	8415	**7650**
GS-10	14	27.05	1352.5		A-30	14	137.7	6885	
			0					0	
W-11	1	8.188	409.4	**415**	M-31	1	37.84	1892	**3062**
W-12	1	8.4	420		M-32	1	84.64	4232	
W-13	2	16.95	847.5	**784**	M-33	2	77.25	3862.5	**4333**
W-14	2	14.41	720.5		M-34	2	96.08	4804	
W-15	4	30.49	1524.5	**1296**	M-35	4	62.45	3122.5	**3412**
W-16	4	21.34	1067		M-36	4	74.02	3701	
W-17	7	56.18	2809	**2805**	M-37	7	102.9	5145	**6428**
W-18	7	56.02	2801		M-38	7	154.2	7710	
W-19	14	80.07	4003.5	**4021**	M-39	14	261.3	13065	**14468**
W-20	14	80.75	4037.5		M-40	14	317.4	15870	

a. Ca (ug resin^{-1}) = Solution Ca * 50

Table III-3. UNIBEST extraction of Cu from unfertilized Grant soil and WTR.

Sample	Day	Solution Cu (mg/L)	Cu ug / resin	AVG	Sample	Day	Solution Cu (mg/L)	Cu ug / resin	AVG
GS-1	1	0.018	0.92	0.73	A-21	1	0.027	1.36	1.21
GS-2	1	0.011	0.55		A-22	1	0.021	1.05	
GS-3	2	0.033	1.63	1.13	A-23	2	0.021	1.04	1.31
GS-4	2	0.012	0.62		A-24	2	0.032	1.58	
GS-5	4	0.020	1.00	1.12	A-25	4	0.017	0.84	1.38
GS-6	4	0.025	1.24		A-26	4	0.038	1.91	
GS-7	7	0.023	1.14	1.20	A-27	7	0.036	1.81	1.45
GS-8	7	0.025	1.27		A-28	7	0.022	1.10	
GS-9	14	0.021	0.72	0.65	A-29	14	0.056	2.78	2.10
GS-10	14	0.012	0.58		A-30	14	0.028	1.42	
W-11	1	0.007	0.34	0.24	M-31	1	0.023	1.13	1.37
W-12	1	0.003	0.14		M-32	1	0.032	1.62	
W-13	2	0.014	0.69	0.59	M-33	2	0.016	0.82	0.92
W-14	2	0.010	0.50		M-34	2	0.021	1.03	
W-15	4	0.015	0.76	0.55	M-35	4	0.016	0.79	0.82
W-16	4	0.007	0.34		M-36	4	0.017	0.85	
W-17	7	0.055	2.74	2.18	M-37	7	0.013	0.64	0.85
W-18	7	0.033	1.63		M-38	7	0.021	1.06	
W-19	14	0.002	0.09	0.09	M-39	14	0.027	1.37	1.72
W-20	14	0.002	0.10		M-40	14	0.041	2.07	

Table III-4. UNIBEST extraction of Fe from unfertilized Grant soil and WTR.

Sample	Day	Solution Fe (mg/L)	Soil Fe ug resin^{-1}	AVG	Sample	Day	Solution Fe (mg/L)	Soil Fe ug resin^{-1}	AVG
GS-1	1	0.20	9.8	6.9	A-21	1	1.24	61.9	57.7
GS-2	1	0.08	3.9		A-22	1	1.07	53.6	
GS-3	2	0.39	19.7	24.4	A-23	2	1.26	62.8	124.0
GS-4	2	0.58	29.1		A-24	2	3.70	185.1	
GS-5	4	0.74	36.9	39.6	A-25	4	1.24	61.9	128.5
GS-6	4	0.85	42.4		A-26	4	3.90	195.2	
GS-7	7	2.08	104.1	110.7	A-27	7	1.78	88.9	150.3
GS-8	7	2.34	117.2		A-28	7	4.24	211.8	
GS-9	14	8.75	306.1	309.1	A-29	14	4.82	240.8	283.0
GS-10	14	6.24	312.2		A-30	14	6.50	325.2	
W-11	1	1.45	72.5	39.9	M-31	1	5.15	257.4	207.3
W-12	1	0.15	7.3		M-32	1	3.14	157.2	
W-13	2	0.59	29.7	22.9	M-33	2	0.41	20.6	25.0
W-14	2	0.32	16.2		M-34	2	0.59	29.4	
W-15	4	1.83	91.6	124.3	M-35	4	1.20	60.0	128.3
W-16	4	3.14	157.0		M-36	4	3.93	196.7	
W-17	7	15.01	750.5	732.3	M-37	7	0.53	26.5	101.0
W-18	7	14.28	714.0		M-38	7	3.51	175.6	
W-19	14	24.58	1229.0	1339.0	M-39	14	5.66	282.8	395.7
W-20	14	28.98	1449.0		M-40	14	10.17	508.5	

Table III-5. UNIBEST extraction of K from unfertilized Grant soil and WTR.

Sample	Day	Solution K (mg/L)	Soil K ug resin^{-1}	AVG	Sample	Day	Solution K (mg/L)	Soil K ug resin^{-1}	AVG
GS-1	1	5.31	266	242	A-21	1	18.18	909	896
GS-2	1	4.35	218		A-22	1	17.64	882	
GS-3	2	7.40	370	333	A-23	2	22.71	1136	1333
GS-4	2	5.92	296		A-24	2	30.61	1531	
GS-5	4	7.81	391	372	A-25	4	25.83	1292	1091
GS-6	4	7.06	353		A-26	4	17.80	890	
GS-7	7	10.66	533	545	A-27	7	14.26	713	1789
GS-8	7	11.12	556		A-28	7	57.28	2864	
GS-9	14	17.85	625	639	A-29	14	48.44	2422	2463
GS-10	14	13.07	654		A-30	14	50.09	2505	
W-11	1	4.13	206	201	M-31	1	4.33	216	227
W-12	1	3.91	196		M-32	1	4.75	237	
W-13	2	5.70	285	272	M-33	2	5.28	264	292
W-14	2	5.18	259		M-34	2	6.39	320	
W-15	4	9.87	493	397	M-35	4	6.26	313	266
W-16	4	6.03	302		M-36	4	4.36	218	
W-17	7	13.92	696	665	M-37	7	8.29	414	389
W-18	7	12.69	635		M-38	7	7.28	364	
W-19	14	17.85	893	902	M-39	14	13.49	675	922
W-20	14	18.22	911		M-40	14	23.37	1169	

Table III-6. UNIBEST extraction of Mg from unfertilized Grant soil and WTR.

Sample	Day	Solution Mg (mg/L)	Soil Mg ug resin^{-1}	AVG	Sample	Day	Solution Mg (mg/L)	Soil Mg ug resin^{-1}	AVG
GS-1	1	3.07	153.7	138.9	A-21	1	1.86	93.2	94.7
GS-2	1	2.48	124.0		A-22	1	1.92	96.1	
GS-3	2	3.77	188.3	188.8	A-23	2	2.51	125.7	140.4
GS-4	2	3.79	189.3		A-24	2	3.10	155.1	
GS-5	4	5.15	257.3	256.0	A-25	4	2.69	134.5	116.0
GS-6	4	5.09	254.6		A-26	4	1.95	97.6	
GS-7	7	7.87	393.4	407.7	A-27	7	2.21	110.7	209.2
GS-8	7	8.44	422.0		A-28	7	6.15	307.7	
GS-9	14	16.21	567.2	585.6	A-29	14	7.64	382.1	351.4
GS-10	14	12.08	604.0		A-30	14	6.41	320.7	
W-11	1	2.28	113.9	114.9	M-31	1	0.51	25.3	38.2
W-12	1	2.32	116.0		M-32	1	1.02	51.2	
W-13	2	4.61	230.6	214.4	M-33	2	0.98	48.8	55.5
W-14	2	3.97	198.3		M-34	2	1.24	62.2	
W-15	4	8.48	424.0	376.2	M-35	4	0.94	47.1	52.7
W-16	4	6.57	328.5		M-36	4	1.17	58.4	
W-17	7	17.61	880.3	866.0	M-37	7	2.02	100.8	125.0
W-18	7	17.04	851.8		M-38	7	2.98	149.2	
W-19	14	24.64	1232.0	1259.4	M-39	14	7.92	396.0	436.5
W-20	14	25.74	1286.8		M-40	14	9.54	477.0	

Table III-7. UNIBEST extraction of Mn from unfertilized Grant soil and WTR.

Sample	Day	Solution Mn (mg/L)	Soil Mn ug resin^{-1}	AVG	Sample	Day	Solution Mn (mg/L)	Soil Mn ug resin^{-1}	AVG
GS-1	1	0.570	28.5	24.4	A-21	1	13.945	697.3	682.4
GS-2	1	0.404	20.2		A-22	1	13.350	667.5	
GS-3	2	0.710	35.5	33.2	A-23	2	14.955	747.8	837.5
GS-4	2	0.619	30.9		A-24	2	18.545	927.3	
GS-5	4	1.003	50.1	49.9	A-25	4	14.215	710.8	622.1
GS-6	4	0.994	49.7		A-26	4	10.670	533.5	
GS-7	7	1.609	80.4	82.6	A-27	7	11.505	575.3	1014.6
GS-8	7	1.695	84.8		A-28	7	29.080	1454.0	
GS-9	14	3.373	118.1	122.2	A-29	14	35.450	1772.5	1703.4
GS-10	14	2.529	126.4		A-30	14	32.685	1634.3	
W-11	1	2.687	134.3	131.0	M-31	1	3.498	174.9	329.0
W-12	1	2.553	127.6		M-32	1	9.662	483.1	
W-13	2	5.811	290.5	267.9	M-33	2	5.861	293.0	370.6
W-14	2	4.906	245.3		M-34	2	8.965	448.3	
W-15	4	10.510	525.5	480.3	M-35	4	6.420	321.0	323.0
W-16	4	8.703	435.1		M-36	4	6.499	325.0	
W-17	7	23.150	1157.5	1135.5	M-37	7	10.180	509.0	652.9
W-18	7	22.270	1113.5		M-38	7	15.935	796.8	
W-19	14	28.460	1423.0	1462.3	M-39	14	31.545	1577.3	1713.1
W-20	14	30.030	1501.5		M-40	14	36.980	1849.0	

Table III-8. UNIBEST extraction of P from unfertilized Grant soil and WTR

Sample	Days	Solution P	Soil P ug resin^{-1}	AVG	Sample	Days	Solution P	Soil P ug resin^{-1}	AVG
GS-1	1	0.299	14.96	**14.1**	A-21	1	0.282	14.12	**12.7**
GS-2	1	0.267	13.34		A-22	1	0.226	11.30	
GS-3	2	0.350	17.51	**19.2**	A-23	2	0.304	15.18	**17.5**
GS-4	2	0.419	20.93		A-24	2	0.394	19.72	
GS-5	4	0.435	21.73	**22.3**	A-25	4	0.316	15.79	**25.5**
GS-6	4	0.457	22.84		A-26	4	0.705	35.26	
GS-7	7	0.516	25.80	**23.0**	A-27	7	0.503	25.17	**30.6**
GS-8	7	0.578	20.24		A-28	7	0.722	36.08	
GS-9	14	1.126	39.41	**37.9**	A-29	14	1.227	61.35	**53.2**
GS-10	14	0.728	36.38		A-30	14	0.903	45.14	
W-11	1	0.087	4.36	**4.4**	M-31	1	1.013	50.67	**52.9**
W-12	1	0.089	4.47		M-32	1	1.103	55.13	
W-13	2	0.232	11.58	**9.6**	M-33	2	0.604	30.21	**37.3**
W-14	2	0.151	7.54		M-34	2	0.888	44.42	
W-15	4	0.403	20.15	**17.0**	M-35	4	0.870	43.52	**38.4**
W-16	4	0.277	13.86		M-36	4	0.665	33.26	
W-17	7	0.636	31.78	**26.4**	M-37	7	0.530	26.49	**37.3**
W-18	7	0.419	20.95		M-38	7	0.962	48.10	
W-19	14	0.303	15.15	**18.1**	M-39	14	1.197	59.85	**66.6**
W-20	14	0.421	21.05		M-40	14	1.469	73.43	

Table III-9. UNIBEST extraction of Sulfur from unfertilized Grant soil and WTR.

Sample	Day	Solution S (mg/L)	Soil S ug resin^{-1}	AVG	Sample	Day	Solution S (mg/L)	Soil S ug resin^{-1}	AVG
GS-1	1	1.77	89	85	A-21	1	11.35	568	564
GS-2	1	1.64	82		A-22	1	11.22	561	
GS-3	2	2.35	117	105	A-23	2	16.44	822	908
GS-4	2	1.87	94		A-24	2	19.87	994	
GS-5	4	2.92	146	136	A-25	4	17.57	879	900
GS-6	4	2.52	126		A-26	4	18.42	921	
GS-7	7	3.54	177	181	A-27	7	13.41	671	1015
GS-8	7	3.70	185		A-28	7	27.19	1360	
GS-9	14	6.96	244	239	A-29	14	11.97	599	740
GS-10	14	4.69	235		A-30	14	17.62	881	
W-11	1	12.28	614	599	M-31	1	19.05	953	964
W-12	1	11.69	585		M-32	1	19.52	976	
W-13	2	19.63	982	922	M-33	2	24.38	1219	1345
W-14	2	17.24	862		M-34	2	29.43	1472	
W-15	4	36.10	1805	1531	M-35	4	24.34	1217	1264
W-16	4	25.13	1257		M-36	4	26.2	1310	
W-17	7	62.02	3101	3049	M-37	7	35.01	1751	2232
W-18	7	59.94	2997		M-38	7	54.27	2714	
W-19	14	67.20	3360	3320	M-39	14	54.82	2741	3072
W-20	14	65.60	3280		M-40	14	68.04	3402	

VITA

Robert J. Zupancic

Candidate for the Degree of

Master of Science

Thesis: Beneficial Utilization of Drinking Water Treatment Residuals as a Soil Substitute in Land Reclamation

Major Field: Plant and Soil Sciences

Biographical:

Education: Graduated for Indian Creek High School, Trafalgar, IN, in May 1992; Received Bachelor of Science degree in Agriculture from Berea College, Berea, Kentucky in December 1996; Completed requirements for Master of Science degree in Plant and Soil Sciences at Oklahoma State University, Stillwater, Oklahoma in May 1999

Professional Experience: Teaching Assistant, Department of Agriculture, Berea College, Berea, KY September 1992 to December 1996; Graduate Research Assistant, Department of Plant and Soil Sciences, Oklahoma State University, January 1997 to March 1999.

Professional Organizations: American Society of Agronomy, Soil Science Society of America, Soil and Water Conservation Society