USE OF WATER TREATMENT RESIDUALS TO REDUCE NUTRIENT RUNOFF AND AS AN ALTERNATIVE GROWTH MEDIA

By

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TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

Table Page

CHAPTER I

CHAPTER II

LIST OF FIGURES

Figure | Page

CHAPTER I

CHAPTER II

FORWARD

This manuscript has been written in the appropriate format for *the Journal of Environmental Quality*. This is to reduce the amount of rewriting required for the information to be ready for publication into a scientific journal.

CHAPTER I

WATER TREATMENT RESIDUAL TO REDUCE NUTRIENTS IN SURFACE RUNOFF FROM AGRICULTURAL LAND

ABSTRACT

Application of animal manures in amounts that exceed agronomic rates based on the nitrogen requirement for crop production can result in surface runoff of nutrients and degradation of surface water. Best management practices that use chemical or by-products to sorb nutrients can reduce nutrient loss from agricultural land. The objective of this work was to determine the ability of water treatment residual (WTR) to reduce N and P runoff from land treated with poultry litter. Different WTR (ABJ or WISTER) were used in two experiments at different locations. Three WTR treatments were applied to plots that received poultry litter at 6.72 Mg ha^{-1} broadcast on bermudagrass (*Cynodon dactylon*) pasture. Treatments were high broadcast (44.8 Mg ha^{-1}), low broadcast (11.2 Mg ha^{-1}), and a buffer strip (44.8 Mg ha^{-1}) to the bottom 2.44 m of the plot. Experimental plots received simulated rainfall for 75 min at 6.35 cm h^{-1} within 24 h of litter and WTR application. Nitrogen, NH_4, P, Al, and dissolved solids in surface runoff were determined. Mean dissolved P of 15.0 mg L^{-1} was reduced to 8.60 mg L^{-1} by the high broadcast and to 8.12 mg L^{-1} by the buffer strip ABJ treatments.

Unlike ABJ, reductions in mean dissolved P using WISTER were <20%. Reductions in runoff P were attributed to amorphous Al in the WTR. Soluble NH_4-N was reduced from 33.7 mg L^{-1} to 11.3 mg L^{-1} (high broadcast) and to 17.9 mg L^{-1} (buffer strip) by ABJ. However, WISTER did not reduce soluble NH_4-N or total N. Reduction in NH_4-N was related to CEC of the WTR. Land application of WTR did not increase dissolved solids or Al in surface runoff.

INTRODUCTION

Surface runoff of nutrients (N and P) from agricultural land is a major source of water quality impairments in surface waters in the USA (Parry, 1998). Application of animal manures in amounts that exceed agronomic rates based on the nitrogen requirement for crop production often results in increased loss of P from agricultural land in surface runoff and potential eutrophication of surface waters (Sharpley, et al., 1994). Excessive concentration of soluble P is the most common source of eutrophication in surface freshwater (Correll, 1998). The greatest potential for surface runoff of nutrients from agricultural land and eutrophication to occur is in regions of intense animal production (Duda and Finan, 1983; Sharpley et al., 1994). Intensive poultry production in eastern Oklahoma has contributed to economic growth (Oklahoma Agricultural Statistics Service, 1998) and raised concerns about surface water pollution. Poultry litter is an inexpensive N fertilizer and often applied to permanent pastures without incorporation. Surface application of poultry litter increases NH_4 and P concentrations in surface runoff (Liu et al., 1997; Sharpley, 1997).

Several best management practices (BMPs) have potential to reduce nutrients in surface runoff. One BMP involves decreasing soluble P by mixing poultry litter with Ca, Al, or Fe chemical amendments (Moore and Miller, 1994). Soluble P in poultry litter was reduced from >2000 to <1 mg P kg^{-1} by mixing CaO, $CaCO_3$, alum, or $FeSO_4$ with poultry litter (Moore and Miller, 1994). Land application of poultry litter treated with chemical amendments (1:5 amendment:litter) had lower soluble P in runoff than untreated poultry litter (Shreve et al., 1995). Alum treatment of poultry litter reduced runoff P from 90 to 10 mg L^{-1} while $FeSO_4$ treatment reduced runoff P from 90 to 20 mg L^{-1}. Another approach to reduce P in surface runoff involves mixing chemical amendments with soil. Addition of 80 g kg^{-1} of fluidized bed combustion flyash to soil reduced Mehlich-III P from >200 to <100 mg kg^{-1} (Stout et al., 1998).

Water treatment residuals (WTR) are primarily sediment, aluminum oxide, activated carbon, and polymer removed from the raw water (Elliott and Dempsey, 1991). Residual by-products from the drinking water treatment process contain chemical constituents capable of adsorbing or precipitating dissolved P (e.g. Al and Fe oxides, resins). Incorporation of WTRs with soil reduces dissolved and extractable P in soil (Cox et al., 1997; DeWolfe, 1990; Peters and Basta, 1996). Lake Wister WTR (WISTER) at 100 g WTR kg^{-1} reduced Mehlich-III from 296 to <200 mg kg^{-1} in soil that had excessive levels of available P from poultry litter application (Peters and Basta, 1996). Residual from the AB Jewell reservoir (ABJ) at 100 g WTR kg^{-1} reduced Mehlich-III P from 553 to 250 mg kg^{-1}. Incorporation of WTR into soil will reduce dissolved P and consequently runoff P from permanent pastures treated with poultry litter. However, incorporation may damage pasture vegetation and is discouraged. Surface application of WTR to pasture land treated with poultry litter may reduce N and P nutrients in surface runoff. The objectives of this work was to determine the ability of WTR to reduce N and P runoff from land treated with poultry litter under field conditions and to evaluate potential environmental impacts associated with land application of WTR.

MATERIALS AND METHODS

Experimental Design

Field experiments were conducted at Adair County, OK and at LeFlore, County, OK. Different WTR were used for each field experiment. Water treatment residual from ABJ was used at the Adair County experiment and WISTER was used at the LeFlore County experiment. Water treatment residuals were collected from storage lagoons and were air-dried before use. The experimental design was a randomized block with three treatments and control replicated four times. Each of the 16 experimental plots was 1.8 m x 9.8 m. Adair County experimental plots were placed on a Dickson silt loam (fine-silty, siliceous, thermic Glossic Fragiudult). Plant available nutrients in the Dickson soil were 5 mg NO_3-N kg^{-1}, 22 mg P kg^{-1}, and 104 mg K kg^{-1}. LeFlore County experimental plots were placed on a Pirum fine-sandy loam (fine-loamy, siliceous, thermic Typic Hapludult). Plant available nutrients in this soil were 6 mg NO_3-N kg^{-1}, 11 mg P kg^{-1}, and 131 mg K kg^{-1}. All plots were placed on similar slopes of <5%. All plots received poultry litter at 6.72 Mg ha^{-1} on a wet weight basis broadcast on bermudagrass (*Cynodon dactylon*) vegetation cut to a height of 7.6 cm. Poultry litter moisture contents averaged 14% in the Adair County experiment and 19% in the LeFlore County experiment. Plots were constructed to channel surface runoff downslope into collection troughs made of 150 mm-diameter PVC pipe split length-wise (Cole et al., 1997). Three WTR treatments were applied over the litter-treated plots. Treatments were high broadcast of 44.8 Mg ha^{-1} (72.6 kg $plot^{-1}$), low broadcast of 11.2 Mg ha^{-1} (18.2 kg $plot^{-1}$), and a buffer strip of 44.8 Mg ha^{-1} (18.2 kg $plot^{-1}$) to the bottom 2.44 m of the plot. The control plot received poultry litter but did not receive WTR.

Chemical Characterization of Residuals and Poultry Litter

Drinking water treatment processes and source waters that produced the WTR used in this study were different. Drinking water treatment coagulation process for ABJ included addition of alum, polymer, and sodium carbonate but WISTER used alum, and calcium hydroxide addition. Chemical properties and metal content of the WTR were determined (Table 1). The pH was determined in 1:2 WTR:0.01 M $CaCl_2$. Salinity (EC) was measured in 1:2 WTR:deionized water. Calcium carbonate equivalence (CCE) was determined by boiling WTR in 0.5 M HCl and back-titrating the excess HCl with standardized 0.25 M NaOH (Rund, 1984). Cation exchange capacity (CEC) of WTR was determined by sodium saturation (Rhoades, 1982). Organic carbon content and total N of the WTR was determined by dry combustion (Schepers et al., 1989). Amorphous reactive Al and Fe oxide content of WTR were determined using the acid ammonium oxalate method (Ross and Wang, 1993). Aqueous Al, Ca, Mg, and P were determined by shaking 1:2 WTR:deionized for 1 h and subsequent analysis using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP). Plant available N (NO_3 and NH_4) in KCl extracts of WTR were determined by automated colorimetric methods (Mulvaney, 1996). Plant available P was determined using Mehlich-III extraction (Mehlich, 1984) and ICP analysis.

Eight samples of poultry litter used at the Adair or the LeFlore County locations were collected and analyzed for total N, P, and K. Total N was determined by dry combustion (Bremner, 1996), total P and K by wet digestion followed by ICP analysis (Kuo, 1996). The mean nutrient content of oven-dried litter used in the Adair County experiment was 29.5 g N kg^{-1}, 15.6 g P kg^{-1}, and 27.9 g K kg^{-1}. The mean nutrient content of the oven-dried litter used in the Leflore County experiment was 34.6 g N kg^{-1}, 17.4 g P kg^{-1}, and 31.4 g K kg^{-1}

Surface Runoff Collection and Chemical Analysis

Experimental plots received simulated rainfall for 75 min at a rate of 6.35 cm h^{-1} within 24 h of poultry litter and WTR application. Runoff samples were collected from the plots at 5 to 10 min intervals. Total runoff volume for each time interval was used to prepare a flow-weighted sample for each plot. Runoff composites were split into two different samples, unfiltered and filtered through a 0.45-μ membrane filter.

Total N and P was determined by wet digestion of the unfiltered surface runoff samples (APHA, 1992). Dissolved NH_4-N and P were determined using filtered surface runoff and the Indophenol blue method (Keeney and Nelson, 1982) and the modified Murphy-Riley ascorbic acid method (Kuo, 1996), respectively. Dissolved Al in filtered surface runoff was determined by ICP analysis.

RESULTS

Effect of WTR on Volume of Surface Runoff

Hydrologic variability of experimental plots resulted in a wide range of runoff volumes within treatments (Table 2). Treatments did not affect runoff volumes ($P<0.05$) at either experimental location. We used nutrient concentration for data analysis instead of the mass of nutrients in surface runoff because of the variability in the hydrologic response of the experimental plots.

Effect of WTR on Phosphorus in Surface Runoff

The high broadcast and buffer strip treatments of WTR applied reduced dissolved P ($P <0.05$) in the surface runoff compared to the control plots in the Adair County experiment (Fig. 1A). Mean dissolved P was 88.3% of the mean total P in the surface runoff for the Adair County site. Because most of the total P was dissolved P, total P results were similar to dissolved P results for all treatments. Mean concentration of total P was 8.60 mg L^{-1} (42.7% reduction compared to control) in the high broadcast treatment and 8.12 mg L^{-1} (45.9%

reduction compared to control) for the buffer strip treatment (Fig. 1A). Small reductions in dissolved P were found for the low broadcast treatment, but these reductions were not significant ($P < 0.05$). Reductions in dissolved P in the surface runoff due to WTR application in LeFlore County (Fig. 1B) were smaller than the results from Adair County (Fig. 1A). In general, WTR treatments showed small but significant reductions in dissolved P ($P < 0.05$) in the LeFlore County experiment. Further reductions in soluble P in the surface runoff were not seen when higher amounts of WTR were applied to the plots (Fig. 1B). Mean dissolved P was 93.6% of the mean total P in the surface runoff from LeFlore County. Because most of the total P was dissolved P, total P and dissolved P results were similar within treatments.

Effect of WTR on Nitrogen in Surface Runoff

Nitrogen measured in surface runoff included NH_4-N, NO_3, and total N. The relative amounts of the three types of dissolved N in surface runoff were total N > NH_4 >> NO_3. Therefore only NH_4-N and total N values are shown. Significant reductions of soluble NH_4-N for the high broadcast treatments and the buffer strip treatments compared to control plots were observed at the Adair County site (Fig. 2A). Total N was not reduced ($P < 0.05$) for any of the treatments compared to the control plots (Fig. 2A). Mean soluble NH_4-N was 49.9% of the mean total N indicating almost half of the dissolved N was in organic forms in surface runoff. WTR treatments did not reduce soluble NH_4-N or total N at the LeFlore County location (Fig. 2B). Both locations had similar amounts of dissolved NH_4-N in the surface runoff from the control plots. However, only 37.1% of total N in surface runoff was NH_4-N indicating most of the dissolved N was in organic forms.

Potential Environmental Impacts

Surface application of WTR on pasture land and increased sediment runoff into nearby water bodies from plots treated with WTR may be a concern. Mean dissolved solids in surface runoff in the Adair County experiment for the high broadcast, low broadcast, and the buffer strip treatments of 0.8, 0.4, and 0.6 g kg^{-1}, respectively, were not different ($P < 0.05$) than the 0.4 g kg^{-1} from control plots. Mean dissolved solids in the surface runoff in the LeFlore County experiment for the high broadcast, low broadcast, and the buffer treatments of 0.6, 0.6 and 0.5 g kg^{-1}, respectively, were not different ($P < 0.05$) than the 0.5 g kg^{-1} from control plots. Land application of WTR did not increase sediment present in surface runoff.

Mean soluble Al (in mg L^{-1}) for the control plots (0.023), the high broadcast plots (0.025), the low broadcast plots (0.027), and the buffered plots (0.029) were not different ($P < 0.05$) in the Adair County experiment (Fig. 3). Similarly, mean soluble Al in surface runoff in the LeFlore County experiment (in mg L^{-1}) from the control plots (0.060), the high broadcast plots (0.048), the low broadcast plots (0.055), and the buffer strip plots (0.049) were not different ($P < 0.05$) (Fig. 3). Land application of WTR did not increase soluble Al in the surface runoff.

DISCUSSION

Treatment of plots with WTR did not significantly affect surface runoff volume or affect the hydrologic properties of the plots (Table 2). Comparison of buffer and low broadcast treatments (Fig. 1A) shows buffer strips were more effective than the broadcast treatments in reducing dissolved P in surface runoff. The buffer strip treatment required 18.2 kg $plot^{-1}$ of WTR, which was the same amount applied in the low broadcast treatment. However, dissolved P in surface runoff for the buffer strip treatment was lower than results from the low broadcast plots. The buffer strip may have provided greater contact between the surface runoff and the WTR than the broadcast treatment resulting in more P removal from surface runoff solution. The high broadcast treatments showed similar reductions in dissolved P as the buffer strip treatment, but the high broadcast treatment required four times the amount of WTR (72.6 kg $plot^{-1}$).

Application of WTR as buffer strips was more effective than broadcast in reducing nutrients in surface runoff in this study, but larger scale field operations may produce different results. Our field study used small plots with even surfaces and constant slopes. The water was channeled to flow directly through the entire width of the buffer strip and into the collection troughs. Application of WTR to a much larger field scale with less homogenous surfaces and slopes may result in "short-circuiting" of surface runoff where runoff flows preferentially through only part of the buffer strip. Short-circuiting may result in a large amount of the buffer strip not interacting or adsorbing nutrients while some of the buffer strip may be saturated with nutrients by the surface runoff. In this case, a broadcast application of WTR may provide more interaction with nutrients in surface runoff and reduce nutrient runoff more effectively than the buffer strip application of WTR.

Differences in dissolved P in surface runoff between locations can result from different sources of poultry litter or different WTR. The poultry litters used at the two locations were from different sources. Laboratory analysis showed the P content of the Adair County litter of 15.6 g P kg^{-1} was similar to the LeFlore County litter of 17.4 g P kg^{-1}. Furthermore, total P concentrations in surface runoff from the control plots from Adair County (15.0 mg L^{-1}) and control plots from LeFlore County (18.8 mg L^{-1}) were similar. Different WTR were used for each experiment; WISTER was used in LeFlore County, while ABJ was used in Adair County. Laboratory P adsorption studies show WISTER removes less P from solution than ABJ WTR (Peters and Basta, 1996). Non-linear Freundlich distribution constant (K_d) values were 2870 L kg^{-1} for ABJ and 35.3 L kg^{-1} for WISTER. Moore and Miller (1994) found that Ca has a tremendous ability to bind P via adsorption and/or precipitation. The Ca content of ABJ was 21.9 g kg $^{-1}$ while WISTER was 2.1 g kg^{-1}. However, analysis of WTR solution data by the geochemical model MINTEQA2 (Allison et al., 1991) indicated WTR solutions were undersaturated with respect to Ca minerals. Other studies have shown amorphous Al was correlated with P adsorption capacity of WTR (Elliott et al., 1990). Amorphous Al content of ABJ of 50.5 g kg^{-1} was much greater than the WISTER amorphous Al content of 11.7 g kg $^{-1}$. Our results suggest adsorption of soluble P by amorphous Al in WTR was an important mechanism for reduction of soluble P in surface runoff.

Soluble NH_4 in surface runoff was decreased by WTR in both experiments. Soluble NH_4 can be absorbed by the CEC of the WTR. The ABJ WTR used at the Adair County site has a CEC of 54.7 cmol kg^{-1} capable of adsorbing significant amounts of NH_4. Soluble NH_4-N can be absorbed by the CEC of the WTR, but NO_3 and organic forms of N have little affinity for WTR CEC sites. The WISTER WTR used at the LeFlore County site has a CEC of 16.4 cmol kg^{-1} which is much smaller than the ABJ WTR CEC of 54.7 cmol kg^{-1}. Larger decreases of soluble NH_4 in surface runoff from plots treated with ABJ than plots treated with WISTER suggest adsorption of soluble NH_4 by CEC sites in WTR.

Because alum-based WTR contains Al, there may be concern that land application of WTR will increase soil solution Al and may increase the potential for Al phytotoxicity. Because alum WTRs used in this experiment were alkaline (Table 1), WTR Al most likely occurs as insoluble amorphous oxide. Application of alkaline ABJ WTR at 100 g kg^{-1} to an acidic Dickson soil (pH 5.3) increased soil pH to 7.0 (Peters and Basta, 1996). Similarly, application of WISTER WTR at 100 g kg^{-1} to the same acidic soil raised the pH to 5.6. Land application of alum-based WTR did not significantly increase dissolved Al in surface runoff (Elliott et al., 1988; Peters and Basta, 1996,) or extractable Al in soil (Peters and Basta, 1996). Aluminum in WTRs exists as an insoluble form of aluminum oxide and does not dissolve in soil environments that are not strongly acidic (pH >5).

CONCLUSION

The ability of WTR to reduce P in surface runoff depends on the amorphous Al content of the WTR. Drinking water treatment plants that use different source water and different treatment chemicals will likely produce WTR that have different chemical composition and nutrient adsorption capacities (Basta et al., 1999). Because various WTR will likely have a wide range of chemical properties, further studies are needed to evaluate the potential of land application of WTR to reduce nutrients in surface runoff. Land application of WTR serves as an alternative to landfilling and will provide financial savings to water treatment plants and protect surface water quality.

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Table 1. Chemical properties, chemical components, and nutrient content of water treatment residuals.

Property or Component	Water Treatment Residual	
	AB Jewell	Wister
Chemical Property		
pH	7.6	7.0
EC, dS m^{-1}	0.58	0.31
CCE, g kg^{-1}	148	18.7
CEC, cmol kg^{-1}	54.7	16.4
OC, g kg^{-1}	66.8	39.3
Chemical Components		
Al oxide, g kg^{-1}	50.5	11.7
Fe oxide, g kg^{-1}	4.2	5.0
Total N, g kg^{-1}	8.98	4.53
Aqueous Components, mg L^{-1}		
Al	0.08	0.10
Ca	375	60.0
Mg	4.70	7.65
P	0.27	0.10
Nutrients, mg kg^{-1}		
NH_4-N	58.4	31.2
NO_3-N	240	34.2
P	11.9	16.8

Table 2. Mean surface runoff volume (L) for treatments at each experiment location.

Location	parameter	Treatment†			
		Br-High	Br-Low	Buffer	Control
Adair County					
	mean	315	138	444	210
	stdev‡	293	112	312	64
LeFlore County					
	mean	907	846	855	872
	stdev	160	167	111	426

† Treatments are broadcast high application (Br-High, 44.8 Mg ha^{-1} or 72.6 kg $plot^{-1}$), broadcast low application (Br-Low, 11.2 Mg ha^{-1} or 18.2 kg $plot^{-1}$), buffer strip (Buffer, 44.8 Mg ha^{-1} or 18.2 kg $plot^{-1}$), and control.

‡Standard deviation

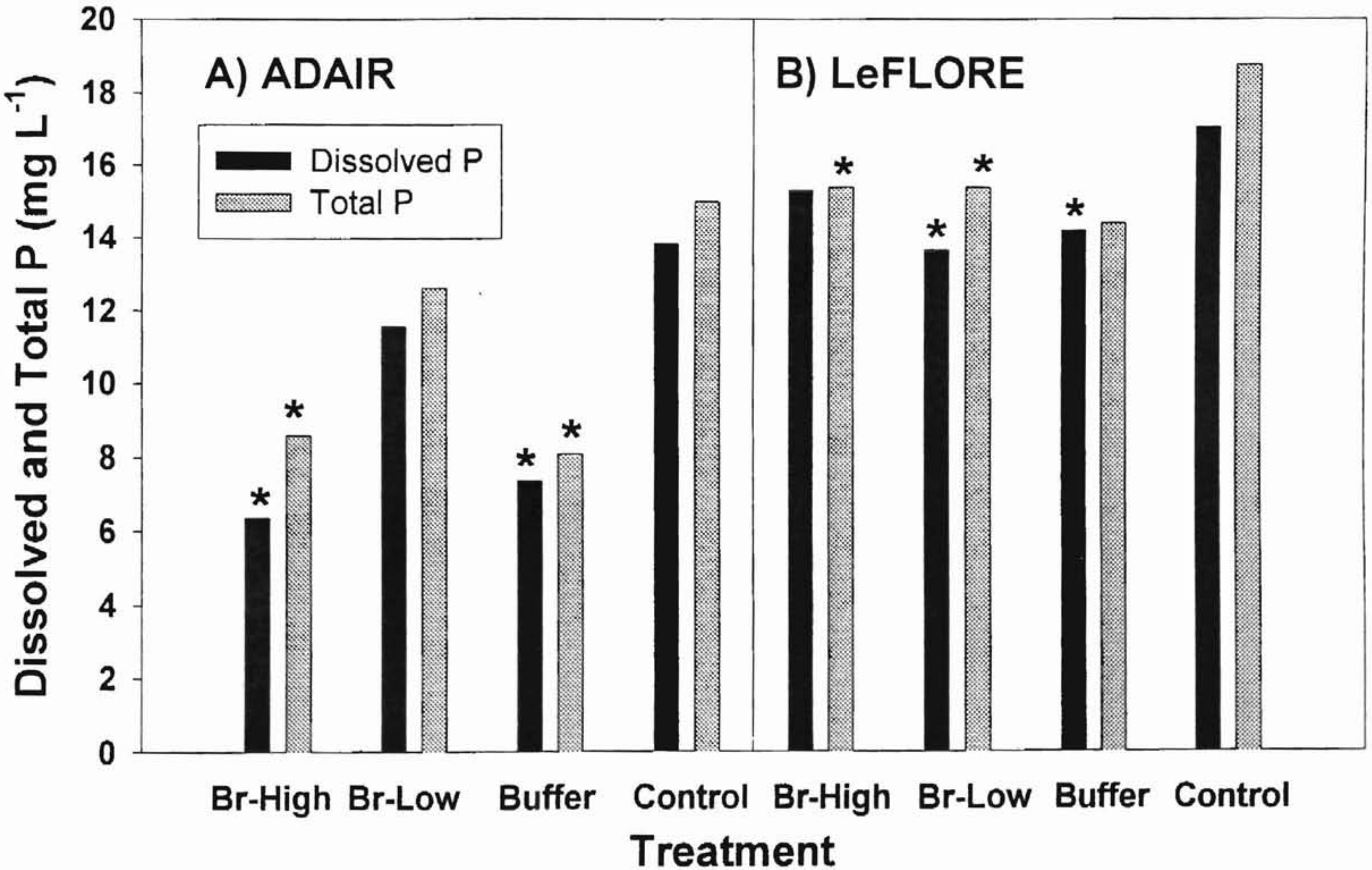

Figure 1. Dissolved and total P in surface runoff from plots treated with poultry litter in the (A) Adair County and the (B) LeFlore County experiment. Treatments are broadcast high application (Br-High, 44.8 Mg ha^{-1} or 72.6 kg $plot^{-1}$), broadcast low application (Br-Low, 11.2 Mg ha^{-1} or 18.2 kg $plot^{-1}$), buffer strip (Buffer, 44.8 Mg ha^{-1} or 18.2 kg $plot^{-1}$), and control. Astericks above bars indicate the treatment is different ($P < 0.05$) than the control.

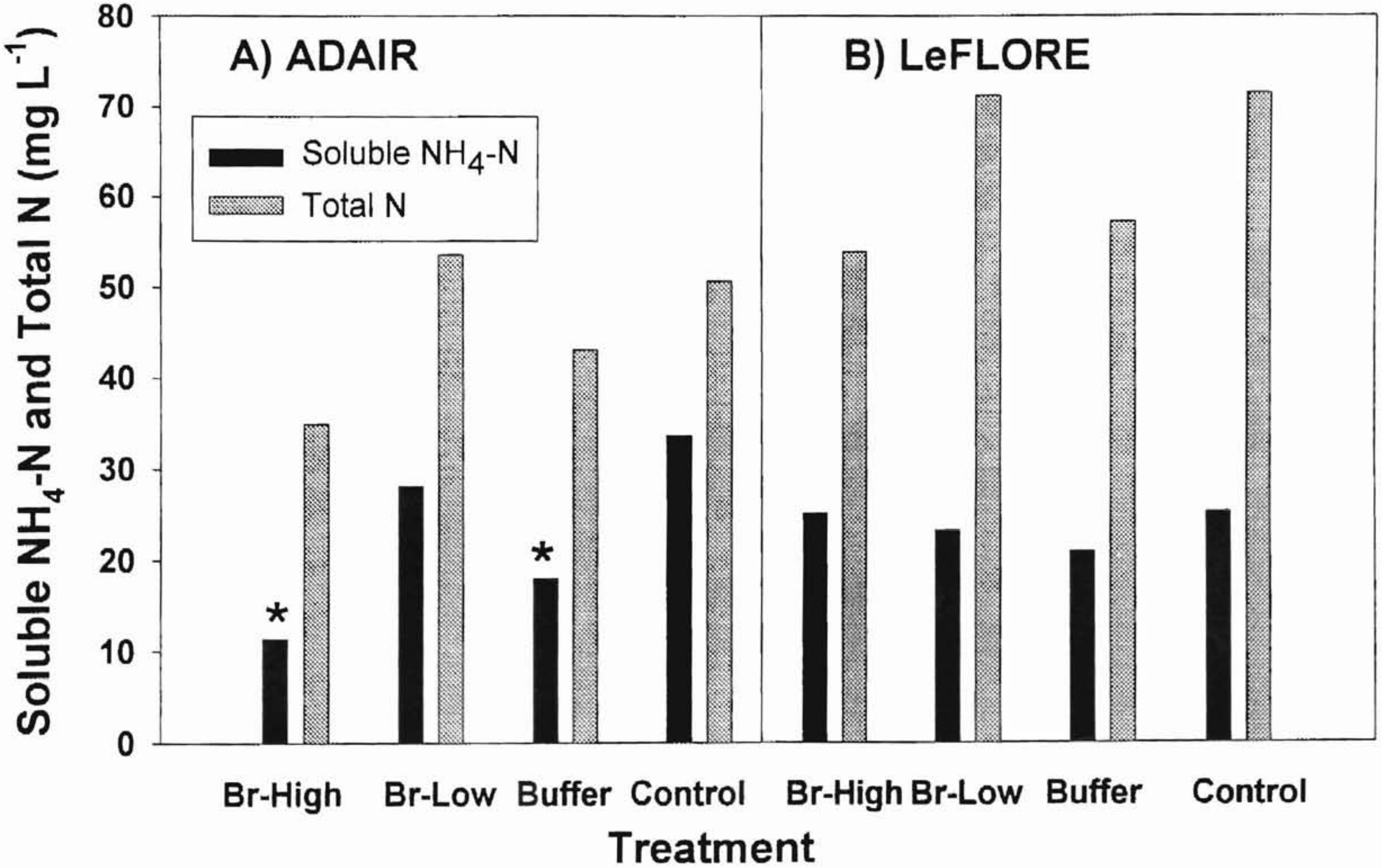

Figure 2. Soluble NH_4-N and total N in surface runoff from plots treated with poultry litter in the (A) Adair County and in the (B) LeFlore County experiment. Treatment designations are the same as in Fig. 1. Astericks above bars indicate the treatment is different ($P < 0.05$) than the control plot.

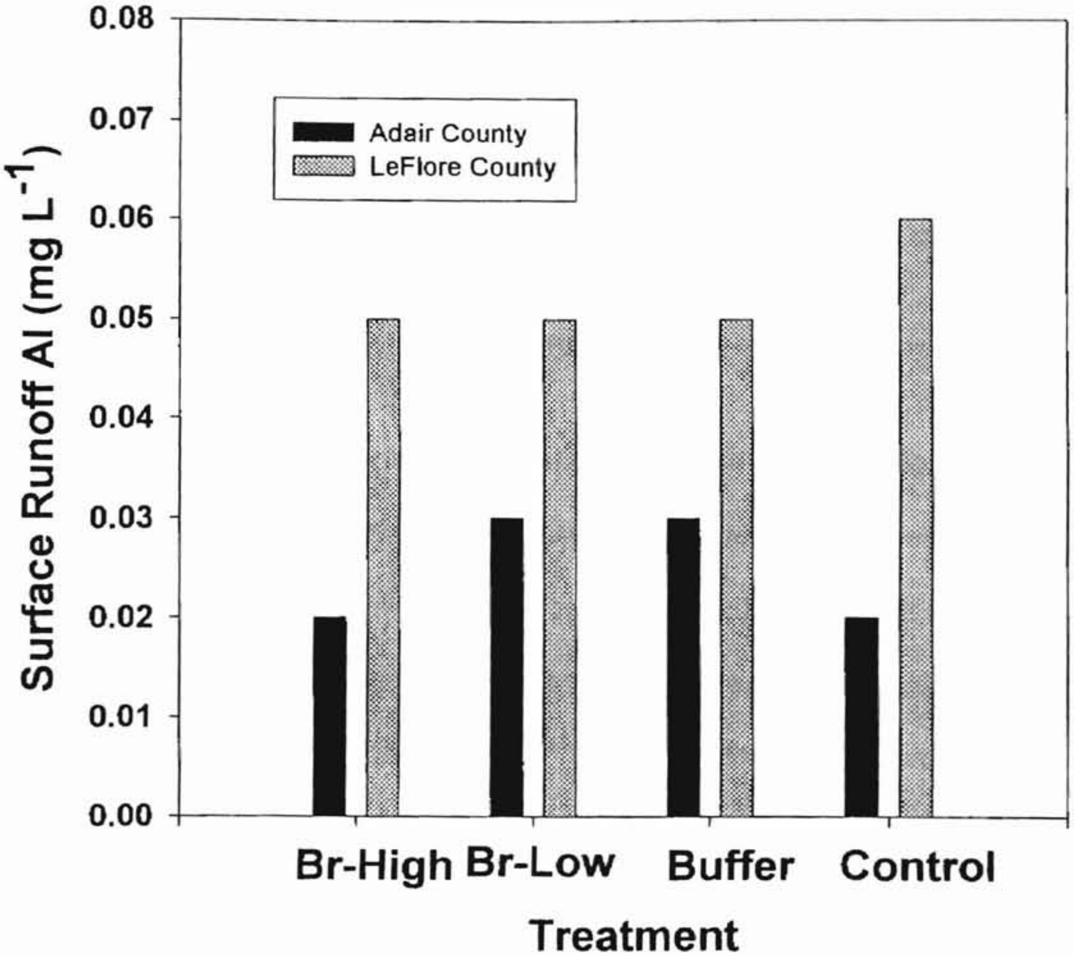

Figure 3. Soluble Al in surface runoff from plots in the Adair and LeFlore County experiments. WTR treatments are high broadcast (Br-High) of 44.8 Mg ha^{-1}, low broadcast (Br-Low) of 11.2 Mg ha^{-1}, buffer strip (Buffer) of 44.8 Mg ha^{-1} and a control with no WTR applied. All treatments received 6.72 Mg ha^{-1} poultry litter. No significant differences were found among the four WTR treatments ($P < 0.05$).

CHAPTER II

VEGETATIVE SPECIES SELECTED FOR GROWTH IN NUTRIENT DEFICIENT WATER TREATMENT RESIDUALS

ABSTRACT

Soil losses from erosion are estimated to be 1 billion Mg each year in the continental U.S. The potential loss of soil is increased when soil is moved during activities such as surface mining or urban construction, thereby disturbing natural vegetation. Soil substitutes may be needed to reestablish vegetation in areas that have undergone severe soil loss. Water treatment residuals (WTR) may be used as a soil substitute providing they supply adequate nutritional requirements for plant growth. Three WTR selected for use as the growth media had adequate plant available N and K, but low Mehlich-III P (4.1 to 16.6 mg P kg^{-1}). Grasses are well known to tolerate low fertility including low available P. The objective of this study was to determine the ability of four vegetations (bermudagrass, tall fescue, weeping lovegrass and white clover) to grow on nutrient (P) deficient WTR without fertilizer additions. After 3 months of growth in a controlled environment, bermudagrass and tall fescue were the only two species that produced substantial dry matter yield and adequate vegetative cover. P deficiencies in plant tissue were found for all species, however, other nutrients were within adequate ranges for each species. No phytotoxic effects from the

use of 100% WTR as a growth media were observed. The effect of this experiment shows that a WTR-grass (bermudagrass or tall fescue) system should be a viable option for reclamation of drastically disturbed land. Use of WTR as a soil substitute will not only be an alternative to landfilling, but will provide substantial financial savings to water treatment plants. It will also provide an economical soil material for reclamation that may not require expensive fertilizer additions.

INTRODUCTION

The potential for topsoil erosion is accelerated from activity that alters and/or removes vegetation. Losses attributed to erosion have been estimated at 1 billion Mg in the continental U.S. each year (Lal, 1994). The number of acres of land disturbed from surface mining and/or urban construction will continue to increase with increased demands from a rising population (Sutton, 1979). In 16 eastern Oklahoma counties, 30,000 acres have been surface mined (OCC, 1997). Soil affected by mining operations can contain sulfur-bearing compounds, particularly pyrite that through oxidation can form sulfuric acid, capable of producing large amounts of acidity (OSM, 1992). The use of heavy machinery during the mining process may also destroy the macropore network that facilitates infiltration and subsurface water movement, aeration, and root system extension (Dunker et al., 1991). These physical and chemical impairments may contribute to the lack of native species establishment. Unfavorable growing conditions at post-mining locations may require the addition of soil amendments or soil substitutes (Vogel, 1997). The most common amendments needed are (1) neutralizing agents and (2) fertilizers to alter the environment so establishment of plant species is possible (Barnhisel and Hower, 1997). These additions help reduce soil loss to erosion and restore mine land to their approximate pre-mine use and/or level of productivity as required by federal and state regulations (Harris et al., 1996).

One potential soil substitute for reclamation may be water treatment residuals (WTR). WTR are a by-product from the drinking water treatment process. Raw untreated water requires chemical additions to remove turbidity, color and/or odor. Some of those chemical additions include alum, ionic polymers and lime. These chemicals in combination with clay particles, the primary suspended solids in raw water, create neutral or alkaline WTR similar to a fine textured soil (Lucas et al., 1994). WTR are currently disposed by landfilling, lagoon storage or land application (Heil and Barbarick, 1989). The cost of landfilling and lagoon storage is costly and may rise due to lack of available land and changes required in treatment processes (Carr et al., 1992). An alternative to the present disposal practices is the use of WTR as a soil amendment or substitute. Bugbee and Frink (1985) used ryegrass in dried WTR and found no inhibition on seed germination. Further, WTR amendments increased aeration and available moisture holding capacity, thus improving the soil quality. In addition, the application of an alkaline WTR (100 g kg^{-1}) increased the pH of an acidic Dickson soil from pH 5.3 to pH 7.0 (Peters and Basta, 1996).

However, the primary concern for use of WTR is its ability to trap P making it unavailable to plants. Rengasamy et al. (1980), using maize (*Zea mays*), found that WTR addition of 1.8 Mg ha^{-1} may increase yields. However, higher additions of 18.1 Mg ha^{-1} caused yield reductions. Geertsema et al. (1994) found that WTR amendments of 33.6 and 56.0 Mg ha^{-1} incorporated into field test plots had no significant effect on the growth of loblolly pine (*Pinus taeda*) trees. Plant establishment may require fertilizer P additions. However, Bugbee and Frink (1985) found that P deficiencies at 5% WTR rate by volume and greater were not overcome by doubling the initial P fertilizer rate for marigolds (*Tagetes* cv. Lemondrop). Similarly, Lucas et al. (1994) found that 0.72 Mg P_2O_5 ha^{-1} (640 lbs P_2O_5 ac^{-1}) would be required to correct the P deficiency induced by a 44.8 Mg ha^{-1} WTR amendment to achieve 90% sufficiency for tall fescue. P additions required to correct deficiencies for many species can be impractical and not cost effective for reclamation.

A secondary goal of reclamation of disturbed land is the reestablishment of diverse vegetative cover, primarily of native species present prior to mining (Doll, 1988). The use of WTR as a soil amendment or substitute would require plant species with lower nutritional requirements or the ability to withstand lower nutrient status than most agricultural crops. Grasses, whether native or exotic, are ideal for reclamation because in many cases they are similar to what was present on a site prior to mining and are tolerant of low fertility. Most roadside revegetation and reclamation projects use grass species due to availability of seed and ease of establishment (Skousen et al., 1997). Another possible reason that Gramineae family members are successful on deteriorated sites may be that most (84%) of the family form mycorrhizal associations allowing for more efficient uptake of nutrients (especially P) from deficient soils (Newman and Reddell, 1987).

The objective of this work was to determine the ability of four vegetations (bermudagrass, tall fescue, weeping lovegrass and white clover) to grow on nutrient deficient WTR without the addition of P fertilizers.

MATERIALS AND METHODS

Collection and Characterization of the Water Treatment Residuals

The three WTRs selected for this study were collected from storage lagoons at the AB Jewell treatment facility (WTR A), Mohawk treatment facility (WTR B), both from Tulsa, Oklahoma and a third residual, WTR C from the Claremore, Oklahoma treatment facility. All three treatment facilities have different raw water sources and different chemical additions. The WTR A facility uses alum ($Al_2(SO_4)_3 \bullet 14H_2O$) and ionic polymers to treat the raw water from Lake Oologah. WTR B facility uses alum, ionic polymers and lime to treat the raw water from Lake Spavinaw/Eucha. The WTR C facility uses alum and lime to treat raw water from Lake Claremore. The three WTRs used for this study were selected due to their low P availability as determined from a previous study (Peters and Basta, 1996). Soil test P (STP) in WTR, measured by Mehlich-III extraction (Mehlich, 1984) ranged from 4.1 to 16.6 mg P kg^{-1}. These STP values are all below the P level of 33 mg kg^{-1} considered adequate for most agricultural crops (Johnson et al., 1997).

All WTR materials were air dried, crushed and sieved to pass a 2.0-mm sieve. A Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustoll) soil was selected for comparison with the WTR. Physical properties and plant nutrient contents of each WTR and of the soil were determined prior to seeding (Table 1). The pH of each growth media was determined using 1:2 WTR:0.01 M $CaCl_2$. Bulk density (D_b) was estimated by dividing a 3 kg weight of dried material by its volume. The electrical conductivity (EC) of the growth media was determined using 1:5 WTR:deionized water and measured with a conductivity meter. Field capacity of the WTR were determined at 1/3 bar (Klute, 1986). Total N of the growth media was determined by automated dry combustion (Schepers et al., 1989). Plant available N (NH_4-N and NO_3-N) was determined by 1:10 WTR: 2 M KCl extract with automated cadmium reduction and indophenol blue colorimetric methods (Mulvaney, 1996). Extractable P, K, Ca and Mg were determined using M-III extraction solution (Mehlich, 1984) followed by Inductively Coupled Plasma Atomic Emissions Spectroscopy (ICP-AES) analysis. Water soluble Al was determined using a 1:10 WTR:deionized water 1-h extraction followed by ICP analysis. Sulfate-sulfur was extracted using a monocalcium phosphate (0.02 M) solution and measured with ICP (Zhang and Kress, 1997). Extractable Fe and Zn concentrations were determined using DTPA extracting solution and ICP analysis (Zhang and Kress, 1997).

Selection of Vegetative Species

Plant species were selected for their potential to withstand the low P availability conditions of the WTR. The four vegetative species chosen were bermudagrass (*Cynodon dactylon*), tall fescue (*Festuca arundinacea*), weeping lovegrass (*Eragrostis curvula*) and white clover (*Trifolium repens*).

Bermudagrass is a warm season perennial and is one of the most common species used in revegetation efforts in southeastern US (Bennett et al., 1978). Its popularity is due primarily to its deep rooting system, which allows it to tolerate drought and low fertility conditions (Burton and Hanna, 1995). Although minimal management is required for bermudagrass pasture, it will respond to intensive management, particularly N and K fertilization (Redmon and Woods, 1996). Bermudagrass can be found from Oklahoma to North Carolina and is capable of producing quality forage from April to October (Ball et al., 1996).

Weeping lovegrass is a warm-season bunchgrass that is widely grown on the deep sandy soils with low fertility of central and western Oklahoma (Rommann and McMurphy, 1974). Establishment of weeping lovegrass under these harsh conditions is possible due to deep rooting which also helps to slow soil erosion (Masters and Britton, 1990). Weeping lovegrass has shown promise as a vegetation cover for revegetation in the Hawaiian islands that have undergone severe soil erosion (Warren and Aschmann, 1993).

Tall fescue is the dominant cool season grass species in mixed and pure stands in the US occupying 12-14 million ha (Sleper and Buckner, 1995). Tall fescue is a perennial bunchgrass with a deep root system, which allows for more efficient plant uptake of nutrients as compared to other species (Burns and Chamblee, 1979). Tall fescue has unique characteristics that separate it from other grasses. Studies have shown that tall fescue will improve soil structural stability better than other cool season grasses (Carter et al., 1994). When provided with adequate moisture (>889 mm y^{-1}), tall fescue can withstand low fertility conditions in eastern Oklahoma (Redmon et al., 1996). Tall fescue has a long growing season that can provide ground cover for most of the year. In regions where tall fescue is adapted it can provide quality forage from March to July and September to December (Ball et al., 1996).

White clover was primarily selected due to its sensitivity to low fertility conditions, specifically P and K (Blue and Carlisle, 1985). Most clovers cannot survive under low fertility situations (Van Keuren and Hoveland, 1985). This vegetation was chosen to help illustrate that low STP of the WTR may inhibit plant growth. Perennial white clover is commonly found in Oklahoma and is often used to improve the quality of mixed pastures (Caddel and Redmon, 1995).

Potting Study

A completely randomized experimental design was used with treatments of four vegetations, and four growth media, in a factorial arrangement of WTR or soil replicated four times. Vegetations were seeded or sprigged into 3 kg pots and placed into a controlled environment growth chamber. The 'Greenfield' variety of bermudagrass was sprigged, 5 g pot^{-1} into sand trays with P deficient Hoagland's nutrient solution for 3 weeks (Jones, 1997). The bottom of the plastic sand tray was removed after 3 weeks and the trays were placed on top of the 3 kg pots with WTR or soil potting media (Standford and DeMent, 1957). Tall fescue (Kentucky-31) was seeded at a rate of 16.8 kg ha^{-1} (Ball et al., 1996). Weeping lovegrass (Morpa) and white clover (Ladino) were seeded at 3.4 kg ha^{-1} (Rommann and McMurphy, 1974; Gibson and Cope, 1985). No fertilizer additions were made to the WTR pots prior to planting. Separate growth chambers were used for warm (bermudagrass and weeping lovegrass) and cool (tall fescue and white clover) season species. Each growth chamber had 14-hour day lengths. The warm season chamber had day temperatures of 30 °C and night temperatures of 24 °C (Burton and Hanna, 1995). The cool season chamber had day temperatures of 24 °C and night temperatures of 18 °C (Redmon et al., 1996). The pots were watered every other day, and water content was adjusted every week by taking the weight of each pot and adding water needed to maintain field capacity moisture. "Field capacity" (moisture content at approximately 1/3 bar pressure) of the growth media was determined and varied from 50% (by weight) for WTR A, 55% for WTR B, 29% for WTR C and 26% for the soil. After three months of growth, dry matter yield was determined by harvesting plants to a 1.3-cm stubble height, rinsing soil from vegetation using deionized H_20, and oven drying for 24 hours at 70 °C (Jones and Case, 1990). Vegetation cover (%) was determined by placing a 1-cm^2 grid screen over the pots and counting the squares that contained vegetation (Firman and Allen, 1989). Dried vegetation was ground (<850 μm) and wet digested with $HNO_3/HClO_4$ (Jones and Case, 1990). Nutrient concentrations (P, K, Ca, Mg, Mn, Fe, Cu and Zn) of the plant tissue digest were analyzed by ICP (Table 2). Total N of the plant tissue was determined by automated dry combustion (Schepers et al., 1989).

Statistical Analysis

Significant differences in dry matter yield and vegetation cover were determined using PROC GLM (SAS Inst., 1988) to generate Analysis of Variance (ANOVA) tables (Appendix 1). Due to interactions among growth media and vegetation, determinations for growth media or vegetation that was significantly greater across all vegetation or growth media was not possible. Using Duncan's multiple range test (α=0.05), multiple comparison of means for each parameter measured was completed (Steele et al., 1997). Each combination of growth media and vegetation was regarded as a treatment, such that 16 treatments were analyzed to determine significance for each variable measured. Statistically different treatments from the Duncan procedure are represented by a different letter above the bars in Fig. 1 and 2.

RESULTS AND DISCUSSION

Comparison of Vegetation

Dry matter yield and percent vegetation cover differences ($P < 0.05$) were observed among the four vegetations (Fig. 1 and 2). In general, the trend for dry matter yield was bemudagrass>tall fescue>weeping lovegrass>white clover across growth medias (Fig. 1). Due to the relationship between dry matter yield and percent vegetation cover, the same general trends were observed. In general, bermudagrass yield in comparison with other vegetation may have been larger due to its lower external P requirement, possibly from the aid of mycorrhizal associations as well as its high responsiveness to N when adequate moisture conditions exist.

A possible explanation for the larger yield of bermudagrass compared to tall fescue is the ability of warm season grasses to produce greater yields than cool season grasses. Bermudagrass is a warm season perennial, which can produce 11.2 to 15.7 Mg ha^{-1} (Ball et al., 1996) under good management. However, tall fescue, a cool season perennial may only produce 4.5 to 6.7 Mg ha^{-1} (Burmester and Adams, 1983). Warm season grasses are considered to have a greater potential to form mycorrhizal associations than cool season grasses under conditions of moisture or nutritional stress. Yost and Fox (1979) stated that plant species that form mycorrhizal associations have 25 times greater P uptake than non-mycorrhizal associated plants. Bermudagrass P uptake was generally higher than the other species studied for all growth media. However, tissue P concentrations for bermudagrass were deficient for all growth media (Table 2). Perhaps, mycorrhizal associations may not have been present in the soil, since these associations are not as pronounced when conditions of stress do not exist. Plant tissue P as well as P uptake for some species has been shown to decrease with increasing P availability in the soil from lack of mycorrhizal contributions (Yost and Fox, 1979).

Weeping lovegrass was generally significantly different from bermudagrass for dry matter yield and percent vegetation cover (Fig. 1 and 2).

Weeping lovegrass has the ability to produce the same if not more yield than bermudagrass when adequate plant nutrients are available (McMurphy et al., 1975). However, when nutrients such as P are limiting, increases in N will not result in higher yield in weeping lovegrass (Matizha and Dahl, 1991). Bermudagrass yield will be larger than weeping lovegrass when P is low and N is high (Taliaferro et al., 1975). Another possible reason for the reduced yield in weeping lovegrass could be in the planting procedures used. Both warm season species (bermudagrass and weeping lovegrass) have very small seeds in comparison to tall fescue. The low bulk density of the WTR used in this study show that the pots had very large macropores (Table 1). Perhaps this condition allowed seeds to be pushed down or washed out when water was added prior to seed germination. Bermudagrass was sprigged into pots; however, weeping lovegrass was seeded. Therefore, greater dry matter yield for weeping lovegrass may be attained under field conditions when sprigs are used instead of seeds compared to pot studies using these growth media.

Although WTR contained large amounts of plant available N that helped to increase yield in grasses, legumes do not respond as well to N. White clover has been shown to have little response to increased N, but responds well to increases in P, K, lime and Mg (Rangeley and Newbould, 1985). Grasses have the ability to produce twice the yield of legumes under low fertility due to legume species intolerance to low P and K (Caradus, 1980; Reith et al., 1973). Only two of the four growth media had clover produce measurable yields and percent vegetation cover (Fig. 1 and 2). White clover also has small seeds similar to the warm season grasses. However, all of the growth media generally had some seeds germinate and then die. The lack of production of clover is not due to loss of seeds, but the lack of available P for growth (Table 1).

A comparison of growth media within bermudagrass vegetation for dry matter yield and percent vegetation cover shows a general trend of WTR B>SOIL>WTR C≥WTR A (Fig. 1 and 2). Analysis of plant tissue P for bermudagrass shows the same trend of WTR B>SOIL>WTR C>WTR A (Table 2). Relationship between yield and tissue P (Fig. 3) of the plant suggests yield was dependent on P availability of the growth media. However, the M-III P trend is SOIL>WTR B>WTR C>WTR A (Table 1).

All growth media had below the practical detection limit (0.42 mg L^{-1}) water soluble Al. This was less than 1 mg L^{-1} water soluble Al, considered the threshold for phytotoxicity (Bohn et al., 1979). This was expected since Al solubility is low when the pH is greater than 5.5, and pH of all the growth media was above 6.0 (Table 1). Potential toxicity of the WTR was determined using USEPA Toxicity Characteristic Leaching Procedure. All elements analyzed (As, Ba, Cd, Cr, Pb and Se) were below regulated levels (Dayton, 1999). Plant tissue analysis did not show any deficiencies from low levels of Fe, Mn, Cu or Zn (Table 2). In addition, plant tissues for all species were not elevated beyond the normal range for Fe (0.07 g kg^{-1}), Mn (3.0 g kg^{-1}), Cu (30 mg kg^{-1}) and Zn (300 mg kg^{-1}) for any of the plant species (Foy et al., 1977; Marschner, 1995). Since these nutrients are within normal ranges, they are unlikely to have an influence on plant growth.

The general trend for dry matter yield for tall fescue was slightly different from bermudagrass (Fig. 1). There were no significant differences in dry matter yield between WTR B, WTR C and SOIL for tall fescue. Vegetative cover was significantly higher for WTR C than soil (Fig. 2). Plant tissue P for tall fescue followed the trend of SOIL > WTR C > WTR B (Table 2). WTR A did not produce enough tall fescue dry matter to be analyzed. The plant tissue P trend generally follows the M-III P of SOIL > WTR B > WTR C > WTR A. Plant available P differs only slightly for WTR B and WTR C (Table 1). Since tall fescue has a higher P requirement than the warm season grasses, M-III P may have had a greater effect on yield.

A similar trend of WTR B ≥ SOIL ≥ WTR C was found for dry matter yield and percent vegetation cover for weeping lovegrass. However, overall yields were lower than for the other warm season grass (Fig. 1 and 2). As mentioned previously, difficulties from sub-optimum planting techniques in growth chamber conditions may have prevented weeping lovegrass from achieving its potential for growth in the WTR pots.

White clover was unable to establish and survive on any of the growth media except for the soil (Fig. 1). The most probable cause of the absence of white clover in the WTR pots was the lack of available P. M-III P for the WTR ranged from 4.1 to 16.6 mg kg^{-1}, while the soil had 29.0 mg kg^{-1} (Table 1). White clover requires adequate P to establish. The data indicates that 16.6 mg P kg^{-1} is below the adequate range for white clover. White clover seeds did germinate in WTR pots. However, once nutritional reserves from the seed were depleted,

depleted, the white clover plants were unable to survive due to an inability to reach critical P and K.

CONCLUSIONS

Grass species can survive and produce ground cover using 100% WTR as the growth media. Analysis of dry matter yield, percent vegetation cover and tissue analysis shows no phytotoxic effect of the WTR existed for these species.

Bermudagrass and tall fescue were able to survive in WTR, producing large amounts of dry matter yield without fertilizer additions for a three month period. However, deficient tissue P levels indicate growth was not optimum and the sustainability of these grasses in P deficient WTR is not known. Weeping lovegrass should be reevaluated; however to obtain accurate results, sprigs should be used to prevent any seed loss due to the macropores of the WTR. The results also show that perhaps the available P of the WTR was below the minimum required for white clover to establish. White clover seeds did germinate in WTR, but due to lack of a deep root system was unable to reach critical nutrients, and therefore was unable to survive. The WTR B had M-III P of 16.6 mg P kg^{-1}, all other WTR had less available P than WTR B. Only SOIL with 29 mg P kg^{-1} had measurable dry matter production of white clover.

Generally, WTR B is an acceptable growth media for the grass species used in this study. However, sensitivity of a site to N loss from leaching may be a concern in using WTR B, since 123 mg NO_3-N kg^{-1} are presently available for loss. The WTR B has adequate, but low levels of plant available K that may make plant growth difficult in the future. WTR C is a good growth media for reclamation because it contains adequate N, large amount of available K, and similar available P levels to WTR B. The longevity of these materials to be used as a growth media remains unknown. A long-term experiment in a field setting is required to determine if fertilizer additions would be required for plant survival and vegetative growth in WTR. The WTR A should not be used as a growth media. None of the plant species evaluated were able to produce enough of a root system to support their survival in WTR A. Basta et al. (1999) showed WTR A had a tremendous ability to adsorb P. Amending soil with WTR A to trap excessive levels of available P in soils may be a suitable alternative to current disposal practices.

Source water and water treatment processes affect the chemical composition of WTR. Suitability of WTR as a soil substitute and a growth media depends on the nutrient status and chemical composition of WTR. Water treatment facilities regularly adjust their chemical treatments required in processing the raw water. The variability in the chemical composition of WTR produced by a treatment plant is not known. Therefore, further studies should evaluate these differences and the affect it will have on WTR to support plant growth.

Although vegetation may respond differently to WTR under field conditions, our results suggest grasses grow well in P-deficient WTR. A WTR-grass system should be a viable option for reclamation of drastically disturbed land. Use of WTR as a soil substitute serves as an alternative to landfilling and will provide financial savings to water treatment plants. It will also provide a resource of soil-like material capable of supporting plant life without addition of expensive fertilizers or other amendments for reclamation efforts.

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Table 1. Physical properties and chemical characteristics of WTR and soil with nutrient requirements for grasses and legumes.

Property or Nutrient	Growth Media				Requirements	
	WTR A	WTR B	WTR C	SOIL	Grasses †	Legumes ‡
pH	7.1	7.5	7.7	6.1	4.5-7.0	6.0-7.0
D_b (g/cm^3)	0.62	0.58	0.79	1.23	na§	na
EC (dS/m)	0.36	0.54	0.37	0.06	<4	<4
FC (%) ¶	50.0	58.2	28.6	26.0	na	na
Nutrients				mg kg^{-1}		
Total N	9770	14400	9160	678	na	na
Available N #	89.8	263	77.0	99.1	75	na
NH_4-N	71.1	140	69.7	23.5	na	na
NO_3-N	18.7	123	7.30	75.6	na	na
P ††	4.10	16.6	13.2	29.0	33	33
K	268	98.3	140	88.6	100	125
Ca	4640	45800	15400	3870	375	375
Mg	74.0	121	761	283	50	50
SO_4-S ‡‡	143	122	188	55.0	4	3
Fe §§	7.60	58.8	110	52.0	4.5	4.5
Zn	0.55	1.30	3.00	0.53	0.30-0.80	0.30-0.80

† Yield goal of 3 ton/acre (Johnson et al., 1997)
‡ Yield goal of 2 ton/acre (Johnson et al., 1997)
§ Not applicable
¶ field capacity by weight
# NH_4-N and NO_3-N by 2 M KCl extract
†† P, K, Ca and Mg from Mehlich-III extract
‡‡ Monocalcium phosphate extract
§§ Fe and Zn from DTPA extract

Table 2. Tissue concentrations for each vegetation and growth media combination at experiment termination.

	Tissue Elemental Concentrations								
	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn
	g kg^{-1}							mg kg^{-1}	
Bermudagrass									
WTR A	---†	0.88	21.1	6.0	1.46	0.28	0.14	6.8	26.0
WTR B	34.9	1.79	20.1	5.6	1.24	0.13	0.47	11.8	11.3
WTR C	34.9	0.98	20.0	4.8	2.63	0.28	0.71	11.2	32.8
SOIL	34.0	1.36	22.9	3.3	1.74	0.17	0.56	12.9	40.0
Adequate level ‡ ¶	26	2.8	19	---	---	0.02	0.04	5	20
Tall fescue									
WTR A	32.1	---	---	---	---	---	---	---	---
WTR B	27.9	0.73	15.1	13.9	3.38	0.26	0.30	15.7	17.3
WTR C	32.0	0.98	24.2	9.6	7.22	0.67	0.30	11.2	30.0
SOIL	30.1	1.35	25.2	7.1	4.87	0.26	0.20	7.0	22.5
Adequate level ‡ ¶	24	2.6	24	---	---	0.02	0.04	5	20
Weeping lovegrass									
WTR A	---	---	---	---	---	---	---	---	---
WTR B	21.6	0.54	6.4	6.1	1.15	0.14	0.13	15.7	17.0
WTR C	26.0	1.17	10.4	3.9	4.05	0.28	0.19	7.8	30.5
SOIL	23.1	0.94	11.5	3.5	1.49	0.08	0.12	6.4	68.3
Adequate level ‡ ¶	26	2.8	19	---	---	0.02	0.04	5	20
White clover									
WTR A	---	---	---	---	---	---	---	---	---
WTR B	---	---	---	---	---	---	---	---	---
WTR C	---	2.11	22.3	20.4	5.57	0.15	0.33	10.2	31.0
SOIL	28.7	0.92	12.5	15.6	6.13	0.17	0.59	5.9	32.0
Adequate level § ¶	---	3.1	18	---	---	0.02	0.04	5	20

† Not enough plant material available for analysis.

‡ Adequate N, P and K tissue concentrations for bermudagrass, tall fescue and weeping lovegrass (Kelling & Matocha, 1990).

§ Adequate P and K tissue concentrations for white clover (Evans et al., 1986).

¶ Adequate Mn, Fe, Cu and Zn tissue concentrations for grasses and legumes (Marschner, 1995).

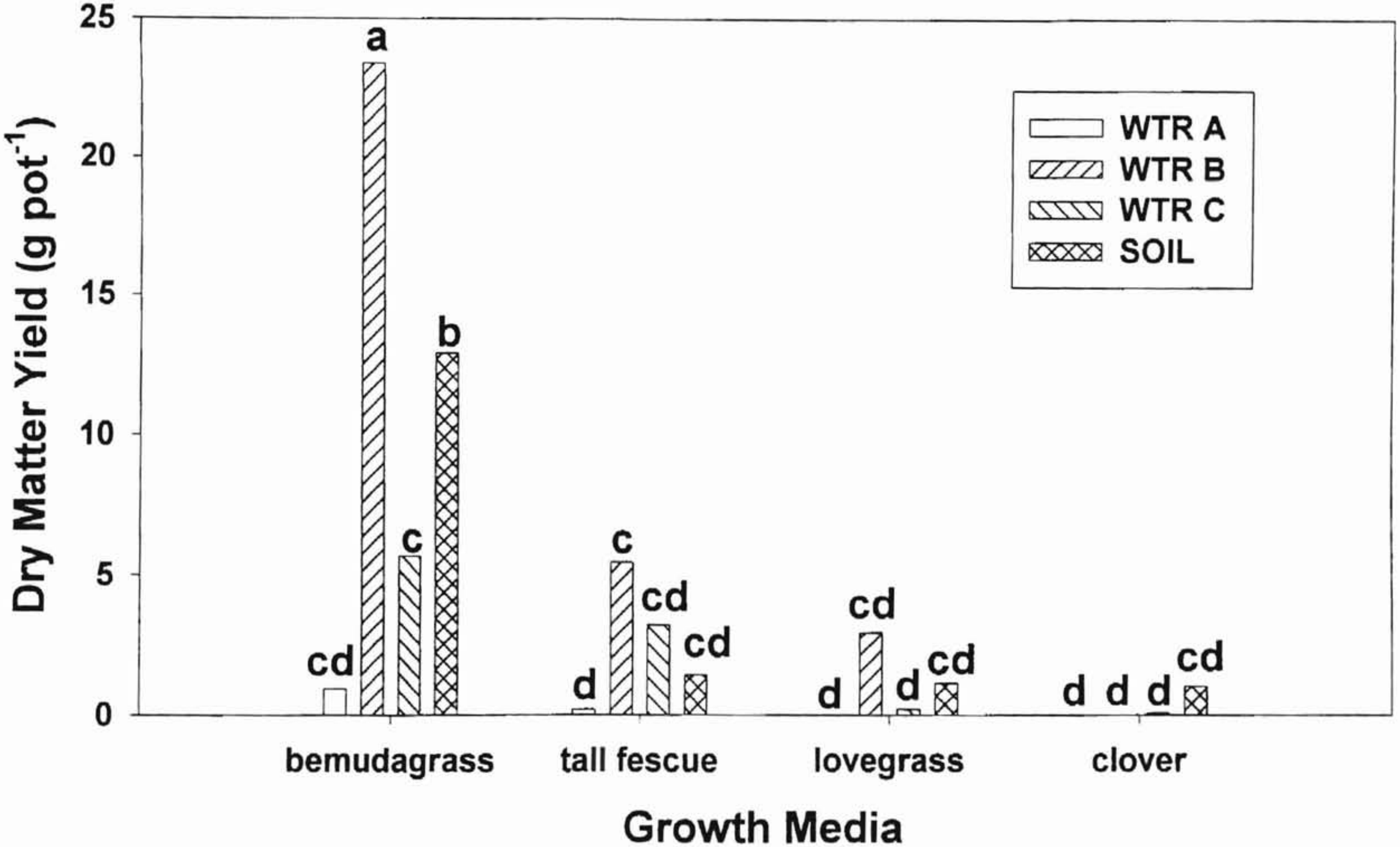

Figure 1. Average dry matter yield for each of the four vegetations and the four growth media combinations. Letters above bars indicate significant differences ($P < 0.05$) for each vegetation and growth media combination.

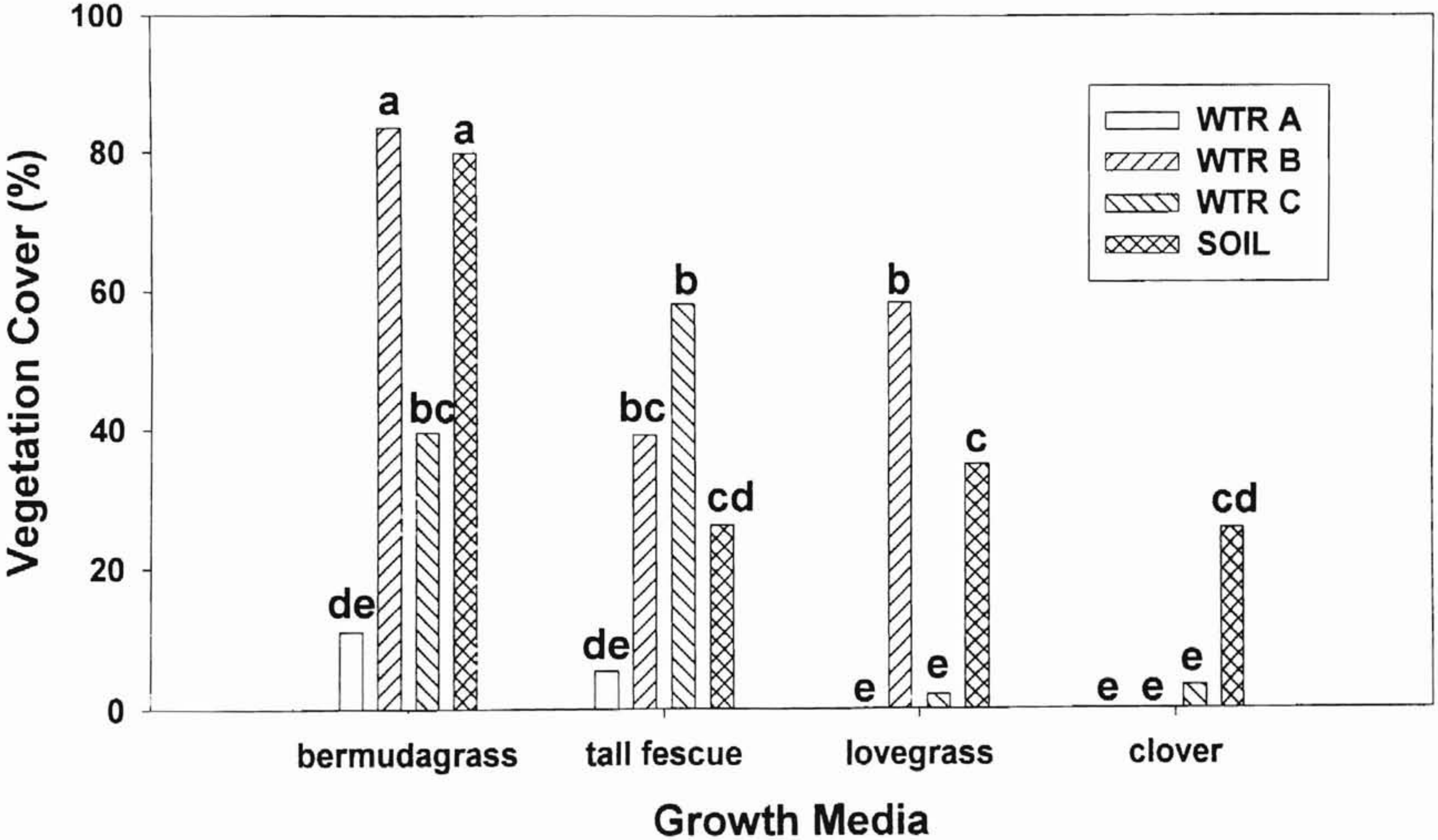

Figure 2. Average vegetation cover for each of the four vegetations and the four growth media combinations. Letters above bars indicate significant differences (P <0.05) for each vegetation and growth media combination.

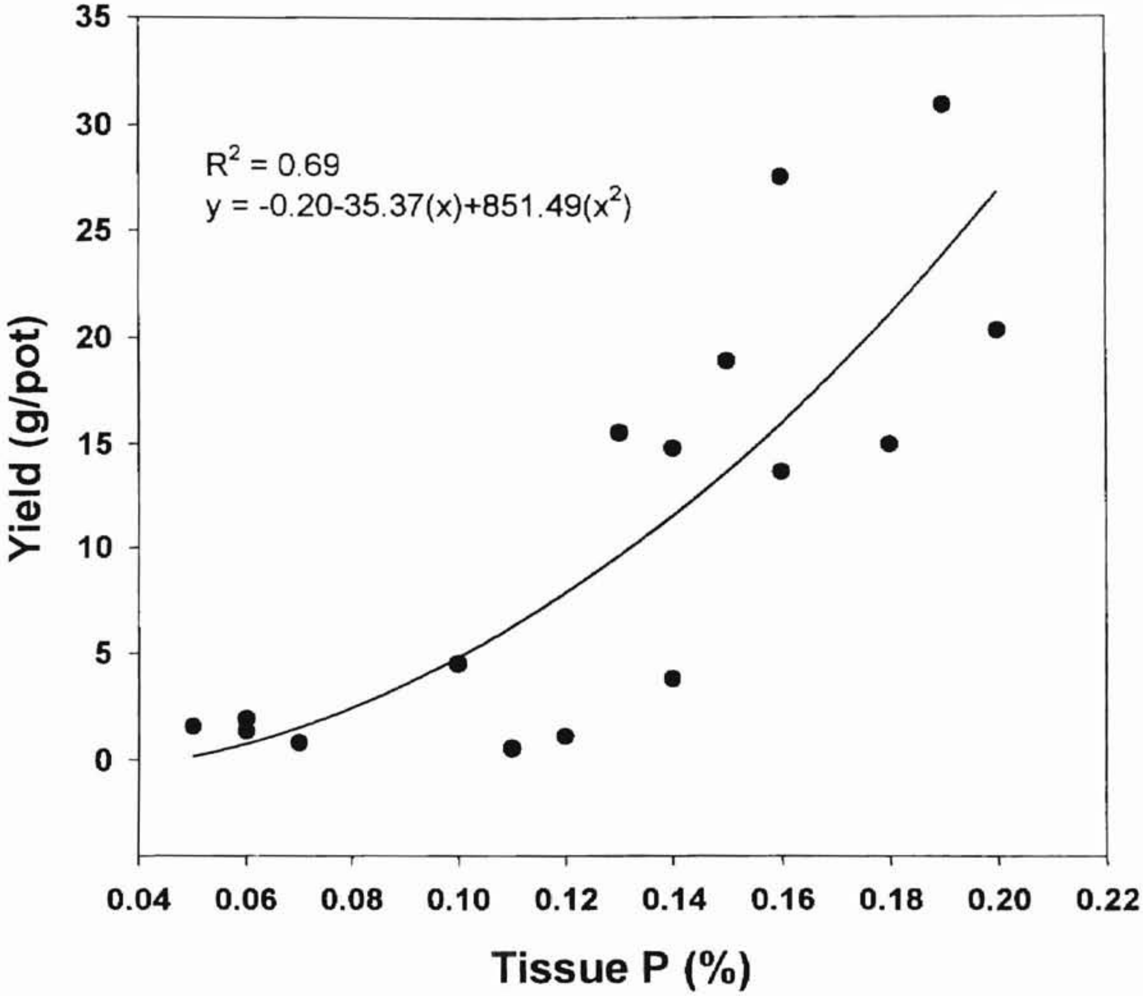

Figure 3. Relationship between tissue P and dry matter yield for bermudagrass vegetation for all growth media.

APPENDIX I

Appendix I-I. Nutrient analysis of runoff water from the Adair county experiment

Treatment	Plot	Total P	Dissolved P	Organic P	Total N	Soluble NH_4-N	Organic N	Soluble Al	Solids in water
		------------mg L^{-1} -----------							g kg^{-1}
A †	1	4.62	4.36	0.26	26.3	10.6	15.7	0.024	0.450
A	2	2.85	2.41	0.43	28.6	5.88	22.7	0.025	0.450
A	3	11.7	7.29	4.38	56.1	17.8	38.4	n/a	0.450
A	4	15.2	11.4	3.87	28.9	11.1	17.8	0.026	1.65
B ‡	1	12.6	12.5	0.12	75.1	30.4	44.6	0.027	0.250
B	2	12.4	11.2	1.12	47.1	27.4	19.7	0.028	0.400
B	3	13.2	11.4	1.82	54.7	27.7	27.0	0.022	0.500
B	4	12.3	11.1	1.22	37.5	27.1	10.5	0.030	0.350
C §	1	6.35	6.08	0.27	51.4	14.8	36.6	0.035	0.600
C	2	6.97	6.03	0.94	21.5	14.7	6.85	0.022	0.700
C	3	9.97	9.24	0.72	54.6	22.5	32.1	0.028	0.550
C	4	9.17	8.07	1.09	45.1	19.7	25.4	0.029	0.500
D ¶	1	11.9	11.1	0.83	47.3	27.1	20.2	0.022	0.450
D	2	14.1	13.9	0.16	43.1	33.9	9.17	0.021	0.500
D	3	15.0	13.9	1.11	64.3	33.8	30.5	0.021	0.350
D	4	19.0	16.5	2.51	48.4	40.1	8.40	0.028	0.450

† High broadcast rate of WTR (44.8 Mg ha^{-1})
‡ Low broadcast rate of WTR (11.2 Mg ha^{-1})
§ Buffer strip of WTR (44.8 Mg ha^{-1})
¶ Control treatment, no WTR added

Appendix I-II. Nutrient analysis of runoff water from the LeFlore county experiment

Treatment	Plot	Total P	Dissolved P	Organic P	Total N	Soluble NH_4-N	Organic N	Soluble Al	Solids in water
		------------mg L^{-1} -----------							g kg^{-1}
A †	1	17.5	17.0	0.49	53.0	19.8	33.2	0.031	0.500
A	2	15.7	15.7	0.00	53.2	28.2	25.0	0.045	0.650
A	3	15.0	15.0	0.00	54.6	27.5	27.1	0.063	0.550
A	4	13.4	13.1	0.34	55.3	25.0	30.3	0.054	0.550
B ‡	1	15.0	13.8	1.25	73.9	19.6	54.3	0.056	0.700
B	2	17.2	15.3	1.93	78.5	27.9	50.6	0.062	0.450
B	3	15.7	13.1	2.63	73.6	22.9	50.7	0.049	0.950
B	4	13.6	12.6	0.99	58.9	22.4	36.5	0.053	0.400
C §	1	16.7	16.7	0.00	59.1	19.8	39.3	0.033	0.350
C	2	15.4	14.1	1.35	68.7	24.6	44.1	0.061	0.250
C	3	13.1	13.1	0.00	47.5	19.3	28.2	0.065	0.750
C	4	12.4	11.8	0.65	53.9	19.7	34.2	0.035	0.500
D ¶	1	20.6	18.7	1.87	106	26.1	79.8	0.057	0.700
D	2	17.8	16.5	1.36	69.7	24.8	44.9	0.050	0.600
D	3	16.8	13.5	3.29	41.6	18.7	22.9	0.088	0.300
D	4	19.8	19.5	0.20	69.1	31.2	37.8	0.043	0.400

† High broadcast rate of WTR (44.8 Mg ha^{-1})
‡ Low broadcast rate of WTR (11.2 Mg ha^{-1})
§ Buffer strip of WTR (44.8 Mg ha^{-1})
¶ Control treatment, no WTR added

APPENDIX II

Appendix II-I. ANOVA tables for yield and vegetation cover.

General Linear Models Procedure

Dependent Variable: YIELD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	15	2343.39685036	156.22645669	17.67	0.0001
Error	48	424.37011875	8.84104414		
Total	63	2767.76696911			

R-Square	C.V.	Root MSE	YIELD Mean
0.846674	80.99292	2.97338934	3.67117188

Source	DF	Type I SS	Mean Square	F Value	Pr > F
WTR	3	510.83059667	170.27686556	19.26	0.0001
VEG	3	1108.35199967	369.45066656	41.79	0.0001
WTR*VEG	9	724.21425402	80.46825045	9.10	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
WTR	3	510.83059667	170.27686556	19.26	0.0001
VEG	3	1108.35199967	369.45066656	41.79	0.0001
WTR*VEG	9	724.21425402	80.46825045	9.10	0.0001

Appendix II-I con't.

Dependent Variable: COVER

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	15	49629.618711	3308.641247	17.56	0.0001
Error	48	9044.343075	188.423814		
Total	63	58673.961786			

R-Square	C.V.	Root MSE	COVER Mean
0.845854	46.79385	13.726755	29.334531

Source	DF	Type I SS	Mean Square	F Value	Pr > F
WTR	3	17076.241442	5692.080481	30.21	0.0001
VEG	3	17797.158817	5932.386272	31.48	0.0001
WTR*VEG	9	14756.218452	1639.579828	8.70	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
WTR	3	17076.241442	5692.080481	30.21	0.0001
VEG	3	17797.158817	5932.386272	31.48	0.0001
WTR*VEG	9	14756.218452	1639.579828	8.70	0.0001

Appendix II-II. Summary of dry matter yield, vegetation cover and tissue concentrations for each plant species

Tall Fescue

			Tissue concentrations								
			in percent							*mg/kg*	
Growth Media	**DM (g)**	**% cover**	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Fe**	**Cu**	**Zn**
WTR A	0.08	3.6	.	.	.	.	.	.	.	.	.
WTR A	0.10	3.6	.	.	.	.	.	.	.	.	.
WTR A	0.28	7.9	3.16	.	.	.	.	.	.	.	.
WTR A	0.36	6.4	3.26	.	.	.	.	.	.	.	.
WTR B	6.62	39.2	2.56	0.07	1.25	1.46	0.39	0.03	0.03	18.44	9.47
WTR B	6.78	37.9	2.83	0.08	1.41	1.38	0.35	0.04	0.03	17.45	9.07
WTR B	4.09	35.4	2.89	0.07	1.63	1.33	0.31	0.03	0.03	11.82	30.63
WTR B	4.40	45.4	2.89	0.07	1.75	1.39	0.30	0.03	0.03	14.96	20.08
WTR C	3.41	55.7	2.96	0.08	2.36	0.87	0.68	0.07	0.03	70.19	38.58
WTR C	5.38	53.6	3.17	0.11	2.36	1.03	0.75	0.05	0.02	7.91	23.45
WTR C	1.04	60.7	.	0.07	2.37	1.06	0.70	0.09	0.05	15.17	25.12
WTR C	3.11	63.4	3.48	0.13	2.57	0.89	0.76	0.06	0.03	10.42	32.88
SOIL	1.74	30.0	2.76	0.11	2.22	0.70	0.48	0.02	0.02	6.07	15.92
SOIL	1.43	23.3	3.26	0.14	2.76	0.67	0.47	0.02	0.02	7.26	21.18
SOIL	1.28	22.2	.	0.18	2.90	0.78	0.54	0.03	0.03	7.98	26.87
SOIL	1.37	30.0	.	0.11	2.18	0.69	0.45	0.03	0.02	6.50	26.45

. Indicates not enough plant material available.

Appendix II-II con't.

White Clover

			Tissue concentrations								
			in percent							*mg/kg*	
Growth Media	DM (g)	% cover	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn
WTR A	.	.	.	.	.	.	.	.	.	.	.
WTR A	.	.	.	.	.	.	.	.	.	.	.
WTR A	.	.	.	.	.	.	.	.	.	.	.
WTR A	.	.	.	.	.	.	.	.	.	.	.
WTR B	.	.	.	.	.	.	.	.	.	.	.
WTR B	.	.	.	.	.	.	.	.	.	.	.
WTR B	.	.	.	.	.	.	.	.	.	.	.
WTR B	.	.	.	.	.	.	.	.	.	.	.
WTR C	0.03	0.7	.	.	.	.	.	.	.	.	.
WTR C	0.24	10.0	.	0.18	1.75	2.28	0.60	0.01	0.01	9.98	26.55
WTR C	0.03	1.0	.	0.24	2.71	1.81	0.51	0.02	0.06	10.46	35.14
WTR C	0.04	1.7	.	.	.	.	.	.	.	.	.
SOIL	1.05	28.8	2.85	0.10	1.77	1.67	0.64	0.01	0.04	5.48	32.83
SOIL	1.59	38.3	2.44	0.08	1.10	1.38	0.56	0.02	0.09	4.81	28.36
SOIL	0.58	18.9	3.41	0.09	1.39	1.65	0.61	0.02	0.06	7.42	37.36
SOIL	0.86	17.8	2.77	0.10	0.98	1.57	0.65	0.02	0.04	5.76	30.36

. Indicates not enough plant material available.

Appendix II-II con't.

Weeping Lovegrass

			Tissue concentrations								
			in percent							*mg/kg*	
Growth Media	**DM (g)**	**% cover**	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Fe**	**Cu**	**Zn**
WTR A	.	.	.	.	.	.	.	.	.	.	.
WTR A	.	.	.	.	.	.	.	.	.	.	.
WTR A	.	.	.	.	.	.	.	.	.	.	.
WTR A	.	.	.	.	.	.	.	.	.	.	.
WTR B	0.85	19.7	2.06	0.04	0.69	0.43	0.11	0.01	0.01	13.87	18.39
WTR B	1.96	49.90	2.06	0.04	0.63	0.56	0.12	0.01	0.02	14.05	11.32
WTR B	4.96	82.1	2.28	0.07	0.56	0.73	0.12	0.02	0.02	18.23	32.23
WTR B	4.05	82.9	2.22	0.06	0.68	0.73	0.11	0.01	0.01	16.6	7.4
WTR C	.	.	.	.	.	.	.	.	.	.	.
WTR C	.	.	.	.	.	.	.	.	.	.	.
WTR C	0.56	5.0	2.49	0.07	0.90	0.30	0.12	0.01	0.01	5.92	16.33
WTR C	0.32	3.2	2.70	0.16	1.18	0.48	0.69	0.05	0.03	9.77	44.93
SOIL	0.69	41.7	2.42	0.10	1.24	0.28	0.14	0.01	0.01	6.77	32.88
SOIL	1.39	28.3	2.09	0.1	1.20	0.26	0.13	0.01	0.01	5.64	25.18
SOIL	1.65	44.4	2.36	0.07	1.15	0.43	0.11	0.01	0.01	6.74	182.09
SOIL	0.88	26.7	2.37	0.10	1.15	0.44	0.21	0.01	0.02	6.28	32.60

. Indicates not enough plant material available.

Appendix II-II con't.

Bermudagrass

			Tissue concentrations								
			in percent							*mg/kg*	
Growth Media	**DM (g)**	**% cover**	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Fe**	**Cu**	**Zn**
WTR A	1.08	11.0	.	0.12	2.33	0.66	0.16	0.02	0.01	8.67	20.76
WTR A	1.34	14.0	.	0.06	1.81	0.60	0.16	0.03	0.02	6.75	22.56
WTR A	0.77	11.0	.	0.07	2.19	0.61	0.13	0.04	0.01	9.78	37.41
WTR A	0.52	8.0	.	0.11	2.11	0.53	0.14	0.01	0.01	6.21	23.49
WTR B	27.49	86.0	3.18	0.16	1.97	0.53	0.12	0.01	0.06	11.76	9.74
WTR B	14.93	88.0	3.29	0.18	1.57	0.64	0.13	0.02	0.05	9.92	10.86
WTR B	30.89	74.0	3.54	0.19	2.38	0.49	0.13	0.01	0.03	11.84	13.47
WTR B	20.28	87.0	3.93	0.2	2.12	0.55	0.12	0.01	0.04	13.82	11.36
WTR C	1.90	12.0	3.49	0.06	1.86	0.50	0.27	0.03	0.06	70.19	56.21
WTR C	1.55	36.0	.	0.05	1.28	0.54	0.24	0.04	0.11	7.91	21.64
WTR C	15.51	98.0	.	0.13	2.60	0.52	0.26	0.02	0.06	15.29	32.86
WTR C	3.76	13.0	.	0.14	2.26	0.65	0.29	0.03	0.05	10.42	20.41
SOIL	13.64	84.0	3.78	0.16	2.58	0.28	0.16	0.01	0.04	16.94	38.93
SOIL	18.85	87.0	3.43	0.15	2.14	0.33	0.17	0.02	0.06	9.41	39.64
SOIL	4.48	61.0	2.80	0.1	.	.	.	.	.	.	.
SOIL	14.76	88.0	3.57	0.14	2.16	0.38	0.18	0.02	0.07	12.27	39.89

. Indicates not enough plant material available.

VITA

Lori Evans Gallimore

Candidate for the Degree of

Master of Science

Thesis: USE OF WATER TREATMENT RESIDUALS TO REDUCE NUTRIENT RUNOFF AND AS AN ARTIFICAL GROWTH MEDIA

Major Field: Plant and Soil Sciences

Biographical:

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Education: Graduated from Stillwater High School, Stillwater, Oklahoma in May 1992; received Bachelor of Science degree in Forestry and a minor in Agronomy from Oklahoma State University, Stillwater, Oklahoma in May 1997. Completed the requirements for the Master of Science degree with a major in Plant and Soil Sciences at Oklahoma State University in May 1999.

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