SPATIAL MODELING OF SOIL HYDRAULIC PROPERTIES

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INTRODUCTION

Interest in ground water research has provided researchers the opportunity to develop models that describe water and solute transport in variably saturated soils. Generally, unsaturated soil hydrologic models are based on numerical solutions of the Richard's equation. The key parameters needed for solving the equation are water retention values, θ(h), and hydraulic conductivity functions, K(h). Further, hydrological processes vary in space. Knowledge of spatial heterogeneity of soil hydraulic properties is essential in quantifying solute and water transport processes from a plot-scale to a regional-scale. Direct measurements of θ(h) and K(h) are time-consuming and expensive (Arya and Paris, 1981; Saxton et al., 1986; Schuh and Bauder, 1986; Wosten and van Genuchten, 1988; Kern, 1995; Scott, 2000 and Cornelis et al. 2001). Their measurements may be cost prohibitive in the short-term for large areas (Arya and Paris, 1981), and are not practical for remote sensing investigations (Saxton et al., 1986). The lack of knowledge of these parameters largely affects our ability to address hydrologic problems when modeling water and solute transport in large and complex watersheds. A progressively more popular alternative to direct measurement of soil hydraulic properties involves the use of pedotransfer functions (PTFs) (Wosten and van Genuchten, 1988, Cornelis et al. 2001, Zhu and Mohanty, 2002). In this research, we used PTFs to predict soil hydraulic properties for Memphis silt loam (fine silty, mixed, thermic, Typic Hapludalf). We further attempted to quantify spatial variability of these parameters and determined their functional relationships.

MATERIALS AND METHODS

The site investigated was a 4-ha conventionally tilled Memphis silt loam field that has undergone corn and cotton rotation for 10 years. The field was located north of Port Gibson in Claiborne County, Mississippi (32° 00' N; longitude 90° 52' W). Soil samples were collected from the 0 to 15 cm depth at 272 nodes on a 15 m x 15 m grid. Bulk density (ρ_b) data for each node was determined by the core method. Sand, silt and clay were quantified using the hydrometer method (Thien and Graveel, 1997). Unsaturated hydraulic conductivity (K_o) and saturated hydraulic conductivity (K_s) were predicted using the computer code RETC, developed by van Genuchten et al. (1990). The van Cenuchten-Mualem equation

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} \qquad [1]$$

$$K_o = K_s S^{0.5}\left[1-\left(1-S^{\frac{1}{m}}\right)^m\right]^2 \quad [2]$$

(Mualem, 1976; van Genuchten, 1980) was used to describe soil hydraulic properties, where θ is the volumetric water content (cm cm^{-3}), h is the pressure head (cm), θ_r and θ_s are the residual and saturated water contents (cm cm^{-3}), respectively, S is the water saturation ratio $(\theta-\theta_r)/(\theta_s-\theta_r)$, m=1-(1/n), and α and n are empirically fitted parameters. Values obtained for each soil property were point kriged and mapped using the geostatistical program GS^+ version 5 (Gamma Design, Plainwell, MI). Linear regression was used to quantify the relationships between measured and model predicted soil properties.

RESULTS AND DISCUSSION

Geostatistical models and model parameters describing the soil properties studied are listed in Table 1. The semivariograms for K_o and α were described by the Gaussian model while all other parameters were described by different model. All parameters measured showed some degree of spatial dependence. The range of influence for all parameters ranged from 47.0 to 610.9 m. Only K_s had the shortest range (47.0 m) followed by silt (222.3 m). There was nugget effect for all other parameters, except for α and ρ_b. Smaller nuggets indicate that the sampling interval is proper to reflect the variance (Nielsen, 1998). The sill on the other hand, reflects the scale of random variation and is the plateau reached when the semivariance does not change significantly with increasing lag distance (Nielsen, 1998).

Variability of Soil Properties

Spatial maps for both measured and predicted soil properties are shown in Figures 1 and 2. Sand content was highest in the central to northeastern portion of the field. Areas in the field with higher sand content had lower silt content (Figs. 1a and 1b). Relatively high silt content was observed in the western portion of the field and relatively lower sand content was observed in similar location. Bulk density (Fig. 1c) followed a similar trend as the sand content. Clay on the other hand did not follow similar pattern as sand or silt. However, higher clay content was observed in the northeastern portion of the field (Fig.1d). Saturated hydraulic conductivity did not show any pattern relative to sand, silt and ρ_b; however, the map of K_o was somewhat similar to the silt content (Fig. 2a). The highest K_o values observed were scattered along the western edge of the field (Fig. 2b). Distribution of n (Fig. 2d) was similar to the distribution of sand. Lower n values were observed on the western edge of the field while higher values were observed mainly across the eastern half of the field. We suggest that the variability observed for the soil parameters investigated may be both intrinsic and extrinsic in nature. Intrinsic variability occurs as a result of soil forming processes and extrinsic variability is caused by soil management practices (Scott and Wood, 1989). The spatial patterns exhibited by the soil parameters investigated may be due to a combined effect of intrinsic and extrinsic factors. Spatial maps of sand, silt and ρ_b (Fig. 1) followed similar patterns as K_o, n and K_s in Figure 2. This implies that these soil parameters are correlated. The maps for sand and silt showed that in location where there is higher sand content, the silt content was relatively lower.

Regression parameters associated with the soil properties measured and estimated are presented in Table 2. Silt was negatively correlated with ρ_b, K_s, n and sand. Negative correlations were observed between sand and K_o and α. There was no significant correlation between clay and any of the other soil parameters. This is an indication that clay is not a good predictor of hydraulic conductivity for the soil investigated. Southhard and Buol (1988) studied subsoil hydraulic conductivity of an Ultisols in relation to soil properties. They observed that sand, silt and clay were not good predictors of K_s because these parameters by themselves did not define the geometry of pores. From a physical perspective, α in the van Genuchten equation relates to the mean pore size magnitude, whereas n relates to the degree of pore size spreading (Zhu and Mohanty, 2002). Scott (2000) suggested that pore size characteristics (size-distribution, shape, roughness and interconnectedness) could vary spatially as texture because soil porosity is influenced by texture. This observation has important implications for hydrologic studies in general.

CONCLUSION

In this study it was found that the magnitude of saturated and unsaturated hydraulic conductivities as well as α and n were influenced mainly by sand and silt. All the soil properties investigated exhibited spatial dependence and were isotropic. However, the magnitude of spatial dependence varied among the various properties. The shortest range was observed for saturated hydraulic conductivity, indicating its extensive spatial variation within an agricultural soil. The linear functions developed in this study are useful because they can provide a basis for developing more complex models for analyzing and understanding hydrologic problems spanning large areas. It must also be noted that the various relationships developed between the soil properties investigated in this study may not hold for soils with greatly different properties, particularly those with much greater clay contents. Investigations on similar and/or different soils are needed to develop a robust data base both for the purpose of comparison and development of more complex models for hydrologic studies in the State of Mississippi.

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Table 1. Geostatistical model parameters describing soil properties studied.†

Soil Properties	Model	Co	Co + C	Ao	r^2
Sand	Spherical	9.4	54.5	374.9	0.99
Silt	Linear	8.4	49.5	222.3	0.99
Clay	Exponential	0.7	1.4	524.8	0.63
Bulk density	Linear to sill	0.0	0.01	526.2	0.98
K_s	Exponential	29.4	102.0	47.9	0.94
K_o	Gaussian	0.3	2.8	286.0	0.98
α	Gaussian	0.0	0.0	610.9	0.98
n	Linear to sill	0.001	0.002	520.4	0.47

†Co = nugget, Co + C = sill, Ao = range

Table 2. Correlation coefficients and slopes of regression lines when correlating sand and silt with other soil parameters quantified.

	Correlation Coefficient		Slope	
	Sand	Silt	Sand	Silt
ρ_b	0.93	0.97	0.008	-8.77
K_s	0.85	0.76	1.46	-1.29
K_o	0.88	0.93	-0.14	0.15
n	0.98	0.99	0.004	-0.004
α	0.94	0.97	-0.0002	0.0002
Sand	--	0.99	--	-0.97

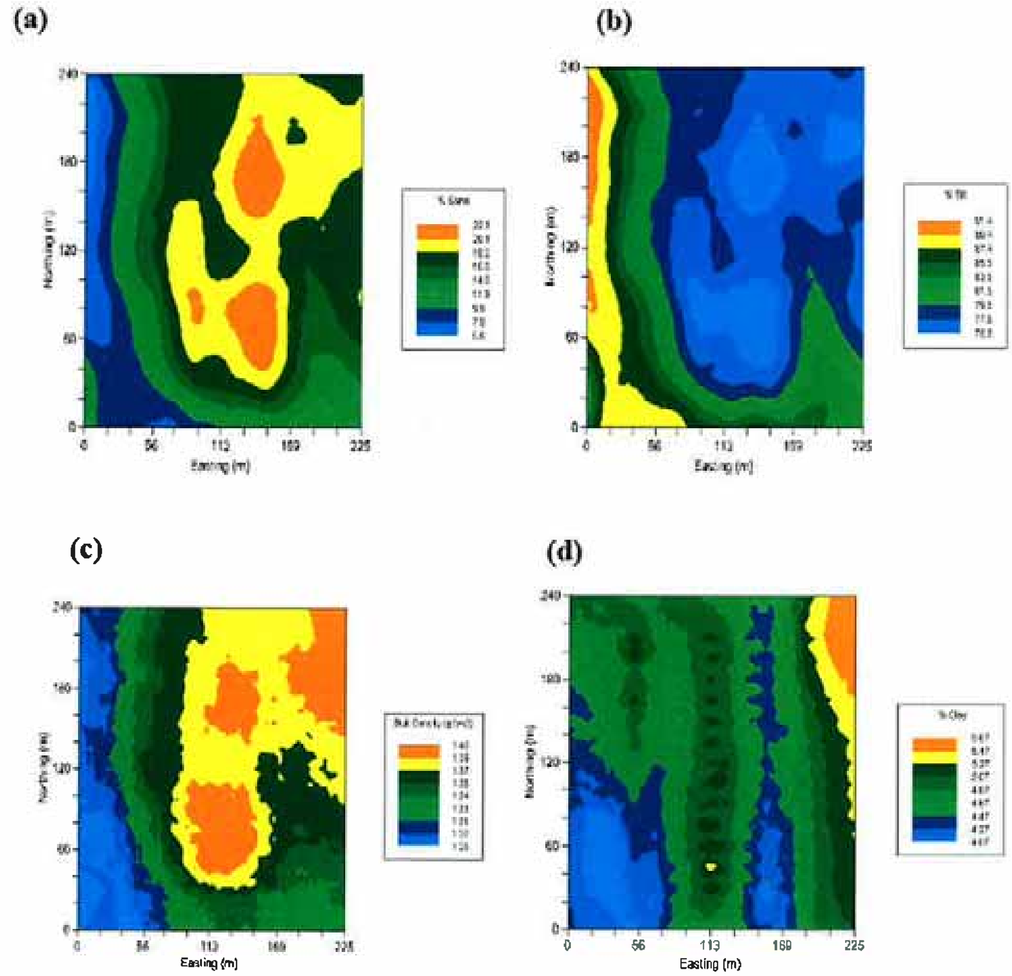

Fig. 1. Kriged maps of measured soil properties for Memphis silt loam under 10-year corn and cotton rotation: (a) sand, (b) silt, (c) bulk density and (d) clay.

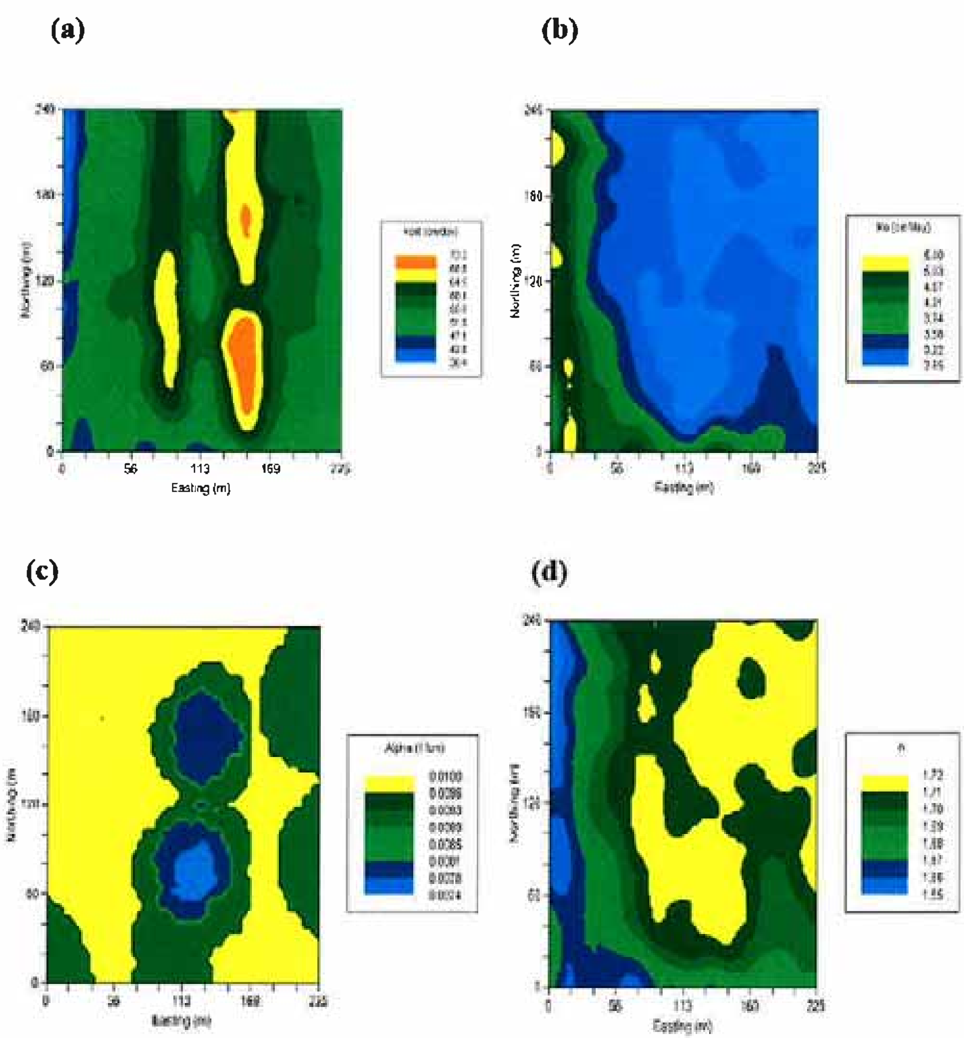

Fig 2. Kriged maps of model predicted soil parameters for Memphis silt loam under 10-year corn and cotton rotation: (a) K_s, (b) K_o, (c) α and (d) n.

How are native wetland plants useful in mitigating nutrient runoff from agricultural fields?

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Introduction

Human activities have altered the global biogeochemical cycle by doubling the rate of nitrogen input into terrestrial ecosystems (Smith et al., 1999). Likewise, land use has a similar effect on phosphorus. The loading of nitrogen and phosphorus into the world's rivers, lakes, and oceans is strongly influenced by human population densities, population densities of livestock, and land use (Pringle, 2003).

Nutrients are the 3rd largest agricultural pollutant in Mississippi, following sediment and pathogens (Moore and Cooper, 2003). Wetlands serve as natural buffers for rivers, lakes, and streams (Holland, 1996). By maintaining these wetlands around agricultural landscapes, significant improvements in water quality may be achieved (Moore and Cooper, 2003).

Drainage ditches surround many agricultural fields for the primary purpose of removing water after rainfall and act as major conduits of nutrients from agricultural lands to receiving waters (Nguyen and Sukias 2002). These ditches possess many of the key characteristics that define wetlands: hydroperiods, hydrosoils, and hydrophytes

(Moore et al. 2001). Many of these ditches maintain some level of water throughout the year, although water levels are dependent on the spatial and temporal variations in precipitation events.

So how useful is native wetland vegetation in mitigating nutrient runoff, specifically, non-point source agricultural runoff, potentially high in both nitrogen and phosphorus concentrations? We report here on two experiments. The first experiment was designed to find plants suitable for planting in agricultural ditches that would serve as efficient buffers for nutrient runoff. The plants chosen for this experiment are *Juncus effusus*, soft rush, and *Paspalum urvillei*, vasey grass. These plants were chosen based on an earlier vegetation survey of dominant native plant species at the University of Mississippi Field Station (Davis and Holland 1998). *Paspalum urvillei* was not on the 1998 list, but has now replaced some of the other species collected earlier at the Field Station. Specimens of each species were planted and grown in a greenhouse, with stable climatic conditions and controlled precipitation events.

The second experiment moves away from a greenhouse-based experiment to a field experiment. This experiment examines *Paspalum urvillei* and another common drainage ditch species *Leersia oryzoides* and assesses the levels of total nitrogen assimilation under stimulated nutrient runoff levels in the field. The goal of the second experiment is to determine, under simulated field conditions, whether or not plants are assimilating nutrients, and if so where?

Methods

Experiment 1

Twelve 55-gallon drums were cut in half and positioned within the University of Mississippi Field Station (UMFS) greenhouse. Soil was collected from the UMFS and placed in the drums. The plants were also collected from the UMFS and planted in the soil in the greenhouse. Ten of the drum-halves were planted with *J. effusus* and ten planted with *P. urvillei*. Four drums were left unvegetated. A five gallon aquarium doser was purchased for each of the 24 drums. A hole was drilled into the side of each of the drum-halves 12 cm above the soil surface to serve as a water outlet. Each drum was filled with water to the outlet point, and all drums contained standing water thought the experiment.

The plants were watered from non-chlorinated well water, by filling each of the dosers and allowing them to drip water into the drums at a rate of 3 L/day. A treatment of five mg/L nitrate, and 0.15 mg/L phosphate was added to half of the dosers: five drums containing each species and two drums without plants. The other seven drums received untreated well water.

The experiment ran for a period of 18 weeks from July 14, 2003 to November 14, 2003. Plant height was measured thought the experiment by measuring the height of the tallest plant. Plant cover was measured by estimating the percent of the drum covered by aboveground tissue.

Experiment 2

Plants for the second experiment were collected in the fall of 2003 from four mesocosms at The University of Mississippi Field Station. The four mesocosms were ponds 210, 212, 216 and 218. Ponds 216 and 218 were regularly subjected to simulated nutrient runoff conditions (25 acre field runoff over a year). Nutrients associated with the runoff were nitrate, ammonia and orthophosphorus. Nutrient levels were below 5mg/L to distinguish between background nutrient concentrations. Ponds 212 and 210 were similar sized mesocosms which were untreated. Nutrient runoff into these ponds, if any, was a factor of natural conditions. *Paspalum urvillei* and *L.oryzoides* were sampled as a bulk sample from each pond.

A comparison of nutrient levels between plant species in these two treatments will suggest whether plants under nutrient enriched conditions have higher levels of nutrients within their above and belowground tissues. Thus, these data will determine whether or not vegetation is assimilating nutrients associated with nutrient enriched runoff.

The water samples were analyzed using a Dionex DX-600 Ion Chromatograph. The plant tissue samples and soil samples were analyzed for phosphorus using a Perkin-Elmer 4300 DV Inductively Coupled Plasma-Optical Emission Spectrometer. The nitrogen in the plant tissue and soil samples was analyzed using a Costech Elemental Analyzer.

Results

Experiment 1

There was no difference in the height of either *J. effusus* or *P. urvillei* between the control and treatment groups. There was no difference in cover between the *P. urvillei* control and treatment groups, but there was a significant difference in cover between the control and treatment groups of *J. effusus*, with the treatment group growing to cover more area than the control (Figure 1). Weeks 7-12 (August 24-October 5, 2003) show that the cover of the treatment groups of *J. effuses* was significantly greater then the cover of the control groups, but weeks 1-6 and 13-18 show no difference in cover.

Experiment 2

There were significant differences between the total nitrogen tissue concentrations between ponds exposed to elevated levels of nutrient runoff than the control treatment (Figure 2). This suggests that plants under elevated nutrient conditions are indeed assimilating high concentrations of nutrients, in above and belowground tissues. Interestingly there was a slight significant difference ($p < 0.01$) between the tissue nitrogen concentrations of *P.urvillei* and *L.oryzoides*. Thus, *L.oryzoides* was more effective at assimilating nitrogen than *P.urvillei*. This might be as a result of its extensive, shallow root network and prolific above ground biomass production, and that it was situated in the middle of the ditches, while *P.urvillei* was often encountered on the edge of the ditch/water level. The results also suggest that there was no significant difference between the total nitrogen concentrations of above and below ground tissue.

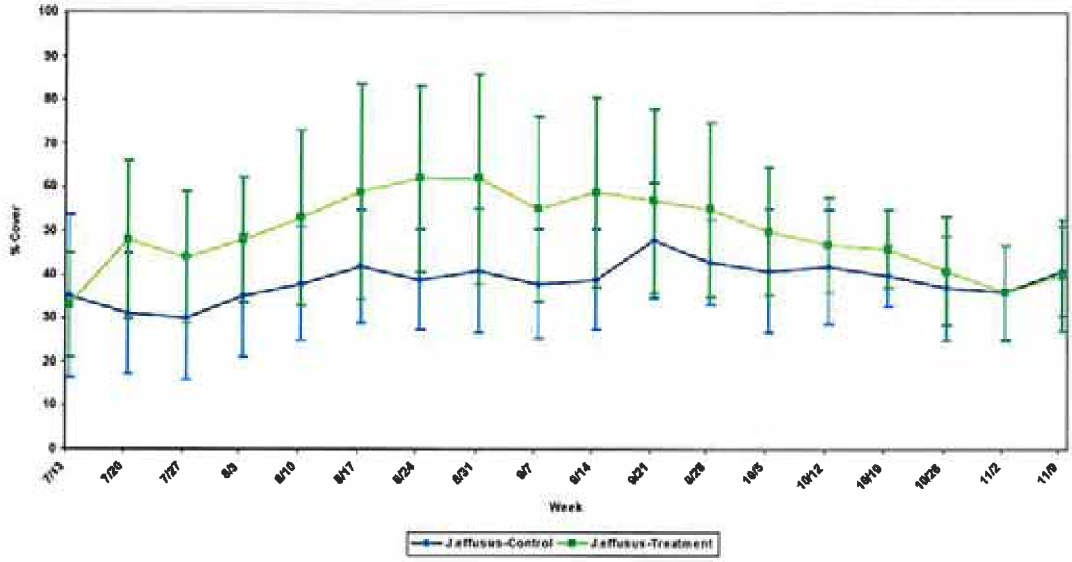

Figure 1. Average percent cover of *Juncus effusus* for Experiment 1. There is a significant difference from August 24-October 5, 2003. Error bars are standard deviation.

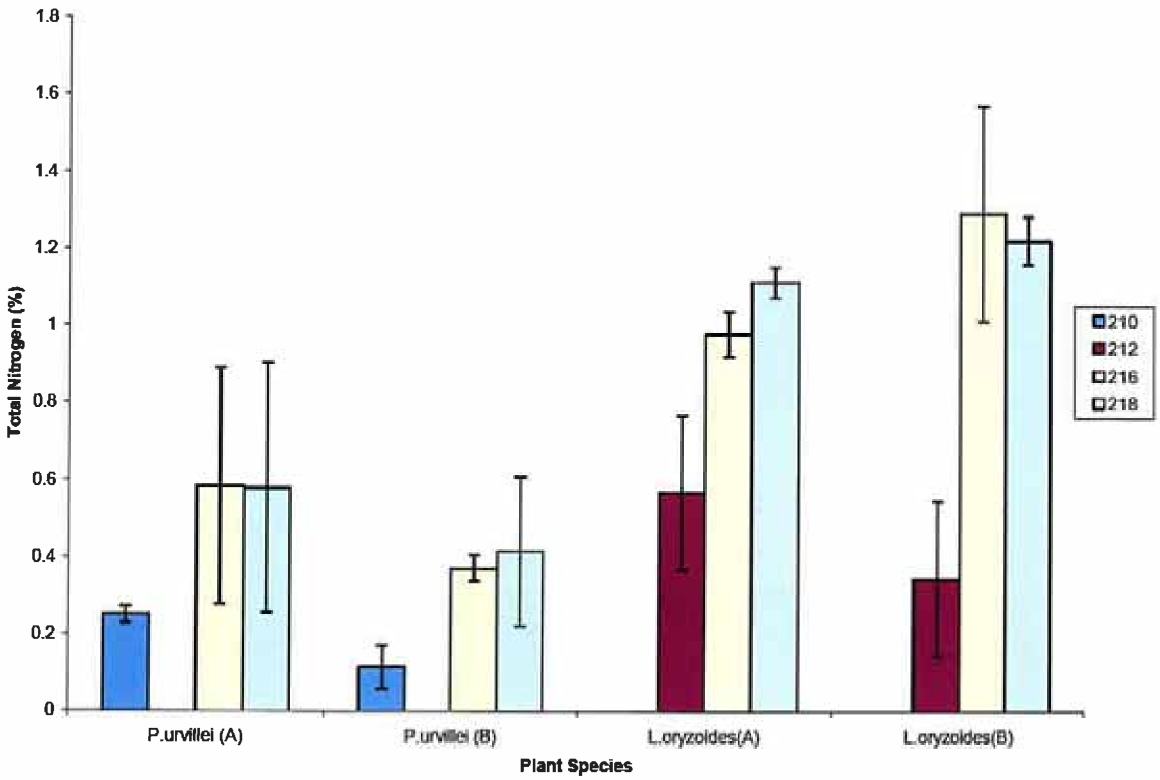

Figure 2. Percentage total nitrogen in above (A) and below (B) ground tissue of two plant species sampled from four mesocosm ponds at the University of Mississippi Field Station.

Conclusion

Experiment 1

When exposed to elevated concentrations of nutrients the aboveground parts of *J. effusus* responds by growing to cover more area. If used in ditches to control runoff, this could provide a double benefit of providing more plant mass to assimilate nutrients, and a greater surface area to slow down the water and trap sediment.

Experiment 2

Plants subjected to elevated nutrient runoff levels, for example in non-point source agricultural runoff, have capability of assimilating a large proportion or concentration of nutrients. Both, *Leersia oryzoides* and *Paspalum urvillei* are plants that occur in drainage ditches and are good candidates in mitigating nutrient runoff.

Next steps? Future research?

There are many further steps that could be done in order to gain a better understanding of this issue: Other wetland plant species could be looked at, both individually and in combinations. Research into the microbial and chemical activities surrounding the rhizosphere of different wetland plants could yield a better understanding of processes such that influence plant uptake of nutrients as well as microbial-basic chemical reactions. On a larger scale it would be useful to evaluate and describe the seasonal nutrient dynamics within drainage ditches in a field experiment. This would be necessary to assess feasibility of utilizing drainage ditches to effectively mitigate nutrient runoff.

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