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Rice (*Oryza sativa*) as a Remediation Tool for Nutrient Runoff

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ABSTRACT Hypereutrophication of U.S. surface waters is one of the leading causes of impairment for water quality. With nutrient criteria development and total maximum daily load (TMDL) issues looming for regulators, agricultural research is focusing on practices aimed at decreasing nutrient contributions to receiving aquatic ecosystems. This study examined the use of rice (*Oryza sativa*) for luxury uptake of nitrogen and phosphorus components associated with agricultural storm runoff. Mesocosms (379 L) planted with rice were exposed to two concentrations (5 and 10 mg/L) of nitrate, ammonia, and orthophosphorus. Results from these mesocosms were compared to unvegetated controls (also amended with 5 or 10 mg/L nitrate, ammonia, and orthophosphorus) to determine efficiency of rice in remediating nutrient runoff. Statistically significant differences in ammonia and nitrate retention of vegetated mesocosms amended with 5 mg/L versus vegetated mesocosms amended with 10 mg/L were noted after the first exposure. Although rice is a nutrient-dependent aquatic plant, this study suggests that more efficient mitigation is possible at lower inflow concentrations as opposed to higher inflow concentrations.

KEYWORDS mitigation, non-point source pollution, water quality, agriculture, wetland

INTRODUCTION

Increasing concerns over the quality of U.S. water bodies led Congress to pass the Clean Water Act (CWA) in 1972. For more than two decades, CWA emphasis was placed on point source pollution and control of pollutants through National Pollution Discharge and Elimination System (NPDES) permits. Since the early to mid 1990s, greater focus has been placed on non-point source (NPS) contributions of pollutants. Without question, agriculture is responsible for at least a portion of NPS pollution. According to U.S. Environmental Protection Agency (US EPA) estimates, 218 million Americans (78% of the U.S. population) live within 16 km of a polluted water body (US EPA, 2005). Over 34000 waters within the United States were classified as impaired based on states' 1998 303(d) lists. Of those waters, nearly 10% of all reported impairments listed nutrients as the primary pollutant, making nutrients the third largest impairment for U.S. surface water bodies behind metals (19%) and pathogens (13%) (US EPA, 2005).

An estimated 11 million metric tons of nitrogen (N) and 4 million metric tons of phosphate (PO_4) are applied annually to U.S. production acreage (USDA

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ERS, 1997). Although most of these nutrients stay within their intended field location, the possibility still exists for runoff following extreme rainfall events. The North American Water Quality Assessment (NAWQA) conducted by U.S. Geological Survey (USGS) reported 57% and 61% of sampled streams were enriched with phosphorus (P) and N, respectively (USGS, 1999). Excessive nutrient runoff into water bodies may lead to hypereutrophication of aquatic ecosystems. This condition has been popularized through research conducted on the U.S. Gulf of Mexico's hypoxic zone (Turner and Rabalais, 2003). Historical data indicate two- to fivefold increases in nitrate (NO_3) concentrations in areas of the Mississippi River and certain tributaries since the early 1900s (Goolsby et al., 2000). Goolsby and Battaglin (1993) estimated that as much as 15% of applied N in the Mississippi River Basin is transported into the Gulf of Mexico.

Phytoremediation, utilizing plants and their associated biological processes to remediate environmental problems, is a potential method for addressing excessive nutrient runoff. Plants require nutrients to survive, and many aquatic plants have the capability of luxury nutrient uptake (Marschner, 1995; Adler et al., 2003). This occurs when plants have enough of a particular nutrient stored for survival and growth, yet they continue uptake of the particular nutrient for future needs.

Ranking second only to wheat (*Triticum aestivum* L.) in terms of surface area planted on Earth, rice (*Oryza sativa*) is a vital cereal crop in 58% of the world's countries (Ghosh and Bhat, 1998). Because rice paddies are inundated with water, anaerobic soils are often present causing instability in NO_3, the most readily available N source for typical plants. To counterbalance this anaerobic condition, rice plants secret oxygen to their shallow root system. Such secretion significantly increases phosphorus availability for rice plants under flooded conditions (Huguenin-Elie et al., 2003; Zhang et al., 2004). Concomitantly, a significant nitrogen loss is occurring in these ecosystems through ammonia volatilization, denitrification, and leaching (Wells et al., 1993). Because N is the critical nutrient for proper rice ecosystem functioning, rice has been documented to compensate for low inorganic N concentrations by absorbing organic N in the form of protein (Ghosh and Kashyap, 2003; Okamoto and Okada, 2004).

Nearly 1.4 million hectares of rice were planted in the United States in 2005, of which 79% was located in the Mississippi River Delta of Missouri, Arkansas, Mississippi, and Louisiana (USDA NASS, 2005). Most rice research has focused on increasing yields and controlling pests in production acreage. Relatively few studies in the United States have examined rice's potential for phytoremediation of agricultural contaminants. The present study involved the use of mesocosms with monocultures of rice to determine if the plants were capable of decreasing concentrations of NO_3, ammonia (NH_3), and *ortho*-PO_4 from nutrient-enriched flowing water.

MATERIALS AND METHODS

Experiments were conducted using 10 379-L Rubbermaidcontainers (132 × 70 × 66 cm) as mesocosms (Figure 1). Each mesocosm contained a 22-cm sediment base of sand, followed by an additional 16 cm of organic silt/clay (50:50) mixture overlay. Sediment was collected from unused ponds at the University of Mississippi Field Station, Abbeville, Mississippi (no added nutrients were required for the establishment of rice plants). Six of the 10 mesocosms were planted with Clearfield variety rice, whereas the remaining four mesocosms were unvegetated to serve as controls. Once seedlings were established, mesocosms were filled with 24 cm of pond water (NO_3, NH_3, and *ortho*-PO_4 concentrations below detection of 0.001 mg/L) and allowed to equilibrate for approximately 45 days. Mesocosm water level was maintained during this preexposure period. Nutrients in the mesocosm sediment provided sufficient nutrition for early rice growth. Rice plants were visually monitored for stress and nutrient deficiency according to Wells et al. (1993).

Identical exposure experiments were conducted twice (August 17, 2004, and August 23, 2004), and for each experiment, nutrient enriched pond water was prepared in reservoirs and pumped into individual mesocosms at the water surface (Figure 1). Nutrient stock was prepared using laboratory-grade sodium nitrate, ammonium sulfate, and potassium phosphate dibasic as sources for N and P species typically encountered in agricultural runoff. Water flowed through each mesocosm and exited at the surface through a discharge hose at the opposite end. FMI metering pumps were used to deliver nutrient enriched water (either 5 or 10 mg/L of each N and P species, depending on the mesocosm) at a constant rate calculated to generate a 4-h hydraulic retention time in each system. During the first experiment, one water sample was collected from the discharge hose of

FIGURE 1 Experimental setup of rice mesocosms and nutrient exposures for mitigation.

each mesocosm at 1-h intervals for 9 h and analyzed for NO_3, *ortho*-PO_4 and NH_3. The cadmium reduction method was used to analyze NO_3, whereas NH_3 and *ortho*-PO_4 were analyzed using the phenate and ascorbic acid methods, respectively, according to Standard Methods (APHA, 1998). All analyses were performed using a ThermoSpectronic Genesys 10 ultraviolet (UV) spectrophotometer. During the second experiment, two additional samples were collected (three total) from discharge hoses of each mesocosm at 1-h intervals for 12 h before being analyzed for the above constituents. Statistical analyses utilized F and t tests for normally distributed parametric data (Ambrose and Ambrose, 1995). Analyses were conducted with an alpha level of.05. Sample means for both percent nutrient removal and overall mesocosm nutrient concentrations were examined.

RESULTS

After the first nutrient exposure, statistically significant differences ($\alpha = .05$) were noted between the two treatment concentrations (5 and 10 mg/L) for rice's removal of NO_3 and NH_3. Although the 5 mg/L exposure of both filtered orthophosphorus (FOP) and total orthophosphorus (TOP) had a greater mean removal than the 10 mg/L exposure, differences were not statistically significant ($\alpha = .05$) (Figure 2). Overall mean concentrations of nutrients in rice mesocosms at 5 mg/L were all lower than those observed in the control (unvegetated) mesocosms amended with 5 mg/L; however, only NH_3 concentrations were statistically significant ($\alpha = .05$) (Table 1). No statistical significance was observed between the 10 mg/L and the control + 10 mg/L exposure overall nutrient concentrations. In fact, NO_3 and FOP 10 mg/L exposure concentrations were actually higher than those measured in the control (unvegetated) + 10 mg/L mesocosms.

Following the second nutrient exposure one week later, statistically significant differences ($\alpha = .05$) existed between the two treatment concentrations for $NH_3$and FOP removal by rice (Figure 3). Responses of FOP and TOP removal in the second exposure were similar to those exhibited during the first exposure, for both the 5 and 10 mg/L amendments. Although mean NO_3 removal in the second exposure was less efficient for both amendment concentrations, neither were statistically significant at $\alpha = .05$. Mean concentrations of NH_3, FOP, and TOP were similar from the first exposure to the second (Table 1). Nitrate removal efficiency in the second exposure was less efficient at 5 mg/L, but more

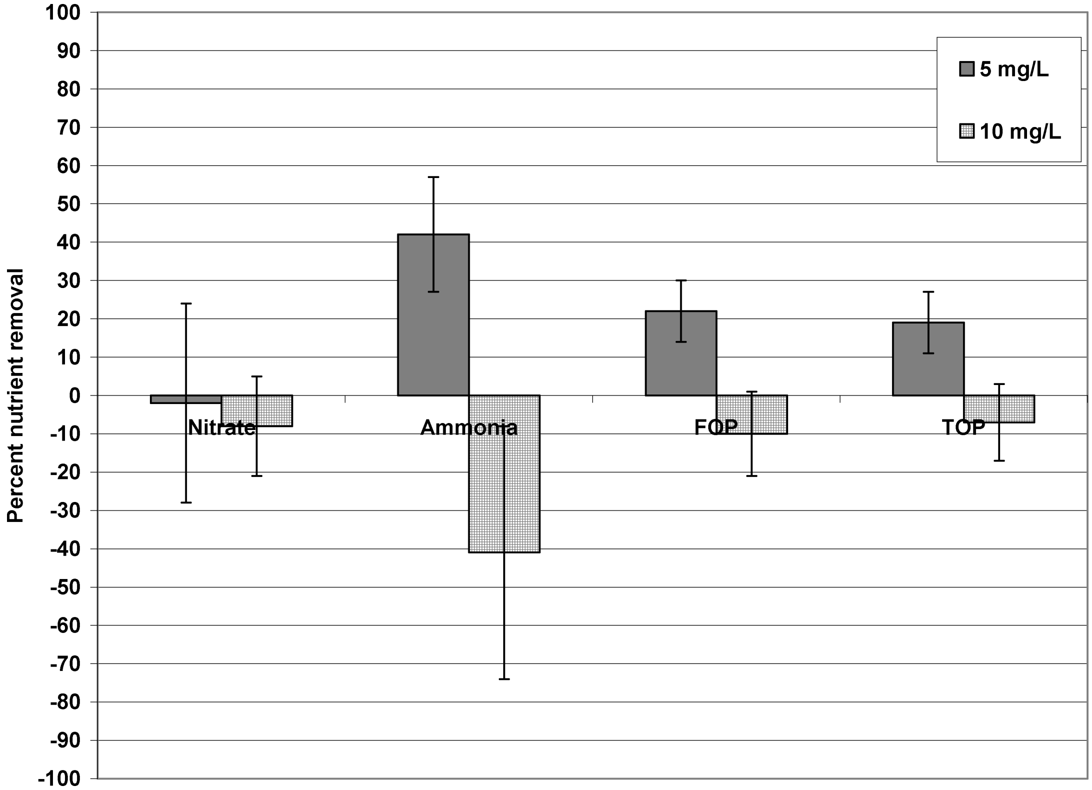

FIGURE 2 Mean percent nutrient removal for mesocosms amended with nutrient enriched water, August 24, 2004. Negative numbers indicate net increases.

efficient at 10 mg/L. Ammonia removal efficiency was slightly less at 5 mg/L in the second exposure, but the 10 mg/L exposure was much less efficient when compared to the first exposure. FOP and TOP removal efficiencies were basically unchanged between the second and first exposures.

DISCUSSION

Phytoremediation of nutrients associated with agricultural runoff is a complex mixture of chemical reactions and rhizosphere microbial processes. Ammonification, nitrification, and denitrification all play a role

TABLE 1 Mean Nutrient Concentrations (mg/L) of Mesocosms Amended with Nutrient-Enriched Water, August 2004

	First exposure				Second exposure*			
	C + 5	5	C + 10	10	C + 5	5	C + 10	10
Nitrate	4.40	2.85	4.89	6.34	4.79	5.69	10.4	11.1
SE	0.58	0.81	0.84	0.98	0.45	1.19	1.48	1.82
S^2	3.06	5.91	6.40	8.70	1.79	12.8	19.6	29.7
Ammonia	0.21	0.08	0.33	0.27	0.15	0.10	0.27	0.26
SE	0.05	0.03	0.07	0.05	0.04	0.03	0.06	0.06
S^2	0.02	0.01	0.04	0.02	0.01	0.01	0.04	0.03
FOP	3.15	2.29	4.67	5.05	3.08	2.49	4.52	4.42
SE	0.25	0.41	0.53	0.65	0.23	0.37	0.48	0.55
S^2	0.54	1.55	2.51	3.85	0.47	1.25	2.07	2.76
TOP	3.32	2.61	4.63	4.38	3.22	2.71	4.63	4.23
SE	0.21	0.36	0.43	0.55	0.18	0.34	0.32	0.51
S^2	0.40	1.18	1.66	2.72	0.28	1.01	0.90	2.32

Note. Control mesocosms (C) were unvegetated.
SE = standard error; S^2 = variance; FOP = filtered orthophosphorus; TOP = total orthophosphorus.
*Data for second experiment were limited to the first 9 h of the 12-h exposure for comparative purposes.

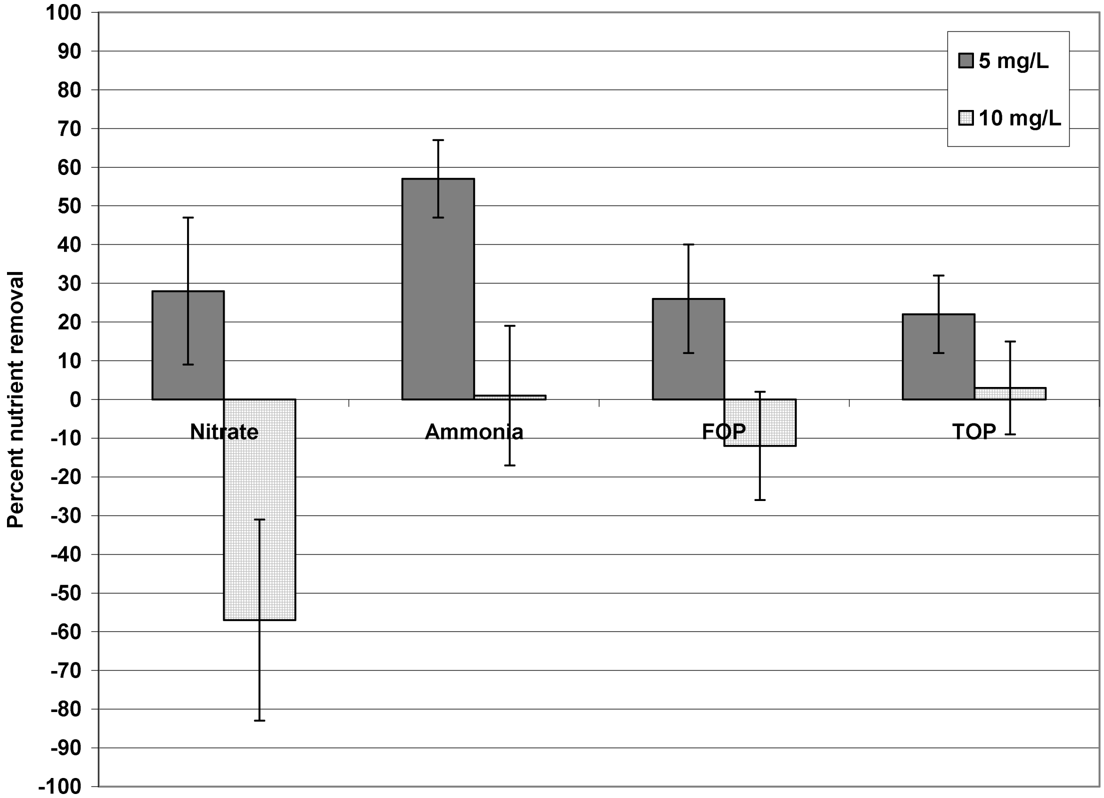

FIGURE 3 **Mean percent nutrient removal for mesocosms amended with nutrient enriched water, August 17, 2004. Negative numbers indicate net increases.**

in the cycling and availability of nitrogen species within the aquatic environment. Cronk and Fennessy (2001) suggested that plant nutrient uptake is not a major source for removal in wetland habitats receiving high N and P concentrations, and in some cases, they may serve as sources rather than sinks for pollutants. Predicted nitrate removal efficiencies in the Maurepas forested wetland (Louisiana, USA) were 40% to 70% in initial cells with high nutrient loading, whereas subsequent cells, receiving lower loading, were predicted to remove nitrate >90% (Lane et al., 2003). As demonstrated by results from the current study, improved removal efficiency is more often recognized in low nutrient-input systems. Because rice paddies have the same characteristics as wetlands (hydroperiod, hydrosoils, and hydrophytes), similar results may be expected. In 2001, Comín et al. examined nutrient removal efficiencies of abandoned rice fields now being used as wetlands. Due to the majority of N entering wetlands as NO_3, 50% to 98% of N species were removed, whereas <50% of soluble P was removed. Increases in phosphorus concentration (from inflow to outflow) were noted in the oldest wetlands (Comín et al., 2001). Results from a 2003 study in which effluent from hybrid catfish cultures was used to fertilize rice indicated 32% of total N and 24% of total P were removed by the rice crop (Lin and Yi, 2003). Kirk and Kronzucker (2005) reported model calculations demonstrating hydroponically grown rice was efficient at producing and absorbing NO_3 in its rhizosphere. These results are important, because NO_3not utilized by the plants is typically lost in bulk soil through denitritifcation.

More recent studies have examined plant specific uptake and mitigation of nutrient runoff. Three common aquatic macrophytes found in the Mississippi Delta (USA) were exposed to 5 mg/L of NO_3, NH_3, and *ortho*-PO_4 (Deaver et al., 2005). *Ludwigia peploides* (yellow primrose) removed more NO_3 and NH_3, 40% ± 8% and 82% ± 3%, respectively, than the softrush *Juncus effusus* (35% ± 7% and 37% ± 14%, respectively) and cutgrass, *Leersia oryzoides* (22% ± 8% and 34% ± 14%, respectively) (Deaver et al., 2005). All three plant species removed <29% of total *ortho*-PO_4 (Deaver et al., 2005). *Eichhornia crassipes* (water hyacinth) is another aquatic plant studied for its nutrient mitigation abilities. Chatterjee and Raziuddin (2002) reported a decrease of 5.33%, 25.5%, and 23.07% in NO_3,NH_3, and *ortho*-PO_4, respectively, when nutrient enriched waters passed

through a slow-flowing river zone laden with *E. crassipes*. In a later study conducted during a 31-day batch growth experiment, *E. crassipes* was capable of decreasing total Kjeldahl N by 91.7% and total P by 98.5% (Sooknah and Wilkie, 2004). Unfortunately, for many parts of the world including the United States, *E. crassipes* is an invasive and exotic species. Careful consideration must be given before choosing plant species for mitigation work. Native species should be chosen whenever possible, in order to avoid introduction of invasive species.

Although rice isn't the most effective plant for mitigating nutrient runoff in the aqueous phase, it is capable of absorbing some excess N and P from agricultural runoff. Results from the current study indicate its effectiveness at lower levels of nutrient loading (5 mg/L) as opposed to higher levels (10 mg/L). As pressure to mitigate agricultural non-point source pollution increases, farmers and landowners must look to innovative, economic options that are environmentally beneficial. The potential of using cereal crops (e.g., rice) for nutrient mitigation will help achieve goals and initiatives of cleaner, safer surface water resources.

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