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Denitrification potential of low-grade weirs and agricultural drainage ditch sediments in the Lower Mississippi Alluvial Valley

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ABSTRACT

To enhance nitrogen transformations and increase agricultural nitrogen removal, best management practices (BMPs) need to focus on identifying and improving mechanistic removal pathways. Best management practices can be implemented which favor denitrification, the single most effective removal pathway in the nitrogen cycle. Low-grade weirs in agricultural drainage ditches provide conditions conducive for denitrification to occur; however, there is very little information on denitrification potential of agricultural drainage ditches, let alone low-grade weirs in these systems. This study aimed to provide the first examination of denitrification potential of agricultural drainage ditches with and without low-grade weirs and highlight how the age of weirs may result in changes in denitrification rates. Samples were collected in three distinct seasons (summer, winter, spring) during 2011 and 2012 from ditches with and without weirs. Sediment cores were plumbed as flow-through chemostats and inflow and outflow samples were analyzed for N_2 gas to determine net denitrification rates. Overall there were no significant differences between net denitrification rates between sites with weirs and sites under conventional drainage ($z = 0.4526$, $P = 0.65$). Average net denitrification rates for weirs and conventional drainage were 2215 ± 440 and $2541 \pm 727\ \mu g\ m^{-2}\ h^{-1}$, respectively. This finding suggests that the potential for denitrification exists within both weired and conventional ditches, but a precipitating environment is limiting. Denitrification rates were significantly different between seasons ($F = 6.1879$, $P = 0.0004$) in all sediment cores, regardless of drainage characteristics, with summer > winter > spring. Differences due to age were also significant ($F = 2.6483$, $P = 0.0224$), with higher rates of denitrification in younger systems (≤1 year) vs. older systems (≥2 years), suggesting denitrification potential of weirs decreases with time. These data suggest that use of weirs can provide enhanced hydrological residence time in these systems, and thus promote conditions conducive for nitrogen removal via denitrification to occur. Thus low-grade weirs should be considered as BMPs for nitrogen removal in source agricultural landscapes, as they promote conditions conducive for denitrification.

1. Introduction

Denitrification is a mechanistic removal pathway in the nitrogen cycle whereby nitrate-nitrogen (NO_3^-–N) can be converted to gaseous products of nitrous and nitric oxide, and eventually N_2 gas (Reddy and DeLaune, 2008). Though biologically driven, denitrification is the mechanism whereby inorganic nitrogen (N) can be effectively removed from the system (Seitzinger et al., 2006). Specifically, when dealing with agricultural landscapes and their impacts on downstream aquatic ecosystems and N delivery to coastal ecosystems, denitrification is a good pathway to target from a management standpoint (Ullah and Faulkner, 2006). Nowhere is this more pertinent than in the Mississippi River Basin, where action plans are calling for 45% reduction of total nitrogen (TN) to reduce impacts in the Gulf of Mexico (GOMA, 2009; USEPA, 2008, 2011). To significantly increase TN reductions, management practices need to focus on enhancing the denitrification pathway at source locations to reduce loads immediately prior to entering downstream aquatic systems (Hernandez and Mitsch, 2007; Poe et al., 2003; Ullah and Faulkner, 2006).

Coastal hypoxia in the Gulf of Mexico occurs on an annual basis and is the result of increased N load, originating from non-point sources (Dagg and Breed, 2003; Goolsby et al., 2000). This

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problemis not solely tied to agriculture, as often urban landscapes contribute just as much N to downstream systems (Dale et al., 2010). Regardless, management of inputs needs to be managed at the source, or as near to the source as possible to reduce the TN loads moving downstream. The Governors Action Plan (GOMA, 2009) calls for reductions in TN and total phosphorus of 45% to achieve the desired reduction in the hypoxic zone in the Gulf of Mexico. Ultimately this reduction will come down to reducing landscape inputs and enhancing biogeochemical pathways for nutrient removal at the source. One such pathway for N removal is denitrification. Enhancing denitrification at source locations will provide an added removal pathway for N lost in runoff.

Facilitating N removal in agricultural landscapes in the Mississippi River Basin requires the creation and enhancement of wetland-like conditions. Often overlooked yet ubiquitous features of agricultural landscapes are wetland-like agricultural drainage ditches (Moore et al., 2001, 2005). In the Lower Mississippi Alluvial Valley, agricultural drainage ditches have the three characteristics of wetlands; namely, ephemerally-inundated hydroperiod, hydrophytic vegetation, and hydric soils (Kröger, 2008). Management of these vegetated drainage ditches has suggested that they offer water quality improvement benefits to downstream aquatic systems (Kröger et al., 2011, 2012b). However, their efficiency in removal may be enhanced by creating more intermittent/perennial hydroperiods to allow for the development of conditions conducive for denitrification.

Constructed wetlands, recirculating aquaculture, and wastewater treatment plants are often designed to maximize denitrification for the effective removal of N. However, not much is known about denitrification of agricultural landscapes, let alone primary aquatic systems (i.e., drainage ditches) associated within these landscapes. In addition to temperature and microbial community structure, three key variables typically determine the occurrence and magnitude of denitrification: (1) anaerobic environments, (2) an energy donor source, typically carbon, and (3) availability of NO_3^-–N to be denitrified. In most agricultural landscapes the limited availability of NO_3^-–N is unlikely. Generally the problem is a failure to manage favorably for anaerobic environments which convert NO_3^-–N to N_2. The ephemeral nature of drainage ditches reduces the potential for N conversion and thus represents a management opportunity. Research is beginning to look at low-grade weirs, a controlled surface drainage strategy, to augment removal of nutrients within drainage ditches.

Low-grade weirs are impendence structures that function like check dams within the agricultural landscape. They are stepped along the gradient of the ditch to create perennial pools of water and sections of decreased water velocity, which in turn creates multiple, enhanced wetland systems within the larger drainage ditch. With the presence of low-grade weirs, hydroperiods within the ditch system are much longer, and thus are hypothesized to create conducive conditions for denitrification to occur (Kröger et al., 2008). This study is the first study to describe denitrification potential of primary drainage ditches in agricultural landscapes in the Lower Mississippi Alluvial Valley. Furthermore, this study looked at seasonality, as well as weir age, to identify potential trends with denitrification. It is hypothesized that systems with weirs will have similar denitrification rates as systems without, and that denitrification potential will remain similar through time as the systems develop and mature.

2. Materials and methods

2.1. Study area

The study was conducted in Yazoo River Basin, in the Lower Mississippi Alluvial Valley, Mississippi. The Lower Mississippi Alluvial Valley is an intensive agricultural landscape with the majority of agricultural lands placed in a corn–corn or corn–soybean rotation. All study sites sampled in the current study were under a corn–soybean rotation for the 2011–2012 cropping season. The Yazoo River Basin receives in excess of 145 cm of rainfall per year; typically the rainfall is quickly removed from the agricultural landscape through efficient surface drainage ditch networks. These drainage ditches are typically channelized, ephemeral headwater streams.

Sites were sampled in three distinct sampling periods throughout the year – spring (May 2011, $n = 12$), summer (July/August 2011, $n = 24$), and winter (February 2012, $n = 12$) (Table 1). Within each sampling period at least four sites sampled were conventionally drained systems. All weir systems were sampled at least once over the course of the year ($n_{weir} = 32$, $n_{conventional} = 16$). Weir and conventional sites were selected randomly to be sampled in each time period. The youngest weirs were four months, and the oldest weirs sampled had been installed five years prior to sampling. Weirs also aged through the sampling period (i.e., weirs were considered to continue aging over the course of the study) (Table 1). Sites located at the Terrace location were sampled at every sampling period. Some sites were sampled multiple times during the same season. This was done to assure good temporal information on a system was collected in systems that were felt to have matured, biogeochemically. Of particular interest was if the systems altered their state on a seasonal basis, and if change was occurring within a single season. Data collected were treated as separate samples in these instances.

2.2. Field sediment core sampling and continuous-flow core experiments

Sediment cores (12 cm diameter × 50 cm length) were collected manually in shallow water. Corers were inserted into sediment and gently removed with approximately 10–25 cm of overlying water in order to preserve conditions at the sediment-water interface. The volume of water overlying the sediments typically ranged between 100–300 ml. Cores were capped on both ends, placed on ice, and returned to the laboratory for experimentation. In the lab, upper core caps were replaced with stoppers outfitted with inflow and outflow Teflon tubing. Inflow tubing extended into the overlying water just above the sediment surface and outflow tubing was cut flush with the stopper on the interior of the core. Aerated tap water was pumped through the cores at rate of approximately 1 ml/min to create the continuous-flow core experiments. Cores were incubated at the ambient temperature measured in the field. In addition to the intact cores, control cores without any sediment were set up identically to measure any potential changes in dissolved gases and solutes along the experimental flow path which was not caused by sediment transformations. Cores were equilibrated overnight and then inflow and outflow ports were sampled daily for two days (Scott et al., 2008). Approximately 20 ml of water sampled from inflow and outflow ports were collected into test tubes fitted with ground glass stoppers for dissolved gas analysis. These samples were preserved with ZnCl and stored at 4 °C until analysis. Another 250 ml of sampled water from inflow and outflow ports were filtered through acid-washed Whatman GFF filters and were frozen for later measurement of NO_3^-–N. At the end of the incubation, overlying water above the sediment surface was drained from the core and the upper 3 cm of sediments were extracted and dried for analysis of percent organic matter and TN concentration.

Membrane inlet mass spectrometry (MIMS) was used to measure nitrogen gas to argon ratios (N_2:Ar) and oxygen gas to argon ratios (O_2:Ar) as described by Kana et al. (1994). The MIMS was constructed with a Pfeiffer Prisma mass spectrometer and a Bay Instruments DGA membrane inlet S-25-75. Potential instrument-specific O_2