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Nitrate removal potential of restored wetlands loaded with agricultural drainage water: A mesocosm scale experimental approach

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A B S T R A C T

Wetland restoration is often conducted in Eastern U.S. coastal plain watersheds alongside agricultural lands that frequently export significant amounts of nitrogen in drainage water. Restoration plans that incorporate the addition of agricultural drainage water can simultaneously increase the success of achieving a target hydroperiod and reduce discharge of nitrogen to nearby surface water. The potential nitrogen removal effectiveness of two wetland restoration sites with such a restoration plan was evaluated in a two-year mesocosm study. Six large wetland mesocosms (3.5 m long × 0.9 m wide × 0.75 m deep) along with unplanted controls were used in this experiment. Three replicates of two soils that differed in organic matter and pH were planted with soft-stem bulrush (Schoenoplectus tabernaemontani) and allowed to develop in the two growing seasons prior to the study. Simulated drainage water was loaded into the mesocosms over eighteen batch studies across seasons with target nitrate-N levels between 2.5 to 10 mg L^{-1}. Grab samples were collected from the water column and analyzed for nitrate-N, dissolved organic carbon, and chloride, along with other environmental parameters such as pH, water temperature, and soil redox. Seasonally, nitrogen and carbon within the wetland plants and soil were also measured. Multivariate statistical analyses were utilized to determine differences in nitrate-N reductions between treatments. Variables included carbon availability, temperature, antecedent moisture condition, nitrogen loading, and water pH. Contrary to the hypothesis that higher nitrate-N removal rates would be observed in the wetlands with higher organic matter, overall removal rates were higher in the wetland mesocosms containing Deloss soils (WET-Min) (maximum of 726 mg m^{-2} d^{-1}) than those containing Scuppernong soil (WET-Org) (maximum of 496 mg m^{-2} d^{-1}) and were dependent on daily NO_3-N concentrations and season. Significant differences in NO_3-N removal were found between seasons and soil types ($\alpha = 0.05$), which helped to provide insight to the expected magnitude of nitrogen removal within these systems throughout the year, and potential mechanisms (i.e. denitrification vs. plant uptake) that will govern these removals.

1. Introduction

1.1. Background

Agricultural production is vital to the economy in coastal regions, but its successes continue to place environmental pressures on nearby shellfishing waters and wetland ecosystems. Drainage water from croplands routed directly into coastal rivers and estuaries can contribute to lower quality of shellfishing waters due to elevated levels of nutrients, sediment, and fecal bacteria. N rich drainage water routed into nutrient sensitive terrestrial, freshwater, and marine ecosystems negatively influences their functionality (Carnicer et al., 2015; Ribaudo et al., 2016; U.S. EPA, 2010; Matson et al., 1997; Vitousek et al., 1997). Hydrologic alterations to the landscape may also lower water tables in surrounding wetland ecosystems, resulting in degraded ecosystem structures and increased potential for peat fires (Ardón et al., 2010; Chescheir et al., 1991).

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Conservation and mitigation programs that invest resources into strategically positioned wetland restoration projects in agricultural areas could lead to a reversal in both declining wetland ecosystem structure and water quality trends in coastal estuaries. As an example, forested wetland restorations in coastal landscapes have been reported to effectively provide water quality treatment, flood abatement, biodiversity, and carbon storage in these areas. (Adame et al., 2015).

Achieving target hydrology is critical for successful wetland restoration projects. It is the driving factor that determines wetland type, time to establishment, structure, function and persistence. It is often considered the most important parameter needed to receive wetland mitigation credits because of its critical impact on establishing at least some acceptable level of wetland vegetation, saturated soils, and internal plant and microbial processes such as denitrification and carbon sequestration common in natural wetlands (Mitsch and Gosselink, 2007; Caldwell et al., 2007). Because of this, wetland restoration designs in coastal regions of North Carolina often include plugging of drainage ditches, constructing berms to impound water, installing water control structures (e.g., flashboard risers), and surface topography manipulations to help restore target wetland hydrology (Jarzemsky et al., 2013; Tweedy et al., 2001). While this can be an effective practice for restoring the wetland hydroperiod and habitat, this type of design does not always maximize other functions such as improvement of downstream ecosystem water quality.

Natural, restored, or enhanced wetlands have also been used to treat NO_3-N from agricultural drainage, but studies report a wide range of removal rates (139–2,800 mg N m^{-2} d^{-1}) indicating variable success (Karpuzcu and Stringfellow, 2012; Ardón et al., 2010; Beutel et al., 2009; Bachand and Horne, 1999; Chescheir et al., 1991). This is not surprising given N cycling in wetlands is complicated. It involves complex biological and microbial processes. Primary NO_3-N removal processes in wetland systems include denitrification and plant uptake (Tanner, 2001; Hunter and Faulkner, 2001; Reddy et al., 1989). Additionally, wetland removal effectiveness depends on factors such as wetland to watershed ratio, soil type, wetland ecosystem type, residence time, and hydraulic and nutrient loading rates (Arheimer and Wittgren, 2002; Woltermade, 2000).

Ideally, in order to determine optimal loading rates to achieve desired NO_3-N removal performance in restored or created wetlands, evaluations should be conducted prior to the development of water management plans for these systems. However, due to a lack of local studies and often a lack of funds, researchers/designers have attempted to establish nutrient management plans at the field scale after pumping to those areas began, which is inefficient and resulted in little control of how the areas were loaded with drainage water, particularly in the first few years following construction. Challenges associated with controlling rates of incoming drainage water often reduce the accuracy in quantifying the maximum nutrient removal potential and identifying NO_3-N removal mechanisms within these systems (Bruland et al., 2006; Chescheir et al., 1991). Results of these “black box” studies in large-scale systems support the need of controlled mass balance approaches to improve predictions of NO_3-N transformations within wetland systems (Kangas and Aday, 1996), prior to initiating loading. Additionally, further research to determine the impact of the varying conditions that effect NO_3-N removal rates within wetland systems is critical to develop more efficient wetland management strategies.

Mesocosm-scale wetlands can be useful tools to examine nutrient transformations within a controlled system with a goal of determining optimum loading rates. Past studies have found mesocosms to adequately model full-scale wetlands for NO_3-N reduction with limitations reviewed by Ahn and Mitsch (2002) and summarized herein. Ahn and Mitsch (2002) did not observe significant differences in the degree of mixing and effects on water quality improvement in a study comparing mesocosms to full-scale wetland evaluations on a 1:10,000 scale. Additionally, Bachand and Horne (2000) concluded that wetlands could be adequately modeled with macrocosms to determine NO_3^--N reductions compared to full-scale wetlands and found no significant differences on a 1:1000 scale. The few discrepancies observed between coupled mesocosm to full-scale studies have found them to underestimate NO_3-N reductions (Ahn and Mitsch, 2002; Bachand and Horne, 2000). Therefore, mesocosms may actually provide conservative estimates of NO_3-N treatment potential due the spatial heterogeneity in full-scale wetlands, which provide NO_3-N removal enhancements (e.g., light penetration, plant density, hydraulic conductivity) as spatial variability increases (Birgand et al., 2007). As summarized in Ahn and Mitsch, 2002; other potential limitations to mesocosm use include difficulties associated with simulating a complex array of interactions found in the natural environment (Clements et al., 1988; Schindler, 1998; Carpenter, 1996) and intrinsic artifacts from controlled experiments (Gry et al., 1999; Schindler, 1998, Carpenter, 1996). Therefore, mesocosm experiments should ideally be coupled with full-scale experiments to ensure findings are not unique to the mesocosm scale.

NO_3-N removal potential of two wetland restoration projects in eastern North Carolina that could be used to treat agricultural drainage water were evaluated in this study. These sites had two distinct soil types in terms of nutrients, carbon, texture, and pH, all of which have been shown to influence NO_3-N removal via microbial processes or plant uptake (Puckett et al., 2004; Engles and Marschner, 1995). At one of the sites situated in Hyde County, NC, the restoration plan called for pumped NO_3-N rich drainage water to enter a degraded wetland ecosystem to reduce the volume of NO_3-N rich water currently pumped to the nutrient sensitive Pamlico Sound. The second site was situated downstream from a major agricultural facility in Carteret County, NC and buffered the North River Estuary in a landscape position that could be ideal for drainage water treatment. Therefore, a clearer understanding of the NO_3-N removal potential of these sites was required to help stakeholders predict the water treatment impacts of the restoration plans. Preliminary investigations are particularly important and useful when planned restorations are near a sensitive environment, as was the case in this effort. While conducting experiments at nearby full-scale systems would have been ideal, nearby sites were not available. Therefore, wetland mesocosms were used as a cost-effective and timely alternative to enhance our understanding of N processes prior to full-scale construction, and to provide useful predictions of the NO_3-N removal capacity of these two future wetland restorations. Development of an advanced understanding of nitrogen removal capacity throughout the year could allow stakeholders to confidently move forward with construction and begin the development of a water management plan for the full-scale restorations.

1.2. Objectives

A laboratory study was conducted to identify the nitrogen removal potential (particularly NO_3-N) for two distinct wetland restoration sites with different soils. The wetland mesocosms were loaded with soils from both sites, planted, and allowed to establish. The impact of the soils (nutrients, bulk density, pH) along with season, N load, water temperature, and antecedent soil moisture conditions on NO_3-N removal rates were investigated. We hypothesized that removal in the wetlands constructed with the Scuppernong soil series (organic soil) would remove NO_3-N more efficiently than the wetlands with a Deloss soil series (mineral soil), due to differences in carbon content ($\alpha = 0.05$), which is often the primary limiting agent for denitrification in restored and con-