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Optimized denitrification bioreactor treatment through simulated drainage containment

Laura E. Christianson[a,*], James A. Hanly[b], Mike J. Hedley[c]

[a] Graduate Student, Department of Agricultural & Biosystems Engineering, 3145 NSRIC, Iowa State University, Ames, IA 50011, United States
[b] Research Officer, Fertilizer and Lime Research Centre, Massey University, Private Bag 11 222, Palmerston North, New Zealand
[c] Professor and Group Leader, Soil and Earth Sciences, Massey University, Private Bag 11 222, Palmerston North, New Zealand

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ABSTRACT

In the design of wood-based, enhanced-denitrification bioreactors to treat nitrate in agricultural drainage, the consideration of the highly variable flow rates and nitrate concentrations inherent to many drainage systems is important. For optimized mitigation of these nitrate loads, it may be best to contain drainage water prior to treatment in order to facilitate longer, more constant retention times rather than to allow cycles of flushing and dry periods in the denitrification bioreactor. Simulated containment prior to bioreactor treatment compared to passing drainage directly through a bioreactor was investigated with the use of six pilot-scale denitrification bioreactors constructed with plywood and filled with *Pinus radiata* woodchips at Massey University No. 4 Dairy Farm (Palmerston North, New Zealand). Initial bromide tracer tests were followed with a series of five simulated drainage events each at successively declining inflow nitrate concentrations. During each drainage event, three pilot bioreactors received a simulated hydrograph lasting 1.5 days (Non-Containment treatment) and three pilot bioreactors received the same total drainage volume treated over 4 days at a constant flow rate (i.e. constant retention time; Containment treatment). Results showed significantly different total mass removal efficiencies of 14.0% vs. 36.9% and significantly different removal rates of 2.1 g N m^{-3} day^{-1} vs. 6.7 g N m^{-3} day^{-1} for the Non-Containment and Containment treatments, respectively, which indicated that treating drainage at constant retention times provided more optimized nitrate removal. While this work was done to evaluate treatment under New Zealand drainage conditions, it also provides valuable information for optimizing agricultural drainage denitrification bioreactor performance in general.

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1. Introduction

The implementation of agricultural drainage worldwide has allowed increased agricultural intensification and productivity (Ritzema et al., 2006), but these gains have not been without environmental impact. Nitrate (NO_3^-) losses from agricultural drainage have been documented in many regions (Mohammed et al., 1987; Randall and Goss, 2001; Singh et al., 2002; Noory and Liaghat, 2009) and regulatory bodies are increasingly trying to address the resulting decline in water quality (European Commission, 1991; Horizons Regional Council, 2007; USEPA, 2007). One of the newest, on-farm approaches for mitigating NO_3^- loadings from agricultural drainage is the use of enhanced denitrification. Drainage waters high in NO_3^- are routed through denitrification bioreactors where NO_3^- transformation is enhanced by an additional carbon source and the maintenance of saturated conditions (Schipper et al., 2010a).

Wood-based denitrification bioreactors for reducing NO_3^- in agricultural drainage have shown promise in American Midwest drainage systems (Jaynes et al., 2008; Chun et al., 2010; Woli et al., 2010), and it is thought this mitigation strategy may also be effective in other locations. In New Zealand, the average annual drainage NO_3^- losses under grazed dairy pastures are approximately 25–30 kg N ha^{-1}, which is similar to loadings from row cropped areas in the US Midwest (Ledgard et al., 1999; Randall and Goss, 2001; Monaghan et al., 2002). A major difference between these two drainage systems is that while Midwestern drainage typically has relatively consistent NO_3^- concentrations over a drainage season at a given site, in New Zealand drainage systems there is a significant trend of declining NO_3^- concentrations over the season with the highest concentrations typically occurring within the

* Corresponding author. Tel.: +1 515 294 4241; fax: +1 515 294 4250.
E-mail addresses: laurac@iastate.edu, lauraechristianson@gmail.com (L.E. Christianson).

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first 100–150 mm of drainage (Monaghan et al., 2002; Houlbrooke et al., 2004). Hydrologically, New Zealand's mole and pipe drainage systems have high peak flows stimulated by storm events (pulsed flow) with significant periods of no flow between events (Bowler, 1980).

Uncontrolled and infrequent pulsed drainage flow rates present a challenge for bioreactor treatment as these fluctuating flow rates result in fluctuating bioreactor retention times. Low bioreactor retention times occurring at peak flow rates may result in dissolved oxygen (DO) concentrations that are too high for NO_3^- to be reduced by denitrifiers. Indeed, past work has documented decreased bioreactor NO_3^- removal at higher flow rates (Woli et al., 2010; Christianson et al., 2011). In addition, short duration, intensive flows present design issues because designing a system for 100% of the peak flow rate requires an impractically large bioreactor volume. Currently in the Midwest, bioreactors are designed using a design flow rate that is only a portion of the peak flow rate, meaning that not all of the total annual volume receives bioreactor treatment (Christianson et al., 2009; USDA-NRCS, 2009).

In New Zealand, drainage water NO_3^- mitigation could focus on capturing and treating early season drainage water when NO_3^-concentrations are the highest (i.e. first 100–150 mm of drainage). In order to achieve this, temporary diversions or impoundment facilities may be constructed in paddock gullies to retain drainage water between drainage events. The controlled, slower discharge of this impounded drainage into a denitrification bioreactor would allow treatment at a longer and more consistent retention time. This two stage containment/treatment system would allow more effective treatment of nearly all the early season drainage volume by maintaining a sufficient retention time. A two stage design is a major departure from current denitrification bioreactor design in the US Midwest. Pre-treatment containment of drainage could provide at least two related benefits including: (1) stabilization of flow rate variability to allow treatment at a longer, more constant bioreactor retention time and (2) treatment of all the critical early season drainage containing the highest NO_3^- concentrations. Though past work documented declining nitrate removal during a simulated hydrograph (Christianson et al., 2011), there has been no direct treatment comparison of uncontrolled rapid drainage discharge with controlled, slower discharge from containment systems.

The objective of this work was to compare bioreactor NO_3^- removal occurring during steady retention times (i.e. simulated drainage containment) with removal occurring during flow rate-varying drainage events. It was hypothesized that the steady retention times would provide improved NO_3^- removal over the course of the simulated drainage season compared to Non-Containment. Moreover, this work assessed the feasibility of denitrification bioreactors for New Zealand drainage systems by simulating declining NO_3^- concentrations over the drainage season, using realistically scaled local drainage hydrograph events, and operating under *in situ* temperatures.

2. Methods

Six pilot-scale bioreactors (2.0 m × 0.31 m × 0.85 m) were constructed with plywood in two sets of three, which were installed in June 2010 at Massey University No. 4 Dairy Farm near Palmerston North, New Zealand (Fig. 1). The site receives an average annual rainfall of 980 mm and has a low average monthly soil temperature in July of 7 °C. The inside surface of each bioreactor was painted with exterior house paint and a non-toxic silicone sealant (Ecoshield™), and all seams were sealed with silicone caulk to prevent leakage.

The bioreactors were filled with pine chips made in May 2010 from 1-year-old *Pinus radiata* prunings at the No. 4 Dairy Farm. The woodchip size distribution by dry weight was: >2.2 cm: 14%, 1.1–2.2 cm: 30%, 0.8–1.1 cm: 24%, and <0.8 cm: 32% with an estimated porosity of 60% and bulk density (dry weight) of 190 kg m^{-3}. Porosity was determined using methods described in Christianson et al. (2010) where 1 L jars were packed with woodchips and then filled with water. After 24 h (i.e. after the woodchips had absorbed some of the initial volume), the water was replenished and this final volume was used to determine porosity. The bioreactors were filled to a depth of 75 cm with woodchips and approximately a 5 cm depth of soil was used to cap the chips. The soil, a Tokomaru Silt Loam, was taken from a grazed long-term (>10 years) pasture at the No. 4 Dairy Farm. 1 L of this soil was also scattered among the woodchips during filling to inoculate the system with native denitrifiers, although no inoculation of other similar systems has been necessary to date (Schipper et al., 2010a).

Outflows from the pilot-scale bioreactors were measured with v-notch weirs and water depth loggers (4 bioreactors; NIWA Hydrologger 2001) or tipping buckets with loggers (2 bioreactors; Odyssey Data Logger). Flow rates were also manually verified with a graduated cylinder and stopwatch. During the trials, one of the v-notch weirs malfunctioned, and manual flow measurements were used instead of logged data for this single replicate. Flow data were logged every 10 min and were then reduced by calculating 30 min average flow rates to be used in the statistical analysis. Two monitoring wells were installed at each end of the bioreactors to document water depth and solution dissolved oxygen (DO) (YSI Model 55). Water temperature was continuously logged every hour (Thermochron iButton® DS1921Z, Dallas Semiconductor) in two of the six outlet wells (within 15 cm from outlet) and in the constant head feed tank. During the testing period (1 July to 1 August 2010), rain at Dairy Farm No. 4 was 45 mm (less than 1% of the water balance for each bioreactor).

Water in a runoff/drainage pond at the No. 4 Dairy Farm was pumped to a 5000 L mixing tank, where it was dosed with fertilizer grade potassium nitrate to mimic nitrate concentrations in agricultural drainage. Water in this supply tank was gravity fed to a constant head tank controlled by a float valve. Each bioreactor received water from this constant head tank through a 15 mm alkathene pipe with flow rates manually controlled by a ball valve. The inflow pipe (15 mm alkathene) extended to the bottom of the bioreactor where a diffuser manifold tee was attached. The outflow side of the bioreactor had an opening approximately 2.5 cm from the bottom of the bioreactor to which a head-controlling stand pipe (25 mm alkathene, 70 cm height) was attached. The depth of water in each bioreactor was set at 70 cm resulting in a saturated volume of 0.434 m^3 (woodchip volume 0.465 m^3). The retention time calculation was based on the entire woodchip volume (to reflect the entire investment) multiplied by the woodchip porosity and divided by the flow rates from the loggers.

2.1. Tracer test

A bromide tracer test was conducted to determine the *in situ* residence times and dispersion indices for the reactors. A 1 L slug containing 28 g NaBr was injected into each pilot bioreactor upstream of the inlet and at least 15 outflow samples were spaced over time to capture at least four pore volumes. A pore volume was defined as the volume equal to the total saturated volume (0.434 m^3) multiplied by the woodchip porosity (60%). During these tests, potassium nitrate was used to dose the inflow pond water to achieve a concentration of 36.5 mg NO_3^--N L^{-1}. Tracer tests were run at four different retention times (i.e. 4.4, 7.7, 10.7, and 15.7 h of retention), two of which were duplicated (4.4 and 15.7 h). Outflow samples were analyzed for bromide, nitrate and sulfate with ion chromatography (Lachat 5000), though there were no significant differences between inflow and outflow sulfate val-

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