TECHNICAL NOTE:

PILOT-SCALE DENITRIFICATION BIOREACTORS FOR REPLICATED FIELD RESEARCH

N. L. Hoover, M. L. Soupir, R. D. VanDePol, T. R. Goode, J. Y. Law

ABSTRACT. *Carbon-based denitrification bioreactors are designed to intercept tile drainage and are a promising technology for reducing NO_3^- export to surface water. While these systems have been tested extensively in the laboratory, the ability to study in-field bioreactors under controlled conditions with statistical replicates has been limited. Nine pilot-scale bioreactors (5.79 × 1.05 × 1.07 m) were designed and installed for systematic field testing, allowing for variation in retention time, fill material, and influent water quality parameters. Each bioreactor is constructed from a concrete trench in-line with influent flow control, dosing port, flow diffusion, and effluent water level control. Sampling ports are installed at two points in each bioreactor for access to water samples or fill materials. A potassium bromide (KBr) tracer study was conducted and Morrill Dispersion Index (MDI) values averaged 2.8 ± 0.3, indicating plug flow characteristics. The average tracer residence time (t) was 2.3 ± 0.3 h, in close agreement with the estimated hydraulic retention time (HRT) value of 2.1 ± 0.3 h, which was calculated using a porosity value of 0.70. Hydraulic efficiency was good (λ = 0.78 ± 0.03) and there was no evidence of short circuiting (S = 0.73 ± 0.03). This system is expected to provide useful insight regarding design for improved field performance of denitrification bioreactors.*

Keywords. *Woodchip bioreactor, Nitrate, Tile drainage, Hydraulic retention time, Hydraulic properties, Tracer test.*

Carbon-based denitrification bioreactors are a promising technology to help meet NO_3^- reduction goals. For example, the Iowa Nutrient Reduction Strategy (INRS, 2014) demonstrated that installing woodchip bioreactors on all tile drained lands in Iowa could reduce NO_3-N loading by 18%. Woodchips have been the predominant fill material for existing bioreactors designed to intercept and treat tile drainage water, leading to the terminology "woodchip bioreactor" to indicate a denitrification bioreactor, and therefore these terms have been used interchangeably. Of the edge-of-field practices assessed (wetlands, buffers, bioreactors, and controlled drainage), bioreactors were identified as the most cost-effective edge-of-field practice for N reduction on a dollar per pound basis (0.92 $/lb).

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The potential of carbon-based bioreactors to enhance NO_3^- removal via denitrification has been extensively studied at the laboratory scale. Previous investigations have considered NO_3^- removal over hydraulic retention times (HRTs) ranging from 2 h to 10.4 d (Blowes et al., 1994; Greenan et al., 2009; Hoover et al., 2016), with generalized findings reporting higher NO_3-N removal efficiency (percent removal), but consistent to lower NO_3-N mass removal rates (load reduction), as HRT increased. Installation of bioreactors at the edge-of-field often necessitates lower HRTs during peak flow conditions; the current NRCS design standard recommends treating at least 15% of the peak tile flow (NRCS, 2015). Further, prolonged retention has the potential to result in near complete NO_3^- removal, creating conditions for potential sulfate (SO_4^-) reduction and methyl-mercury (CH_3Hg) production (Blowes et al., 1994; Shih et al., 2011).

Other studies have been designed to consider a range of influent NO_3-N concentrations and temperatures. Increasing NO_3^- removal can be related to 10°C increase in temperature using a Q_{10} factor (Davidson et al., 2006; Ghane et al., 2015), and reported values range from 2 to 4.7 (Cameron and Schipper, 2010; Elgood et al., 2010; Warneke et al., 2011; Hoover et al., 2016). NO_3-N mass removal was found to increase as influent concentrations increased from 10 to 50 mg L^{-1}; however, the increase in removal rates slows at higher influent NO_3-N concentrations (Hoover et al., 2016), representative of Michaelis-Menten kinetics (Ghane et al., 2015).

In conditions where NO_3-N concentrations are abundant, denitrification has been shown to follow zero-order kinetics (Robertson, 2010; Warneke et al., 2011; Ghane et al., 2015). At lower influent concentrations, such as those reported in Elgood et al. (2010), denitrification follows first-order kinetics, adding NO_3-N concentration as a confounding variable for Q_{10} determination.

Variation of the carbon source material has been evaluated previously and, in addition to various forms of woodchips, includes leaf compost (Blowes et al., 1994); cardboard, barley straw, pine needles (Healy et al., 2012); maize cobs, green waste, wheat straw (Cameron and Schipper, 2010); corn stover and barley straw (Feyereisen et al., 2016). Many studies have identified denitrification as the primary fate of NO_3-N in woodchip bioreactors (Greenan et al., 2009; Robertson, 2010; Schipper et al., 2010). Recent field work by Ghane et al. (2015) reported mean N_2O emissions of 0.12 μg N m^{-2} min^{-1} from a woodchip bioreactor, and more recently, David et al. (2016) reported nitrous oxide (N_2O) emissions in field bioreactors were less than 1% of the total NO_3^- removed during a two-year study. However, the substrate carbon source has been identified as an important parameter impacting the ultimate fate of NO_3-N (Healy et al., 2012, 2015) and potential for incomplete denitrification, dissimilatory NO_3^-N reduction to NH_4^+ (DNRA), or NH_3 volatilization (Fenton et al., 2014).

Studies monitoring field performance of bioreactors are limited and a wide range of NO_3^- removal has been reported. A comprehensive study conducted by Christianson et al. (2012) evaluated nitrate removal in four field-scale horizontal flow woodchip bioreactors over two years. Average bioreactor NO_3-N mass removal rates ranged from 12% to 76%. The authors identified warmer temperatures and retention times as the primary factors affecting NO_3-N load reduction, a conclusion confirmed by David et al. (2016), who added the age of the woodchips as a factor. Pilot-scale bioreactors were utilized by Christianson et al. (2011) to evaluate bioreactors with varying cross-sectional geometries on HRT and NO_3-N removal; however, the bioreactors were not replicated. Hydraulic properties of woodchip bioreactors are needed to better understand and assess bioreactor performance. Potassium bromide tracer studies have been conducted recently at the laboratory, pilot, and field scale (Christianson et al., 2013; Ghane et al., 2015; Hoover et al., 2016; Jaynes et al., 2016). Assessment of flow hydraulics is useful for diagnosing poor performing systems and for consistency in design calculations. For example, Christianson et al. (2013) identified short circuiting (non-ideal flow regime) and associated unutilized spaces in a woodchip bioreactor for poor nitrate removal under high flow conditions using tracer testing.

While current studies have clearly identified the importance of HRT, carbon substrate, influent water quality, and temperature on bioreactor NO_3-N removal, these properties have not been systematically tested with statistical replicates in the field. Here we describe the design and installation of the pilot-scale system with nine replicates, as well as the results of a tracer study which was performed to evaluate early flow characteristics and confirm similar flow characteristics among each bioreactor. These denitrification bioreactors are designed for statistical evaluation of the impacts of variation in retention times, fill materials, and influent properties on water quality and potential gas emissions.

Materials and Methods

Site Description

The nine pilot-scale bioreactors are installed at Iowa State University's Agronomy and Agricultural Engineering Research Farm west of Ames, Iowa (42°01'01"N, 93°46'48"W). An 11,356 L (3,000 gal) storage tank intersects the 30.5 cm (12 in.) diameter main county tile line, which serves as the water source for the experimental bioreactors. Installation occurred in September 2014, and the tracer study was conducted in May 2015.

Bioreactor Installation

A large 16.5 × 13.7 × 1.7 m (52 × 45 × 5.5 ft) pit was excavated in two stages. The initial dig was approximately 11.6 × 13.7 × 1.7 m (38 × 45 × 5.5 ft) for installation of the concrete trench components, maintaining a reasonable reach for the excavator to fill the constructed bioreactors with woodchips after installation. Each bioreactor frame consists of two prefabricated 3.1 m (10 ft) concrete trenches designed by Weiser Concrete (Maiden Rock, Wis.), modified for this project with a 15.2 cm (6 in.) concrete endcap at one end. The internal dimensions of the completed bioreactor frame, consisting of two connected trenches, are 5.8 × 1.0 × 1.1 m (19 × 3.4 × 4.5 ft). The concrete frame of each bioreactor maintains a more closed system than often observed in field conditions, reducing the potential for flow loss through seepage.

The trench serving as the influent end was fitted with a flexible rubber boot installed at approximately 12.7 cm (5 in.) from the open top of the poured endcap for installation of 5.1 cm (2 in.) PVC influent plumbing (fig. 1). The trench serving as the outflow/effluent end was also fitted with a flexible rubber boot installed at the base of the poured endcap for installation of 10.2 cm (4 in.) PVC outflow plumbing. The two trench ends were pieced together during installation, with a watertight mastiff seal pressed between a ridge and groove connection between the open ends of the two trench components. The outflow trench was set first, and a mastiff seal was pressed onto the ridge at the open end of the trench. The inflow trench was carefully lowered and guided into place so that the grooved edge of the open end lined up with the ridge of the outflow trench component. The frames were further secured and attached with 30.5 cm (12 in.) long 1.6 cm (5/8 in.) bolts inside a bolt pocket built into the concrete walls, 40.6 cm (16 in.) from the base, at the junction of both trenches.

Influent Control Structure and Dosing Port

A 5.1 cm (2 in.) brass gate valve was installed for precise adjustment of flow into the bioreactors, enabling a wide range of achievable HRTs (fig. 1). The 5.1 cm (2 in.) PVC ball valve can be opened or closed to route the drainage into the bioreactor or back flow up to an additional 5.1 cm (2 in.) ball valve for influent sample collection and instantaneous flow measurements. Actual flow measurements in the bioreactor may differ, but this feature allows for convenient initial

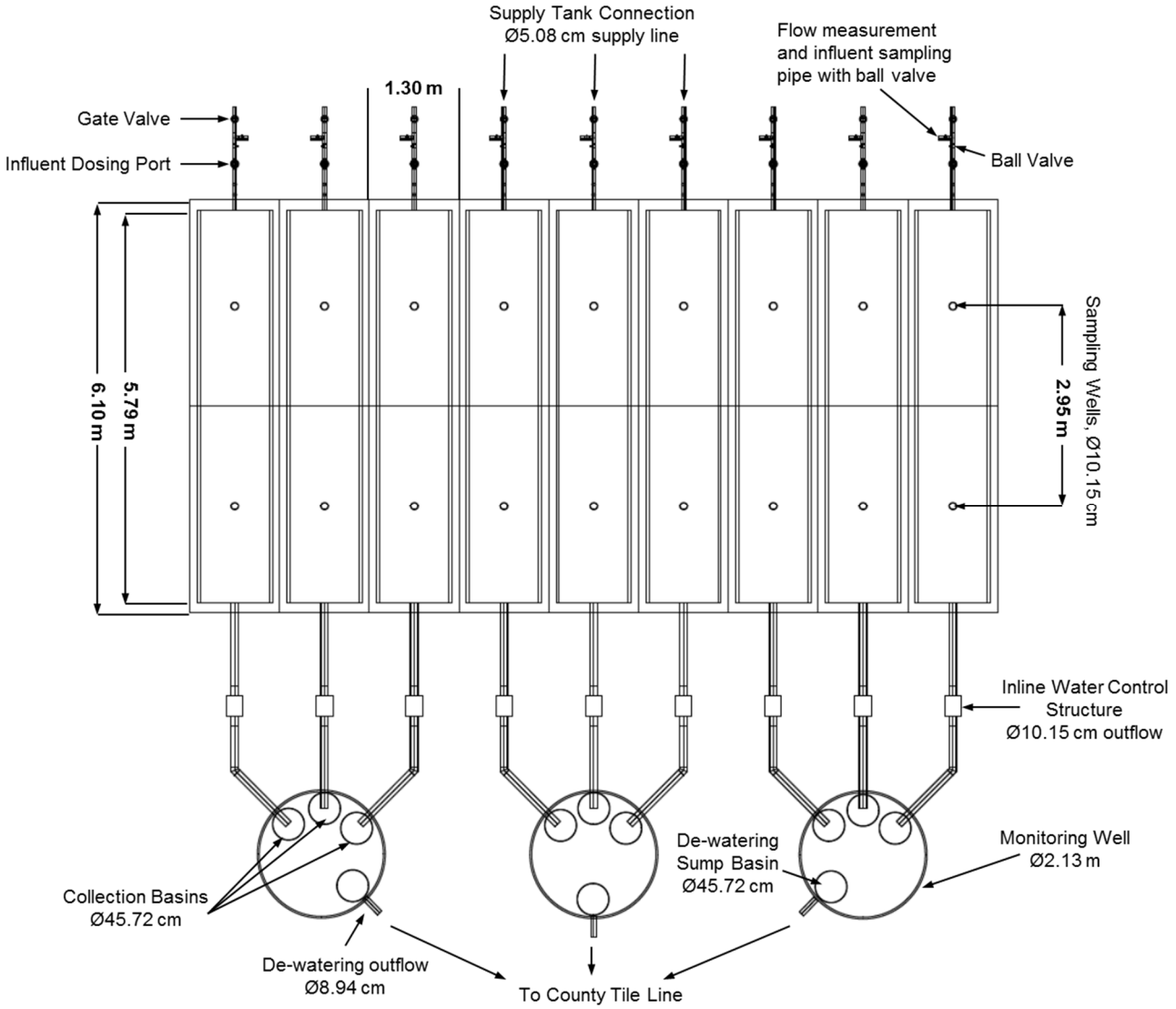

Figure 1. Schematic of nine pilot-scale denitrification bioreactors.

flow calibration and comparison of flows among bioreactors. The influent sample collection valve is opened for sample collection and flow rate measurements, and closed to maintain normal flow to the bioreactors. A 10.2 cm (4 in.) dosing port was connected after the in-line 5.1 cm (2 in.) PVC ball valve.

Internal Plumbing

A 90° elbow was connected to the 5.1 cm (2 in.) PVC inserted through the rubber gasket/boot at the influent trench end, routing a 91.4 cm (36 in) length of 5.1 cm (2 in.) PVC to the base of the trench. A tee was then connected at the base end of the PVC, and two 38.1 cm (15 in.) lengths of 5.1 cm (2 in.) diameter PVC connected at both ends. The two lengths of PVC were capped and 0.5 in. holes were drilled semi-randomly to diffuse influent flow over the internal width of the bioreactor to within 5 cm (2 in.) of the sidewalls.

Sampling Wells

Two 1.8 m (6 ft) sampling wells constructed of 10.2 cm (4 in.) PVC were installed along the centerline of the length of each bioreactor (fig. 1), attached directly to the floor of the bioreactor with a 10.2 cm (4 in.) diameter PVC flange positioned with the plastic ring at the base. Each PVC well was slotted at approximately 1.3 cm (0.5 in.) increments to a depth of 1.1 m (42 in.) to allow for sampling in the bioreactors to various depths, and along the length of the bioreactors. Each sampling well is capped to keep out unwanted debris and contaminants.

Bioreactor Fill Material

For initial experiments, the bioreactors were filled and mounded with a mix of local hardwood woodchips obtained from Golden Valley Hardscapes (Story City, Iowa). Woodchips from this supplier have been described in detail by Christianson et al. (2010). Woodchips were extracted from the surface 76 to 101 mm (3 to 4 in.) of the bioreactors 15 months after the tracer study (described below) and particle size analysis (PSA) was conducted. Prior to analysis, woodchips were oven dried at 60°C to constant weight. ASTM standard sieves with screen sizes of 25, 19, 12.7, 9.5, 4.75, and 2.36 mm screen sizes were used to partition 430 g of woodchips. Fractionation was analyzed using a Ro-Tap

Test Sieve Shaker (Model B S/N:4837, Mentor, Ohio, for 5 min in triplicate. The woodchip-filled bioreactors were covered with nonwoven geotextile (Mifafi® 160N, TenCate Geosynthetics Americas, Pendergrass, Ga.). An overburden of 15 to 30 cm (5.9 to 11.8 in.) topsoil was then mounded over the series of bioreactors. The bioreactors were seeded to a mix of Midwestern wildflowers in the spring of 2015, and again in late fall just before freeze.

Outflow Structures

After the bioreactor frames were in place and filled with woodchips, the pit was expanded another 3.05 to 4.57 m (10 to 15 ft) at the outflow end for installation of the inline water control structures (Agri Drain, Adair, Iowa) and three 1.83 m (6 ft) diameter corrugated steel sample collection and monitoring sumps. Integral to the inline control structures are 5 and 7 in. stoplogs, which may be added or removed to adjust the active volume within the individual bioreactors. Three collection basins, fed from individual bioreactor outlets, were installed within each large sump, and equipped with $^{3}/_{10}$ HP submersible pumps (Mighty-Mate m53, Zoeller Company, Louisville, Ky.) to empty each individual bioreactor basin during bioreactor flow. Outlet flow volume is measured with a Neptune water meter equipped with a Tricon® S register. An additional dewatering basin was installed to a depth of approximately 54 cm below the floor in each large sump to remove excess ground water when necessary, and equipped with a ½ HP sewage pump (model #UT58150, Utilitech Pro) for quick water removal. Each 1.8 m (6 ft) monitoring well is equipped with seven electrical outlets, one designated for each pump, plus three for future monitoring equipment such as automated samplers.

System Operation

The water source (intercepted county tile line) is approximately 150 m from the storage tanks, with an elevation increase of 3.7 m (12 ft). The flow in the cistern generally far exceeds the bioreactor flow volume requirements, with the rare exception due to extended extreme dry weather. To operate the bioreactors, water is pumped from the underground storage cistern fed from the main county tile line to three above ground 11,356 L (3,000 gal) storage tanks (Snyder Industries 30° Cone Bottom Tank, Heartland Ag, Ames, Iowa). The three storage tanks are housed on a portable tank trailer, allowing indoor storage of the empty tanks when not in use. A 7.6 cm (3 in.) submersible 3 hp Meyers 230 V, electric-powered pump is controlled with two float switches working in conjunction: one in the underground water storage cistern to signal drainage availability, and the other in the first above ground storage tank to signal demand for water at the tank trailer. The storage tanks are equipped with a 7.6 cm (3 in.) banjo plastic ball valve which is connected at the tank trailer base to allow use of all or individual supply tanks. Each individual tank has a valve to adjust flow out of the tank. The output of these three valves is then connected to a manifold with 9 ball valves to regulate flow to each bioreactor via 5.1 cm (2 in.) discharge hose.

Tracer Study

A KBr tracer test was conducted to evaluate the flow and dispersion characteristics of the bioreactors and to confirm similar conditions among the nine bioreactors. Flow rates were adjusted at the start of the tracer study to achieve an estimated 2 h HRT, and measured at the outflow of each bioreactor once during the tracer study over a 10 s period, with an estimated flow accuracy ranging from ±10%. Flow meters have since been installed, allowing for more accurate flow volume measurements for future studies.

A one L plug of 36.5 g L^{-1} KBr was instantaneously introduced into each dosing port, and outflow samples were collected for 375 minutes at predetermined time intervals of 5, 10, and tail end samples of 15 min. The results at 10 min sample intervals (every other 5 min sample, and each of the 10 min samples) were used for MDI calculations to maintain even sampling intervals. The bioreactor tracer study samples were analyzed by State Hygenic Lab (University of Iowa, Ankeny, Iowa) for KBr using a Dionex ICS-2100 Ion Chromatography System (ThermoScientific, 2012) using method EPA 300.0.

Drainable Porosity Measurement

The drainable porosity of the bioreactors was measured in June of 2016. The saturated volume was calculated using the average saturated depth of the individual bioreactors, measured at each sampling well, and the internal length and width of the bioreactors. The stop logs were systematically removed from the outlet control structures, so that each bioreactor was drained gradually, allowing all of the flow volume to be recorded by the individual flow meters installed at the outlet of each bioreactor. The bioreactors were left to continue draining for 2 d, and the final flow volume was recorded.

Analysis

The flow rate in each bioreactor was calculated during the tracer study by collecting and measuring outflow at the effluent pipe of each bioreactor for 10 seconds. The HRT was estimated using the saturated flow volume (known internal bioreactor dimensions and average measured water depth in the sampling ports of each bioreactor) and media porosity of 0.70 (NRCS, 2016). Our 'estimated' HRT, which is a measure of theoretical HRT, is the measurement used for all calculations requiring a theoretical HRT.

$$HRT = \frac{V_s n}{Q} \tag{1}$$

where V_s is the saturated volume of the bioreactor, n is the media porosity, and Q is the flow rate.

Tracer residence time ($\bar{t}$) was evaluated as the sum of the incremental time steps (t) times the incremental concentration values (C), divided by the sum of the concentration values.

$$\bar{t} = \frac{\sum t_i c_i}{\sum c_i} \tag{2}$$

The effective *in-situ* porosity (θ) is based on the tracer residence time and is calculated by substituting $\bar{t}$ for HRT into equation 1.

The bioreactor flow and dispersion characteristics were evaluated using the Morrill Dispersion Index (MDI). MDI is defined as (Metcalf and Eddy, 2003):

$$MDI = \frac{t90}{t10} \quad (3)$$

where t_{90} is the time at which 90% of the cumulative tracer mass has eluted the column, and t_{10} is the time at which 10% of the cumulative tracer mass has eluted.

A simplified equation to evaluate hydraulic efficiency in a bioreactor with plug flow conditions can be written as (Persson et al., 1999):

$$\lambda = \frac{tp}{T} \quad (4)$$

where t_p is the time to peak tracer eluted, and T is the theoretical, or estimated, HRT. A hydraulic efficiency greater than 0.75 is considered good, while an efficiency below 0.5 is poor. Hydraulic efficiencies between 0.50 and 0.75 are considered satisfactory.

Short circuiting, S, may be evaluated from tracer test analysis as (Ta and Brignal, 1998):

$$S = \frac{t16}{t50} \quad (5)$$

where t_{16} is the time at which 16% of the cumulative tracer mass has eluted the column, and t_{50} is the time at which 50% of the cumulative tracer mass has eluted. Short circuiting is indicated with an S value nearer to zero, and an S value near 1.0 indicates a more ideal flow. The results at 10-min sample intervals (every other 5 min sample, and each of the 10 min samples) were used for MDI, λ, and S calculations to maintain even sampling intervals.

Results and Discussion

Particle Size Analysis

The percentage by mass of oven dried woodchips retained in the 25 mm screen was 8.95%, 19 mm screen was 10.9%, 12.7 mm screen was 25.7%, 9.5 mm screen was 18.4%, 4.75 mm screen was 23.6, 2.36 mm screen size was 6.65%, and 5.93% of the woodchips passed through the 2.36 mm screen. The effective size, or $D_{10,}$ is the diameter corresponding to 10% by mass finer. The woodchips approximately 21 months after installation and 15 months after the tracer study had an effective size of 3.82 mm, less than the 6.5 mm effective size of fresh woodchips from the same source reported by Christianson et al. (2010). The uniformity coefficient value (D_{60}/D_{10}) was 3.67 mm, greater than the previously reported value of 2. The lower effective size of the woodchips in this study is likely indicative of an increase in small particles due to degradation. The woodchips were collected from the top 76 to 101 mm (3 to 4 in.) of the bioreactors, and increased woodchip degradation is expected in the unsaturated zone. The smallest particles within the bioreactor would be more readily degraded or flushed from the system. This could also potentially reflect the change in the PSA that occurs over a nearly two-year period in the unsaturated zone of a functioning woodchip bioreactor.

Porosity Analysis

Effective porosity is defined as the pore volume or space contributing to fluid flow, whereas the total porosity also considers pore-bound water, typically assessed by drying. Table 1 presents *in-situ* porosity (as calculated from the tracer residence time) and drainable porosity since both have been used to calculate estimated HRT in previous studies. *In-situ* porosity ranges from 0.60 to 0.68 among the nine bioreactors, while drainable porosity ranges from 0.48 to 0.54. Drainable porosity was measured in June 2016, a full year after the reported tracer tests, and was therefore not used for HRT calculations. Woodchip total porosity has been reported as 0.85 or 0.89 (Ghane et al., 2014; Hoover et al., 2016). A standard porosity value of 0.70 has also been frequently reported in the literature (van Driel, 2006; Addy et al., 2016; NRCS, 2016). Christianson et al. (2010) reported a range of porosities of 0.66-0.78 for similar woodchips (same supplier and type). Van Driel (2006) indicated a 0.7 porosity, attributed to the coarse woodchips. In addition, an Iowa amendment to the National Engineering Handbook (NRCS, 2016), specified use of the 0.70 porosity for field bioreactor design.

Different methods have been reported in the literature for HRT determination, including effective porosity as drainable porosity (Cameron and Schipper, 2010; Feyereisen et al., 2016), and effective porosity determined by tracer residence time (van Driel et al., 2006). The 5-gal bucket method (Rosen et al., 2000; Ima and Mann, 2007), which likely leaves a substantial proportion of the internal pore spaces unsaturated, has also been utilized to evaluate porosity (Christianson et al., 2012; Lepine et al., 2016). We used a standard 0.70 porosity for the estimated HRT calculation, but have also reported alternative HRT values for comparison (table 1). The estimated HRT during the tracer test, based on flow rate, saturated volume, and 0.70 porosity, was 2.1 $\pm$ 0.3 h. The average tracer residence time (($\bar{t}$) was 2.3 $\pm$ 0.3 h, in close agreement with our estimated HRT value. Further evaluation indicates both good hydraulic efficiency ($\lambda = 0.78 \pm 0.03$), and no evidence of short circuiting ($S = 0.73 \pm 0.03$).

Tracer Study

Time series concentration of KBr from the pilot-scale bioreactors is presented in figure 2. An MDI value of 1.0 indicates ideal plug flow, with an MDI value of approximately 22 or above indicating a complete-mix reactor (Metcalf and Eddy, 2003). Calculated MDI values of 2.8 $\pm$ 0.3 indicate plug flow characteristics with low dispersion, consistent with previously reported values from field scale woodchip bioreactors of 3.5 and 4.2 (Christianson et al., 2011). The highest dispersion rate was observed for Bioreactor 1, with an MDI of 3.3. Bioreactor 8 had the lowest dispersion rate of 2.4.

Table 1. Summary of bioreactor hydraulic properties for each pilot scale bioreactor.

Bioreactor No.	1	2	3	4	5	6	7	8	9	Avg±SD
In-Situ Porosity	0.66	0.60	0.63	0.67	0.60	0.65	0.66	0.63	0.68	0.64 ± 0.03
Drainable Porosity[a]	0.54	n/a	0.51	0.53	0.53	0.48	0.50	0.52	0.50	0.51 ± 0.02
Estimated HRT[b]	1.8	2.4	2.0	1.9	2.2	2.0	2.0	2.6	1.9	2.1 ± 0.3
Theoretical HRT[b]	2.3	3.1	2.5	2.4	2.8	2.5	2.5	3.3	2.4	2.6 ± 0.4
Drainable HRT[c]	1.4	n/a	1.4	1.4	1.6	1.4	1.4	2.0	1.4	1.5 ± 0.2
Tracer Residence Time	2.0	2.5	2.1	2.1	2.2	2.2	2.2	2.8	2.2	2.3 ± 0.3
Tracer Recovery[d]	83%	69%	77%	72%	80%	78%	78%	79%	78%	77 ± 4%
MDI	3.3	2.7	2.7	2.8	2.7	2.6	2.8	2.4	3.1	2.8 ± 0.3
Hydraulic Efficiency (λ)	0.80	0.79	0.81	0.77	0.73	0.79	0.80	0.79	0.74	0.78 ± 0.03
Short Circuiting (*S*)	0.68	0.74	0.74	0.75	0.74	0.74	0.75	0.76	0.69	0.73 ± 0.03

[a] Drainable porosity was measured in June, 2016, and is not necessarily representative of values at time of the tracer test. Due to misreading the bioreactor 2 meter, a drainable porosity measurement is not available.

[b] Estimated and theoretical HRTs were calculated using porosities of 0.70 and 0.89, respectively. Both measures of HRT are theoretical values, but have been termed 'estimated' and 'theoretical' to differentiate the two.

[c] Drainable HRT is based on drainable porosity determined 11 months after the tracer test.

[d] Tracer recovery percentages were estimated using a single point discharge rate measurement for each bioreactor toward the end of the tracer test.

The average Br^- recovery was 77 ± 4%, which is slightly lower than the 84% Br^- recovery measured by Jaynes et al. (2016) in a polyethylene-enclosed pilot-scale woodchip bioreactor (table 1). Christianson et al. (2011) reported a tracer recovery range of 40-101% for sealed pilot-scale bioreactors. Jaynes et al. (2016) determined that a mobile-immobile (MIM) system of transport could be used to describe Br^- tracer movement through a woodchip bioreactor, where Br^- may be temporarily retained in dead end and internal pore spaces within the woodchips, which may account for lower than expected recovery rates. Bromide has previously been considered an ideal tracer, but information on Br^- adsorption to wood has not been reported in the literature (Jaynes et al., 2016). It is also important to highlight that the tracer study was conducted at an estimated 2 HRT with some variation between bioreactors, which is shorter than a typical HRT in a field scale bioreactor. A longer HRT might have allowed for additional Br^- retention or sorption to wood and thus potentially lower recovery rates.

Multiple approaches to statistical design are possible with this system. Experimental designs may be completely randomized, or a blocked randomized design in sets of three based on predetermined bioreactor characteristics such as MDI values. Bioreactors might also be blocked based on experimental factors such as flow, influent water quality, or fill materials. The design of the pilot-scale bioreactor system allows for near complete isolation of each bioreactor for analysis, with the supply tanks as the common factor.

CONCLUSIONS

These pilot-scale bioreactors were designed to achieve a wide range of HRTs, with 2 h being the lowest target retention time. With adjustment of the influent control structure gate valves, and the outflow water control structure stoplog depth, it is conceivable that most experimental HRTs within a range of flow conditions expected in field settings can be achieved, including HRTs below 2 h and above 48 h.

Future modification of the supply tank manifold may enable further isolation, utilizing an individual tank as the

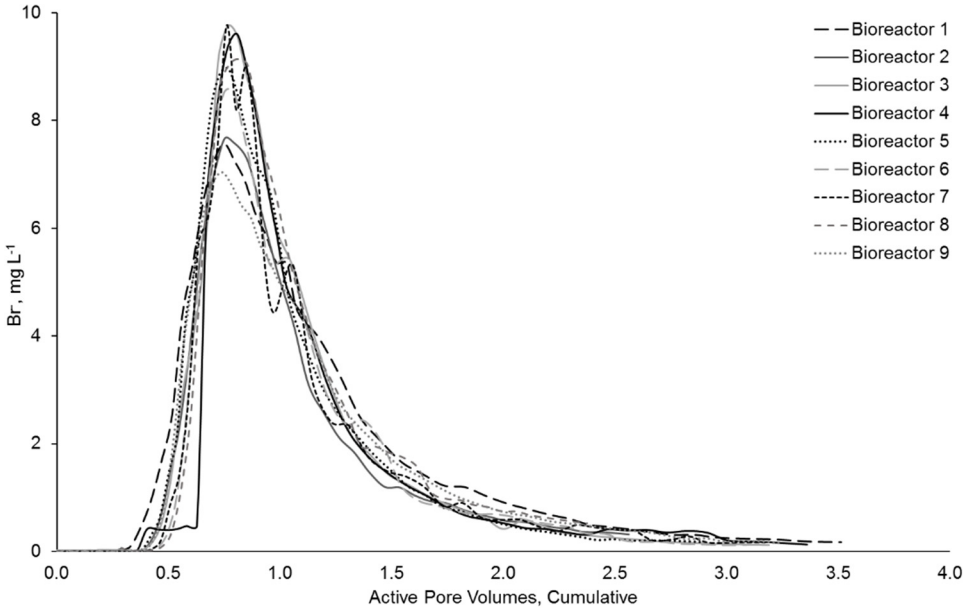

Figure. 2. Concentration vs. time tracer response for nine pilot-scaled denitrification woodchip bioreactors.

source water, or a combination of the three, depending on needs. The dosing ports at each pilot-scale bioreactor inlet enable specific modification, such as nutrient concentrations or pathogen indicators. Future modifications to the pilot-bioreactor are possible, such as excavation of the existing woodchips and refilling with alternate materials. The flexible design of the system is useful for answering scientific questions related to bioreactor performance and to inform engineering design.

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REFERENCES

Addy, K., Gold, A. J., Christianson, L. E., David, M. B., Schipper, L. A., & Ratigan, N. A. (2016). Denitrifying bioreactors for nitrate removal: A meta-analysis. *JEQ, 45*(3), 873-881. http://dx.doi.org/10.2134/jeq2015.07.0399

Blowes, D. W., Robertson, W. D., Ptacek, C. J., & Merkley, C. (1994). Removal of agricultural nitrate from tile-drainage effluent water using in-line bioreactors. *J. Contam. Hydrol., 15*(3), 207-221. http://dx.doi.org/10.1016/0169-7722(94)90025-6

Cameron, S. G., & Schipper, L. A. (2010). Nitrate removal and hydraulic performance of organic carbon for use in denitrification beds. *Ecol. Eng., 36*(11), 1588-1595. http://dx.doi.org/10.1016/j.ecoleng.2010.03.010

Christianson, L. E., Bhandari, A., & Helmers, M. (2011). Pilot-scale evaluation of denitrification drainage bioreactors: Reactor geometry and performance. *J. Environ. Eng., 137*(4), 213-220. http://dx.doi.org/10.1061/(ASCE)EE.1943-7870.0000316

Christianson, L. E., Bhandari, A., Helmers, M., Kult, K., Sutphin, T., & Wolf, R. (2012). Performance evaluation of four field-scale agricultural drainage denitrification bioreactors in Iowa. *Trans. ASABE, 55*(6), 2163-2174. http://dx.doi.org/10.13031/2013.42508

Christianson, L. E., Castello, A., Christianson, R., Helmers, M., & Bhandari, A. (2010). Technical note: Hydraulic property determination of denitrifying bioreactor fill media. *Appl. Eng. Agric., 26*(5), 849-854. http://dx.doi.org/10.13031/2013.34946

Christianson, L. E., Helmers, M., Bhandari, A., & Moorman, T. (2013). Internal hydraulics of an agricultural drainage denitrification bioreactor. *Ecol. Eng., 52*, 298-307. http://dx.doi.org/10.1016/j.ecoleng.2012.11.001

David, M. B., Gentry, L. E., Cooke, R. A., & Herbstritt, S. M. (2016). Temperature and substrate control woodchip bioreactor performance in reducing tile nitrate loads in east-central Illinois. *JEQ, 45*(3), 822-829. http://dx.doi.org/10.2134/jeq2015.06.0296

Davidson, E. A., Janssens, I. A., & Luo, Y. (2006). On the variability of respiration in terrestrial ecosystems: Moving beyond Q10. *Global Change Biol., 12*(2), 154-164. http://dx.doi.org/10.1111/j.1365-2486.2005.01065.x

Elgood, Z., Robertson, W. D., Schiff, S. L., & Elgood, R. (2010). Nitrate removal and greenhouse gas production in a stream-bed denitrifying bioreactor. *Ecol. Eng., 36*(11), 1575-1580. http://dx.doi.org/10.1016/j.ecoleng.2010.03.011

Fenton, O., Healy, M. G., Brennan, F., Jahangir, M. M. R., Lanigan, G. J., Richards, K. G.,... Ibrahim, T. G. (2014). Permeable reactive interceptors: Blocking diffuse nutrient and greenhouse gases losses in key areas of the farming landscape. *J. Agric. Sci., 152*(S1), 71-81. http://dx.doi.org/10.1017/S0021859613000944

Feyereisen, G. W., Moorman, T. B., Christianson, L. E., Venterea, R. T., Coulter, J. A., & Tschirner, U. W. (2016). Performance of agricultural residue media in laboratory denitrifying bioreactors at low temperatures. *JEQ, 45*(3), 779-787. http://dx.doi.org/10.2134/jeq2015.07.0407

Ghane, E., Fausey, N. R., & Brown, L. C. (2014). Non-Darcy flow of water through woodchip media. *J. Hydrol., 519*(Part D), 3400-3409. http://dx.doi.org/10.1016/j.jhydrol.2014.09.065

Ghane, E., Fausey, N. R., & Brown, L. C. (2015). Modeling nitrate removal in a denitrification bed. *Water Res., 71*, 294-305. http://dx.doi.org/10.1016/j.watres.2014.10.039

Greenan, C. M., Moorman, T. B., Parkin, T. B., Kaspar, T. C., & Jaynes, D. B. (2009). Denitrification in wood chip bioreactors at different water flows. *JEQ, 38*(4), 1664-1671. http://dx.doi.org/10.2134/jeq2008.0413

Healy, M. G., Barrett, M., Lanigan, G. J., Serrenho, A. J., Ibrahim, T. G., Thornton, S. F.,... Fenton, O. (2015). Optimizing nitrate removal and evaluating pollution swapping trade-offs from laboratory denitrification bioreactors. *Ecol. Eng., 74*, 290-301. http://dx.doi.org/10.1016/j.ecoleng.2014.10.005

Healy, M. G., Ibrahim, T. G., Lanigan, G. J., Serrenho, A. J., & Fenton, O. (2012). Nitrate removal rate, efficiency and pollution swapping potential of different organic carbon media in laboratory denitrification bioreactors. *Ecol. Eng., 40*, 198-209. http://dx.doi.org/10.1016/j.ecoleng.2011.12.010

Hoover, N. L., Bhandari, A., Soupir, M. L., & Moorman, T. B. (2016). Woodchip denitrification bioreactors: Impact of temperature and hydraulic retention time on nitrate removal. *JEQ, 45*(3), 803-812. http://dx.doi.org/10.2134/jeq2015.03.0161

Ima, C., & Mann, D. (2007). Physical properties of woodchip: Compost mixtures used as biofilter media. Manuscript BC 07 005. *9*. International Commission of Agricultural Engineering (CIGR, Commission Internationale du Genie Rural) E-Journal Vol. 9.

INRS. (2014). Iowa nutrient reduction strategy: A science and technology-based framework to assess and reduce nutrients to Iowa waters and the Gulf of Mexico. Retrieved from http://www.nutrientstrategy.iastate.edu/sites/default/files/documents/NRSfull-141001.pdf

Jaynes, D.B., Moorman, T.B., Parkin, T.B., Kaspar, T.C. (2016). Simulating woodchip bioreactor performance using a dual-porosity model. *JEQ, 45*(3), 830-838. doi:10.2134/jeq2015.07.0342

Lepine, C., Christianson, L. E., Sharrer, K., & Summerfelt, S. (2016). Optimizing hydraulic retention times in denitrifying woodchip bioreactors treating recirculating aquaculture system wastewater. *JEQ, 45*(3), 813-821. http://dx.doi.org/10.2134/jeq2015.05.0242

Metcalf, L., & Eddy, H. P. (2003). *Wastewater engineering: Treatment and reuse* (4th ed.). Boston, MA: McGraw-Hill.

NRCS. (2015). Conservation practice standard denitrifying bioreactor. Code 605.

NRCS. (2016). Iowa Amendment to the Engineering Field Handbook. NEH Part 650 Amendment IA68, 650.1429 Denitrifying Bioreactor. Retrieved from https://efotg.sc.egov.usda.gov/references/public/IA/EFH_IA-68_Chap14_DenitrifyingBioreactors.pdf

Persson, J., Somes, N. L. G., & Wong, T. H. F. (1999). Hydraulics efficiency of constructed wetlands and ponds. *Water Sci. Technol., 40*(3), 291-300. http://dx.doi.org/10.1016/S0273-1223(99)00448-5

Robertson, W. D. (2010). Nitrate removal rates in woodchip media of varying age. *Ecol. Eng., 36*(11), 1581-1587. http://dx.doi.org/10.1016/j.ecoleng.2010.01.008

Rosen, C. J., T. R. Halbach, and R. Mugaas. 2000. Composting and Mulching: A guide to Managing Organic Yard Wastes. University of Minnesota Extension Service, BU-3296- F.

Schipper, L. A., Robertson, W. D., Gold, A. J., Jaynes, D. B., & Cameron, S. C. (2010). Denitrifying bioreactors: An approach for reducing nitrate loads to receiving waters. *Ecol. Eng., 36*(11), 1532-1543. http://dx.doi.org/10.1016/j.ecoleng.2010.04.008

Shih, R., Robertson, W. D., Schiff, S. L., & Rudolph, D. L. (2011). Nitrate controls methyl mercury production in a streambed bioreactor. *JEQ, 40*(5), 1586-1592. http://dx.doi.org/10.2134/jeq2011.0072

Ta, C. T., & Brignal, W. J. (1998). Application of computational fluid dynamics technique to storage reservoir studies. *Water Sci. Technol., 37*(2), 219-226. http://dx.doi.org/10.1016/S0273-1223(98)00027-4

ThermoScientific. 2012. Dionex ICS-2100 Ion chromatography system operator's manual. Document No. 065291, Rev 03.

van Driel, P. W., Robertson, W. D., & Merkley, L. C. (2006). Denitrification of agricultural drainage using wood-based reactors. *Trans. ASABE, 49*(2), 565-573. http://dx.doi.org/10.13031/2013.20391

Warneke, S., Schipper, L.A., Brueswitz, D.A., McDonald, I., Cameron, S. (2011). Rates, controls and potential adverse effects of nitrate removal in a denitrification bed. *Ecol. Eng., 37*(3), 511-522. http://dx.doi.org.proxy.lib.iastate.edu/10.1016/j.ecoleng.2010.12.006