Moving Denitrifying Bioreactors beyond Proof of Concept: Introduction to the Special Section

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Abstract

Denitrifying bioreactors are organic carbon-filled excavations designed to enhance the natural process of denitrification for the simple, passive treatment of nitrate-nitrogen. Research on and installation of these bioreactors has accelerated within the past 10 years, particularly in watersheds concerned about high nonpoint-source nitrate loads and also for tertiary wastewater treatment. This special section, inspired by the meeting of the Managing Denitrification in Agronomic Systems Community at the 2014 Annual Meeting of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, aims to firmly establish that denitrifying bioreactors have moved beyond the proof of concept and to show that these systems can now be considered an effective tool to reduce nitrate loads in certain point and nonpoint source nitrate-laden waters. A total of some wastewaters have moved beyond the proof of concept. This collection of 14 papers expands the peer-reviewed literature on denitrifying bioreactors into new locations, applications, and environmental conditions. There is momentum behind the pairing of wood-based bioreactors with other media (biochar, corn cobs) and in novel designs (e.g., use within treatment trains or use of baffles) to broaden applicability into new kinds of waters and pollutants and to improve performance under challenging field conditions such as cool early season agricultural drainage. Concerns about negative bioreactor by-products (nitrous oxide and hydrogen sulfide emissions, start-up nutrient flushing) are ongoing, but this translates into a significant research opportunity to develop more advanced designs and to fine tune management strategies. Future research must think more broadly to address bioreactor impacts on holistic watershed health and greenhouse gas balances and to facilitate collaborations that allow investigation of mechanisms within the bioreactor "black box."

Core Ideas

• Research on denitrifying bioreactors has accelerated within the past 10 years.
• Bioreactors are a demonstrated option for nitrate mitigation in appropriate contexts.
• Bioreactors have now moved beyond the proof of concept.
• Future research must think beyond the bioreactor "black box."

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doi:10.2134/jeq2016.01.0013
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Received 13 Jan. 2016.
Accepted 10 Mar. 2016.
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THE UBIQUITY and mutable nature of the nitrogen (N) cycle across multiple temporal and spatial scales makes it notoriously challenging to manage the negative unintended environmental consequences of human activities. However, enhancing the natural process of denitrification through addition of a solid organic carbon source and maintenance of anoxic conditions has proven successful as a relatively simple, passive treatment technology for removal of nitrate from wastewaters and agricultural outflows. Such “denitrifying bioreactors” commonly refer to a wood media-filled trench that either receives flow perpendicular to its longitudinal axis (i.e., denitrification wall, sawdust wall) or along its longitudinal axis via inflow and outflow manifolds (Schipper et al., 2010). Original studies of this concept in Canada (Blowes et al., 1994; Robertson and Cherry, 1995) and New Zealand (Schipper and Vojvodic-Vukovic, 1998) and later work in the United States (Cooke et al., 2001) formed the foundation from which this field has grown. Research on enhanced denitrification practices has accelerated within the past 10 years with a nearly exponential trend of related published work (Addy et al., 2016).

The recent inclusion of woodchip bioreactors in several US midwestern states’ official nutrient reduction strategies (IDALS, 2014; Illinois Nutrient Loss Reduction Strategy, 2015; MN PCA, 2014), as well as the release of a federal USDA Natural Resources Conservation Service conservation practice standard (USDA-NRCS, 2015), speaks to the acceptance of bioreactors for treatment of nitrate in agricultural drainage (i.e., tile drainage). This technology also presents a marketable opportunity with several private groups now offering design services. At the 2014 Annual Meeting of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, the ASA Managing Denitrification in Agronomic Systems Community identified the opportunity to capture the meeting’s discussion through this special section to more broadly communicate the momentum within this field. Our aim is to demonstrate that denitrifying bioreactors have moved beyond the proof of concept and to show that these systems can now be considered an effective tool to reduce nitrate loads in certain point and nonpoint source nitrate-laden waters. A total of...
14 papers are contained in this special section, which concludes with a meta-analysis of denitrifying bioreactor performance by Addy et al. (2016), including data from papers within this special issue. Here, we highlight some of the main findings of these papers and suggest priorities for future research directions.

Overview of the Special Section

Improvements in Denitrifying Bioreactor Design and Placement

Denitrifying bioreactor fill media has remained an active research area as we seek treatment systems optimized not only for efficient N removal but also for removal of other water and air pollutants. Bock et al. (2016) and Pluer et al. (2016) both studied the addition of biochar to woodchip bioreactors, finding that its inclusion improves nitrate removal to some degree. Bock et al. (2016) observed this benefit most notably at higher bioreactor influent nitrate concentrations, but these findings require field-scale verification in additional locations. While it is unlikely that biochar acts directly as a carbon substrate for denitrification, its capacity to act as a short-term sorbent of nitrate needs to be explored to identify the most appropriate biochar composition. Moreover, the greater cost of biochar in comparison to woodchips will need to be considered (Bock et al., 2016) relative to any enhanced nitrate removal performance provided by the biochar. Incorporation of on-farm agricultural residues could help keep bioreactor installation costs low. Feyereisen et al. (2016) measured improved nitrate removal and reduced nitrous oxide (N₂O) production from woodchips amended with corn cobs. In this column study, nitrate removal rates ranged from 1.4 to 35 g N m⁻³ d⁻¹ at 15.5°C and 1.6 to 7.4 g N m⁻³ d⁻¹ at 1.5°C, with the greatest removal rates from corn cob and corn cob + woodchip treatments.

In addition to potential fill media, Fenton et al. (2016) present an advance on the trench-style design by using baffles to create a zig-zag flow pattern. Their bioreactor also allowed them to trial a modular or sectional design concept with separate compartments of soil and woodchips, and they recommend use of a postbed adsorption chamber (e.g., zeolite to sorb ammonium). Fenton et al. (2016) develop a sustainability index that might be used to understand the tradeoffs and benefits associated with adding additional treatment materials in-line with woodchips. Modular designs that allow pairing of multiple processes for additional contaminant removal are further explored by Choudhury et al. (2016), who paired a sedimentation basin and woodchip bioreactor for total suspended solids and total phosphorus (P) removal, as well as by Feyereisen et al. (2016), who paired a section of corn cobs followed by woodchips within their column experiment.

Several studies in this collection investigate the design parameter of hydraulic retention time (HRT), with increasing retention time generally improving N concentration or load reduction efficiency (Hoover et al., 2016; Lepine et al., 2016; Pluer et al., 2016). Several studies also establish that the N removal rate can have an inverse relationship with HRT, since long retention times can result in denitrification becoming nitrate limited, thus reducing removal rates at a bioreactor scale. Lepine et al. (2016) relate this HRT-removal rate relationship to N loading and find that lower retention times (i.e., higher flow rates and greater loading), as well as higher influent N concentrations at a consistent HRT (i.e., also higher loading), maximize N removal rates. David et al. (2016) observed decreasing N removal rates with increasing hydraulic retention time in the first year of operation of a field-scale bioreactor, but no relationship in the second or third year. Hoover et al. (2016) report removal efficiency increased from 8 to 55% as the retention time increased from 2 to 21 h, while removal rates remained relatively consistent across all detention times (ranging from 7.5 to 16 g N m⁻³ d⁻¹).

While many studies have assumed homogenous flow through all pores in bioreactors, Jaynes et al. (2016) explore flow through woodchips in both mobile and immobile domains. They developed a dual-porosity model that was able to closely model nitrate removal measured in a 2-yr field-scale study with little variation in fitted parameters, suggesting that accounting for immobile and mobile phases in bioreactors is an important consideration for models. The mobile phase was a relatively low percentage of the total porosity and should also be examined in other field-scale bioreactors. Improving our understanding of the movement of nitrate from inflow water to active sites of denitrification (potentially within woodchips) through diffusion will likely benefit modeling—and potentially, design—efforts.

While design of bioreactors continues to improve, it is equally important to optimize their position within the landscape to maximize interception of nitrate-laden water. Cui et al. (2016) used a three-dimensional flow and reactive transport model to evaluate several hypothetical sawdust bioreactor wall placements adjacent to a stream. Nitrate removal was optimized at locations where N flux to the stream was greatest, which was not necessarily the location of greatest groundwater flux to the stream.

The concluding paper in this special section by Addy et al. (2016) used a meta-analysis to summarize results of more than 50 individual bioreactors from the past two decades (including denitrifying walls, beds, and laboratory columns). Their analysis confirms many previously assumed properties of bioreactors, including that denitrifying beds have greater N removal rates than walls, that bioreactors require sufficient hydraulic retention time for anoxic denitrification conditions to develop, and that initial N removal rates (i.e., within the first year of operation) are greater than long-term N removal rates for wood-based enhanced denitrification systems. They also show nitrate removal rates to be dependent on temperature, although nitrate removal was still substantial at low water temperatures.

New Opportunities and Locations

One of the most exciting aspects of this special section was the expansion of the denitrifying bioreactor peer-reviewed literature into new areas, applications, and environmental conditions. The present collection includes studies from new locations such as New York, West Virginia, Maryland, and Minnesota (Cui et al., 2016; Feyereisen et al., 2016; Lepine et al., 2016; Pluer et al., 2016), as well as expansion of the technology in areas where bioreactors have been previously trialed (e.g., Iowa, Illinois, Ontario, New Zealand, and Ireland). Exploring different locations is important because testing performance under a wide range of environments allows stakeholders such as farmers and regulators to assess suitability of these systems within their local context. It is particularly important to evaluate bioreactors under a wide range of climates around the world to capture a variety of...
seasonal temperature and flow dynamics. Several of the present studies evaluate temperature impacts (Feyereisen et al., 2016; Hoover et al., 2016), with cool temperatures extremely relevant for bioreactors treating early-season agricultural tile drainage in northern locations such as Minnesota where there can be significant losses of nitrate during periods of snow melt or other areas of the US Midwest where there is tile flow during the winter. The meta-analysis that concludes this special section determined the $Q_{10}$ (or the factor by which N removal rates change for every 10 degree change in temperature) to be approximately 2.15 across bioreactor literature (Addy et al., 2016).

Beyond treatment of nonpoint-source pollutants, Choudhury et al. (2016) studied a bioreactor-sedimentation basin paired system for treatment of vegetable wash water. Their woodchip filter combined with an upstream sedimentation basin removed 71% of particulate P and 99% of total suspended solids in the wash water; dissolved P removal was not observed. Over 7 mo of operations, less than 10% of the woodchip’s primary pore space was infilled with sediment, suggesting a lifespan of several years for particulate P trapping (given an appropriately sized pretreatment settling basin).

Another use of denitrifying bioreactors is the treatment of wastewater. Lepine et al. (2016) measured very high nitrate removal rates when treating aquaculture wastewater (>39 g N m⁻³ d⁻¹) compared with previous agricultural tile drainage bioreactor studies. This was due in part to the wastewater’s chemical oxygen demand load supplementing carbon supply from woodchips to support additional denitrification. Because these systems are also used for tertiary treatment of effluents (see Rambags et al., 2016), nitrate-removal design criteria may need to consider carbon inputs to the bioreactor. With these new wastewater applications may come an associated desirable treatment of bacteria, viruses, and pathogens. Rambags et al. (2016) show that a woodchip bed in New Zealand removed bacteria (Escherichia coli, 2.9 $\log_{10}$ reduction) and viruses (F-specific RNA bacteriophage, 3.9 $\log_{10}$ reduction), removal that occurred mostly near the bioreactor inlet. This exciting early work points toward a need to understand woodchip bioreactor bacterial and virus removal mechanisms and to assess the longevity of bacterial/pathogen removal.

Ongoing Unwanted Effects

This focused collection contains several evaluations of enhanced-denitrification technology by-products, including N₂O production and loss, sulfate reduction leading to hydrogen sulfide (H₂S) production, and leaching of dissolved carbon, particularly during start up. Hoover et al. (2016) report that naturally weathered chips released less total organic carbon (TOC) than “fresh” woodchips and that column effluent TOC concentrations reached stream background levels within approximately 10 and 50 cumulative pore volumes for the two types of chips, respectively (or 5 and 24 d at a 12 h HRT, respectively). Feyereisen et al. (2016) found that although N removal rates were greater for corn cobs than woodchips, the corn cobs also released greater amounts of carbon into the effluent. Initial nutrient flushes of N (Bock et al., 2016), P (Pluer et al., 2016), and carbonaceous biochemical oxygen demand (cBOD₃; Rambags et al., 2016) are also reported. Fenton et al. (2016) prewashed woodchips before construction of their bioreactor to successfully reduce initial losses of TOC, N, and P. The practice of prewashing fill media before bioreactor construction could be more widely adopted to mitigate some of the start-up flushing, so long as the wash water is appropriately treated and not directly released to receiving waters.

Regardless of bioreactor age, ongoing emissions of H₂S, N₂O, or methane (see Fenton et al., 2016) can be detrimental to the environment. Lepine et al. (2016) determined sulfate reduction and sulfide formation is exacerbated under prolonged N-limited conditions; in other words, bioreactors consistently removing 100% of the nitrate load under extended overly long retention times resulted in sulfate reduction to a greater extent than bioreactors operating under shorter HRTs that sporadically achieved 100% N removal. This sulfide formation could be reduced through manipulation of hydraulic retention time to ensure N is not limiting. A number of studies generally found N₂O to be a small part of the N balance, which was consistent with previous work. For example, David et al. (2016) found <1% of the nitrate removed was released as N₂O from the surface of an Illinois bioreactor, although dissolved N₂O losses were not measured. Proportionally, releases of N₂O may be greater under lower temperatures; Feyereisen et al. (2016) report the production of N₂O was 7.5% of nitrate removed at 1.5°C and only 1.9% at 15.5°C. Lepine et al. (2016) and Jones and Kult (2016) both investigated alkalinity production, and Jones and Kult (2016) suggest that alkalinity monitoring could be used as a proxy to evaluate potential N₂O emissions. They report that while several established bioreactors in Iowa removed 50 to 80% of the annual average N load, alkalinity/inorganic carbon data indicate that N₂O may have been regularly produced in at least three of the bioreactors. Bioreactor influent and effluent dissolved N₂O concentrations showed that when N₂O was produced across a bioreactor, the effluent inorganic carbon concentrations were lower than what was predicted by stoichiometry; conversely, when N₂O was not produced, the effluent inorganic carbon concentrations were greater than predicted (Jones and Kult, 2016).

An Eye on the Horizon: The Future of Denitrifying Bioreactors

Although significant advances in understanding of bioreactor functioning and design have been made over the past two decades, the positive momentum in this field indicates that many research opportunities remain. Looking to the coming years, we encourage community members to move beyond laboratory-scale studies unless truly novel questions can be answered. At laboratory scales, the effects of hydraulic retention time, temperature, and carbon media on nitrate removal have been well studied. Nevertheless, controlled evaluations in the laboratory could be useful to test novel designs for the removal of multiple contaminants and the reduction of unintended by-products and to increase understanding of microbial and fungal dynamics within these treatment systems. There is an increasing need for large-scale, translational research that evaluates field-scale issues such as longevity and management. End-of-life media replacement and design rejuvenation are timely applied research issues facing this field. The future must hold studies that look beyond the bioreactor “black box” through use of more advanced
monitoring techniques. Real-time, continuous sensors can help more closely evaluate bioreactor performance under relatively rapid temperature and flow changes. The research community would benefit from publication (perhaps in supplemental materials) of semiprocessed data to allow testing of developed models. Such data would include, at a minimum, bioreactor location, construction date, nitrate concentrations at the inlet and outlet, flow rate, and bed temperature through time. Careful reporting of saturated bioreactor volume (see below) is also important to allow accurate calculation of removal rates.

Long-term monitoring continues to be important as a bioreactor’s high N removal during the first season can be misleading (David et al., 2016). Goeller et al. (2016) propose a more holistic approach to monitoring by considering bioreactors within the context of stream health. They suggest looking beyond the standard nitrate “in–out” balance to additionally evaluate other environmental factors and processes that underpin important ecosystem functions. Bioreactors and the health of downstream waters are intrinsically linked; for example, nitrate loading affects both bioreactor N removal and leaf and woody organic matter breakdown in streams, which is a fundamental ecological process (Goeller et al., 2016). Fenton et al. (2016) also think along these “holistic” lines through use of their sustainability index to assess not only bioreactor nitrate removal but also ammonium and dissolved reactive P generation. While still in the early days of development, this approach will highlight research areas that need further exploration to reduce adverse effects of denitrifying bioreactors while improving nitrate removal. Any such sustainability weighting factors should be based on local, national, or international environmental policy priorities (Fenton et al., 2016). These studies point toward a more integrated direction for future work; thinking beyond the bioreactor “black box” is the next frontier for this field.

As work continues, calculation of N removal metrics and comparison between studies will become increasingly important. In this special section, we encouraged both reporting of N removal rate (g nitrate-nitrogen removed per m³ of bioreactor per d) and N removal efficiency (% reduction). Annual percentage N load reduction (i.e., total annual N removal efficiency, including untreated by-pass flow) is an important metric for bioreactors that are designed to include by-pass flow under high flow events. For example, David et al. (2016) report N removal rates of 1.2 to 11 g N m⁻³ d⁻¹ from a bioreactor in Illinois, which is within a reasonable range compared with other field-scale tile drainage bioreactors, but their total annual N load removal efficiencies were only 3 to 7%. Removal efficiencies are important for context within state-based nutrient reduction strategies and comparison of bioreactors with other agricultural practices, but the removal rate metric is best for comparing across bioreactors, which is necessary to advance the design science.

Specifically regarding N removal rate, it is important to clearly specify how the volume of the bioreactor is defined within the calculation—total volume of woodchips or saturated volume of the reactor. In theory, it is desirable for those two volumes to be equal so the entire woodchip investment is being used for treatment; in practice, bioreactors are often installed with a top layer of unsaturated woodchips to provide additional carbon as the chips settle or are consumed. Consideration of the total bioreactor volume (saturated + unsaturated zones) best reflects the entire investment from a producer’s capital expense standpoint and may reduce some calculation uncertainty as the saturated depth is rarely exactly known (i.e., a linear head drop across bioreactor length may be an incorrect assumption; Christianson et al., 2013). Nevertheless, including the unsaturated portion is less appropriate to compare actual N removal on a volumetric basis between designs. Others have recommended calculating N removal rate based on the water-filled pore space (Ghane et al., 2015), although at the field scale, the actual saturated volume needs to be closely monitored, and fill media porosity must also be assumed or measured. Regardless of the method chosen, it is imperative to explicitly describe the calculation and provide details or estimates of saturated volume and media porosity for readers.

Looking to the future of this field, there is untapped potential to collaborate broadly to expand the technology and to improve performance and applicability. Potential overlap exists with forestry and wood products specialists, civil engineers, sensor developers, stream ecologists, microbiologists, sociologists, and many others. Inclusion of GIS specialists on denitrifying bioreactor teams may help better target bioreactor placement, and modelers can help evaluate performance both hydraulically and biochemically. A careful cost–benefit assessment of bioreactors at a catchment scale where spatial positioning is optimized is needed to determine where and to what extent bioreactors can be dove-tailed with other mitigation efforts.

As interest in bioreactors continues to grow outside of the research realm, opportunities for private sector involvement have increased. There is a significant need for additional technical capacity across rural landscapes to design, implement, and monitor practices like denitrifying bioreactors for treatment of agricultural drainage. Perhaps most important within the context of achieving significant water quality improvement, farmers, landowners, and agribusiness groups will continue to be vital partners for denitrifying bioreactor research, demonstration, and implementation. Measureable reductions in nonpoint-source N pollution due to enhanced denitrification practices will require open dialogue, sharing of results, and honest feedback between those in the laboratory, in regulatory offices, and with boots on the ground. The ability to share the installation cost of these practices with society (i.e., through federal incentive payments) will play a vital role in widespread adoption and resulting water quality improvement. Ultimate successful implementation will occur when landowners view installation of a bioreactor in the same light as tillage or planting operations.

Acknowledgments

The guest editors for this special collection, Drs. Christianson and Schipper, were among the participants in the American Society of Agronomy’s “Managing Denitrification in Agronomic Systems Community” session at the annual meeting of the American Society of Agronomy, Crop Science Society of American, and Soil Science Society of American held in Long Beach, CA, 2–5 November 2014. This special section was developed from presentations during that session, supplemented with other recent studies. We extend a special thanks to the authors, reviewers, editors, and staff at the Journal of Environmental Quality for their insight, guidance, and cooperation in assembling this timely special section.