

Core Ideas

- Bioreactors can be designed to remove nitrate from drainage ditches.
- Designing bioreactors for ditch drainage requires site-specific flexibility.
- All mid-Atlantic ditch bioreactors tested removed nitrate from drainage water.
- Practical concerns will require adjustments to design and installation.

Enhanced Denitrification Bioreactors Hold Promise for Mid-Atlantic Ditch Drainage

L. E. Christianson,* A. S. Collick, R. B. Bryant, T. Rosen, E. M. Bock, A. L. Allen, P. J. A. Kleinman, E. B. May, A. R. Buda, J. Robinson, G. J. Folmar, and Z. M. Easton

Abstract: There is strong interest in adapting denitrifying bioreactors to mid-Atlantic drainage systems to help address Chesapeake Bay water quality goals. Three ditch drainage-oriented bioreactors were constructed in 2015 in Maryland to evaluate site-specific design and installation concerns and nitrate ($\text{NO}_3\text{-N}$) removal. All three bioreactor types removed $\text{NO}_3\text{-N}$, as measured by load and/or concentration reduction, showing promise for denitrifying bioreactors in the mid-Atlantic's low gradient Coastal Plain landscape. The ditch diversion bioreactor (25% $\text{NO}_3\text{-N}$ load reduction; $0.97 \text{ g NO}_3\text{-N removed m}^{-3} \text{ d}^{-1}$) and the sawdust denitrification wall adjacent to a ditch (>90% $\text{NO}_3\text{-N}$ concentration reduction; $1.9\text{--}2.9 \text{ g NO}_3\text{-N removed m}^{-3} \text{ d}^{-1}$) had removal rates within range of the literature. The in-ditch bioreactor averaged 65% $\text{NO}_3\text{-N}$ concentration reduction, but sedimentation is expected to be one of the biggest challenges. A robust water balance is critical for future assessment of bioreactors' contribution to water quality improvement in low gradient mid-Atlantic landscapes.

L.E. Christianson, Dep. of Crop Sciences, Univ. of Illinois at Urbana-Champaign, Urbana, IL; A.S. Collick, A.L. Allen, and E.B. May, Univ. of Maryland Eastern Shore, Princess Anne, MD; R.B. Bryant, P.J.A. Kleinman, A.R. Buda, and G.J. Folmar, Pasture Systems and Watershed Management Research Unit, USDA-ARS, University Park, PA; T. Rosen, Midshore Riverkeeper Conservancy, Easton, MD; E.M. Bock and Z.M. Easton, Biological Systems Engineering, Virginia Tech, Blacksburg, VA; J. Robinson, Earth and Environmental Sciences, Rutgers Univ., Newark, NJ. Mention of trade names does not constitute endorsement by the US Department of Agriculture.

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*Corresponding author (LEChris@illinois.edu).

SOME OF THE OLDEST US agricultural drainage improvements are in the mid-Atlantic region (Shirmohammadi et al., 1995). Although these drainage networks provide essential agricultural production benefits, they also contribute to off-site water quality challenges, particularly regarding the Chesapeake Bay. There is strong interest in adapting wood-based denitrifying bioreactors—which have shown success in removing nitrate ($\text{NO}_3\text{-N}$) from agricultural subsurface “tile” drainage in the US Midwest—to mid-Atlantic drainage systems that are dominated by ditch networks. However, adapting these practices to nearly level (<2% slopes) Coastal Plain landscapes presents a challenge for traditional bioreactors because of low landscape gradients and proximity to sea level. Although midwestern drainage systems are also characterized by low gradients, the typically larger scale of drainage networks allows for greater overall head change across the drainage system. Moreover, surface drainage networks in the mid-Atlantic are fed in part by shallow groundwater, treatment of which requires a different approach than pipe-based tile drainage. Design innovations for this landscape are necessary to expand use of this practical technology.

The most common type of denitrifying bioreactor is designed to treat tile drainage and generally has annual nitrogen (N) load removal efficiencies and removal rates averaging 25 to 45% and $4.7 \text{ g N removed m}^{-3} \text{ d}^{-1}$, respectively (Addy et al., 2016; Rosen and Christianson, 2017). A modification of the tile drainage bioreactor is the in-ditch bioreactor, where the bed of a drainage ditch is excavated and replaced with woodchips topped with gravel (Robertson and Merkley, 2009). Another modification to treat ditch drainage involves diverting the water into a bioreactor constructed to the side of the ditch. Lastly, sawdust-amended denitrification walls, which consist of mixtures of native soil and sawdust, can be installed parallel to drainage ditches to treat groundwater flowing to the ditch (Schipper and Vojvodic-Vukovic, 1998; Schipper et al., 2004; Schmidt and Clark, 2012).

Abbreviations: UMES, University of Maryland Eastern Shore.

Our objective was to evaluate the practical design and installation concerns and early NO₃-N removal of these three categories of ditch-treatment bioreactors to determine the feasibility of implementing these practices within the mid-Atlantic's low gradient Coastal Plain landscape.

Materials and Methods

Ditch Diversion Bioreactor

A ditch diversion bioreactor (35 × 7.9 × 0.9 m) was designed to meet specifications of the USDA-NRCS Maryland denitrifying bioreactor conservation practice standard (USDA-NRCS, 2015) and installed in Caroline County, MD, in November 2015 to treat drainage from a 35-ha surface watershed (Table 1). A large control structure (AgriDrain Corp.) diverted the ditch drainage to the bioreactor, which was routed back to the ditch after treatment. Bioreactor and bypass flow were estimated using pressure transducers (Solinst, Levelogger Model 3001) and weir equations. Inlet and outlet samples were collected daily over 14-d periods (ISCO Avalanche refrigerated auto-samplers) and analyzed at the University of Maryland Eastern Shore (UMES) Nutrient Analysis Laboratory.

Sawdust Denitrification Walls

In February 2015, an enhanced-denitrification groundwater wall (22 × 0.6 × 1.5 m; 1:1 sawdust and native soil mixture with a total carbon/nitrogen ratio >70) was constructed at the UMES Research and Teaching Farm (Princess Anne, MD). The wall was paired up gradient of an existing 22-m permeable reactive barrier of gypsum (a "curtain" as described by Bryant et al., 2012) bordering a field drainage ditch (Table 1). The gypsum curtain was installed in 2010 using flue gas desulfurization gypsum to immobilize P in shallow groundwater.

Groundwater flow rate was measured using time-lapse imagery of the movement of a tracer using electrical resistivity

imaging (Syscal Pro, IRIS Instruments). Flow velocities were also estimated using the MODFLOW model. Three transects of monitoring wells were spaced equally along the length of the wall. Each transect consisted of four nests of wells to allow groundwater sampling (i) up-gradient of the sawdust wall (near field edge), (ii) in the wall, (iii) between the wall and gypsum curtain, and (iv) down-gradient of the gypsum curtain (near the ditch edge). Each well nest contained a polyvinyl chloride well screened at 1.2 and 2.2 m. Groundwater samples were collected monthly and analyzed at the UMES Nutrient Analysis Laboratory. Due to potential analytical interference with high sulfate concentrations associated with the gypsum wall, only NO₃-N results from up-gradient of and within the sawdust wall were presented.

In-Ditch Bioreactor

A 92-m in-ditch bioreactor was installed in December 2015 on a private farm near Crisfield, MD, in three sections of 27, 38, and 27 m (designed for hydraulic retention times of 4.6–11.5 h). The ditch bottom was excavated to ≈0.6 and 0.3 m below the bed elevation at the upstream (inlet) and downstream (outlet) ends, respectively (Fig. 1). Three reinforced wooden berms (91, 76, and 61 cm height) separated the bioreactor sections, which were filled with woodchips to depths of 46, 30, and 15 cm, respectively. Each bioreactor segment was covered with approximately 10 to 15 cm of #57 stone to secure the woodchips, although wire or plastic mesh could also be used.

To drain the individual bioreactor segments, a flow collection manifold (two 1.5-m lengths of 10-cm perforated tile connected by a "T") was installed upstream of each of the three wooden berms. Water from each bioreactor segment emptied into an underdrain (76-m nonperforated tile; 10-cm diam.). When an upstream bioreactor section filled to capacity, water that overflowed the berm was then treated by the next section. Bioreactor inlet and outlet samples were collected monthly

Table 1. Description of three enhanced denitrification bioreactors in the mid-Atlantic.

Site	Location	Farm	Soil type	Cropping rotation†	Installation date	Drainage treatment area	Ditch dimensions (width × depth)	Bioreactor dimensions (length × width × depth)	P removal
Ditch diversion bioreactor	Caroline County, MD	Private farm	Fallsington, Hambrook, Woodstown, Lenni, and Ingleside soil series; fine-loamy, siliceous, semiactive Typic Hapludults and fine-loamy, mixed, active, mesic Aquic Hapludults	soybean, lima bean, or sweet corn followed by spinach	Nov. 2015	35 (surface watershed)	4.0 (top) × 1.1	35 × 7.9 × 0.9	–
Drainage ditch sawdust wall	Somerset County, MD	UMES‡ Research and Teaching Farm	Quindocqua and Othello silt loam surface soils; mixed, active, mesic Typic Endoaquults	corn–winter wheat cover crop–soybean rotation	Feb. 2015	Shallow groundwater flowing to drainage ditch; 0.08-ha area of influence§	5.4 (avg.) × 1.0	22 × 0.6 × 1.5	Installed up-gradient of a gypsum curtain
In-ditch bioreactor	Somerset County, MD	Private farm	Woodstown, Manokin, and Annemessex soil series; fine-loamy, mixed, active, mesic Aquic Hapludults	corn–wheat–soybean	Dec. 2015	6.6 (surface watershed)	6.1 (top) × 0.7	Three in-line segments of 27–38 × 1.1 × 0.7	–

† Soybean, *Glycine max* (L.) Merr.; lima bean, *Phaseolus lunatus* L.; corn, *Zea mays* L.; spinach, *Spinacia oleracea* L.; wheat, *Triticum aestivum* L.

‡ UMES, University of Maryland Eastern Shore.

§ Area of influence for the sawdust wall was based on the length of the wall, lidar surface topography, and expert opinion of the site.

over a 4-mo period and sent to the UMES for analysis. Flow was not measured, so only $\text{NO}_3\text{-N}$ concentrations were available to assess this design. However, it was estimated that during base flow and high flows, approximately 10 to 30% and >50%, respectively, bypassed over the top of the bioreactor.

Laboratory Analysis

Water samples were stored at 4°C. Concentrations of $\text{NO}_3\text{-N}$ were determined colorimetrically with a QuikChem 8500 Series 2 Flow Injection Analyzer System (Lachat Instruments) using QuikChem method 10-107-04-1-R (Lachat Instruments, 2008).

Results and Discussion

Design and Installation Considerations

The sawdust wall was the easiest (based on person-hours) and least expensive of the three bioreactor types to install, with installation occurring within 1 d. The relatively more complicated in-ditch design required 2 d for installation and was more intensive considering the more complicated design (i.e., to prevent ditch overtopping). While a ditch diversion bioreactor may require removing land from production, the ditch diversion bioreactor's design process was more aligned with the design of tile drainage bioreactors, for which more experience exists (Christianson et al., 2013a; USDA-NRCS, 2015). They can be designed to fit within a minimum-width (10-m) Conservation Reserve Enhancement Project buffer adjacent to ditches (USDA-NRCS, 2012).

Approximate installation costs for the ditch diversion bioreactor (\$27,000; \$770 ha^{-1} treated), sawdust wall (<\$3,000; \$39,000 ha^{-1}), and in-ditch bioreactor (\$18,000; \$2,700 ha^{-1}), included wood media, estimated labor, and parts (e.g., wooden berms, control structures, miscellaneous piping, engineering fees where required). In comparison, Christianson et al. (2012) estimated costs of \$4,400 to \$11,800 (\$220 ha^{-1} to \$590 ha^{-1}) for tile

drainage bioreactors in the midwestern United States. The higher costs per hectare found here were a function of the estimated surface watersheds (diversion and in-ditch) or area of influence (sawdust wall), and may not be directly comparable with tile drainage treatment areas in the Midwest. The overall cost efficiencies of \$20 to \$30 kg N^{-1} and \$41 kg N^{-1} for the sawdust wall and ditch diversion bioreactor, respectively (using N removal rates discussed below; assuming a total annual flow period of 9 mo. and design life of 10 yr), were also higher than midwestern bioreactors assessed at

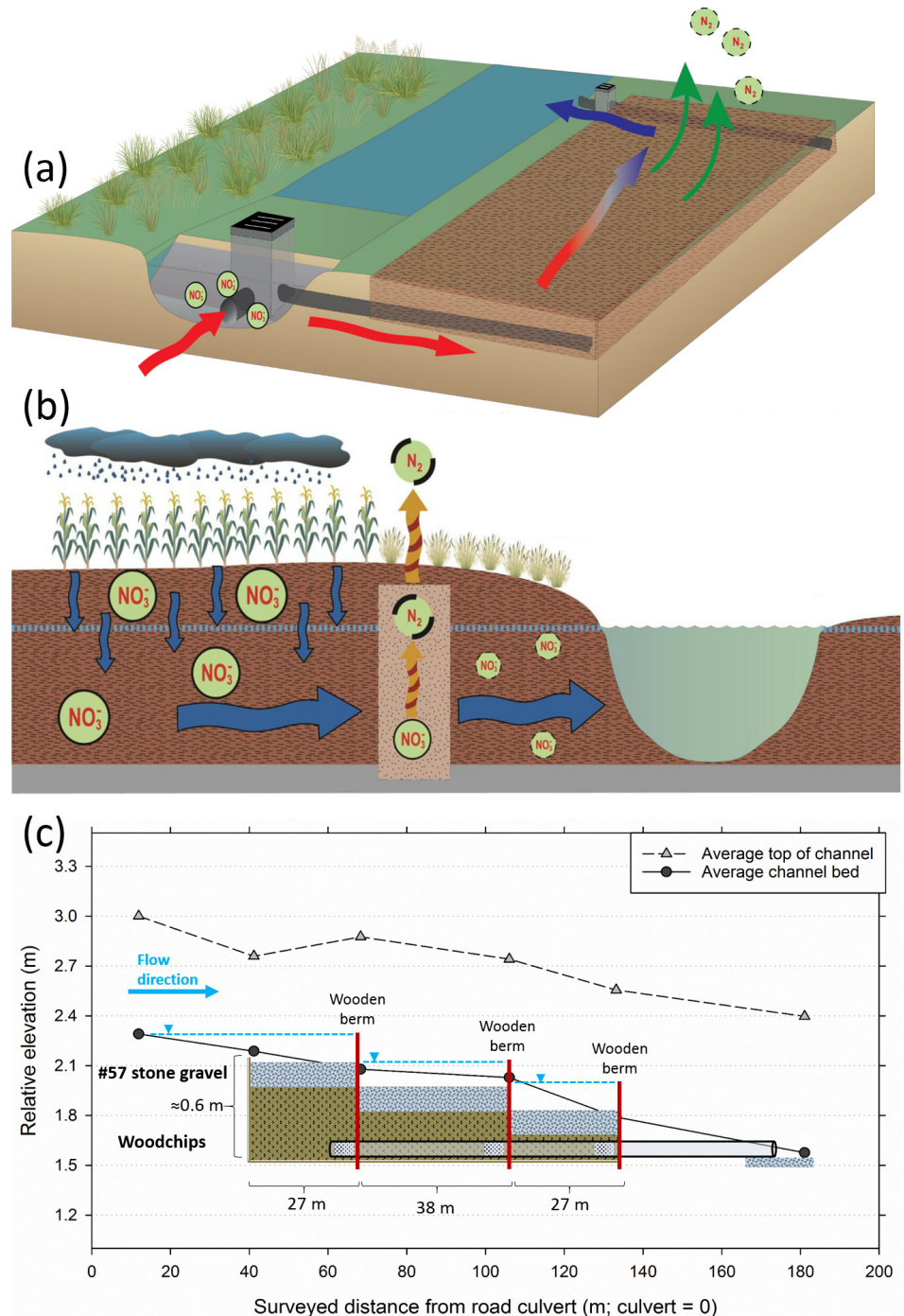


Fig. 1. Three categories of ditch-treatment bioreactors studied within the mid-Atlantic: (a) a ditch diversion bioreactor, (b) a sawdust denitrification wall, and (c) a cross-section schematic of the in-ditch bioreactor. Note x and y scales differ, and the road culvert was used as survey reference for practicality in (c).

\$2.10 kg N⁻¹ (Christianson et al., 2013b). While these costs point to the magnitude of start-up expense, they are difficult to extrapolate to other sites due to factors such as drainage configuration and local availability of wood media.

Bioreactor Performance

All bioreactors removed NO₃-N from drainage and/or ground waters. The ditch diversion bioreactor treated 33% of the ditch flow (24,750 m³ treated and 50,100 m³ bypassed), and provided average NO₃-N concentration and load reductions of 75 and 25%, respectively (3.98 and 0.98 mg NO₃-N L⁻¹ mean inflow and outflow, respectively; *n* = 67) over the 295-d monitoring period. The total load reduction of 72.8 kg N over this period resulted in an average removal rate of 0.97 g NO₃-N removed m⁻³ d⁻¹ given the full bioreactor dimensions. This removal rate was lower than a recent bioreactor meta-analysis's average of 4.7 g N m⁻³ d⁻¹ (Addy et al., 2016) but is certainly within range of tile drainage bioreactors (0.38–7.76 g N m⁻³ d⁻¹; Christianson et al., 2012). Performance could have potentially been improved by increasing the width to allow greater treatment volume capacity, although a major trade-off would be the need for greater land to be removed from farm production.

At the sawdust wall, groundwater NO₃-N concentrations up-gradient of the wall averaged 5.45 and 4.94 mg NO₃-N L⁻¹ in the 1.2-m- and 2.2-m-depth wells, whereas inside the wall, NO₃-N concentrations averaged 0.14 and 0.47 mg NO₃-N L⁻¹ for the two depths, respectively (*n* = 12 to 15), a >90% concentration reduction. Electrical resistivity imaging measurements of groundwater flow velocities and MODFLOW results indicate that saturated hydraulic conductivity at this site ranged from 0.26 to 0.33 m d⁻¹, resulting in sawdust wall hydraulic retention times of approximately 24 h. These conductivities, along with the average groundwater NO₃-N concentrations, yielded removal rates of 1.9 to 2.9 g N removed m⁻³ d⁻¹, which overlapped with sawdust wall performance reported elsewhere (0.5–2 g N removed m⁻³ d⁻¹; Schipper et al., 2010). Overall, there were few maintenance concerns with the walls, although the persistence of a spoil berm adjacent to the wall could be undesirable in some locations. There was some evidence that reduced permeability of the gypsum curtain may have eventually slowed the rate of water movement to the ditch. However, in regard to the sawdust wall, this reduced flow rate may have resulted in longer residence times and increased nitrate removal.

The in-ditch bioreactor performed well during the 4-mo monitoring period, with a 65% reduction in NO₃-N concentration between inlet and outlet, averaging 2.53 and 0.88 mg NO₃-N L⁻¹, respectively. In Ontario, Robertson and Merkley (2009) reported mean inlet and outlet NO₃-N concentrations of 4.80 and 1.04 mg NO₃-N L⁻¹ (78% concentration reduction) for an in-ditch bioreactor over a 1.5-yr period. After 6 mo, a layer of sediment was observed covering the third section of the bioreactor studied here, highlighting a key maintenance requirement also noted by Robertson and Merkley (2009). Some of this sediment undoubtedly derived from the over-steepening of ditch banks during the initial installation, something that could have been better mitigated

with stabilization practices. Nevertheless, this proof of concept in-ditch stepped bioreactor provided distinct benefits for adoption since no land was removed from production and no reduction in drainage capacity occurred as a result of installation. Indeed, feedback from the collaborating operator was positive. Further study is suggested to better understand the effects of sedimentation on in-ditch bioreactor hydraulics and NO₃-N removal as well as to develop improved design (e.g., an upstream sedimentation area) and maintenance recommendations.

Implications for Drainage Water Management on the Mid-Atlantic Coastal Plain

Results of this study show promise for a variety of bioreactor designs in the low gradient Coastal Plain landscapes of the US mid-Atlantic. The ditch diversion bioreactor had NO₃-N removal effectiveness similar to that of tile drain bioreactors common in the Midwest and offered the advantage of having standard design criteria that ensured greater success. However, the ditch diversion bioreactor was also the most expensive design to install and had a footprint of 277 m² for the 35-ha drainage catchment it treated. When paired with a riparian buffer, where land has already been taken out of production, subsidized versions of the ditch diversion bioreactor may be palatable to some landowners and conservation organizations as they are based on a simple, reliable design that does not require much maintenance. Similarly, the sawdust wall followed a simple design that was easily constructed, relatively effective in removing NO₃, and inexpensive, although it had a relatively small contributing area and therefore relatively expensive treatment efficiency. Documenting NO₃-N removal effectiveness for the sawdust wall was difficult due to the challenge of measuring lateral groundwater flow rates. To give credit for NO₃-N reduction with this practice, a practical solution would be to develop regional estimates of groundwater flow rates and accept those as applicable to certain soil and landscape conditions. Finally, the stepped-in-ditch bioreactor provided the unique quality of being compatible with existing drainage systems and not requiring a footprint outside of the drainage ditch. Its large catchment area suggests a high cost efficacy, even though it was intermediate in expense between the diversion and wall designs. Maintenance concerns were greatest with this design, particularly related to sediment deposition. In conclusion, our efforts point to the feasibility of implementing denitrifying bioreactors on low gradient landscapes of the mid-Atlantic Coastal Plain, and more work is needed to promote their adoption where excess nutrients in the Chesapeake Bay are of concern.

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