
Bioreactor construction at a New Zealand dairy farm. Photo by Brandon C. Goeller.

# Denitrifying Bioreactors

## Moving beyond proof of concept to optimization, implementation | By Will Cushman

Bioreactors have proven themselves as a best practice for effectively removing nitrates from agricultural runoff before it reaches our watersheds. However, scientists are still figuring out how to optimize them, especially during the early spring. This article provides an overview of the state of the science of bioreactors along with summaries of five recent research articles published in the *Journal of Environmental Quality* as part of a special collection of papers on "Bioreactors: Moving beyond Proof of Concept." **Earn 1 CEU in Soil & Water Management** by reading this article and taking the quiz at www.certifiedcropadviser.org/certifications/self-study/778.

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Nitrogen: one of the many elements with which humans seem to have a love–hate relationship. We need it in our agricultural soils—it's literally what makes our crops grow—but when it percolates into our waterways, nitrogen becomes hazardous to wildlife and public health.

The risk of too much nitrogen in the form of nitrates entering our water system is not a new one. Scientists and farmers have long known about the risks associated with agricultural nitrogen runoff: high nitrate levels in water contribute to large algae blooms that negatively impact aquatic wildlife; too much nitrate can also pose health risks to humans.

The problem has gotten so serious in some areas that it's pitting urban communities against their agricultural neighbors. The Des Moines Water Works—the public utility responsible for providing safe drinking water to hundreds of thousands of Iowans—has filed a lawsuit against three counties in northwest Iowa alleging that nitrates from agricultural runoff in their jurisdictions threatens downstream Des Moines' water supply. It's set to go to trial in August of 2016, but no matter how the case turns out, it's already brought the issue of nitrogen leaching to the forefront of political conversations in one of the nation's largest farming states.

What many are not talking about is that there is already a proven concept for effectively removing nitrates from agricultural runoff before it reaches our watersheds.

Enter the bioreactor.

## A best practice for reducing nitrate runoff

Don't be fooled by the high-tech name; bioreactors are rather humble, low-tech instruments. Essentially, they are buried trenches filled with wood chips. That's it. The secret to their denitrifying power lies in bacteria that sustain themselves on the wood chips and respire nitrogen. In so doing, these bacteria are able to convert nitrates into nitrogen gas, effectively removing the nitrates from agricultural runoff when the bioreactors are connected to agricultural drainage systems.

The idea behind denitrifying bioreactors isn't new, but they haven't reached agricultural fields until relatively recently. They're already proving themselves as a best practice for reducing nitrate runoff, along with planting grass cover crops like cereal rye and oats.

"In 2016, we know that denitrifying bioreactors work. There is no question," says Laura Christianson, University of Illinois assistant professor of water quality and guest editor of a special collection of articles (see http://bit.ly/1TLFykv) on bioreactors in the May–June 2016 issue of the *Journal of Environmental Quality*. Progress from when scientists first floated the idea to finally proving of concept was slow at first, with researchers proposing bioreactors first in the mid-1990s.

"Research was kind of slow and trickling in, in the early 2000s," Christianson says. Then around 2008, bioreactor research took off and spread from universities to agricul-

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The following are summaries of articles appearing in the *Journal of Environmental Quality* as part of a special collection on "Bioreactors: Moving beyond Proof of Concept." See http://bit.ly/1TLFykv

# Impact of temperature and hydraulic retention time on nitrate removal

In this article, researchers report the results of a laboratory-scale triplicate upflow packed-bed wood chip bioreactor experiment, under a range of controlled conditions. Hydraulic retention time (HRT), which increases when flow rate is decreased, was systematically modified from less than 2 to 21 hours at 50°F and room temperature. Although nitrate percent removal increased with higher HRTs, nitrate removal on a daily mass basis did not follow the same trend, with relatively consistent mass removal measured as HRT increased. The average $NO_3$–N load reduction was lower at an influent concentration of 10 ppm and higher at 30 and 50 ppm. Using weathered wood chips as a denitrification bioreactor packing material resulted in lower carbon losses while denitrification function remained the same.

Results from this study provide information for improving the future design of wood chip denitrification bioreactors for specific climatic conditions and existing nitrate loads. Based on a combination of expected flow volumes, temperature, and nitrate concentration history, stakeholders and engineers can determine the proportion of drainage to treat and the optimal HRT required.

*Adapted from Hoover, N.L., A. Bhandari, M.L. Soupir, and T.B. Moorman. 2016. Woodchip denitrification bioreactors: impact of temperature and hydraulic retention time on nitrate removal. J. Environ. Qual. 45(3). View the full article at http://bit.ly/1TuxEsS*

# Wood chip age and temperature control bioreactor nitrate removal

End-of-tile nitrate removal techniques such as wood chip bioreactors are compatible with current farming practices and do not take land out of production. However, there have been few multi-year studies of bioreactors examining controls on nitrate removal rates.

In this article, researchers evaluated nitrate removal performance of two wood chip bioreactors (20 ft wide by 50 ft long by 4 ft deep) during the first three years of operation. They examined the major factors that regulated nitrate removal and determined $N_2O$ emission from the bioreactors.

Bioreactor 2 functioned but was subject to river flooding, which compromised outlet flow measurements and performance analysis. Bioreactor 1 had average monthly nitrate removal rates of 23 to 44 g $N/m^3/d$ in Year 1, which de-

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Dr. Laura Christianson stands on top of an "out of sight, out of mind" woodchip bioreactor and explains how it works during a field day at the Iowa State University Northeast Research Farm. Photo by J. Comito/Iowa Learning Farm.

tural groups, environmental nonprofits, and government agencies like NRCS.

## Optimizing spring performance

Today bioreactors are an established practice, though scientists are still figuring out how to optimize them, especially during the early spring. It's a critical period for nitrogen loss as frost and snowmelt, washing away nutrients from soils before farmers have a chance to sow their fields and fix those important nutrients in their crops. Instead, free nitrates can be washed out of fields through drainage systems in meltwater and early-season rains. This is when denitrifying bioreactors could be most useful.

But Christianson says that as they currently work, bioreactors often become overloaded during the spring thaw. There is simply too much water flowing through them, and it's too cold for the microbes that convert the nitrates to work very efficiently. While bioreactors still remove some nitrate from the drainage water under these conditions, they could work much better. If researchers can solve the problem, Christianson says bioreactors could potentially solve most of our nitrate issues.

"If you could take all the nitrate out of that early spring drainage, you would be addressing most of the problem for the whole year," Christianson says. "So the number one thing for improving nitrate removal at this point is to figure out a way to treat *more* water and treat it *better* (when) the water is cool."

One potential solution is to increase the amount of time the water sits in a bioreactor. The simplest way to achieve that is to build larger bioreactors, but Christianson says that's not going to be an attractive—or affordable—solution for most farmers.

"It gets expensive," she says. Farmers would have to build much larger trenches for their bioreactors and would have to fill them with more wood chips, all to capture the extra nitrates flowing out of the system during a relatively brief time in early spring. "You're wasting money most of the year because you don't need that capacity."

Researchers are still working on the issue, testing bioreactor designs in an effort to determine the optimal size for all conditions.

Meanwhile, Midwestern farmers are beginning to pick up the practice. Christianson estimates that there are currently between 50 and 100 bioreactors on working farms in Illinois, Iowa, and Minnesota.

"They are definitely the early adopters," she says, noting that agricultural practices with no yield benefits tend to be adopted at a slower rate.

## Easy to manage, no annual investment

Still, the benefits are proven, and denitrifying bioreactors are easy to manage and do not require an annual investment like cover crops. After an upfront investment of around $10,000, denitrifying bioreactors are designed to last 8 to15 years and require little maintenance.

Christianson hopes more farmers consider installing bioreactors soon.

"One of the biggest hurdles with any sort of water quality effort is that we're asking producers to voluntarily provide the benefit of clean water to the public using practices that more often than not don't provide a private benefit such as a yield bump. Right now it's voluntary. The voluntary part means that we get to choose *how* we're going to meet our water quality goal, not that we get to choose *if* we're going to meet our water quality goal."

The USEPA expects the agricultural economy to meet its water quality goals one way or another, and Christianson says a voluntary approach is likely to be more preferable than new regulations. And if the Des Moines Water Works case is any indication of the nitrate spats to come, farmers would be well served by getting ahead of the issue on their own terms.

creased to 1.2 to 11 g N/m$^3$/d in Years 2 and 3. The greater N removal rates in Year 1 and early in Year 2 were likely due to highly degradable carbon in the wood chips. Only late in Year 2 and Year 3 was there a strong temperature response in the nitrate removal rate. Due to large tile inputs of nitrate (1,600–4,700 lb N) at high concentrations (~30 ppm nitrate-N) in Years 2 and 3, overall removal efficiency was low (3 and 7% in Years 2 and 3, respectively). In addition, there were small $N_2O$ emissions from either Bioreactor 1 or 2 wood chip beds. Based on a bioreactor performance model, Bioreactor 1 would have needed to be nine times as large as the current system to remove 50% of the nitrate load from this 49-ac field.

*Adapted from David, M.B., L.E. Gentry, R.A. Cooke, and S.M. Herbstritt. 2016. Temperature and substrate control woodchip bioreactor performance in reducing tile nitrate loads in east-central Illinois. J. Environ. Qual. 45(3). View the full article at http://bit.ly/1T1VSrg*

# Alkalinity monitoring to optimize bioreactor performance

Although wood chip denitrification bioreactors are becoming more common to treat high-nitrate water from agricultural drainage pipes, information about how to integrate water monitoring into bioreactor management strategies is sparse. In this article, researchers use bioreactor water monitoring to optimize nitrate removal from field tiles and minimize the unwanted side effect of nitrous oxide formation.

The team found nitrate removal rates of 50 to 80% in five Iowa bioreactors. But most importantly, they also demonstrated that inexpensive alkalinity monitoring of bioreactor influent and effluent water was a good indicator of bioreactor performance. Alkalinity results appear to indicate whether or not nitrous oxide is forming within the bioreactor. Nitrous oxide is a greenhouse gas 300 times more powerful than $CO_2$.

The work highlights the idea that denitrification bioreactors are essentially treatment plants and need to be managed as such. Management must include water monitoring to ensure proper operation of this nitrate-trapping practice.

*Adapted from Jones, C.S., and K.J. Kult. 2016. Use alkalinity monitoring to optimize bioreactor performance. J. Environ. Qual. 45(3). View the full article at http://bit.ly/1UeMN3B*

# Denitrifying bioreactor performance at low temperatures

Denitrifying bioreactors can be effective for removing nitrate from agricultural tile drainage; however, questions about cold springtime performance persist. The objective of this study was to improve the nitrate removal rate of denitrifying bioreactors using corn cobs (CC), corn stover (CS), barley straw (BS), and CC followed by a compartment of wood chips (CC+WC), rather than WC.

Tests were run in laboratory columns at 60 and 35°F. Nitrate removal rates were highest for CC and lowest for WC at 60°F, 0.059 and 0.002 lb N/yd$^3$/day, respectively. At 35°F, CC (0.012) and CC+WC (0.011) were highest. However, the ag residues released more carbon into the outflow water than WC. The microbial populations were measured and found to be higher for the ag residues than WC at 60°F, and CS and BS were higher than WC at 35°F. Nitrous oxide, a greenhouse gas, was measured and found to be a higher percentage of nitrate removed at 35°F (7.5%) than at 60°F (1.9%).

Overall, the combination of CC followed by WC has the potential to increase nitrate removal at cold and warm temperatures and to keep greenhouse gas production to a minimum. This idea awaits field trial.

*Adapted from Feyereisen, G.W., T.B. Moorman, L.E. Christianson, R.T. Venterea, J.A. Coulter, and U.W. Tschirner. 2016. Performance of agricultural residue media in laboratory denitrifying bioreactors at low temperatures. J. Environ. Qual. 45(3). View the full article online at http://bit.ly/1SMwc8m*

# Denitrifying bioreactors reduce water quality degradation

In this article, researchers report the meta-analysis results assessing how different designs and site conditions alter nitrate removal in denitrifying bioreactors. Passive denitrifying wood chip bioreactors usually consist of wood chip-filled beds that intercept subsurface drainage water or trenches (walls) that intercept groundwater. The team found that nitrate removal in beds were significantly higher than walls. Within denitrifying bed studies, higher influent nitrate concentrations, longer hydraulic residence times (HRT), age under 13 months old, non-N limiting conditions, and higher temperatures promoted higher nitrate removal rates.

Lessons from this meta-analysis can be incorporated into bed designs, especially extending HRT to increase nitrate removal under low temperature and high flow conditions. Additional field-based studies to assess in situ conditions, especially in aging beds, are warranted with careful reporting of design and environmental data. Future assessment should review other processes, including production of greenhouse gases and other unfavorable byproducts.

*Adapted from Addy, K., A.J. Gold, L.E. Christianson, M.B. David, L.A. Schipper, and N.A. Ratigan. 2016. Denitrifying bioreactors for nitrate removal: a meta-analysis. J. Environ. Qual. 45(3). View the full article online at http://bit.ly/1SxwsCE*