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Denitrifying Bioreactors: An Emerging Best Management Practice to Improve Water Quality

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What is a Denitrifying Bioreactor?

Denitrifying bioreactors (DNBRs) are an alternative best management practice (BMP) that can reduce the amount of nitrogen reaching surface waters. DNBRs function by supporting soil microorganisms that are capable of *denitrification*** in a favorable environment (see Figure 1). Denitrification is the process by which microorganisms transform *reactive nitrogen*** in the form of nitrate-nitrogen (NO_3-) into nitrogen gas (N_2). Denitrifiers are *heterotrophic microbes*** found in most soil that utilize energy from organic carbon sources to transform NO_3- to N_2 in the absence of oxygen. These anaerobic (meaning without oxygen) conditions are created when soils become saturated with water. Fundamentally, DNBRs consist of an organic carbon medium that is saturated, at least periodically, with sufficient duration to allow anaerobic conditions to develop and naturally occurring denitrifiers to flourish.

Problem: Water Quality

NO_3- moves easily with water through the soil profile. When shallow groundwater intersects the plant rootzone where nutrients are present; NO_3- can *leach*** from the rootzone, and phosphorus (P) can be a water quality concern at very low concentrations although it is not considered highly mobile in the soil. One way to minimize NO_3- and P loss is to effectively manage the amount of fertilizer applied to a crop by actively following a nutrient management plan (NMP). Even with active fertilizer management, NO_3- and P can be lost when shallow groundwater intersects the rootzone (see Figure 1). This risk is particularly high during periods of prolonged or excessive rainfall, which can cause a rise in the shallow water table whereby it can intersect with the rootzone where nutrient levels can be high and ultimately casue leaching (see Figure 1). Thus, alternative edge-of-field technologies are needed that can remove nutrients from shallow groundwater and runoff. DNBRs, an emerging technology, hold promise to treat both excess N and P in ground and surface water.

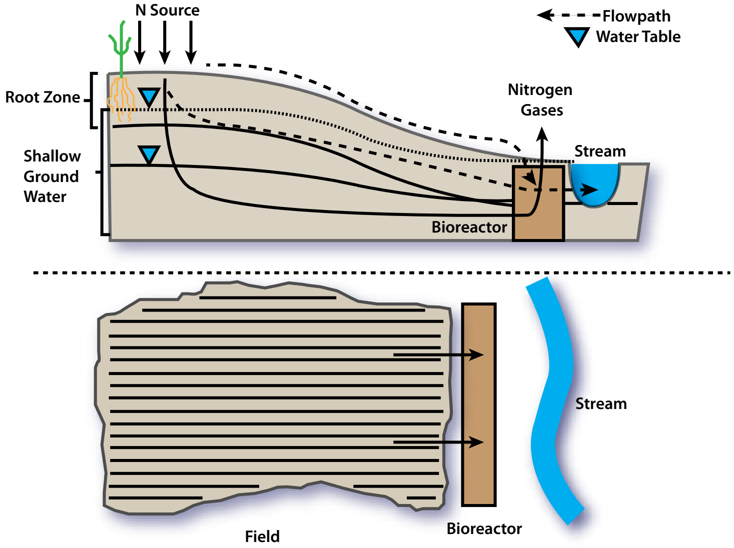

Figure 1. The top figure shows an example of a DNBR placed strategically in the landscape to intercept and treat ground and surface water before entering the stream. The dashed line shows how the groundwater table might respond to precipitation, rising to intersect with the rootzone and mobilizing nutrients. The bottom figure shows a plan view of a DNBR as it might be installed adjacent to a field.

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**Terms defined in the glossary at the end of this publication are italicized the first time they appear in the text.

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Denitrification is important because it is the only permanent removal of *bioavailable*** nitrogen from an ecosystem. Even relatively low N concentrations in receiving water bodies can cause *eutrophication*** and damage fisheries. The U.S. Environmental Protection Agency (EPA) recommends that the maximum stream nitrate-N concentration be less than 0.3 parts per million (ppm) for the Coastal Plain region. Higher levels of NO_3-, particularly in drinking water, can lead to infant toxicity (methemglobinemia or Blue Baby Syndrome) or formation of carcinogenic compounds. The EPA has set a *maximum contaminant level (MCL)*** for nitrate-N in drinking water at 10 ppm.

Applications

DNBRs have been used to treat a range of nitrate-laden waters including greenhouse effluent, contaminated groundwater, septic system plumes, domestic wastewater, and agricultural runoff. Common designs include walls intercepting shallow groundwater (as in Figures 1 and 2), reactor vessels that receive tile drainage from agricultural fields, beds where the influent is piped in, and streambed bioreactors. The different designs are adapted and employed in the various settings. Many types of organic carbon have been tested for use in DNBRs, but woodchips are the most widely used because of their superior hydraulic properties and general availability in larger quantities.

Research has shown that successful nitrogen removal can be obtained in these *field scale*** systems for up to 15 years even with fluctuating influent nitrate concentrations and flow rates. This tolerance to variable influent enables application of DNBRs to treat a wide range of *non-point source pollution*,** such as that created by agriculture, where conventional wastewater treatment is cost-prohibitive. Some of the greatest potential for DNBR use is in agricultural settings, where nitrogen loss to groundwater is the dominant pathway.

Current Research

The denitrification wall DNBR receiving shallow groundwater and surface runoff from agricultural land at the Eastern Shore AREC, as shown in Figure 2, has been monitored since August 2011. The DNBR consists of two separate compartments with two types of carbon media: woodchips only and woodchips with biochar. The addition of the biochar, a form of organic carbon produced by burning organic material, is a novel media in DNBR research and holds promise for increasing NO_3- and P removal. Previous studies have shown that biochar increases microbial activity, which may enhance the rate of denitrification, and reduce nitrogen leaching. Biochar also has the potential to remove P in groundwater by *adsorption.***

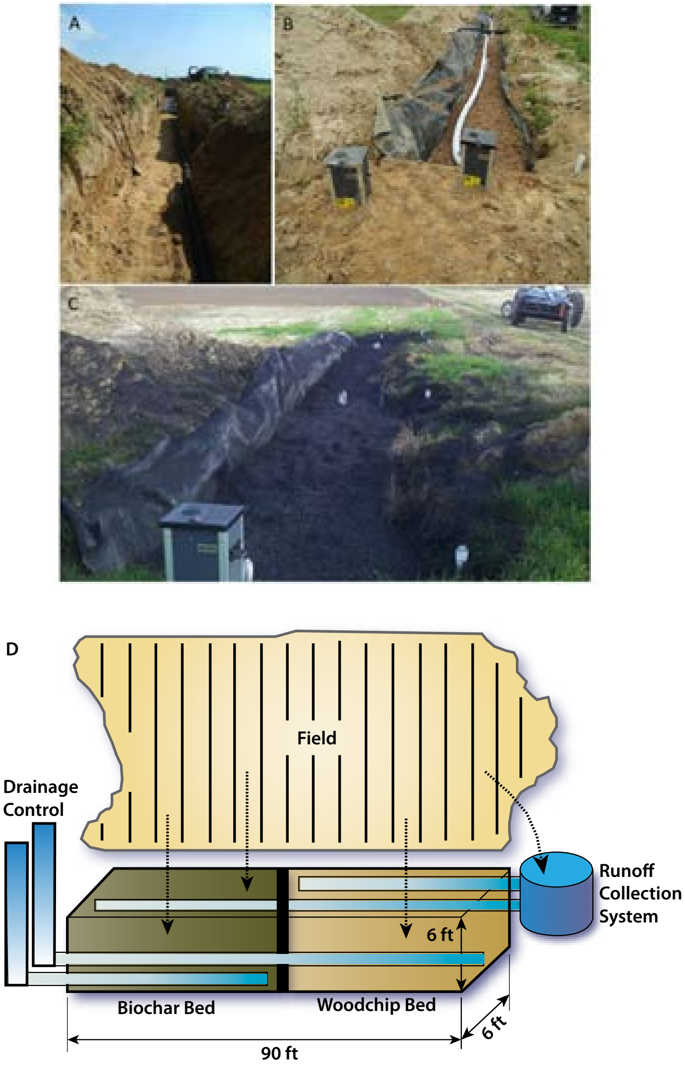

Figure 2. Design and application of the Eastern Shore Agricultural Research and Extension Center (AREC) "wall" type DNBR. Image A shows excavation of DNBR trench; B shows wood chip substrate in the DNBR; C shows addition of *biochar*,** and D a schematic of the design. The two treatments have separate outlets with drainage control. The upslope sides of each DNBR are lined with permeable filter fabric to allow shallow groundwater to enter. The volume of the two DNBRs together is approximately 100 m^3 and it receives drainage from 12 acres of cropped farmland.

The data displayed in Figure 3 show that the DNBR achieved significant nitrate reductions in groundwater. Nitrate concentrations were, on average 60 percent (and as high as 90 percent) lower in groundwater that had passed though the DNBR than in the groundwater draining from the contributing fields. Groundwater samples were collected from six wells located in the 12 acres of agricultural land draining to the DNBR. The maximum nitrate-N concentration observed in the groundwater is almost 30 ppm, or three times the EPA MCL limit for drinking water, and more than 100 times the levels recommended for stream health. The average nitrate-N concentration observed in the groundwater approaches the 10 ppm drinking water MCL. This specific DNBR includes a runoff collection and dosing system (see Figure 2) to allow treatment of surface runoff in addition to groundwater. The runoff well collected overland flow from the 12 acre contributing area of the farm. Drainage control units (Figure 2) allow for water table control in order to achieve adequate residence time for denitrification to occur as well as for sampling the outflow.

Both the woodchip and biochar beds performed well, and both carbon source materials achieved the same maximum level of nitrate reduction. On average, both substrate treatments in the DNBR were able to reduce nitrate-N to the 0.3 ppm level recommended by the EPA as the maximum concentration to maintain stream health in the Coastal Plain region (Figure 3). These results indicate that DNBR implementation in strategic locations intercepting shallow groundwater and/or runoff has the potential to provide NO_3- removal levels on site that translate into measureable downstream water quality improvement.

The DNBR also reduced the dissolved phosphorus concentrations as shown in Figure 4. Note that all phosphorus concentrations observed in the groundwater in this study were higher than the 0.04 ppm level recommended by the EPA as the maximum concentration to maintain stream health in the Coastal Plain region. Although phosphorus does not have direct toxic effects in humans, excess can stimulate the growth of microorganisms undesirable in potable water.

Both DNBRs were able to significantly reduce P concentrations in groundwater. The biochar addition substantially increased phosphorus removal as compared to the woodchips alone. The outlet concentration from the biochar treatment approaches the 0.04 ppm maximum recommended level set by the EPA for stream health in this region. DNBRs with biochar amendment have the potential to consistently reduce dissolved phosphorus concentrations by 75 percent or more.

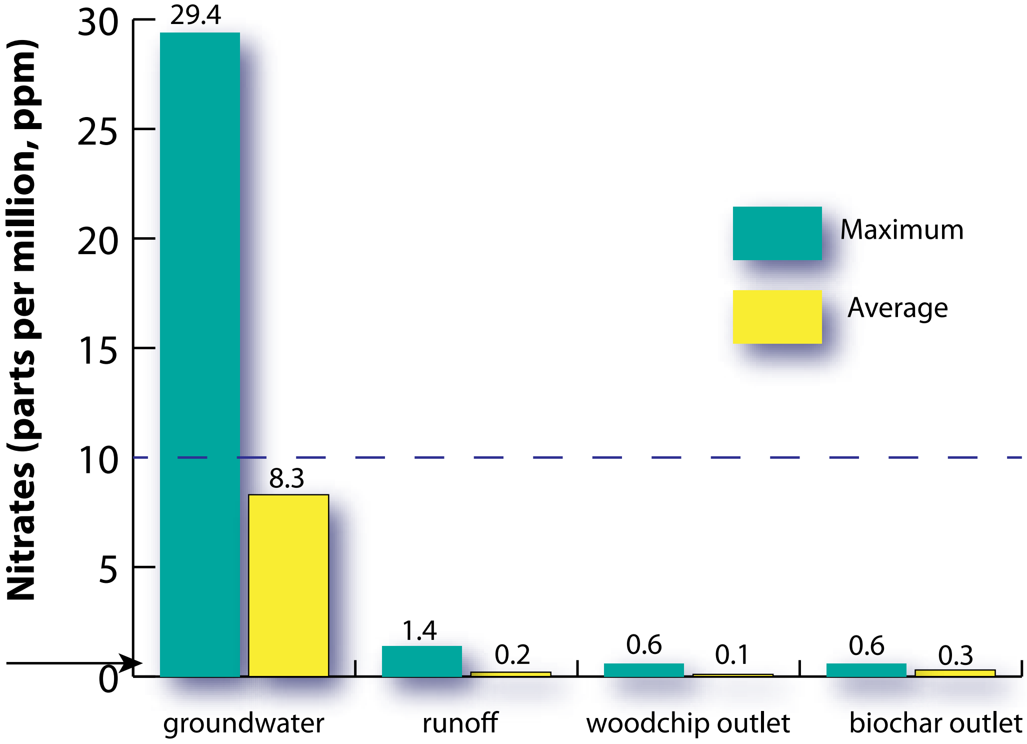

Figure 3. Maximum and average concentrations of nitrate-N (ppm) measured in water samples collected from groundwater wells and the DNBR between January and May 2012. The dotted black line indicates the EPA MCL for nitrate-N in drinking water (10 ppm). The arrow indicates the EPA recommended maximum concentration for stream health (0.3 ppm)

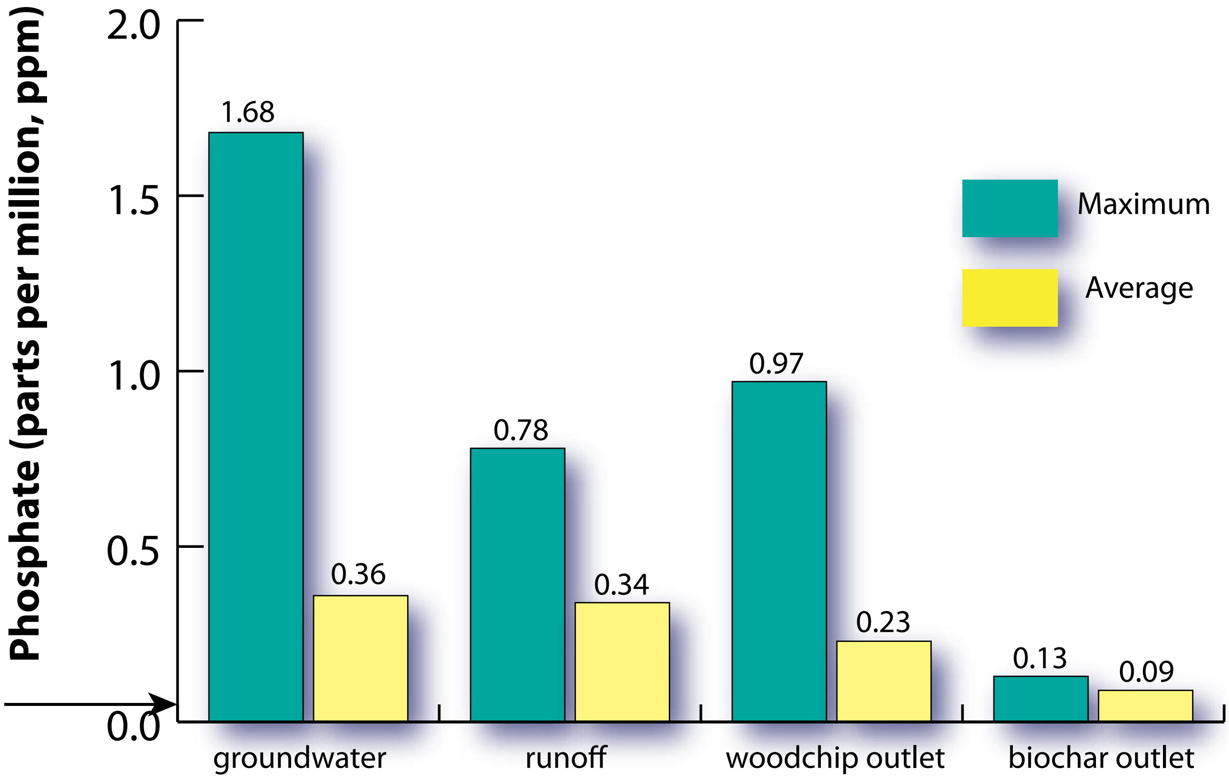

Figure 4. Maximum and average concentrations of phosphorus (ppm) measured in water samples collected from groundwater wells between January and May 2012. The arrow indicates the EPA recommended maximum concentration for stream health (0.04 ppm)

Cost

DNBRs are inexpensive to install and generally maintenance-free. For instance, the DNBRs located at the Virginia Tech Eastern Shore AREC cost less than $200 per acre treated. If this is extended out over the expected lifetime of the system (15-20 years), the cost of the DNBR system approaches $10-15 per acre per year. This is comparable to, or less than, other water quality BMPs such as riparian buffers, exclusionary fencing, or nutrient management planning. The only costs are incurred at installation, which include excavation and the purchase of substrates such as woodchips and biochar. If DNBRs prove to be a valuable BMP, cost share dollars from federal (such as the U.S. Department of Agriculture-Natural Resources Conservation Services (USDA-NRCS)) or state and local (such as Soil and Water Conservation Districts) sources might offset much of the initial cost.

Future Work

Continued study of the Eastern Shore AREC DNBR and other installations in Virginia will focus on monitoring inlet an outlet nitrate-N concentrations in real time in order to develop a nitrogen balance, which will allow for quantification of nitrate removal and assessment of downstream water quality benefits. This work will provide data that can be used to develop DNBR engineering guidelines, inform site selection, and update interim NRCS conservation standards. Additionally, the gaseous products of denitrification, nitric oxide (NO) and nitrous oxide (N_2O) and dinitrogen gas (N_2), dissolved in the DNBR, will be quantified to ensure that the bioreactors are not creating an air quality concern. This research will provide insight into the fate of nitrogen in DNBRs and allow for estimation of the quantity of reactive nitrogen removed by these systems. Additional data will also isolate the effect of biochar addition on nitrate and phosphorus removal in DNBRs.

Acknowledgements

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Additional Resources

U.S. Environmental Protection Agency. “Basic Information About Nitrate in Drinking Water.” http://water.epa.gov/drink/contaminants/ basic information/nitrate.cfm. (August 29, 2012)

U.S. Environmental Protection Agency. “Ecoregional Criteria.” http://water.epa.gov/scitech/swguidance/standards/criteria/nutrients/ecoregions/index.cfm. (August 30, 2012)

Virginia Tech College of Agricultureand Life Sciences. Innovations October 2012. “Curbing Pollution, Saving Agriculture. http://news.cals.vt.edu/innovations/2012/10/curbing-pollution-saving-agriculture/. (October 17, 2012)

Glossary of Terms

Adsorption – The physical bonding of one substance to another.

Bioavailable—in a form that can be used by organisms (i.e. plants uptake NO_3- but cannot use N_2.)

Biochar—Similar to charcoal, this form of organic carbon is produced by burning organic material, such as plant material or animal waste, at low temperature in the absence of oxygen. The resulting product is more resistant to decomposition. The method of production determines its best final use, which can be anything from a horticultural soil amendment to the charcoal for a barbeque.

Denitrification—The stepwise transformation of nitrate to nitrite, nitric oxide, nitrous oxide and ultimately dinitrogen gas, which comprises nearly 80 percent of the atmosphere.

Eutrophication—refers to natural or artificial addition of nutrients to water bodies that cause undesired effects, such as algal blooms or lowered dissolved oxygen levels.

Field Scale—Refers to use of a product or methodology in the application for which it was designed as opposed to testing in the laboratory.

Heterotrophic Microbes – Obtain energy, carbon, and reducing equivalents for reactions from organic compounds.

Leach—draining of a dissolved material as it moves with water.

Maximum Contaminant Level (MCL)—the highest concentration of a chemical that can be encountered without adverse affects to human health.

Non-Point Source Pollution—also called diffuse pollution (as opposed to point source pollution that discharges from a defined origin such as a pipe), results from land-use activity and is transported intermittently primarily by rain events.

Reactive Nitrogen—Nitrogen in a form that can participate in chemical or biological reactions, said to be bioavailable, as opposed to nonreactive (inert) nitrogen gas (N_2), which is very stable and cannot be used by organisms directly.