DENITRIFYING WOODCHIP BIOREACTOR PERFORMANCE IN A CASCADIA CLIMATE REGIME

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ABSTRACT

Runoff and tile drainage from agricultural activity is known to be a significant contributor of nitrogen pollution to surface waters. Denitrifying woodchip bioreactors, also known as Permeable Reactive Barriers (PBR), have been studied as a possible edge-of-field technology for reducing nitrogen concentrations in agricultural runoff. These studies have been done mostly in the US Midwest and primarily for irrigated crop systems. Little work has been done in alternative climate regimes such as those found in the Cascadia Region of Oregon and Washington State where agricultural runoff is most likely to occur during the winter rain season. A field-scale denitrifying woodchip bioreactor was installed at Oregon State University (OSU), designed to treat drain-tile runoff from about 40 acres of forage fields for the OSU Dairy Farm. Samples were collected daily from 12/19/2019 to 5/27/2020 and tested for nitrate, nitrite and ammonia/ammonium concentrations. Samples were also collected approximately weekly, 3/30/20 – 5/27/20 and tested for fecal coliform concentrations via IDEXX Colilert Quanti-tray MPN tests. Preliminary results showed significant nitrate reductions even during colder winter months, with average percent reduction in concentrations of 48% (STD +/- 41.5%) from influent concentrations ranging from 87.7 to 2.0 mg NO_3/L. Results for ammonia/ammonium [mg NH_4^+-NH_3/L] were much more variable, with an average percent change of just 7.8% (STD +/- 31.4%), mostly related to changes in influent concentrations. This, however, was to be expected as the conditions in the PBR were inherently anaerobic and reducing, and were not conducive to ammonium oxidation. Fecal coliform results were inconclusive, with some sample sets showing good reductions while others showed count increases between the inlet and internal positions.

INTRODUCTION

Ever since the development of industrial fertilizer manufacture, the nitrogen cycle has been out of balance: nitrogen has been added to surface systems at rates far in excess of what would occur naturally. Agricultural activities can be a major contributor to excess nutrients in surface waters and reducing nutrient runoff from fields and livestock operations has been a concern for many years. Drain-tile systems are of particular concern as they can provide direct transit for leached nutrients to reach surface waters (David et al, 1997, 2010)

Denitrifying woodchip bioreactors, also known as "permeable reactive barriers" (PRB), have been under study as a possible "edge-of-field" treatment method since 1994 (Blowes et al, 1994). The functional concept behind PRB is that they provide a readily available carbon source for denitrifying organisms (bacteria, archaea, fungi) to colonize, which then respond by consuming nitrogen compounds present in the drainage outflow for their metabolic processes. The denitrification process is a series of biotic enzyme catalyzed reactions that convert nitrogen in the form of nitrate (NO_3^-) to N_2 gas as follows: $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O_{(gas)} \rightarrow N_{2(gas)}$. If the denitrification process is incomplete, byproducts such as nitric and nitrous oxide, both powerful green-house gases, can be released. For denitrification to occur, conditions must be anaerobic at minimum. However, if redox conditions are too reducing, pollution swapping can also occur with the formation of undesirable compounds such as CH_4 (methane), H_2S (hydrogen sulfide gas) and methyl-mercury. Since denitrifying organisms are biotic in nature, conditions such as contact time with the nutrients as controlled by hydraulic retention time (HRT), water temperature, pH and oxidation state can all play a role in the functional success of a denitrification system.

The majority of the research into denitrifying woodchip bioreactors has been conducted by groups in New Zealand and the mid-west U.S.A. Louis Schipper's 2010 paper (Schipper et al, 2010) reviewing developments in the technology up to that time has been a foundational paper for successive researchers, and Laura Christianson's work in Iowa, along with that of J.A. Chun (Iowa), Ehsan Ghane (Ohio) and others, has focused on treatment bed parameters for optimizing PRB design. Thus, the majority of the research to date into woodchip bioreactors has been conducted in regions with quite different climate regimes than that found in the U.S. Pacific Northwest. There is little information for how such units might perform in a "Cascadia" or "Mediterranean" climate regime where most runoff occurs in the colder winter months. There is also little information regarding how these units might perform with respect to pathogenic bacteria. In lab studies, Soupir, (Soupir et. al., 2018) and Rambags (Rambags et al., 2019) found consistent reductions in pathogenic bacteria; however, there is currently no known study using a field-scale denitrifying bioreactor unit.

In the summer and fall of 2019, a research PRB unit was installed at Oregon State University in order to process tile-drainage effluent at the OSU Dairy Farm, Oregon State University, Corvallis, OR. The tile system drains approximately 40 acres of forage fields that are rotationally grazed or harvested. Liquid manure is applied seasonally in Spring and early Fall. In the first season of operation (Dec. 2019 – May 2020), a pilot study was conducted to establish baseline performance characteristics and to address the following questions: 1) How does a field scale unit perform with respect to nitrogen constituents under Western Oregon climate conditions? and 2) Would these units be effective against fecal coliform bacteria?

METHODS

Project Site and Design: The PRB was designed largely per guidelines from Christianson, et. al. (Christianson 2011, 2012, 2013) to treat approximately 15% of the local estimated peak flows in 10-24 hour HRT. Unit dimensions were 12'W x 60'L x 3.3'D (3.64m x 18.2m x 1m), a 5:1 L:W aspect ratio, with a rectangular cross-section and level base (minimal slope). AgriDrain flow control boxes were installed at the inlet and outlet as well as a dosing well for injection of tracer and/or nutrient pulses. The treatment pit was lined with 4 ml plastic and filled with 1" mixed hardwood chips as available from a local landscape supply center. 10' lengths of 6" diameter perforated ADS drain pipe were used at each end for flow diffusion and collection, stabilized with 1 ½" round drain rock prior to adding the woodchips. In addition, PVC sampling wells were installed at 3 internal heights (0.25m, 0.5m and 0.75m from base) approximately every 10' of the longitudinal length of the unit along with flow baffles to discourage development of preferential flow paths. The treatment bed was capped with soil to bring the surface back to existing ground level; plans are to seed the cap to grass cover once the soil has settled. No bacterial inoculation was performed; microbial colonization was allowed to occur naturally by species present in the drainage flow. Once the soils were saturated with seasonal rains, this PRB experienced almost "steady-state" flow conditions at maximum treatment volume until the early cessation of the rainy season in April 2020.

Sampling and Testing: Near-daily water samples were drawn via ISCO 2900 automated water samplers from Dec 19, 2019 to May 27, 2020. The samples were collected 1x per week, taken directly to a lab at the university where they were filtered through 0.45µm MCE filters and frozen until they could be tested for concentrations of nitrate (NO_3^-), nitrite (NO_2^-) and ammonia/ammonium (NH_3/NH_4^+) via colorimetric Vanadium reduction and salicylate/sodium nitroprusside/sodium hypochlorite reaction (method details available upon request). In addition, "manual" samples were collected from internal monitoring wells approximately 1x per week from March 30 – May 27. 100 ml of these samples were immediately processed for fecal coliform testing per the IDEXX Colilert Quanti-tray method. The remainder was filtered, stored and tested for nitrogen constituents as for the daily samples.

RESULTS

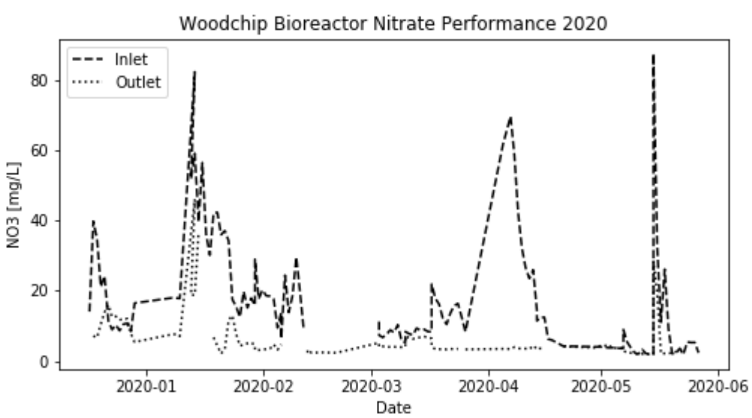

Figure 1. Inlet/Outlet Nitrate Performance, Winter/Spring 2020

Inlet/Outlet daily samples: As shown in **Figures 1, 2** and **3**, as well as **Tables 1-3**, nitrate concentrations saw consistent reductions between the inlet and outlet, over a variety of conditions. Concentration spikes were observed after high precipitation events and after liquid manure was spread on the forage fields in April/May. Inlet concentrations for the season ranged from a maximum of 87.7 to a minimum of 2 mg/L, and outlet concentrations ranged from 46.2 to 2 mg/L. The average percent reduction was 39.8%. This value differs from that presented in Abstract due to data-entry errors discovered during development of tables and plots. Results for nitrite showed a tendency to an increase from inlet to outlet, but on a very small scale. When larger inlet concentrations were experienced, the nitrite concentrations were also significantly reduced. Inlet/Outlet concentrations of ammonia/ammonium did not demonstrate any consistent changes overall.

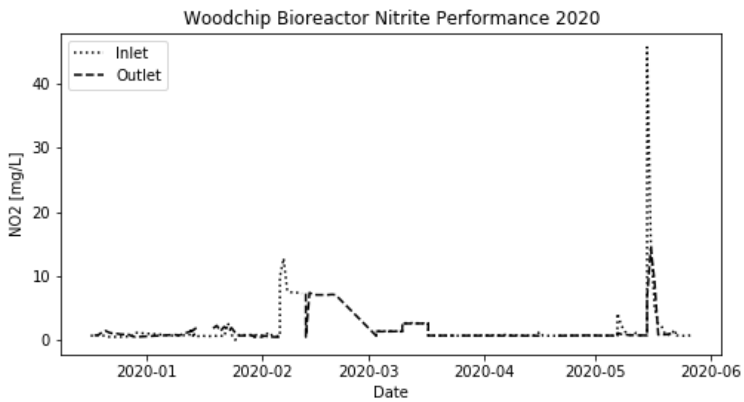

Figure 2. Inlet/Outlet Nitrite Performance, Winter/Spring 2020

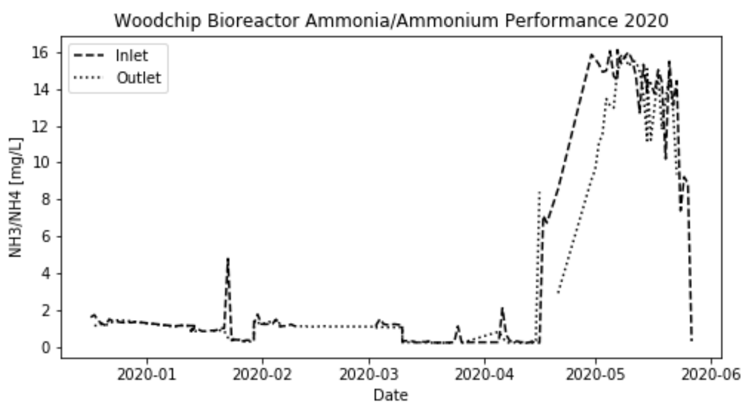

Figure 3. Inlet/Outlet Ammonia/Ammonium Performance, Winter/Spring 2020

Table 1. PBR Nitrate Inlet/Outlet Statistics

	NO_3 in [mg/L]	NO_3 out [mg/L]	Δ In-out [mg/L]	NO_3 %reduction
Mean	17.979	6.079	12.642	39.80
St.Dev	17.078	6.506	16.908	1.10
Min	2.004	1.938	-28.328	-86.51
Max	87.685	46.179	68.314	97.60

Table 2. PBR Nitrite Inlet/Outlet Statistics

	NO_2 in [mg/L]	NO_2 out [mg/L]	Δ In-out [mg/L]	NO_2 %reduction
Mean	1.988	1.748	0.397	-37.5
St.Dev	4.590	2.240	3.298	215.3
Min	0.493	0.472	-1.589	-1860.5
Max	45.736	14.331	31.405	94.6

Table 3. PBR NH_4 Inlet/Outlet Statistics

	NH_4 in [mg/L]	NH_4 out [mg/L]	Δ In-out [mg/L]	NH_4 %reduction
Mean	4.132	3.722	0.443	-26.30
St.Dev	5.706	5.311	1.364	317.20
Min	0.230	0.220	-4.388	-2901.80
Max	16.107	15.805	6.248	91.00

Internal Water Quality: As presented in **Figure 4**, samples taken from the longitudinal centerline showed a clear utilization of nitrate within the first 20' of the treatment unit during the month of April. Internal water quality results for the May sampling dates showed less change over the profile, but outlet concentrations were still less than the 10 mg/L dictated by EPA regulatory requirements. Nitrite and ammonium showed a less clear relationship; nitrite tended to be reduced somewhat early in the treatment bed, but small increases were also sometimes observed further down the profile. Ammonium showed no clear relationship along the profile of the treatment bed.

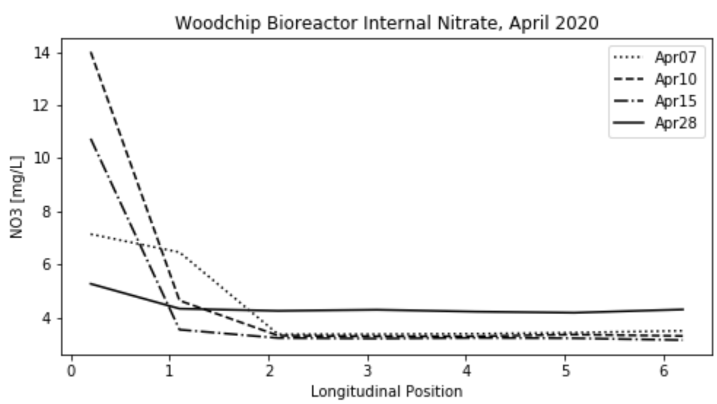

Figure 4. PBR Longitudinal Nitrate Concentrations, April 2020

E.Coli **and Total Fecal Coliform MPN counts:** Early spring (late March to mid-April) results for both Total Fecal Coliform (TFC) and *E.coli* MPN counts seemed promising, showing significant reductions in counts taken between the inlet and internal locations. However, results from later in the season showed a less clear pattern, with internal increases in MPN counts being observed on several occasions.

DISCUSSION

Results for this first year of operation of a denitrifying woodchip bioreactor in Western Oregon are quite promising. Significant reductions of nitrate were observed, even with winter water temperatures. Large reductions were observed during concentration spikes, although not always sufficient to bring outlet concentrations to below 10 mg/L during periods of highest inlet concentrations. This is in line with previous research reporting reductions of 23% to 98% (Schipper et al., 2010, Christianson et al, 2012). Relatively good performance is expected in early years due to the presence of readily available carbon from the "fresh" woodchips. It is expected that performance will decrease somewhat once that carbon source is fully utilized. Changes in nitrite concentrations are of interest as they may be potential indicators of the progress through the denitrification series. Nitrite is inherently a transitional molecule and doesn't tend to be of long duration in a natural environment. An observed increase in the longitudinal profile of the treatment unit may indicate that the first step of denitrification is occurring, but perhaps not as much of the following steps and could indicate incomplete denitrification. Nitrite is becoming a "contaminant of concern" with even more strict guidelines proposed than that for nitrate. Any increase in nitrite must be further investigated. The lack of response for ammonia/ammonium is as expected as the treatment bed is inherently anaerobic and does not provide an environment conducive to ammonium oxidation. Initial fecal coliform results are inconclusive: some sample sets show good reductions while others may actually show MPN increases. Current hypotheses are that internal conditions of the PBR (temperature and pH/redox) are likely playing a role in changes to fecal coliform populations. With the weekly testing regime, it was not possible to closely relate changes in internal MPN to inlet counts. To test this question more fully, a sampling regime where several samples are collected within a single volume change of the reactor would likely be required.

CONCLUSION

A definite conclusion from this pilot study is that denitrifying woodchip bioreactors can work in a "Cascadia" climate regime, providing good reductions in nitrate concentrations even during the colder winter runoff season. Less conclusive are results regarding nitrite and fecal coliform reductions.

Questions for continuing research include:

- How does performance in the PRB change over time, particularly once the readily available carbon is fully utilized?
- How does the unit perform under varying hydraulic regimes? i.e., how do changes in outlet control box settings change HRT, internal conditions and resulting water quality results?
- Questions abound regarding fecal coliforms. A more rigorous test method that can capture changes within a treatment volume exchange should be considered.
- Is there pollution swapping? Potential aqueous (H_2S, methyl-mercury) and/or gaseous (NO, N_2O and CH_4) byproducts should be investigated.

- Does the colder temperature regime show significantly different results than other units operating in a warmer climate? Would it be possible to tease out in-situ temperature related microbial kinetics?

Acknowledgements:
Funding and support for this project was provided by the Oregon Dairy Farmers Association, the Oregon Department of Agriculture and the Department of Biological and Ecological Engineering at Oregon State University. Special thanks go to Seth Spencer, Farm Manager, for providing on the ground assistance for the installation of this project.

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