Performance of an under-loaded denitrifying bioreactor with biochar amendment

Emily Bock, Brady Coleman, and Zach Easton

Abstract

Denitrifying bioreactors are recently-established agricultural best management practices with growing acceptance in the US Midwest but less studied in other agriculturally significant regions, such as the US Mid-Atlantic. A bioreactor was installed in the Virginia Coastal Plain to evaluate performance in this geographically novel region facing challenges managing nutrient pollution. The 25.3 m³ woodchip bed amended with 10% biochar (v/v) intercepted subsurface drainage from 6.5 ha cultivated in soy. Influent and effluent nitrate-nitrogen (NO_3–N) and total phosphorus (TP) concentrations and flowrate were monitored intensively during the second year of operation. Bed surface fluxes of greenhouse gases (GHGs) nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) were measured periodically with the closed dynamic chamber technique. The bioreactor did not have a statistically or environmentally significant effect on TP export. Cumulative NO_3–N removal efficiency (9.5%) and average removal rate (0.56 +/- 0.25 g m^{-3} d^{-1}) were low relative to Midwest tile bioreactors, but comparable to installations in the Maryland Coastal Plain. Underperformance was attributed mainly to low NO_3–N loading (mean 9.4 +/- 4.4 kg ha^{-1} yr^{-1}), although intermittent flow, periods of low HRT, and low pH (mean 5.3) also likely contributed. N removal rates were correlated with influent NO_3–N concentration and temperature, but decreased with hydraulic residence time, indicating that removal was often N-limited. GHG emissions were similar to other bioreactors and constructed wetlands and not considered environmentally concerning. This study suggests that expectations of NO_3–N removal efficiency developed from bioreactors receiving moderate to high NO_3–N loading with influent concentrations exceeding 10 to 20 mg L^{-1} are unlikely to be met by systems where N-limitation becomes significant.

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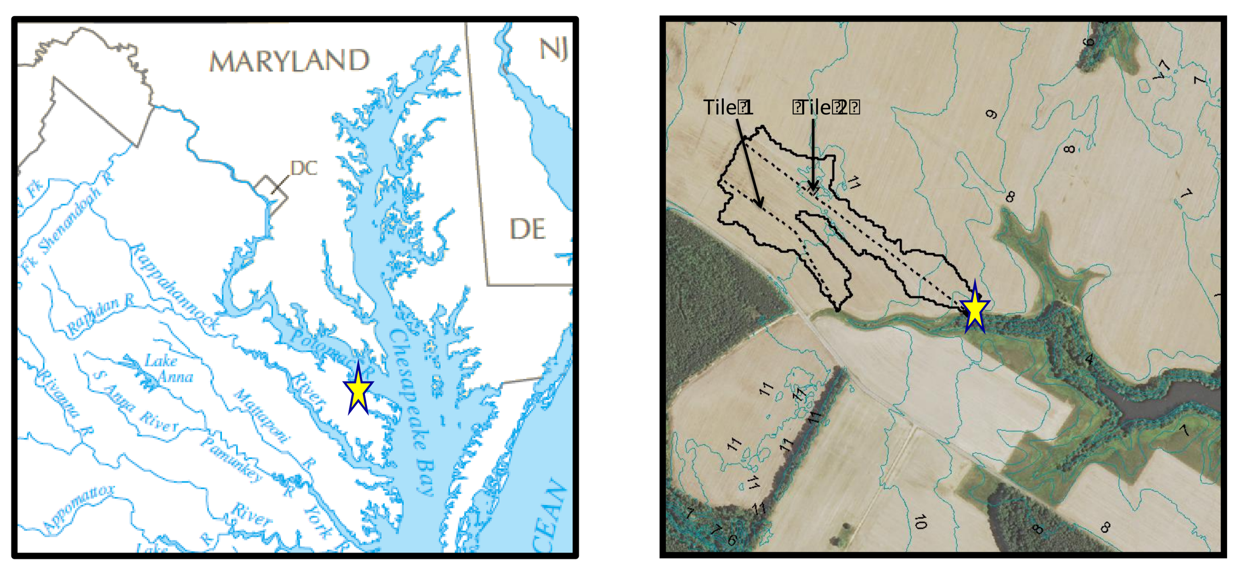

Fig. 1 Location virginiaplaces.org

Table 1. Cumulative rainfall and drainage volume flowing through the bioreactor as well as average temperature and flow rate on an annual basis and separated by growing and non-growing season.

		Annual	Growing	Non-growing
Total	drainage (cm)	22.8	6.0	16.8
	rainfall (cm)	151.9	77.4	74.5
Mean	temp (˚C)	17.9	21.7	12.5
	flow (L s^{-1})	28.1	15.5	39.3
	pH	5.3	5.2	5.5

Low nitrogen loading and influent concentration, compounded by seasonal flow and temperature constraints, resulted in low nitrogen removal (0.56±0.25 g m^{-3} d^{-1}) and modest efficiency (9.5%)

	NO_3–N	Annual	Growing 1	Non-growing
Loading	kg ha^{-1} yr^{-1}	8.5 (4.1-12.9)	4.0 (2.5-5.5)	14.2 (7.8-20.6)
	g m^{-3} d^{-1}	6.0 (2.9-9.1)	2.8 (1.7-3.9)	10.0 (5.5-14.5)
Removal	g m^{-3} d^{-1}	0.56 (0.31-0.81)	0.56 (0.34-0.82)	0.57 (0.24-0.91)
Conc.	inlet mg L^{-1}	3.7 (2.8-4.6)	2.9 (2.4-3.4)	4.7 (3.6-5.7)
	outlet mg L^{-1}	3.1 (1.8-4.4)	2.1 (0.1-4.2)	4.4 (3.3-5.5)
	Total P	**Annual**	**Growing 1**	**Non-growing**
Loading	kg ha^{-1} yr^{-1}	0.19 (0.05-0.33)	0.04 (0.00-0.08)	0.48 (0.22-0.73)
	g m^{-3} d^{-1}	0.27 (0.07-0.47)	0.03 (0.00-0.05)	0.34 (0.16-0.51)
Conc.	inlet mg L^{-1}	0.13 (0.08-0.20)	0.03 (-0.01-0.07)	0.19 (0.13-0.25)
	outlet mg L^{-1}	0.03 (0.07-0.18)	0.02 (0.00-0.04)	0.17 (0.11-0.23)

Table 2. Mean and 95% confidence interval (α=0.05) of nutrient loading rate, bed-normalized removal rate, and flow-weighted influent and effluent concentrations. Removal rates for total phosphorus are not reported because they are not statistically significant. Annual values are seasonally-weighted based on the duration of the growing (April 10 to September 29 2016) and non-growing seasons (September 30 2015 to April 9 2016).

Bioreactor had no significant effect on phosphorus

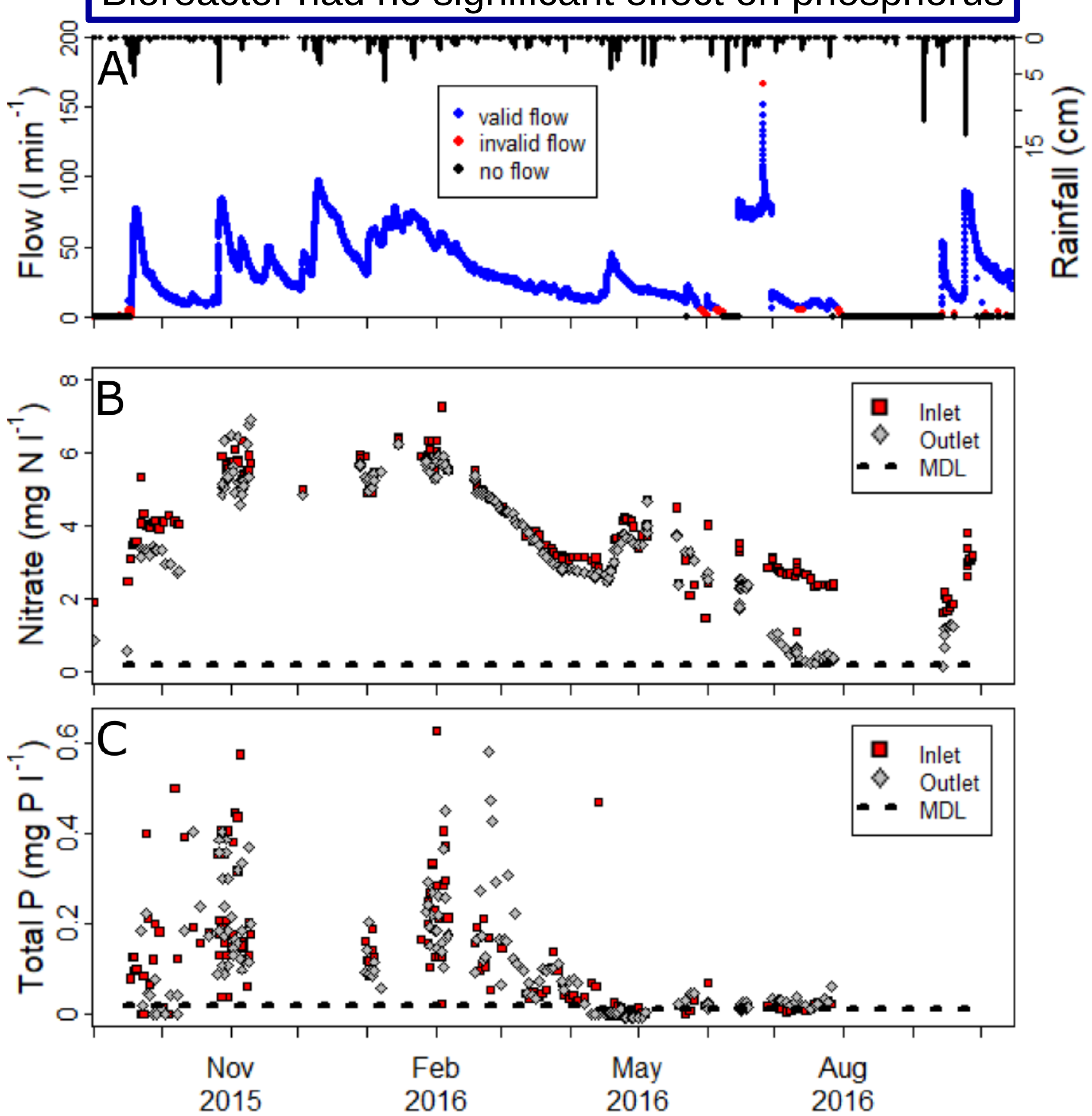

Figure 1a-c. Measured flowrate of water leaving the bioreactor and daily rainfall (a); concentrations of nitrate-nitrogen (b) and total phosphorus (c) in bed influent and effluent water samples. Dashed lines represent method detection limits (MDL).

Greenhouse gas emissions were similar to other bioreactors and constructed wetlands

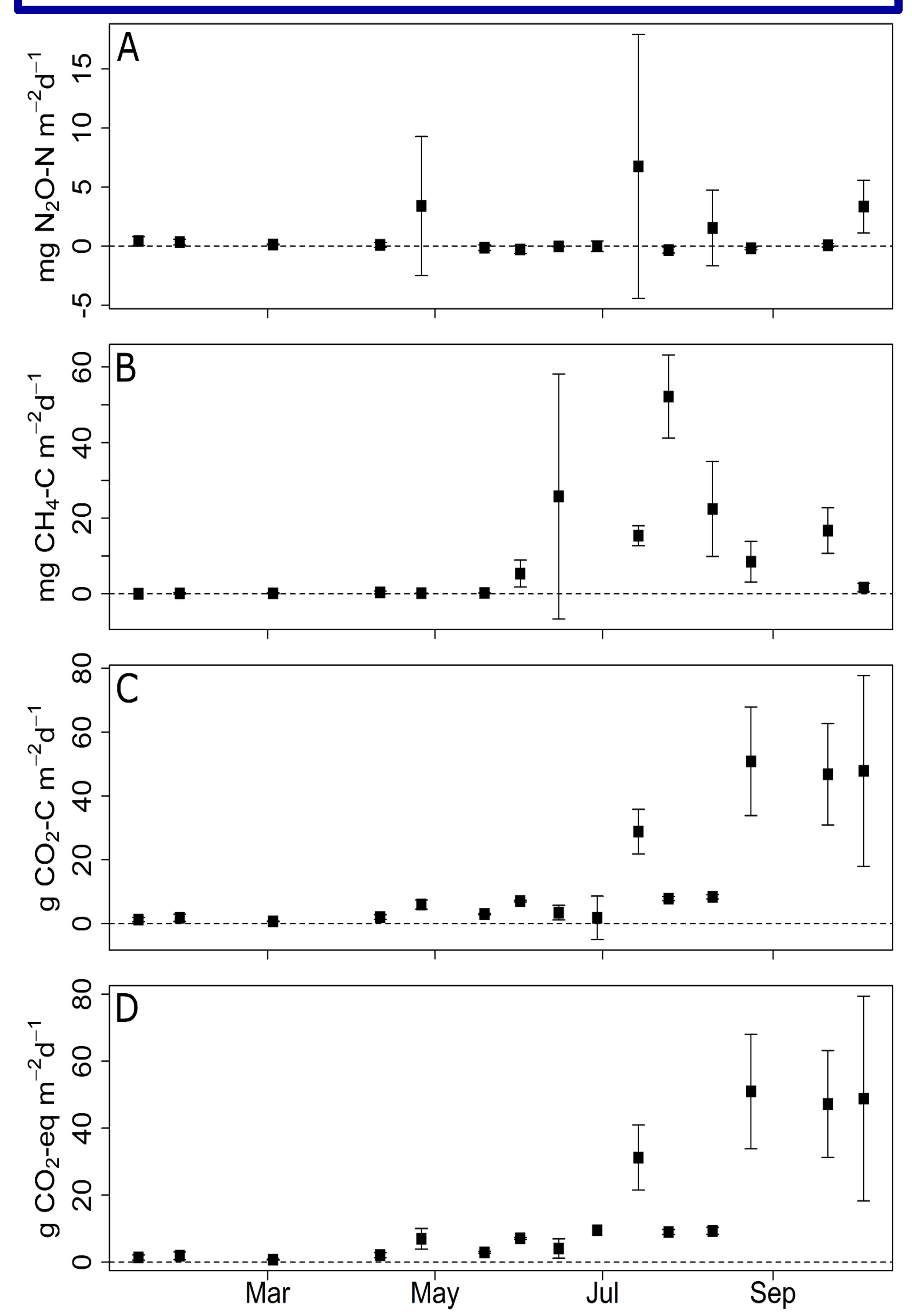

Figure 2a-d. Average flux measurements of N_2O (a), CH_4 (b), CO_2 (c), and the combined warming potential of the three gases as CO_2 equivalents (d) from three soil collars installed in a denitrifying bioreactor. Error bars represent +/- one standard deviation, and the dashed line is positioned at zero net flux. Note y axes are different scales and units differ between 3a-b (mg m^{-2} d^{-1}) and 3c-d (g m^{-2} d^{-1}).

Flux methodology

Closed dynamic chamber
- Three 50 cm soil collars
- Picarro G2508 GHG analyzer

Fig. 5. Bioreactor with soil collars.

Linear regression
- most common method
- Simple to apply
- Bias, can underestimate flux

$$F = S{\cdot}V{\cdot}A^{-1}$$

Variables
- F flux
- S slope of analyte conc. over time
- V total volume of recirculating system
- A surface

Physically-based non-steady state diffusive flux estimator
- Application of Fick's Law (Livingston et al., 2006)
- Nonlinear response due to altered concentration gradient
- Estimates pre-deployment flux

$$C_t = C_0 + f_0\tau\left(\frac{A}{V}\right)\left[\frac{2}{\sqrt{\pi}}\sqrt{t/\tau} + \exp(t/\tau)\mathrm{erfc}(\sqrt{t/\tau}) - 1\right]$$

Parameters
- t time
- C_t headspace concentration at t
- C_o ambient trace gas concentration
- f_o pre-deployment flux
- A surface area within collar
- V total volume of closed system

Starting values
- f_o LR flux calculation
- τ $(V/A)^2/D$

Constant
- D diffusivity

Fitting
Levenberg-Marquard least-squares

Functions
erfc is complementary error function

Livingston, G.P., Hutchinson, G.L., Spartalian, Kevork, N.D. 2006. Trace gas emission in chambers: a non-steady-state diffusion model. Soil Sci. Soc. Am. J. 70(5):1459-1469. doi:10.2136/sssaj2005.0322

Conclusions

This study provides a unique assessment of bioreactor performance at the lower boundary of N inputs. Understanding performance under low N loading is relevant not only to cropping and drainage systems with relatively low N export, but, perhaps more importantly, informs expectations for N removal efficiency in bioreactors used in conjunction with drainage water management, which alone can reduce N losses from fields by 17–80% (Skaggs et al., 2010), or other practices such as conservation tillage. Low pH and site constraints necessitating suboptimal bed dimensions may have also suppressed removal. Managing bed pH may be important for bioreactor applications with acidic agricultural drainage to enhance N removal and mitigate N_2O emissions, although concerning rates of GHG flux were not observed in this system. Conceptualizing how regional differences impact in-bed controls on N removal will guide adaptation of bioreactor designs to a wider range of agroecosystems, ultimately contributing to water quality improvement goals. Although bioreactor effectiveness relies on site-specific design, regional difference in artificial drainage networks, cropping systems, soil types, and hydrologic regimes can inform assessment of bioreactor utility and cost-effectiveness in the Mid-Atlantic.