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Artificial Sinks to Treat Legacy Nutrients in Agricultural Landscapes

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Background

A Persistent Water Quality Problem

Legacy nutrients introduce a critical time lag between changes in nutrient application or implementation of best management practices (BMPs) and observable reductions in loads delivered to downstream waters. Nitrogen and phosphorus leached through soils into groundwater may take decades to eventually be discharged to surface waters and, consequently, often prevent the attainment of water quality improvement goals. For example, the National Resource Council has cautioned that in the Chesapeake Bay watershed legacy nutrients, particularly nitrogen (N), could delay achievement of nutrient load reductions needed to meet Total Maximum Daily Load (TMDL) requirements.. Groundwater discharge transporting legacy N has been identified specifically as a significant nutrient source to the Bay.[2,3] Unfortunately, most existing BMPs cannot remediate these nutrient reservoirs and the Chesapeake Bay Program has not active policy to address legacy nutrients; better management options are needed.

A Potential Solution and Novel Application

Artificial nitrogen sinks, particularly denitrifying bioreactors (Fig. 1), have the potential to augment natural nutrient assimilation processes to remove legacy nutrients (NO_3^-) directly from emerging groundwater.

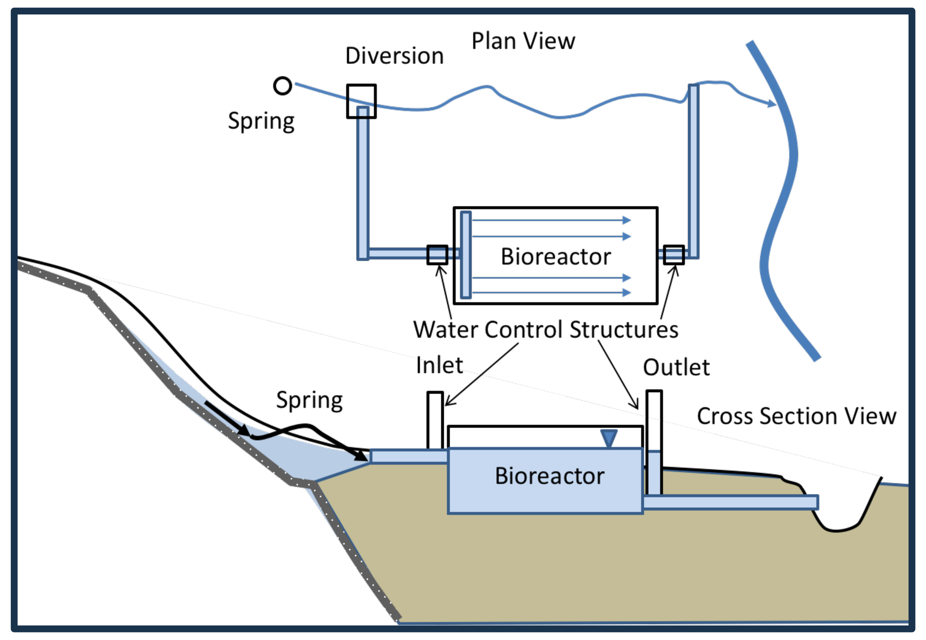


Figure 1. Application of a denitrifying bioreactor to a spring. Off-channel design allows a portion of the flow to be diverted for treatment and minimizes Clean Water Act permitting concerns.

Approach

The objective of this work is to evaluate the N removal potential and costs of adapting traditional edge-of-field bioreactor design to treat legacy N discharged via springs in the Mid-Atlantic Region. We first assess data from springs monitored by the United States Geologic Survey (USGS) in MD, PA, VA, and WV to identify distributions of flow rates, N concentrations, and estimated N loads (Figure 3). We then estimate the potential N load reductions bioreactors could achieve and estimate unit removal costs by applying N removal efficiencies—derived both from literature values and from a pilot spring bioreactor.

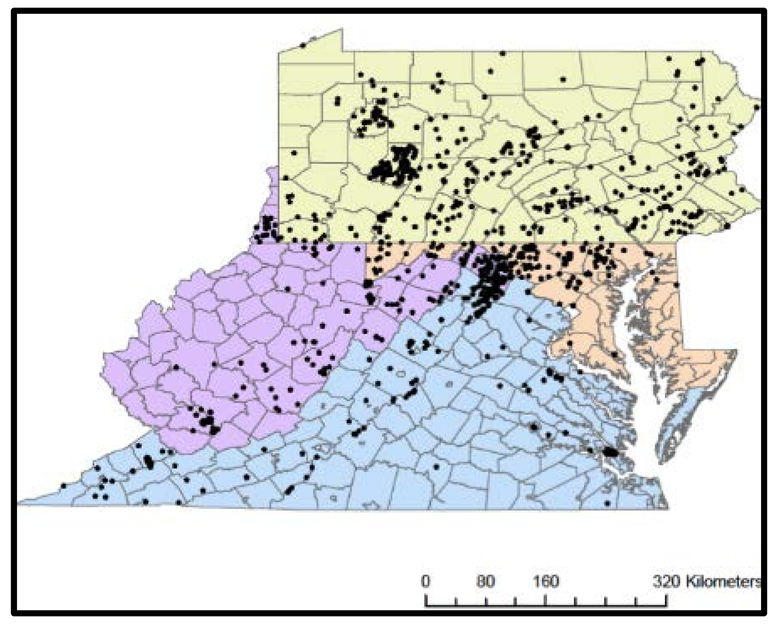


Figure 2. Springs (1034) identified by USGS in the Mid-Atlantic.

Highlights

- **Emergent groundwater delivers 1000s of kg of nitrate-N a day to surface water in the Mid-Atlantic region of the US.**
- **Adapting denitrifying bioreactors to remove N from springs is a means to treat legacy N.**
- **Spring bioreactors can remove N at costs lower than most conventional nonpoint source control technologies.**

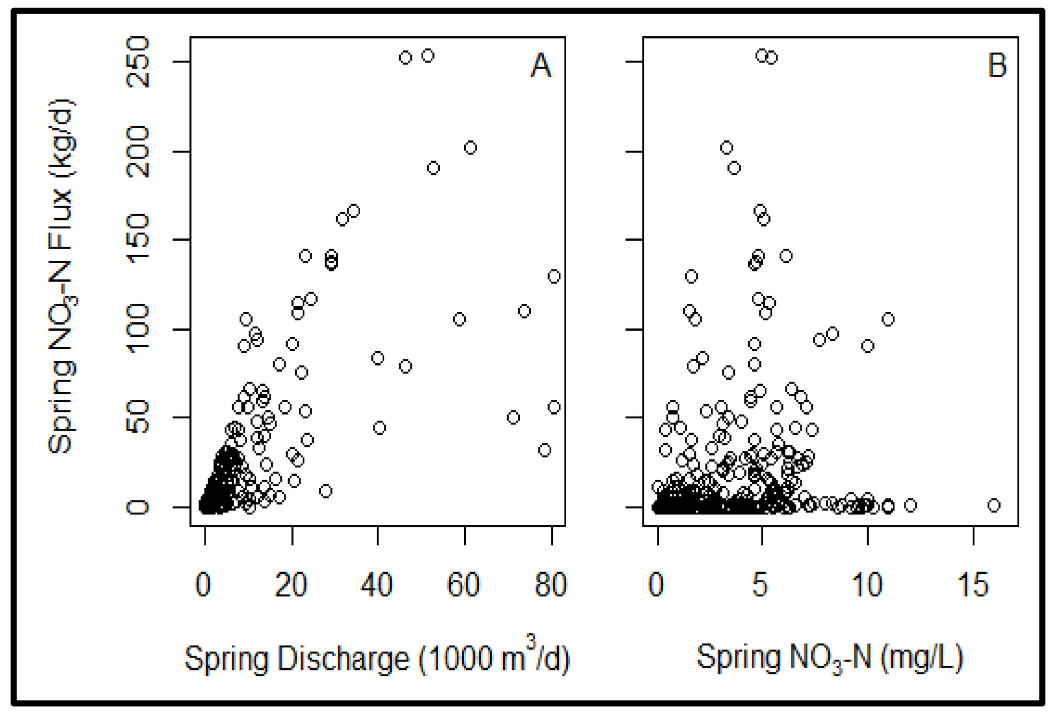
Results

Extent of the Opportunity: Legacy Nitrogen in Springs

Table 1. Descriptive statistics of instantaneous discharge and nitrate-nitrogen (NO_3-N) concentration for the USGS-monitored springs. Note springs are not continuously monitored, and discharge and water chemistry sampling do not always occur simultaneously. Data are summarized separately for all springs and for the subset with simultaneous discharge and NO_3-N concentration measurements.

	All Springs		Concurrent Discharge and Concentration		
Statistic	Discharge (m^3/d)	NO_3-N (mg/L)	Discharge (m^3/d)	NO_3-N (mg/L)	NO_3-N Flux (kg/d)
Min	0	<0.001	0	<0.001	0
Q1	15.8	0.72	25.6	0.49	0.02
Median	54.5	3.80	273	1.90	0.43
Mean	7,720	5.73	5,948	2.89	14.7
Q3	2,435	7.32	4,405	4.74	10.1
Max	274,064	31.00	274,064	16.00	253.8
Samples	n=922	n=1,577	n=407		
Springs	n=278	n=537	n=231		

Figure 3. Relationship between spring discharge and nitrate-nitrogen (NO_3-N) flux (A) and NO_3-N concentration and flux (B) for the 231-spring subset with concurrent flow and water chemistry measurements.



Estimating Potential N Removal with Spring Bioreactors

We derived bioreactor N removal efficiencies from the literature (0.6-44.4 g N/m3/d, which corresponded to reported removal efficiencies of 4-85%) and selected a conservative removal efficiency of 30% and a more optimistic 55% efficiency to estimate spring treatment potential.

The performance of a pilot spring bioreactor (32 m^3, woodchips with 10% biochar v/v), which achieved 41% N removal over two years, suggests 30-55% removal efficiency is achievable. For this pilot system, the median NO_3-N concentration was 8.7 mg/L, a median flow 27 m^3/d, and the estimated median NO_3-N flux of 0.23 kg/d. The bioreactor consistently removed more than 0.1 kg/d during periods of active flow and often considerably more. The median NO3-N removal rate of 4.9 g/m^3/d is very similar to the mean 4.7 g/m^3/d reported in a bioreactor meta-analysis,[7] but the mean of 8.8 g/m^3/d was substantially greater.

Discussion

Potential Nitrogen Load Reductions and Cost-effectiveness

Agricultural bioreactors in the Midwest typically treat drainage from 10-35 ha,[4] and annual N loadings are on the order of 300-1050 kg/yr, assuming 30 kg/ha/yr is exported via drainage.[5] **Targeting high N flux springs could provide opportunities for a single bioreactor to treat significantly greater nitrogen loads more cost-effectively than their agricultural counterparts.** Considering hypothetical spring bioreactor installations, Figure 3 shows bioreactor NO_3-N removal rate potential across a range of treated flows for the two representative removal efficiencies (30 and 55%), across of range of concentrations (median, 3rd quartile, and half of the maximum in the 664-spring data set). For a relative comparison, Between 55 and 180 urban bioretention BMPs (removing 5 to 9 N kg/yr/ha) would need to be installed to achieve the equivalent level of N removal as single modestly sized spring bioreactor (500 m^3, 30-55% N removal efficiency, 3.8 mg/l influent).

The N removal potential of spring bioreactors dwarfs many nonpoint source practices currently in use.

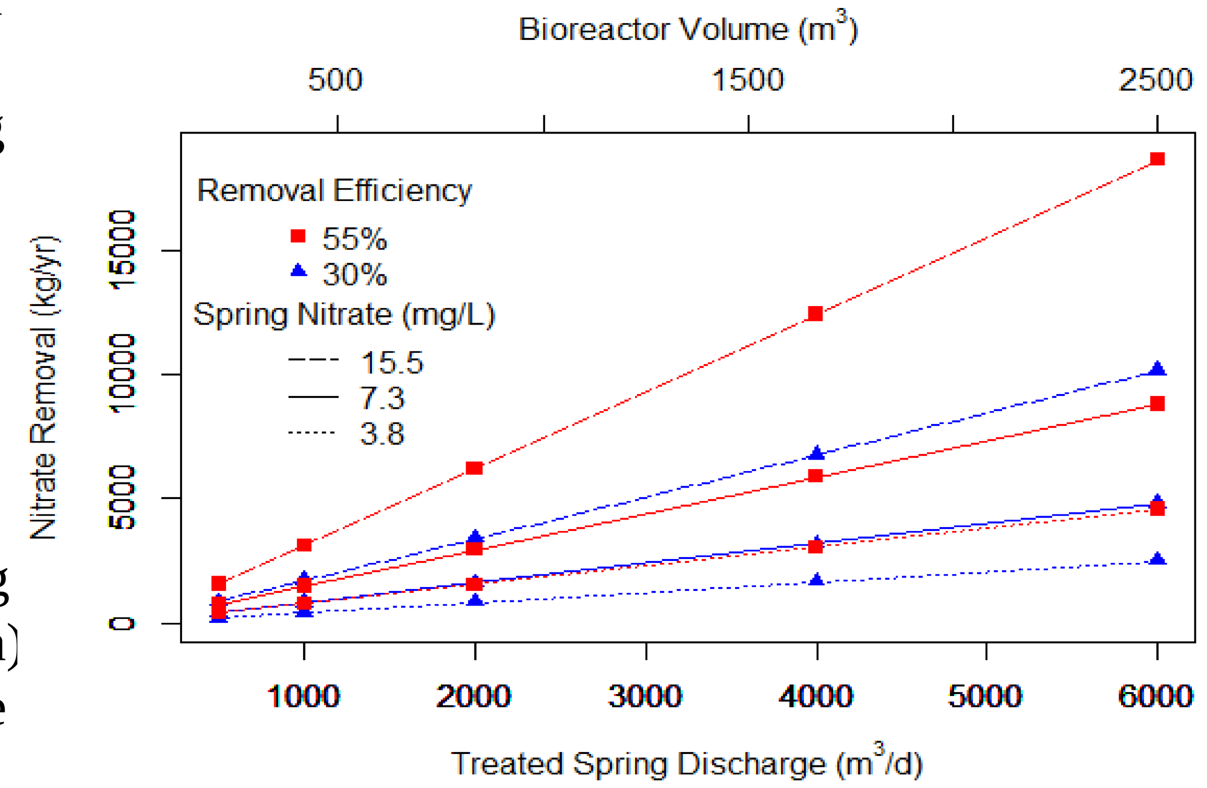


Figure 4. Estimated annual nitrate removal for a spring bioreactor across a range conditions.

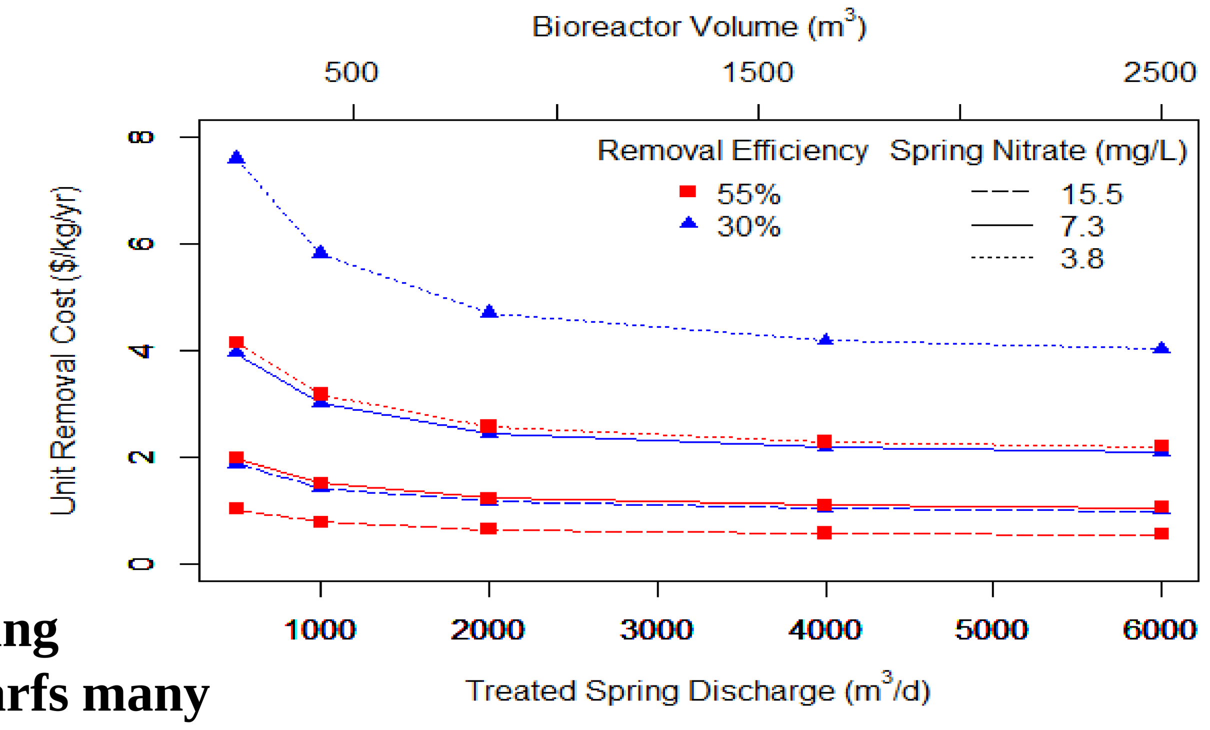


Figure 4. Unit nitrate removal cost estimates ($/kg/yr) for hypothetical spring bioreactors.

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