CLEAN RESOURCES FINAL PUBLIC REPORT TEMPLATE

1. PROJECT INFORMATION:

Project Title:	Advancing Denitrifying Bioreactors as a Beneficial Management Practice for Agricultural Drainage Waters in Alberta
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AI Project Advisor:	Dallas Johnson

2. APPLICANT INFORMATION:

Applicant (Organization):	**Alberta Agriculture, Forestry and Rural Economic Development**
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3. PROJECT PARTNERS

We would like to acknowledge the staff from Alberta Agriculture, Forestry and Rural Economic Development (AFRED) who made the completion of this project possible and meaningful. Thank you to the Taber Irrigation District (TID) staff for their help with the installation and decommissioning of the bioreactors and for their field work. Thank you to Cameron Stevenson for his ongoing support with the installation and decommissioning of the bioreactors at Crop Diversification Center North (CDCN).

A. EXECUTIVE SUMMARY

Tile drainage is a widely adopted agricultural water management practice for removing excess water from the soil profile to improve soil moisture conditions for seeding and crop growth. However, tile drainage systems provide direct conduits that can transport nutrients from agricultural fields to surrounding irrigation canals, reservoirs and natural water bodies. Elevated concentrations of dissolved nutrients, such as nitrogen (N) and phosphorus (P), in tile drainage water can lead to water quality impairments including eutrophication in rivers and lakes and potential damage of irrigation infrastructure from weed and algae blooms. Simple, low cost technologies are needed to reduce nutrient export from agricultural tile drainage to sensitive aquatic ecosystems. A potential solution is the use of denitrifying bioreactors– a passive treatment approach where drainage water is routed through solid carbon substrates to remove dissolved nutrients through physicochemical and biological processes. This edge-of-field water treatment technology is gaining popularity in the mid-western United States and eastern Canada, but has not gained widespread acceptance in the Canadian Prairies. Consequently, there remains uncertainty in whether these technologies are appropriate for the Canadian Prairies considering agricultural drainage is greatest during spring snowmelt and the bioreactors are driven by biological processes, which may be inhibited by cooler spring temperatures.

This study evaluated the performance of pilot-scale denitrifying bioreactors for removing dissolved nutrients under Alberta agricultural field conditions at two representative geographic locations. Substrates were sourced from local materials and included wood chips, hemp straw, and barley straw. The substrates were tested under varying retention times (flow rates) and air temperatures during year-round operation from the beginning of the irrigation season in the spring to the end of irrigation season in fall for nutrient removal potential. Results from this study identified air temperature, flow rate, carbon source material and bioreactor age as primary factors affecting nitrate removal. The flow design demonstrated that the lowest flow rate maximized nitrate removal efficiency, and was further optimized in the summer season. There appears to be a possible decline of nitrate removal capacity over time.

Overall, the average nitrate-N load reduction as a percentage of inlet load for the various treatments was 45%, 59% and 36% for spring, summer and fall, respectively. The load reductions were significantly lower for the wood chips (32%) compared with the agricultural residues (hemp at 50%, barley at 58%). Denitrifying bioreactor performance appears to be improved with the use of agricultural residues (barley

straw and hemp straw) as fill media as compared to wood, although the retention time also influenced the overall nitrate removal capacity.

B. INTRODUCTION

Sector Introduction

Tile drainage is a widely adopted agricultural water management practice for facilitating crop growth improvements by reducing excess soil water in the rooting zone. The practice is gaining popularity in Alberta's agricultural sector in response to increasing land values and a desire to maximize yield and achieve product consistency under variable topography, soil texture and precipitation patterns. The practice can also increase the soil absorption capacity between rain events and reduce overland sediment and contaminant transport in areas prone to surface runoff. By managing soil saturation, tile drainage can result in a net reduction of non-point source pollution occurring through surface runoff. However, this results in sub-surface transport of soluble nutrients with a point source discharge at a central outlet. The accumulation of nutrients discharged from several outlets can have wide-ranging consequences to receiving water bodies including rivers, reservoirs, irrigation canals and return flow channels.

Knowledge or Technology Gaps

Recent research and development efforts in the Midwestern United States have demonstrated the applicability of denitrifying bioreactors as an end-of-pipe treatment method for mitigating impacts from agricultural drainage waters. However, unlike the Midwestern United States, the highest drainage rates in Alberta generally occur during snowmelt in early spring under cool temperature periods in which biological activity may be substantively reduced. Consequently, significant uncertainty exists in applying denitrifying bioreactors to Alberta’s agricultural landscape as design parameters have not been tested or optimized for the Canadian Prairies. This project evaluated bioreactor performance based on Alberta climate conditions and will allow stakeholders such as farmers, irrigation districts and regulators to assess the suitability of these systems within their local context.

C. PROJECT DESCRIPTION

Knowledge or Technology Description

The goal of this study was to evaluate the feasibility and optimize the design criteria of denitrifying bioreactors as an edge-of-field beneficial management practice (BMP) for mitigating environmental effects of agricultural drainage in Alberta. Project objectives outline the need for comparisons to be made between bioreactor performance in different geographic locations and with different design parameters to better understand such influences on bioreactor nutrient removal in Alberta.

Objective 1: Construct nine replicated pilot-scale bioreactors at each of the central (Edmonton) and southern (Taber) Alberta locations.

To account for interprovincial climatic variation, nine pilot-scale bioreactors were installed at each of two sites: one set was located in central Alberta at the Crop Diversification Centre North (CDCN) and one set was located in southern Alberta within the Taber Irrigation District (TID). These locations represent different climate conditions common to Alberta's primary agricultural region and, as such, differ in their relative temperatures, precipitation patterns, day lengths, growing degree days, growing season lengths and soil types. These climates were humid continental in central Alberta and semi-arid in the south. At the CDCN site, the soil was a Black Chernozem and at the TID site, the soil was a Brown Chernozem.

Objective 2: Assess the efficacy of local carbon feedstocks for reducing annual nutrient loading under climatic conditions common to Alberta.

Much of the field-based research completed on denitrifying bioreactors focuses on the use of woodchips as a carbon-based feedstock to stimulate biological denitrification. Wood-based substrates are recommended for their physical durability, but laboratory studies have shown that denitrification rates in wood-based bioreactors are hampered under cold temperatures due to lower emission of labile carbon. Agricultural residues such as straw, have demonstrated greater success at stimulating denitrification in cold temperatures, but have not been subject to field-performance testing to any significant degree that could inform their suitability as a bioreactor feedstock in Alberta. In this study, hemp straw and barley straw were compared against wood chips, a byproduct of power pole manufacturing, as a bioreactor feedstock at each site.

Objective 3: Evaluate the effect of hydraulic retention time on nutrient load reductions by changing the retention times over year round operation from the beginning of snowmelt runoff in spring to the end of irrigation season in the fall.

Cool temperatures reduce the rate of biological processes, such as denitrification, increasing the time required to achieve equivalent levels of biological activity under warmer temperatures. Much of the literature on field applications for denitrifying bioreactors describe studies that have been completed in warmer climates where agricultural drainage is primarily driven through growing-season rainfall events. As a result, the recommended hydraulic retention times reported in the literature may be unsuitable for conditions in Alberta, where agricultural drainage is primarily snowmelt-driven and occurs in the spring when temperatures are cool. Hydraulic retention times (HRT) of 4, 8 and 12 hours were compared to evaluate the relative effectiveness of increasing retention time on nutrient removal.

Updates to Project Objectives

Changes that have occurred compared to the original project objectives are as follows:

Objectives	Update
Objective 1	No changes to Objective 1 (construction of bioreactors at two sites in Alberta).
Objective 2	Objective 2 (assessment of the efficacy of feedstocks) was completed as planned. However, due to logistical challenges associated with workforce adjustments at AFRED at the end of 2020, the central site did not operate in the second year of the project (2021). This meant that only one year of data was available for feedstock

	comparison for the central site instead of the originally planned two years. Two years of data was available for the southern site.

Objective 3	Objective 3 (evaluation of the effect of hydraulic retention times) was completed as planned. However, due to logistical challenges associated with workforce adjustments at AFRED at the end of 2020, only the bioreactors located at TID were active and the conditions were as follows:
	• Each TID bioreactor ran through a flow-recession design, which mimicked natural conditions of high- to low-flow conditions of a runoff event.
	  ○ The limits of the pumps and flow meters required that bioreactors be run between 2 gallons per minute (GPM) to 1 GPM.
	  ○ Bioreactors were set at 2 GPM (~5 h HRT) to start, followed by successive declines to 1.5 GPM (~7.5 h HRT) and then finally to 1 GPM (~10 h HRT).
	• Every bioreactor at TID ran according to the same flow schedule, which allowed for a direct comparison of treatment performance between feedstocks during the assessment period.
	• Solute tracer tests, using sodium chloride (NaCl), were conducted at the beginning of each seasonal assessment period, and operated at 2 GPM at the TID bioreactors only.

Performance Metrics

The performance metrics originally identified for the project were unchanged and are as follows:

Metrics of Results	Performance
Metric 1: Bioreactor Installation	18 bioreactors constructed and installed in TID and CDCN.
Metric 2: Bioreactor performance assessment	Bioreactor design with varying hydraulic retention times and varied carbon feedstock selection under different climate conditions were evaluated based on nutrient removal.
Metric 3: Factsheets, progress reports, presentations and field tours.	Results shared with Alberta water regulation staff and water consulting specialists/agrologists via factsheets and reports. Presentations/field tours made to the agricultural organizations listed as project partners.
Metric 4: Paper publication	Two papers published in peer-reviewed journals.

D. METHODOLOGY

Site Selection

Two sites that represent different climatic areas of Alberta were selected to install replicated pilot-scale bioreactors. These locations were at the Crop Diversification Centre North (CDCN; central Alberta outside of Edmonton) and in the Taber Irrigation District (TID; southern Alberta outside of Taber). The CDCN site represented a humid continental climate and the TID site represented a semi-arid climate. Alberta's primary agriculture region spans both these climates.

Bioreactor Design and Construction

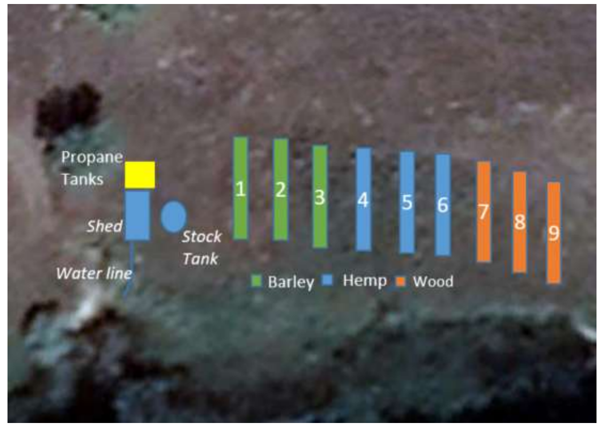
Nine replicated pilot-scale bioreactors were installed at each site (Figure 1-CDCN and Figure 2-TID). A trench-style bioreactor design was used in this study, as it represents a simple and practical way for producers to use bioreactor technology to intercept and treat subsurface drainage water. Each trench was excavated to approximate dimensions of 6 m length × 0.6 m width × 1.3 m depth. Prefabricated liners (30 mil Linear Low Density Polyethylene) were then fixed within the trenches to cover the bottom and sides with extra to fold over the top after filling. The trenches were filled with one of three types of carbon-rich organic substrates. Wood chips, hemp straw and barley straw were used at both sites; the wood shavings were obtained from a common source (by-product of power pole manufacturing) and hemp straw and barley straw were procured from a local producer proximal to each site. Each bioreactor was filled with approximately 1.3 m of organic substrate. The plastic liner was then folded over the top of the material and covered with a minimum of 0.3 m of soil. Inflow and outflow pipes were placed at both ends of the bioreactors. Four wells made of 10.2 cm (4 in.) polyvinyl chloride (PVC) tubing were installed at the start and end positions of the bioreactors, and at two middle positions located at 1.8 m and 3.6 m from the first well. Water levels within the bioreactors were continually monitored throughout the study using pressure transducers to calculate the depth of the saturated zone (Figure 3). The wells allowed for collection of water samples from the bioreactor interior. The inlet water was fed from the top of the inlet well, and the outlet port was positioned to maintain a saturated depth of approximately 1 m within the bioreactors (Figure 4).

(a)

(b)

Figure 1. (a) Bioreactors at CDCN (b) CDCN Bioreactor identification and feedstock schematic.

(a)



(b)

Figure 2. (a) Bioreactors at TID (b) TID Bioreactor identification and feedstock schematic.

Figure 3. Sampling well with pressure transducer removed and resting on cap awaiting downloading.

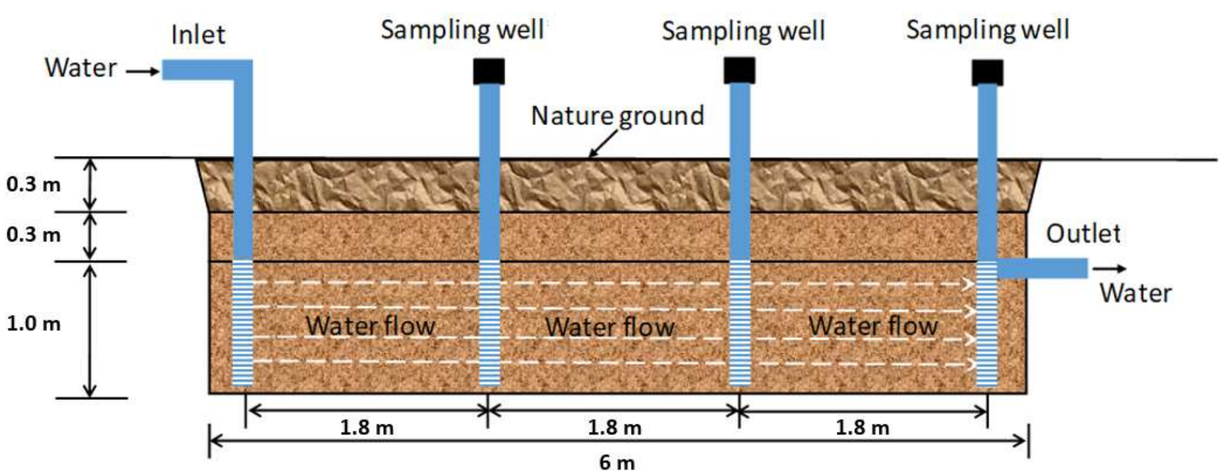


Figure 4. Dimensional schematic of pilot-scale bioreactors in longitudinal cross-section.

Water was diverted from an adjacent stream for the CDCN site and from an irrigation canal for the TID site to supply water to the bioreactors. Water was pumped from the stream or canal, filtered to <100 µm using an automated self-cleaning filter, and dosed to ~20 mg/L of nitrate using a dosing pump attached to a large stock tank. Stock solutions of nitrate were prepared weekly using filtered stream water and potassium nitrate fertilizer. Flow into each bioreactor was controlled with valves and flow meters attached to each inlet pump. Flow control was required to achieve the desired (theoretical) HRT in order to compare the effect of different HRTs on nutrient removal performance.

2020 Experimental Design

The study was designed in a way that at each site (CDCN and TID), each feedstock material (three bioreactors each of wood, hemp, and barley) would be combined with each HRT treatment (4 h, 8 h, 12 h), to test the interactive effect between the treatments. As a result, these target HRTs were cycled between seasons throughout 2020, and corresponding tracer studies were conducted at the start and end of the seasonal assessment. Each feedstock bioreactor had its flow rate adjusted to a different HRT level in each season. The tracer tests and the slug tests allowed for the calculation of a suite of hydraulic properties.

2021 Experimental Design

The 2021 field season was altered to account for logistical challenges associated with workforce adjustments at AFRED. Bioreactors at CDCN did not operate in 2021 and each bioreactor at TID was run through the same flow-recession design each season, which allowed for a direct comparison of treatment performance between feedstocks during each assessment period. This flow-recession design mimicked natural conditions of high- to low-flow conditions during a runoff event. The bioreactors started at the flow rate of 2 GPM (~5 h HRT), followed by successive declines to 1.5 GPM (~7.5 h HRT), and 1 GPM (~10 h) each season. The duration of each flow rate was approximately one week. Three seasonal assessment periods were conducted (May, July, September) to account for seasonal differences in treatment performance. Corresponding tracer studies were conducted at the start of each seasonal assessment with slug tests performed at the end.

Physical and Hydraulic Properties

Tracer tests were conducted using solute mass transport with salt-dilution methods. One kilogram of sodium chloride (4 L of 250 mg/L solution) was added to each bioreactor and the change in specific conductance (SpC) was monitored at the outlet well using deployable conductivity sensors capable of continuous monitoring. Calibration curves were established from each event to calculate solute mass transport from conductivity measurements. These measurements enabled the calculation of the actual hydraulic retention time as well as additional hydraulic properties such as in-situ porosity, solute dispersion using the Morrill Dispersion Index (MDI), hydraulic efficiency, and a short-circuiting index (S) for each substrate under different flow conditions.

Hydraulic efficiency was calculated as the ratio of mean solute retention time to the time of peak concentration and it indicates the departure of the average retention time of solutes added to the system from the target HRT. Hydraulic efficiency values fall within 0 – 1, with 1 being the most ideal as it represents unimpeded flow. However, values above 0.5 indicate conditions that still allow for some effective flow and are considered satisfactory for a working bioreactor[1]. The MDI is an indicator of mixing within the bioreactor, where lower values indicate less mixing and less contact with feedstock and MDI values of 2.0 or lower indicate plugged flow. The S indicates the degree of preferential flow paths occurring in the bioreactors; a value of 1 indicates uniform flow across the bioreactor, which is most effective for nitrate removal. Values less than 1 indicate that preferential flow or short-circuiting is occurring, which means the water quickly flows through the feedstock with little opportunity for nitrate removal.

These three hydraulic properties were used to determine the flow rates needed to achieve the various retention times for each type of feedstock bioreactor.

Saturated hydraulic conductivity was calculated using a slug test in which a 9 cm diameter bailer (~5 L volume) was lowered into one of the internal wells in the bioreactor to remove a volume or 'slug' of water. The recovery of the water level was measured using a pressure transducer set to record water levels every 0.5 seconds to account for the rapid recovery of the water level in the substrates. The slug tests were performed at each site during each season.

Bioreactor Assessment

Assessment of bioreactor performance for removing dissolved nitrogen was conducted on a seasonal basis throughout the growing period, focusing on spring (May–June), summer (July–August), and fall (September–October) seasons. During each seasonal assessment, nitrate-dosed water was pumped through the bioreactors continuously for approximately four weeks with a three- to four-week shutdown period in between seasons during which no water flowed in the bioreactors. Bioreactor performance was assessed using the difference in concentrations from the inlet to the outlet well positions. During each seasonal assessment, weekly water samples were collected using a bailer; water obtained from the stream and the canal were also collected to be analyzed prior to mixing with nitrate. The sample bottles were triple rinsed with sample water before filling with as little headspace as possible. Collected samples were placed in coolers with ice packs and shipped to the laboratory. They were analyzed for pH, EC, NH_4-N, NO_3-N, NO_2-N, and alkalinity content. Mass loading of NO_3-N into and out of the bioreactors was calculated using cumulative flow (measured at the inlet wells using continuous loggers) and nitrate concentrations. The laboratory analysis for this project was conducted at AFRED laboratories in Lethbridge for the first year and at the ALS laboratory in Calgary for the second year.

Statistical Analysis

In this study, three feedstock treatments were repeated in triplicate, with four HRT treatments within feedstocks, and repetition of HRT treatments within bioreactors. Therefore, nutrient removal

[1] Hoover, N. L., Soupir, M. L., VanDePol, R. D., Goode, T. R., & Law, J. Y. (2017). Pilot-scale denitrification bioreactors for replicated field research. Applied Engineering in Agriculture, 33(1), 83– 90. https://doi.org/10.13031/aea.11736

performance was analyzed using Microsoft® Excel® (2016) and RStudio[2] according to a crossover repeated measurement design to account for within-bioreactor variability and potential carry-over between HRT treatments. Cumulative load reductions were also calculated in both trial years to assess the temporal resilience in load reductions after overwintering.

Concentrations were displayed graphically using boxplots and scatterplots (R Studio). The Mann-Whitney Rank Sum test (using SigmaPlot[3]; $P < 0.05$) was also carried out to compare the hydraulic proprieties at TID for both years of operation.

Bioreactor decommissioning

The bioreactors were excavated and the feedstock material and plastic liners were removed and disposed of. Displaced soil from the installation was transported from where it was stored during the duration of the study, back to the bioreactor site with more soil added to fill in the excavations as needed. The surface landscape was then leveled.

E. PROJECT RESULTS

Completion of Bioreactor Installation

Using local carbon feedstocks of wood chips, hemp straw, and barley straw, nine replicated pilot-scale bioreactors were installed at two sites: Taber Irrigation District (TID; Southern Alberta) in August 2019 and Crop Diversification Centre North (CDCN; Central Alberta) in September 2019.

Physical and Hydraulic Properties of the Pilot-Scale Bioreactors (first year – CDCN and TID)

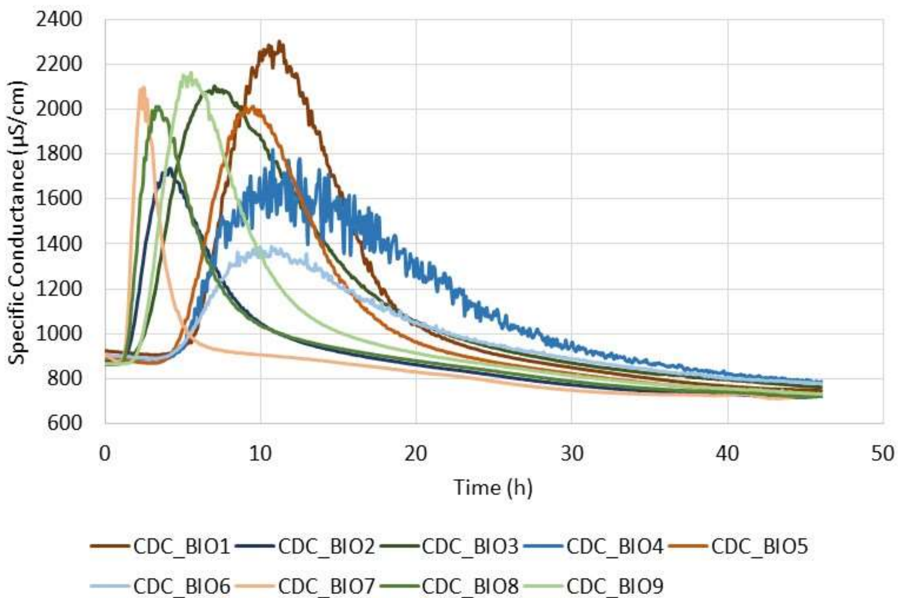
Tracer tests were run at different targeted (theoretical) HRTs (4, 8 and 12 h) prior to each of the three assessment periods of 2020 (spring, summer and fall) to collect hydraulic information on each bioreactor. Figure 5 shows time series of the specific conductance of the bioreactors following the injection of NaCl tracer prior to the summer sampling season in 2020 at both sites. In CDCN, all the peaks occurred less than 15 hours while in TID, all the peaks occurred less than 10 hours after the injection (time 0). Overall, the time required for the salt wave to pass varied from one hour to over 15 hours. The change in specific conductance during the salt wave passage depended on the characteristics of the bioreactors).

The physical and hydraulic properties measured in the bioreactors through slug and tracer tests were hydraulic conductivity, hydraulic efficiency, dispersion and short-circuiting.

These properties, according to the feedstock and HRT for the first year of operation are presented in Figure 6.

[2] RStudio Team 2020. RStudio: Integrated Development for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com/.
[3] SigmaPlot® 2011, Version 12.5, Systat Software, Inc., San Jose, California, United States.

(a)



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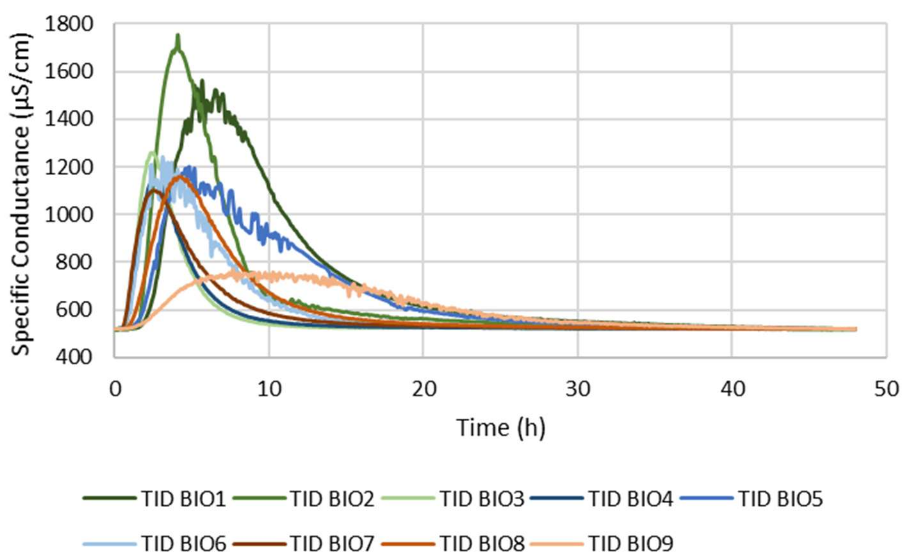

Figure 5. Specific conductance (uS/cm) of (a) CDCN and (b) TID bioreactors after the tracer tests in July 2020 and June 2020. Results are differentiated by feedstock type.

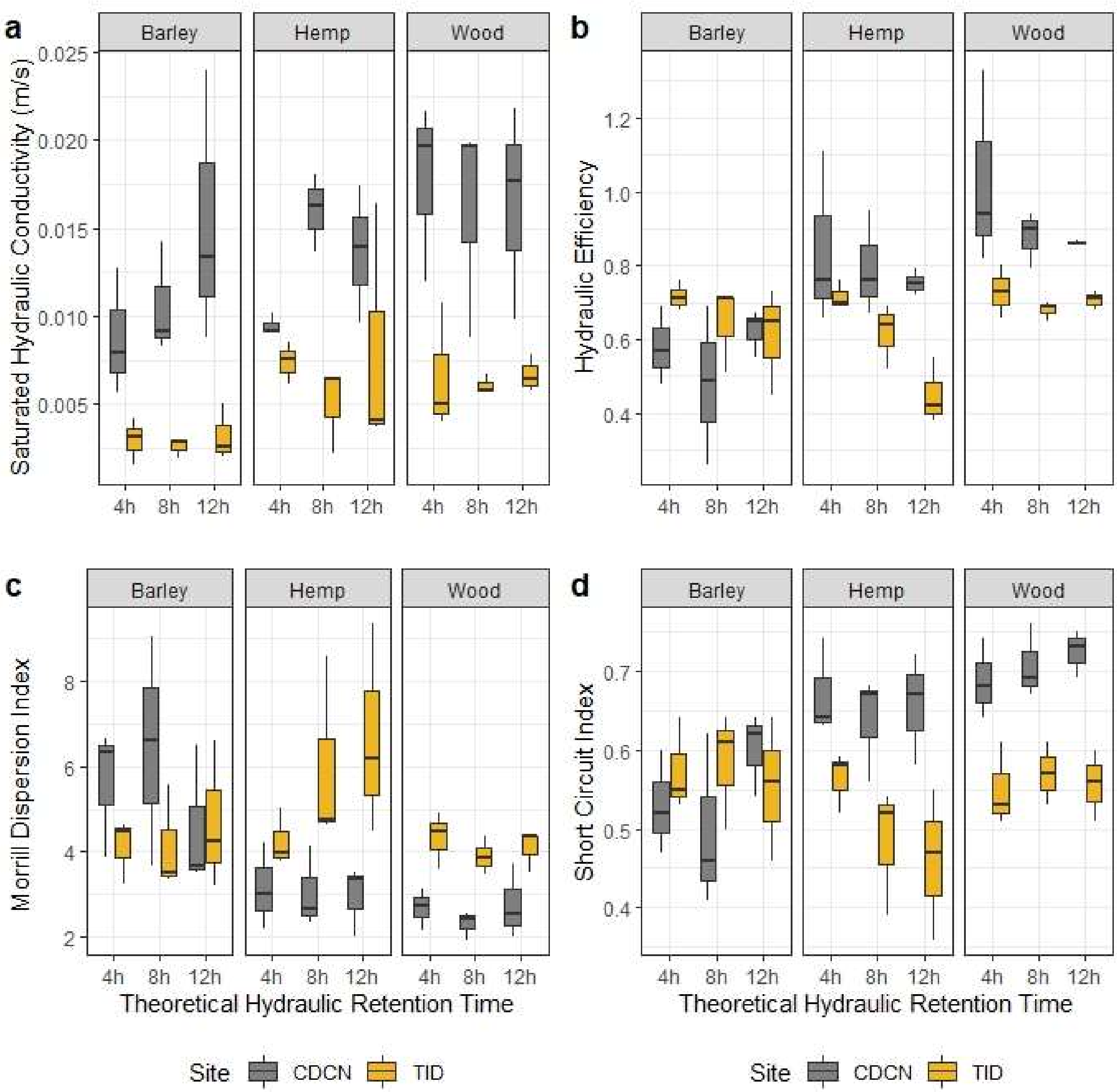

Figure 6. Hydraulic properties of the bioreactors as measured by (a) saturated hydraulic conductivity (m/s), (b) hydraulic efficiency (unitless), (c) Morrill Dispersion Index (unitless), and (d) Short-circuiting index (unitless) in 2020. Results are differentiated by feedstock type (Barley, Hemp, Wood), theoretical hydraulic retention time (4 h, 8 h, 12 h), and sites (CDCN and TID).

For the first year of operation, clear differences can be observed between sites. Saturated hydraulic conductivity (Ksat) demonstrated a consistent trend between feedstock types at both sites, where wood and hemp straw demonstrated greater conductivity than barley straw. The Ksat values were substantially greater at the CDCN sites for all feedstock types, perhaps due to differences in the way the material was packed during construction of the bioreactors.

The wood bioreactors showed greater hydraulic efficiency values than other feedstock types at both sites with hydraulic efficiency values being greater at the CDCN sites for hemp and wood than the TID site. However, all the values (except for hemp at TID for 12 h HRT) were greater than 0.5, which is considered satisfactory[4].

The degree of dispersion, or mixing, within the bioreactors at CDCN appeared to be greater in the barley straw bioreactors than the other feedstocks and was consistently lower in the hemp and wood bioreactors, as indicated by lower hydraulic efficiency and greater MDI values for barley straw. Conversely, the degree of dispersion was relatively consistent among the barley and wood bioreactors at the TID site, but was greater in the hemp straw.

The CDCN site had more ideal flow (i.e., less short-circuiting) in the order of wood>hemp>barley, whereas at the TID site barley straw had less short-circuiting than either hemp or wood, in the order of hemp=wood>barley. Taken together, these first year results indicate that the physical and hydraulic properties of the bioreactors seemed to be more influenced by the degree of packing that occurred during bioreactor construction than as a functional attribute of either feedstock or hydraulic retention time.

Physical and Hydraulic Properties of the Pilot-Scale Bioreactors (second year – TID)

For the second year of operation, the experiment was only conducted at the TID site. The tracer tests were run at a fixed flow rate of 2 GPM (~5 h HRT). Figure 7 shows time series of the specific conductance from the bioreactors following the injection of NaCl tracer prior to the summer sampling in 2021. Like in 2020, all the peaks occurred within 10 hours after the injection, and the time required for the salt wave to pass varied from one hour to over 10 hours.

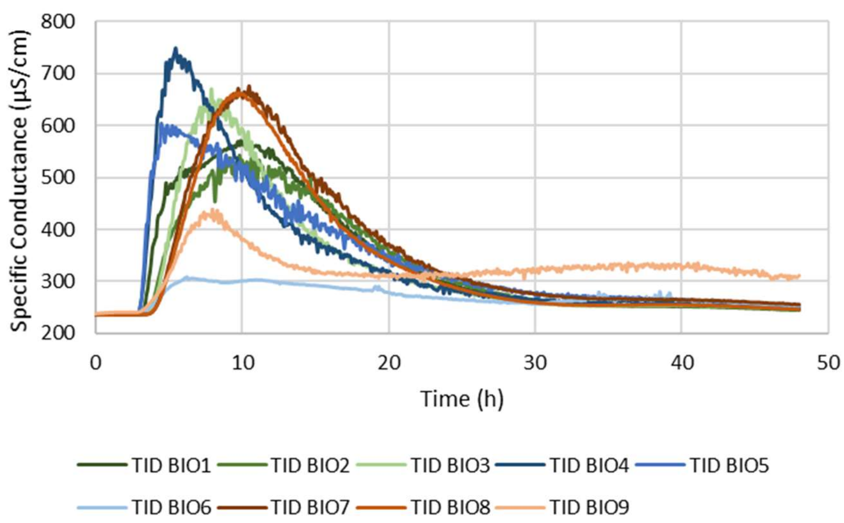

Figure 7. Specific Conductance vs. time tracer response for nine pilot-scaled denitrifying bioreactors for the summer 2021 test at TID. Results are differentiated by feedstock type.

[4] Persson, J., Somes, N.L.G., Wong, T.H.F., 1999. Hydraulics efficiency of constructed wetlands and ponds. Water Sci. Technol. 40, 291-300. https://doi.org/10.1016/S0273-1223(99)00448-5.

Physical and hydraulic properties (hydraulic conductivity, hydraulic efficiency, dispersion and short-circuiting) are presented in Figure 8. Wood chips demonstrated greater Ksat than hemp and barley straw. The wood and barley bioreactors showed hydraulic efficiency values greater than 0.5, while the hemp bioreactor showed lower values as in the first year of operation. The MDI was relatively consistent among all the bioreactors at the TID site, but were slightly greater in the hemp bioreactors. Like the first year of operation, barley straw showed a lower degree of short-circuiting than either hemp straw or wood chips at the TID site.

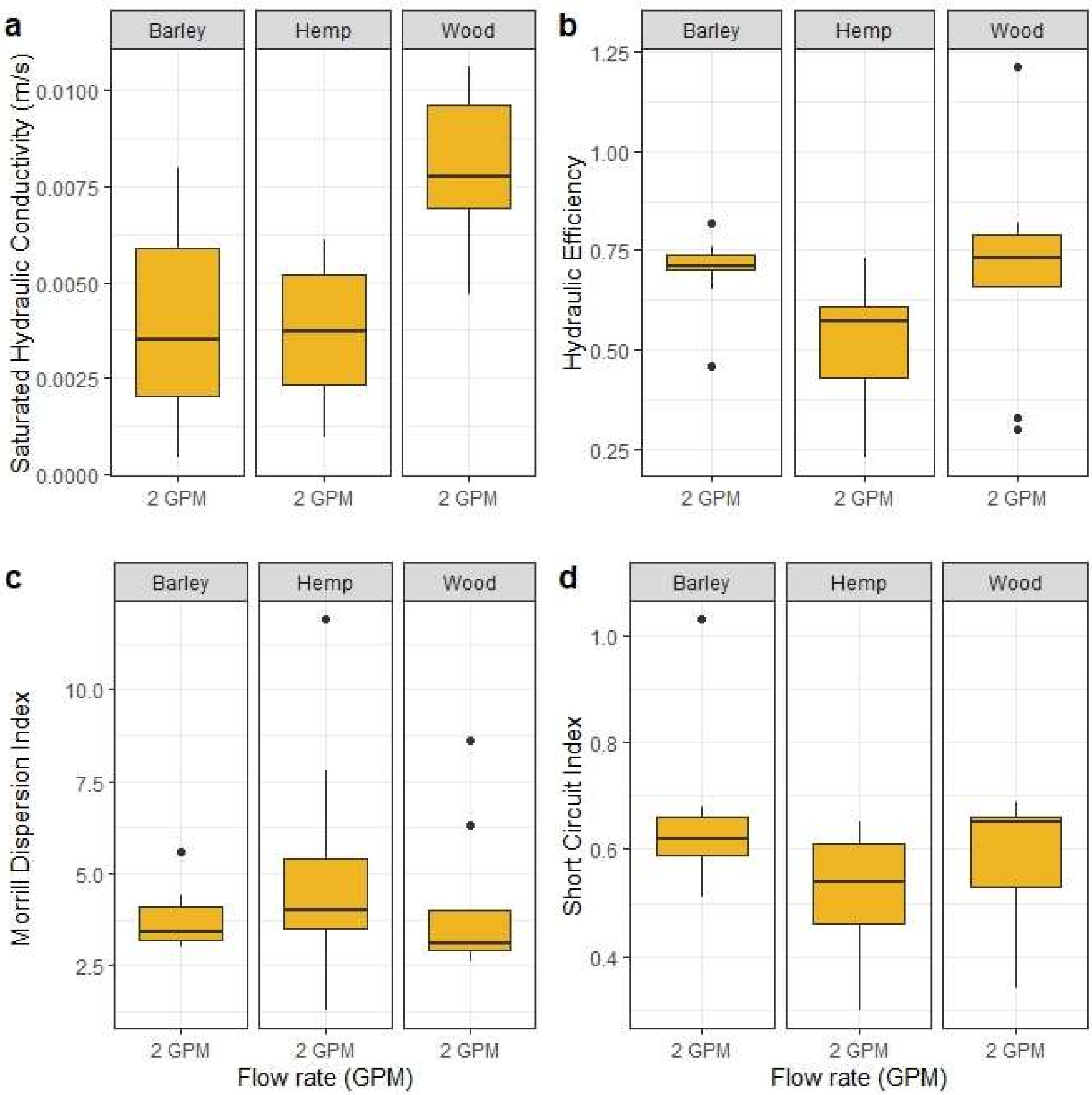

Figure 8. Hydraulic properties of the TID bioreactors as measured by (a) saturated hydraulic conductivity (m/s), (b) hydraulic efficiency (unitless), (c) Morrill Dispersion Index (unitless), and (d) Short-circuiting index (unitless) in 2021. Results were run at 2 GPM (~5 h HRT), and are differentiated by feedstock type (barley, hemp, wood).

Two-year Assessment

After two years of operation, the hydraulic proprieties at TID were compared. Table 1 and Table 2 report the mean and median values, respectively.

Table 1. Mean values for the assessment periods for 2020 and 2021 for TID according to the feedstock material.

	2020			2021		
Feedstock	Barley	Hemp	Wood	Barley	Hemp	Wood
Saturated hydraulic conductivity (Ksat)	0.00291	0.00685	0.00644	0.00383	0.0037	0.00794
Hydraulic Efficiency	0.657	0.594	0.706	0.698	0.512	0.7
Morrill Dispersion Index (MDI)	4.317	5.641	4.104	3.789	5.011	4.056
Short Circuiting (S)	0.57	0.502	0.559	0.649	0.523	0.584

Table 2. Median values for the assessment periods for 2020 and 2021 for TID according to the feedstock material.

	2020			2021		
Feedstock	Barley	Hemp	Wood	Barley	Hemp	Wood
Saturated hydraulic conductivity (Ksat)	0.00285	0.00641	0.00577	0.00351	0.00371	0.00777
Hydraulic Efficiency	0.71	0.64	0.7	0.71	0.57	0.73
Morrill Dispersion Index (MDI)	4.26	4.77	4.35	3.4	4	3.1
Short Circuiting (S)	0.56	0.52	0.56	0.62	0.54	0.65

There was a statistically significant difference in the median Ksat values for hemp in 2020 compared to 2021 (Mann-Whitney Rank Sum Test, $P < 0.05$) with 2021 significantly greater than 2020 for all feedstocks. This might explain the differences in performance of these bioreactors. There were no statistical differences between medians for the other parameters or feedstocks.

The range of the hydraulic efficiency remained the same for both years with no statistically significant difference.

The mean MDI values for 2020 (4.1 to 5.6) were greater than the 2021 MDI values for all bioreactors (3.8 to 5.0). This suggests a slightly greater flow dispersion in the first year of operation; however, there were no statistically significant differences in the median between years. Calculated MDIs in this study are similar to other reported MDI values for wood feedstock[5].

[5] Christianson, Laura & Bhandari, Alok & Helmers, Matthew. 2011. Pilot-Scale Evaluation of Denitrification Drainage Bioreactors: Reactor Geometry and Performance. Journal of Environmental Engineering. 137. 213-220. 10.1061/(asce)ee.1943-7870.0000316.

Average short-circuiting values increased in all the bioreactors in 2021: the mean S values for 2020 (0.5 to 0.57) were lower than the mean 2021 S values for all bioreactors (0.52 to 0.65). This suggests that short-circuiting conditions decreased in 2021, however there was not a statistically significant difference in the median S values between years.

Nitrate Removal Performance of Bioreactors

First year-2020

The capacity of bioreactors to remove nitrate under conditions of varying feedstock material and HRT was assessed through weekly sampling during the target seasons. The observed percentages of nitrate removal, as a function of the ratio of the concentration of nitrate at the inlet and outlet positions, compared against the total mass of nitrogen added during the assessment period for 2020 are presented in Figure 9. In general, the nitrate removal performance of bioreactors filled with agricultural residues (hemp and barley straw) tended to fluctuate around a mean value and did not exhibit positive or negative trends as nitrate was cumulatively added to the systems in 2020. However, the wood chips, particularly at 8 h and 12 h retention times, had increased nitrate removal performance as the cumulative mass of nitrate increased in the system. This may reflect a difference in the capacity of the materials to harbor populations of denitrifying bacteria, or it may be a function of assimilatory nitrate uptake given the greater carbon-to-nitrogen ratio present in woody biomass compared to agricultural residues. Thus, it appears that in the first year of operation, agricultural residues demonstrate a stable and relatively consistent capacity to remove nitrate. However, the retention time and material type have clear influence on overall nitrate removal capacity.

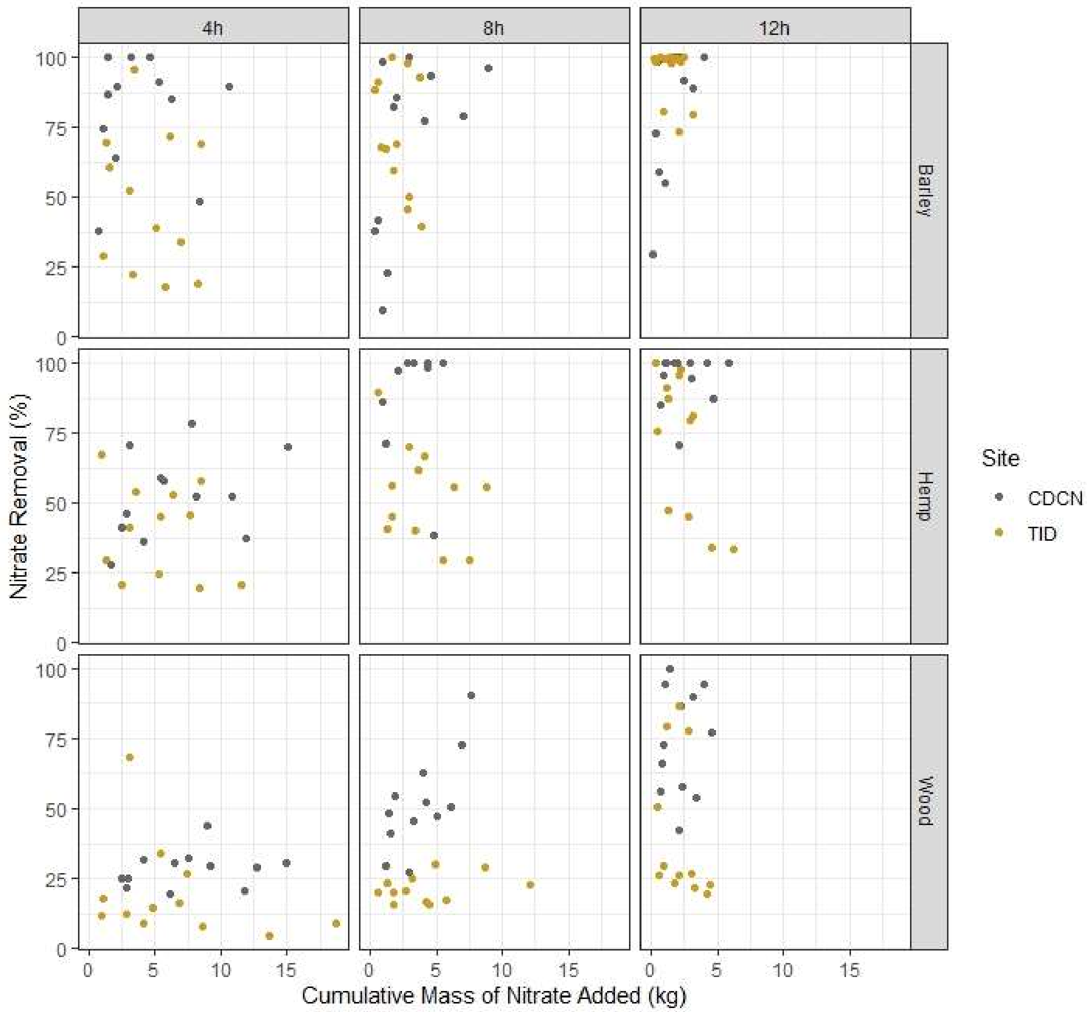

Figure 9. Percentage of nitrate removal between inlet and outlets of bioreactors according to the target hydraulic retention time (4 h, 8 h, or 12 h) and feedstock material for all the sampling dates in 2020.

As mentioned, nitrate removal performance was determined as a function of the percentage of nitrate mass removed as water flowed from the inlet to outlet well positions. Substantive differences in overall nitrate removal performance between feedstock types were evident during the spring, summer and fall assessment periods for both sites, in the 1,544 samples collected (Figure 10). The agricultural residues tended to exhibit greater denitrification, or nitrate removal, than wood chips under all design HRTs. The cooler temperatures during the fall assessment period seemingly decreased the denitrification rates observed in all bioreactors.

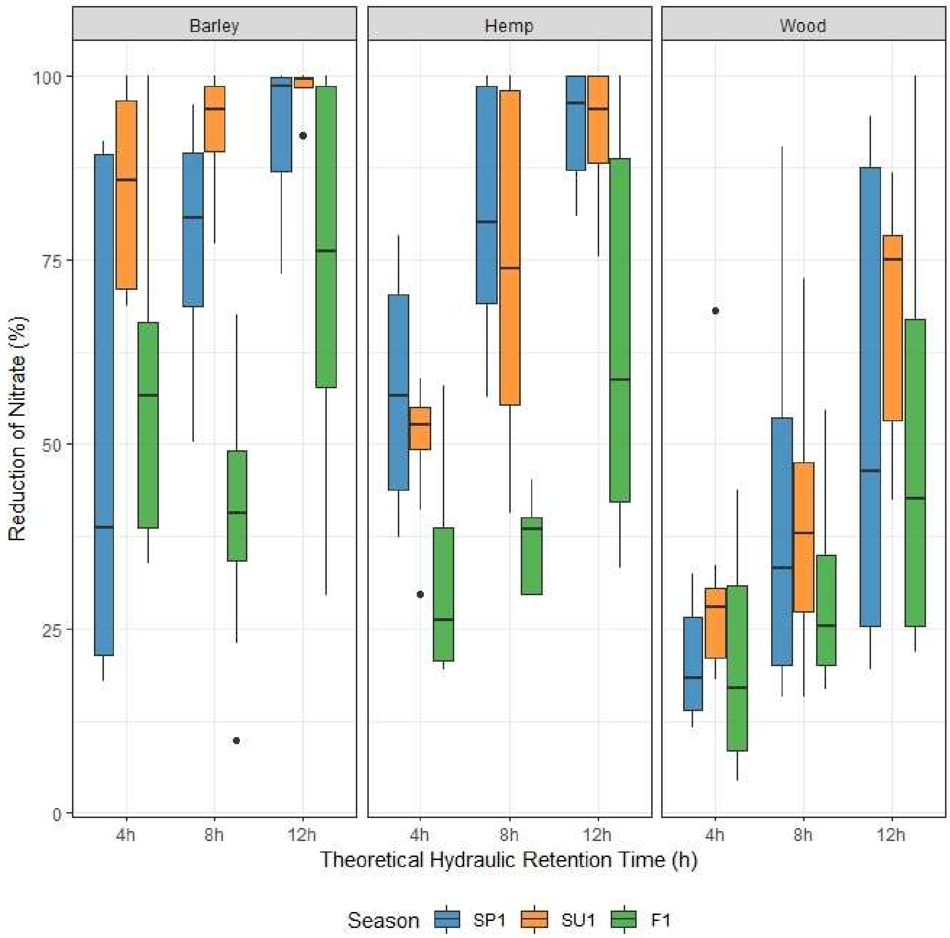

Figure 10. Overall percentage of nitrate removed during the spring (SP1), summer (SU1) and fall (F1) assessment periods according to the theoretical hydraulic retention time (4 h, 8 h, or 12 h) and feedstock material for 2020 (TID and CDCN combined, N=1,544 samples).

Table 3 shows the mean values per assessment period and feedstock. Wood chips showed the lowest mean value at each season for the TID site and at spring and summer for the CDCN site. Barley straw showed the greatest mean value at the summer for both sites.

Table 3. Mean values of nitrate reduction (%) in each assessment period for 2020 and feedstock material at the CDCN and TID site.

	CDCN			TID		
Feedstock	Barley	Hemp	Wood	Barley	Hemp	Wood
Spring	87	83	54	59	70	19
Summer	95	81	44	91	62	46
Fall	45	55	45	68	34	21

Taking all the results together, barley straw was more effective (58%) than wood chips (32%) for nutrient removal while hemp straw showed a nitrate reduction of 50%.

At both sites, water prior to mixing showed nitrate values below 10 mg/L and their pH values fell in the range known to be appropriate for denitrification (pH ≈ 7.5–9.5), outside this range, denitrification slows[6].

As an example, measured nitrate concentration from May through October 2020 from one of the wood-filled bioreactors at the CDCN site is shown in Figure 11. The closer the concentrations at the inlet compared to the outlet are, the less nitrogen is being removed.

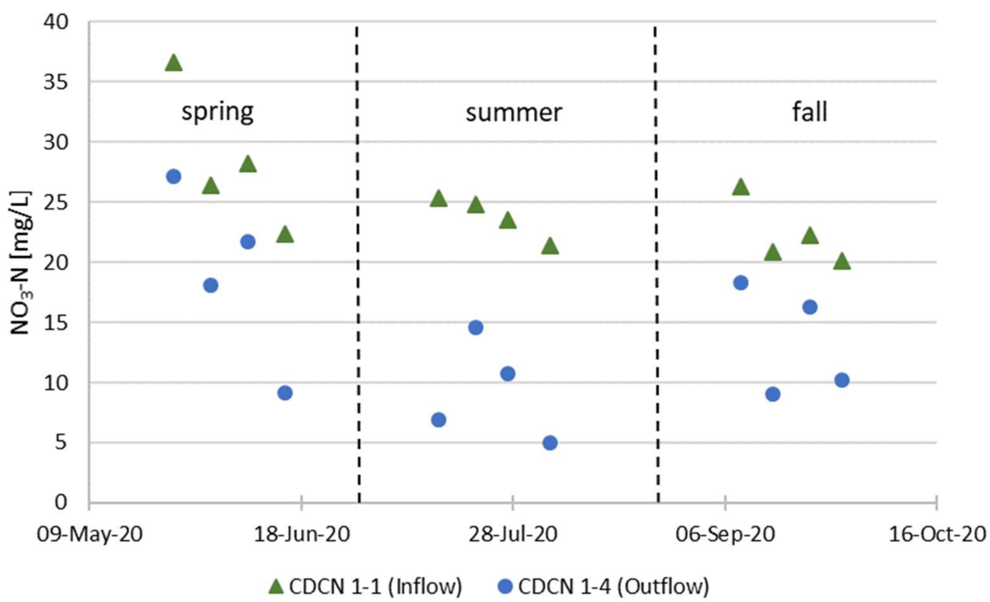

Figure 11. Measured concentration of nitrate during the spring, summer and fall assessment periods at the inlet well (CDCN 1-1), and monitoring well (CDCN 1-4) at the first bioreactor (wood chips).

Second Year-2021

In 2021, only the TID bioreactors were operational. All nine bioreactors operated on the same flow schedule, which allowed for a direct comparison of treatment performance between feedstocks during the assessment period. As the total mass of nitrate injected into the system increased over time, the flow rate was decreased to evaluate the effect of HRT on nitrate removal.

[6] Albina, P., Durban, N., Bertron, A., Albrecht, A., Robinet, J.C., et al., 2019. Influence of hydrogen electron donor, alkaline ph, and high nitrate concentrations on microbial denitrification: a review. Int. J. Mol. Sci. 20 (20) https://doi.org/10.3390/ijms20205163

The observed percentages of nitrate removal, as a function of the ratio of the concentration of nitrate at the inlet and outlet positions, compared against the total mass of nitrogen added during the assessment periods for 2021 are presented in Figure 12.

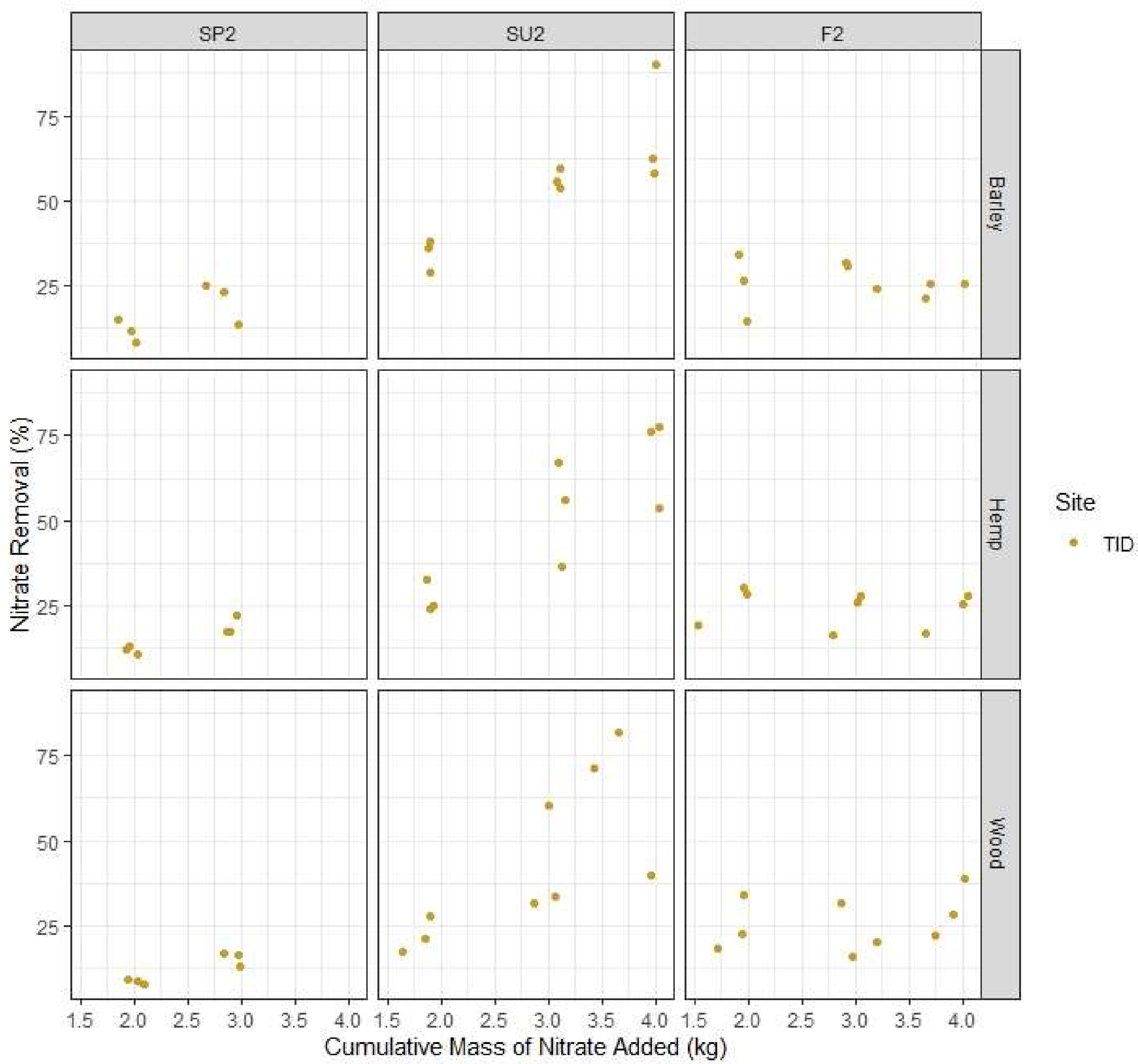

Figure 12. Percentage of nitrate removal between the inlets and outlets of TID bioreactors during the three assessment periods (Spring (SP2), Summer (SU2) and Fall (F2)) and feedstock materials.

Like in 2020, nitrate removal performance was determined as a function of the percentage of nitrate mass removed as water flowed from the inlet to outlet well positions. Substantive differences in overall nitrate removal performance among the feedstock types was evident during the spring, summer and fall assessment periods (Figure 13). The bioreactors tended to exhibit greater denitrification under lower flow rates and in summer. The warmer temperatures during the summer assessment period likely increased the denitrification rates in all bioreactors.

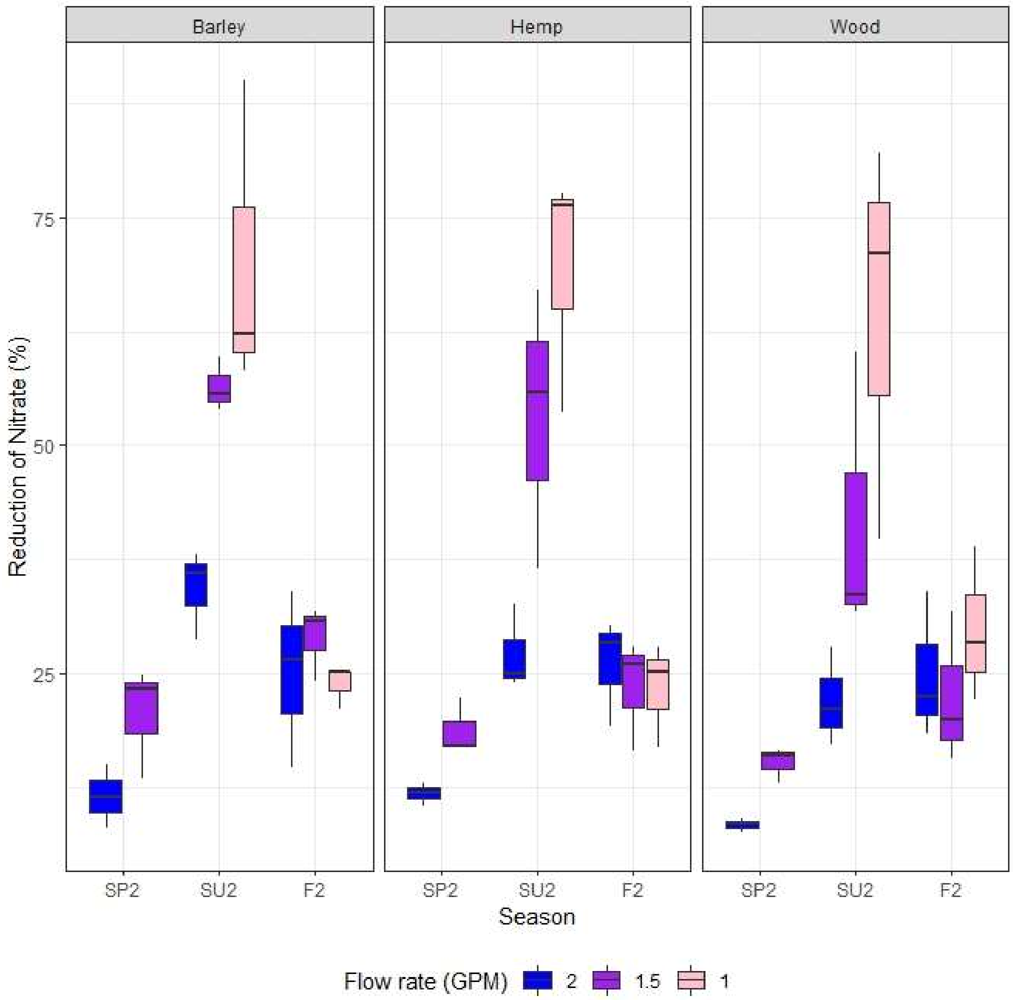

Figure 13. Overall percentage of nitrate removed during the spring (SP2), summer (SU2) and fall (F2) assessment periods according to the flow rate (2 GPM, 1.5 GPM, or 1 GPM) and feedstock material for 2021.

Overall Assessment

The overall nitrate removal performance at both sites, as a function of the percentage of nitrate mass removed from the inlet and outlet well positions, between the feedstock types during the spring, summer and fall assessment periods is shown in Figure 14. This includes only 2020 for CDCN and both 2020 and 2021 for TID.

Looking at the bioreactors at the TID site in the first year of operation, they showed a greater rate of nitrate removal while the overall performance during the second year decreased, especially for the spring and fall periods. Overall, barley showed the best performance while wood showed the poorest (Figure 14).

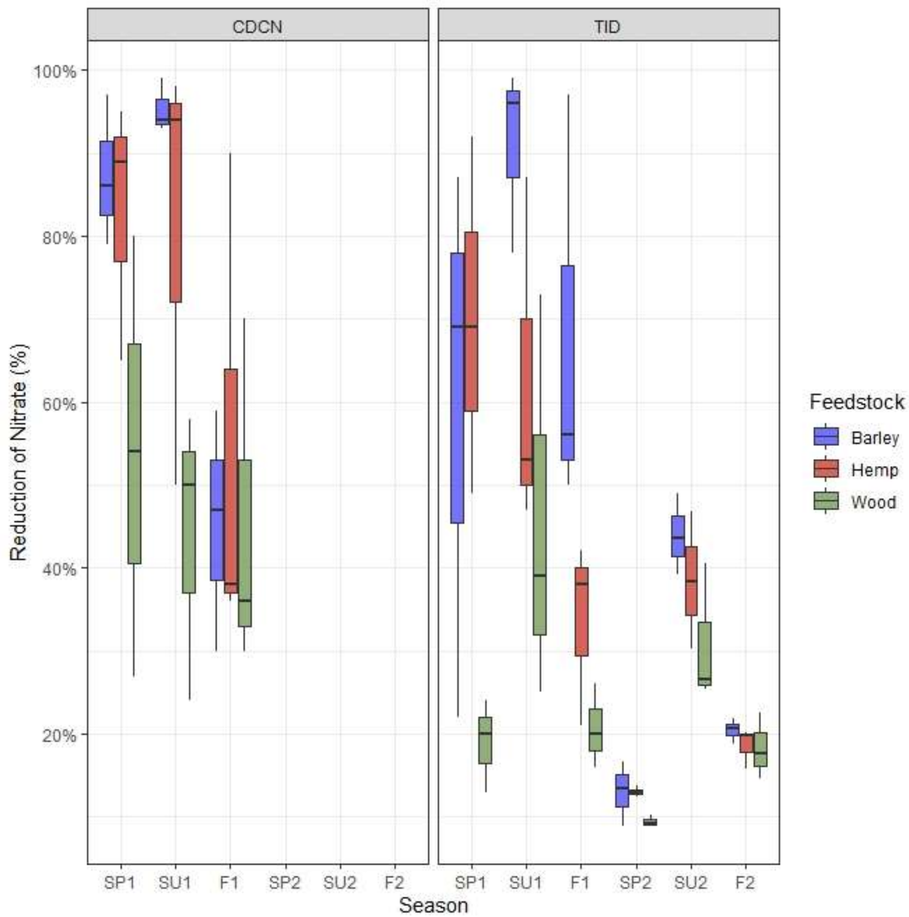

Figure 14. Overall percentage of nitrate removed during the six assessment periods according to the feedstock material for CDCN and TID. Recall that CDCN only operated in 2020.

After two years of operation at TID, the nitrate removal performance of all feedstocks combined in 2020 were compared to that of all feedstocks combined in 2021. It was found that nitrate removal performance in 2021 was significantly less than in 2020 (p= 0.002) using the Mann-Whitney Rank Sum Test. Table 4 shows the mean values per assessment period and feedstock. Wood chips showed the lowest mean value at each season.

Table 4. Mean values of nitrate reduction (%) in each assessment period for 2020 and 2021 and feedstock material at the TID site.

	2020			2021		
Feedstock	Barley	Hemp	Wood	Barley	Hemp	Wood
Spring	59	70	19	13	13	9
Summer	91	62	46	44	39	31
Fall	68	34	21	20	19	18

Nitrate concentration from May to Sept 2020 and May through October 2021 at the TID site is shown in Figure 15. The lowest nitrogen values present in the outflow monitoring well (indicating the most nitrate removal) occurred during the first year of operation and during the summer of the second year.

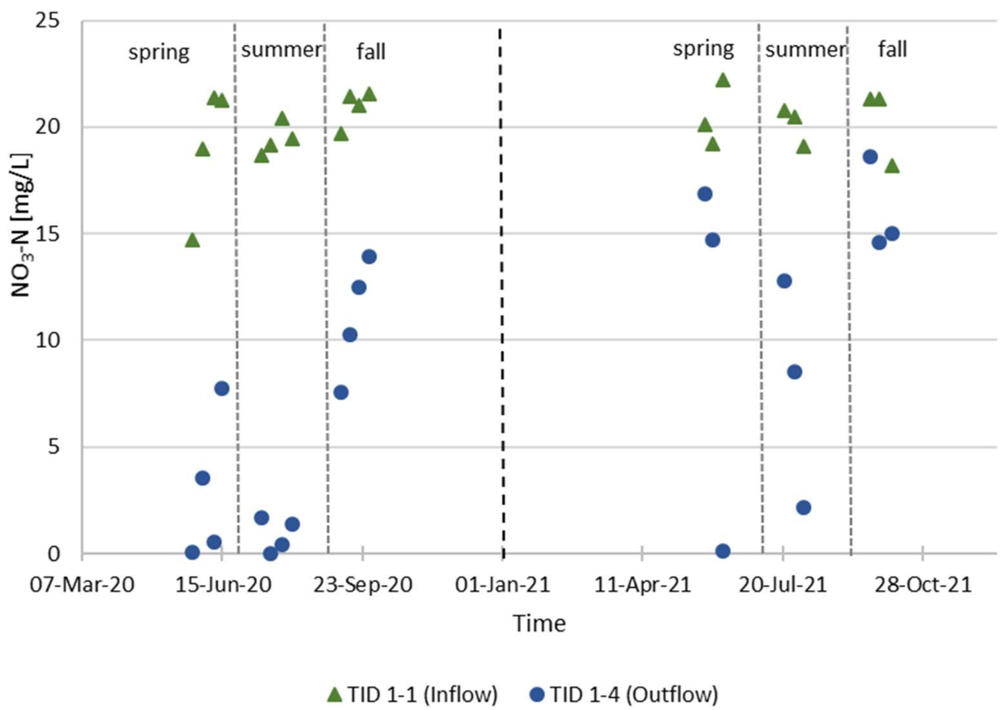

Figure 15. Concentration of nitrate removed during the spring, summer and fall assessment periods for 2020 and 2021 at the inlet well (TID 1-1) and monitoring well (TID 1-4) at the first bioreactor (barley) at the TID site.

Bioreactor Decommissioning

The bioreactors were decommissioned on October 13, 2021 at both sites. The way the sites were left after the surface landscape was leveled is shown in Figure 16.

Figure 16. Landscape after the decommissioning of the bioreactors at CDCN (left) and TID (right).

Project-specific Metrics and Variances Between Expected and Actual Performance

Table 5 outlines the metrics between expected and actual performance. Metric 1 has been completely fulfilled. Metric 2 was completed with alterations to account for logistical challenges associated with workforce adjustments at AFRED. Specifically, the bioreactors at CDCN did not operate in 2021. Metric 3 was also completed but without the field tour component due to the COVID-19 pandemic. Presentations and a progress report were completed. It is expected that Metric 4 will be fulfilled by December 2022.

Table 5. Metrics and variances between expected and actual performance.

Metrics of Results	Expected Performance	Actual Performance
Metric 1: Bioreactor Installation	Total of 18 bioreactors constructed and installed in TID and CDCN.	Total of 18 bioreactors constructed and installed in TID and CDCN.
Metric 2: Bioreactor performance assessment	Bioreactor design with varying HRTs and carbon feedstocks under different climate conditions are evaluated based on nutrient removal over two years.	Bioreactor design with varying HRTs and carbon feedstocks under different climate conditions were evaluated based on nutrient removal over one year at CDCN and two years at TID.
Metric 3: Factsheets, progress reports, presentations and field tours.	Results shared with Alberta water regulation staff and water consulting specialists/agrologists via factsheets and reports. Presentations/field tours made to the agricultural organizations listed in the project partners.	Presentation at the Nutrient Management Workshop on November 2019. Presentation at the Alberta Soil Science Workshop on February 2020 Progress report submitted to Alberta Innovates in 2021. Field tours were cancelled due to the pandemic.
Metric 4: Paper publication	Two papers published in peer-reviewed journals.	Manuscripts in preparation.

F. KEY LEARNINGS

Physical and Hydraulic Properties of the Pilot-Scale Bioreactors

Based on the physical and hydraulic properties measured by slug and tracer tests at both sites, agricultural residues (barley straw and hemp straw) functioned well as feedstocks for this plot-scale experiment with denitrifying bioreactors. Hydraulic conductivity and efficiency, as well as optimal mixing and consistent flow patterns throughout the bioreactors were achieved and sometimes optimized by agricultural residues. There were no trends in properties among feedstocks or sites, which may indicate that the hydraulic properties of the bioreactors are more influenced by construction methods during bioreactor installation rather than the functional attributes of either feedstock material, hydraulic retention time or geographic location in the province. Construction methods that may affect physical or hydraulic properties of the bioreactors could be the method of packing or amount of feedstock used. One way to mitigate this could be to use a pre-measured volume for each bioreactor to ensure the same amount of measured feedstocks are used and that the same placement techniques are performed. It is recommended that slug and tracer tests be conducted upon installation of denitrifying bioreactors to ensure physical and hydraulic properties are conducive to effective operation.

Nitrate Removal Performance of Bioreactors

Agricultural residues of barley straw and hemp straw provided a stable and relatively consistent capacity to remove nitrate from drainage water using bioreactors. When compared to wood chips, the amount of nitrate removed by agricultural residue was consistent over the seasonal operation of the bioreactor (i.e., similar performance at beginning and end of month-long seasonal trials). In contrast, the removal of nitrate by the wood chips was maximized as the cumulative mass of nitrate increased with time. The differences in surface area or size of the feedstock pieces might have influenced the differences between the performance of wood chips and agricultural residues in that the feedstocks act as a filter, and the 'filter size' is defined by the size of the feedstock pieces. However further research on this possibility is needed.

Nitrate removal by bioreactors was optimized by longer hydraulic retention times and warmer temperatures as evidenced by slowest flow rates and the most nitrate removal during the warmer summer seasonal trials, respectively.

Looking at performance over time, the bioreactors at the TID site showed greater rates of nitrate removal during the first year of operation, while the overall performance during the second year decreased, especially for the spring and fall periods. Overall, barley straw showed the best performance while the wood showed the poorest. The barley straw performance was optimized in summer suggesting that the warm weather played an important role.

When comparing the two sites, the bioreactors at CDCN showed greater mean values of nitrate reduction in almost all assessment periods and feedstocks.

The observed results are promising, given that agricultural residues are readily available in agricultural landscapes throughout Alberta. These results only reflect one year of operation for the bioreactors located in central Alberta and two years for the bioreactors located in southern Alberta and so do not reflect the temporal stability and durability of agricultural residues under longer-term operation.

Broader Impacts of the Learnings to the Industry and Beyond

This project is a valuable contribution to the development of strategies that help the agricultural industry minimize their impact on the environment. The use of denitrifying bioreactors may offer drainage water management options in Alberta that help protect downstream water bodies. The agricultural industry, as well as drainage contractors, have demonstrated interest in assisting with field-scale bioreactor installations, project coordination, and communication of learnings. The use of agricultural residues instead of wood chips provides an attractive option at least in the short-term, and an incentive to further explore this technology.

Alberta Environment and Parks is drafting a Surface Water Load Management Policy, under which a nutrient offsets program is being proposed. Science-based data on the range of conditions, optimal design parameters, and performance of agricultural BMPs for water quality improvement, including denitrifying bioreactors are required to inform the offset program. This project provides important information on the suitability and optimal conditions under which this technology can be applied in the Alberta landscape.

G. OUTCOMES AND IMPACTS

Project Outcomes and Impacts: The project outcomes fit well with Alberta's Water for Life Strategy (2008) as it relates to the Water Management Principles section which states "best available practices will be used to manage agricultural tile drainage water" as well as the statement from the Knowledge and Research section that aims to "use applicable research to make informed agricultural tile drainage water management decisions".

The outcomes of this project have contributed to filling knowledge gaps regarding denitrifying bioreactor performance in Alberta. The use of agricultural residues as fill media and evaluation of bioreactor performance during different seasons provides a better understanding of the feasibility of applying this technology in Alberta given varying geographical landscapes and climatic conditions.

Clean Resources Metrics: Two pilot sites, each with nine pilot-scale bioreactors, were installed in central and southern Alberta. A partnership agreement was established between AFRED and TID to complete the project work, as funded from both Alberta Innovates and the Canadian Agricultural Partnership (CAP). It is expected that two publications in peer-reviewed journals will be produced from this study. There was a deviation from the original project plan as the CDCN site could not operate in the second year due to logistical challenges that resulted from workforce changes in the Government of Alberta in late 2020.

Program Specific Metrics: The project team proposed the percent reduction of waterborne pollutants as a metric to be demonstrated throughout the study, given that the intent of this program is to empirically evaluate nutrient mass reduction of denitrifying bioreactor technologies. The target was to demonstrate a 50% reduction in nitrate removal from drainage waters and this target was partially reached (i.e., for bioreactors filled by barley straw). This study has found that barley straw is more effective (58%) than wood chips (32%) for nutrient removal while maintaining hydraulic properties similar to woodchips.

Project Success Metrics: Successful acquisition of the Alberta Innovates funding enabled the Taber Irrigation District project partner to successfully obtain matching funds through the Canadian Agricultural Partnership. Our Project Success Metric reflects the dollar value of funds leveraged through the Alberta Innovates grant.

Project Outputs:

- Presentation at the Nutrient Management Workshop on November 2019 in Lethbridge, AB.
- Presentation at the Alberta Soil Science Workshop on February 2020 in Calgary, AB.

H. BENEFITS

Economic: Drainage of agricultural land can be economically desirable to increase productivity of already cultivated land or to bring more land into production. However, drainage activities must be balanced with potential degradation of water quality caused by the addition of poorer quality drainage water to receiving water bodies. Denitrifying bioreactors offer an option of improving the quality of drainage water and thus offering protection to the receiving water bodies. Adoption of science-based BMPsby the agricultural industry can help to protect the water and soil resources that the industry relies on for their livelihood, as well as maintaining the social license to operate granted by society.

Environmental: Denitrifying bioreactors are a passive treatment approach where drainage water is routed through solid carbon substrates to remove dissolved nutrients through physicochemical and biological processes. Although sub-surface drainage can result in a net reduction of non-point source pollution occurring through surface runoff, it can create point source pollution by transferring distributed nutrients to a central sub-surface drainage outlet. This concentration effect can have adverse effects on receiving systems, such as streams, wetlands, or irrigation canals. This project validates the use of passive bioreactors as an agricultural BMP option and provides important information on the suitability and optimal conditions under which this technology can be applied in Alberta. This study suggests maximized nitrate removal at warmer temperatures and at longer hydraulic retention times.

Social: This project contributes to science-based information on the implementation and effectiveness of agricultural BMPs that help to mitigate agriculture's impact on the environment. The distribution of this information is necessary for further adoption of these strategies by the agricultural industry. The physical removal of dissolved nutrients from drainage water by denitrifying bioreactors may result in a reduction of eutrophication of waters receiving drainage water. This may allow for more recreational opportunities (wildlife viewing, angling, swimming), and continued assurance of good quality agricultural water for crops and livestock.

Building Innovation Capacity: Identification of the optimized conditions and design of plot-scale denitrifying bioreactors under Alberta conditions is a step towards producers having confidence when implementing bioreactors as a BMP. The information collected from this initial study allows for the potential for spinoff projects to build on the innovative capacity of bioreactors and opportunities for businesses to engage in new product development that may make bioreactors more efficient, easier or more cost effective to install.

I. RECOMMENDATIONS AND NEXT STEPS

This project is a valuable contribution to the development of commercial applications of bioreactor technologies for drainage water management in Alberta. However, prior to implementing the knowledge acquired, additional research is necessary on the following areas:

1) This pilot project should be implemented and tested on a larger scale and for an extended time period (> 2 years) prior to making recommendations for commercialization. A comparison with

other comparable edge-of-field technologies for drainage water management such as wetlands, buffer strips and sediment control would be warranted. There is also a need for testing these practices and verifying the performance in different ecoregions in Alberta.

2) Tiling of irrigated farmland can reduce saturation periods that may promote salinization in some soils. It is uncertain how the use of bioreactors could interact with this. It is possible for the bioreactors to retain the water draining from the tiles for a given period, negating the purpose of tile drainage. This interaction should be further examined.

3) A longer-term study will be necessary to make recommendations about how often the feedstock should be replaced. According to Lepine et al. (2018)[7], only a bioreactor with fresh woodchips (i.e., one-year woodchip replacement schedule) is likely to demonstrate maximum removal rates due to ideal flow conditions and available labile C. They highlighted that while N removal rates will likely be inconsistent from year to year; they show a general trend of decreased performance after one year of operation, though years two and onward tend to be similar.

4) Differences between the performance of wood chips and agricultural residues are reported in this study and in the literature. Mixing the woodchips with the agricultural residues is an option to explore in further research. Expecting better performance from mixing substrates is speculative, but it could be assumed that mixing a good performing substrate with a poorer performing substrate would result in a performance somewhere in the middle.

Due to redirection away from agricultural research, AFRED does not have plans to directly further these research areas but the groundwork has been laid for other organizations to continue the work to advance the development and learnings from this project.

J. KNOWLEDGE DISSEMINATION

In Alberta, tile drainage installation requires approval under the Water Act. However, tile drainage approvals may be delayed or determined as non-compliant if tile drainage effluents are presumed to be detrimental to receiving environments. The application of validated BMPs for tile effluent management may facilitate the approval process for tile drain applications, thus benefiting agricultural production while mitigating environmental risks associated with the practice. Since tile drainage is increasing in popularity in Alberta, there remains a need to validate BMPs for tile effluent management in the region and compare their relative efficacy. The results from this project validate the use of plot-scale passive bioreactors as an agricultural BMP option and provides important foundational information on the suitability of and optimal conditions under which this technology can be applied in Alberta's agricultural landscapes. The knowledge

[7] Christine Lepine, Laura Christianson, John Davidson, Steven Summerfelt, Woodchip bioreactors as treatment for recirculating aquaculture systems' wastewater: A cost assessment of nitrogen removal, Aquacultural Engineering, Volume 83, 2018, Pages 85-92, ISSN 0144-8609, https://doi.org/10.1016/j.aquaeng.2018.09.001

gained from the project contributes to the industry with regard to the development of BMPs for water quality improvement following a tile drainage installation.

Learnings from the project have been disseminated through presentations at industry conferences and will also be disseminated through manuscripts.

K. CONCLUSIONS

This project evaluated the performance of pilot-scale denitrifying bioreactors for removing dissolved nutrients under varying Alberta agricultural field and climatic conditions. Two representative geographic locations were selected for the study (Objective 1). Local waste biomass materials (woodchips, hemp straw and barley straw) were tested for nutrient removal potential under varying retention times and ambient temperatures during year-round operation, from the beginning of snowmelt runoff in spring to the end of irrigation season in the fall (Objective 2). After installation of bioreactors at the two sites, sodium chloride tracer tests were conducted on each replicated bioreactor to determine physical characteristics and flow parameters (Objective 3). This information was used to determine the flow rates needed to achieve the various retention times for each type of feedstock bioreactor.

The tracer test results indicated that the hydraulic properties of the bioreactors seemed to be more influenced by the degree of packing during bioreactor construction and subsequent settling rather than the functional attributes of either feedstock or hydraulic retention time.

The 2020 experimental design was based on a treatment-comparison study, where replicated treatments of hydraulic retention time (HRT) were established at three levels (4 h, 8 h, 12 h) with three different feedstocks (barley, hemp, wood). Three seasonal assessments were conducted at two sites (TID and CDCN); each feedstock bioreactor had its flow rate adjusted to a different HRT level in each season.

The 2021 field season was altered to account for logistical challenges associated with workforce adjustments at AFRED and thus the bioreactors at CDCN did not operate. Each bioreactor at the TID site was run through a flow-recession design, which mimicked natural conditions of high- to low-flow conditions during high water-levels. The limits of the pumps and flow meters required all bioreactors to be run between 2 GPM to 1 GPM. Bioreactors were set at 2 GPM (~5 h HRT) to start, followed by successive declines to 1.5 GPM (~7.5 h HRT) and 1 GPM (~10 h HRT). Every bioreactor was run according to the same flow schedule, which allowed for a direct comparison of treatment performance between feedstocks during the assessment period. Three seasonal assessment periods were conducted (May, July, September) to account for seasonal differences in treatment performance.

In summary, this study identified warmer air temperatures, flow rate, carbon source material and age of the bioreactor as the primary factors affecting nitrate removal. The flow-recession design demonstrated that the lowest flow rate maximized the nitrate removal efficiency; however, it was highly related to the season, in that nitrate removal was greater in summer. In general, there appears to be a possible decline of nitrate removal capacity over time; however the effective bioreactor lifespan is still unknown.

It also appears that agricultural residues tended to exhibit greater denitrification than wood chips under all design HRTs. However, the retention time and material type have clear influence on the overall nitrate removal capacity in the bioreactors.

This project offers valuable information for the development of commercial applications of bioreactor technologies for drainage water management in Alberta. These results will be disseminated to academia and industry for further consideration for their research efforts related to potential implementation of field-scale denitrifying bioreactors as an agricultural BMP.