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RESULTS FROM AN IN-STREAM WOODCHIP DENITRIFYING BIOREACTOR FIELD TRIAL IN SOUTH CANTERBURY.

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Abstract

Woodchip denitrification beds (WDBs) are an edge-of-field nitrate-mitigation practice that are aligned with the theme of farming within [nutrient] limits. Several pilot trials of these end-of-pipe nutrient mitigation tools have been conducted in New Zealand recently for cases where they intercept subsurface tile drainage. In this work we present the initial results from a WDB trial being made in the Barkers Creek catchment, South Canterbury. A key difference of the denitrifying bioreactor we are testing compared to others so far examined in NZ is its placement within an open drain. The ‘in-stream’ WDB comprises 430 m^3 of pine woodchip sealed within EPDM rubber membrane through which the drain water is fed. The system was optimally designed to treat an average flow rate of 6 L/s and drain water containing 6 mg N/L.

As with previous woodchip bioreactor field trials, the example at Barkers Creek has not been without complications caused by extreme climatological events that we had not forecast. After surviving a one in 200-year rainfall event, the in-stream bioreactor was fully commissioned in August 2021. Despite efforts to wash the woodchip beforehand to reduce the amount of labile DOC the bioreactor could export to the farm drain where it could present an environmental hazard, DOC concentrations measuring as high as 84 mg/L were measured in the effluent leaving the woodchip bioreactor on start-up. This is far above the 2 mg/L DOC increase permitted under Canterbury Land and Water Regional Plan rules and highlights that careful and considerate planning is required to manage such pollution-swapping phenomenon inherently linked to woodchip bioreactors.

The in-stream bioreactor has proven effective at reducing nitrate. Since operations were undertaken to rectify flows in the farm drain and increase them to flows for which the bioreactor was designed to intercept, N-removal rates have been in the range of 1.2 – 1.7 kg N/day. Long-term study of the WDB is on-going and includes evaluation of greenhouse gas emissions, as a potential pollution-swapping phenomenon.

1. Introduction

Woodchip denitrification beds (WDBs) are a specific class of woodchip denitrifying bioreactor technology (Schipper et al., 2010), the core function of which is to filter nitrate from drainage water. As an ‘edge-of-field’ nitrate-mitigation strategy, WDBs fit within the theme of farming within [nutrient] limits, as legislated in the National Policy Statement for Freshwater Management (MfE, 2020). Several WDB pilot trials have been conducted in New Zealand recently, for cases where they intercept subsurface tile drainage (Hudson et al., 2019; Goeller et al., 2019; Rivas et al., 2020; Pratt, 2020). In this work we present the initial results from a WDB trial being made in the Barkers Creek catchment, South Canterbury. A key difference of the WDB we are testing compared to others so far examined in NZ is its placement within an open drain.

Christianson and Schipper (2016) described WDBs as having surpassed the ‘proof of concept’ stage. Within the USA, design standards have been specified and within some states WDBs are recognised as good farming practice (Cooke and Bell, 2014; USDA, 2015). In New Zealand however, WDBs remain largely experimental with results from each field case study contributing valuable information towards assessing whether they are a viable (i.e., practicable and cost-effective) nutrient-mitigation option for the agricultural sector and water resource management in general. It is well documented that upon start-up, woodchip bioreactors export labile organic carbon, phosphorus and organic nitrogen that is leached from the woodchip (e.g., Schipper et al., 2010; Rivas et al., 2019; Burbery et al., 2022). Release of such reactive compounds into the aquatic environment is undesirable, because there is a risk it can induce a saprobic state. Section 15 (part 3) of the Resource Management Act (1991) legislates on discharge of such contaminants into the environment, which is enforced and regulated through regional plan rules. Presently, plan rules make no exemptions for WDBs, partly due to a lack of knowledge of the magnitude of effects they might have on the receiving environment. An improved understanding is thus required of the scale of adverse pollution-swapping phenomena associated with start-up and operation of WDBs, to enable resource managers to reliably assess the risk of WDBs and address the regulatory barriers that currently limit their application (Milne and Luttrell, 2020).

Schedule 5 in the Canterbury Land and Water Regional Plan (CLWRP) prescribes the water quality standards that discharges to the region's waterways must adhere to, to be classified a permitted activity. It effectively sets the criterion that discharges from WDBs must meet to be exempt from requiring resource consent. Evaluation of the attributes listed in Table S5a of the CLWRP, in effluent from the WDB formed one of the objectives of our work, the results of which are presented herein.

2. *Materials and method*

2.1 Environmental setting

The in-stream WDB is positioned on an open surface drain of a dairy farm located towards the bottom-end of the Barkers Creek catchment, near Woodbury, South Canterbury (44° 3' 22.37" S, 171° 12' 36.18" E). The drain meets the definition of an 'artificial watercourse' in the CLWRP, which is advantageous from the perspective of constructing a WDB, since 'artificial watercourses' are exempt from rules that regulate streambed disturbance and fish passage etc., which apply to natural waterways. Flow in the farm drain is perennial, sourced by natural groundwater discharge and tile drainage, with some drains on the farm being set below the shallow water table. The drain runs along the foot of the bund of an irrigation pond and its channel was deepened to a depth of almost 3 m below the natural ground level, during the construction of the pond bund. It is helpful to note that the 3 m depth of the drain channel provided ample accommodation space for an in-stream WDB, obviating the need to excavate below the stream bed or impede the drainage function of the drain itself.

A single grab sample of water from the drain collected in May 2016 revealed the drain water to contain 10 mg NO_3-N/L. In September 2016, the drain was instrumented with an optical nitrate sensor (OPUS model, TriOS, Germany) and a flume (Cascade T-120, NIWA) from which continuous measurements of nitrate, temperature and flow were made every 15 minutes for a period of one year, to provide a baseline dataset that could be used to inform optimal design of the WDB. Over the period of baseline monitoring, the interquartile range for nitrate in the drain water was 4.8 – 7.5 mg NO_3-N/L (median 6.5 mg NO_3-N/L). Monthly-averaged drain flows were estimated to range between 6 and 8 L/s.

2.2 Bioreactor design

The concept of the in-stream WDB followed that originally trialled by Robertson and Merkley (2009). Figure 1 shows a schematic of our woodchip bioreactor, the core and reactive component of which comprises 430 m^3 of coarsely-chipped (nominal chip size 40 mm) virgin *Pinus radiata*. Constrained by the trapezoidal cross-sectional profile of the drain, the bioreactor measures 1.5 m high and 75 m long. The bioreactor was sized to treat (on average) 6 mg NO_3-N/L, flowing at 6 L/s. Details of the methods applied in optimally designing the in-stream WDB (within a stochastic framework) are described in Sarris and Burbery (2018).

Construction of the in-stream WDB required a temporary diversion of the drain water around the reach within which WDB was to be placed. The woodchip was sealed within 1 mm EPDM rubber liner with two up-ended reinforced concrete floor panels (5 m x 2 m) placed at either end to act as bulkheads. Inflow to, and outflow from, the WDB is via 150 mm diameter galvanised steel pipes that penetrate the concrete bulkheads/rubber liner. To mitigate head losses and promote uniform flow distribution across the cross-sectional profile of woodchip bioreactor, diffuser devices (improvised from perforated, 1.2 m diameter plastic drum units) are placed on the ends of the pipework inside the reactor. The height of the up-stream dam-end was raised to provide an additional 0.5 m driving head, thus forming a 2 m-deep reservoir immediately up-stream of the bioreactor. The idea being that drain flows in excess what the WDB can handle spill over the top of the reactor.

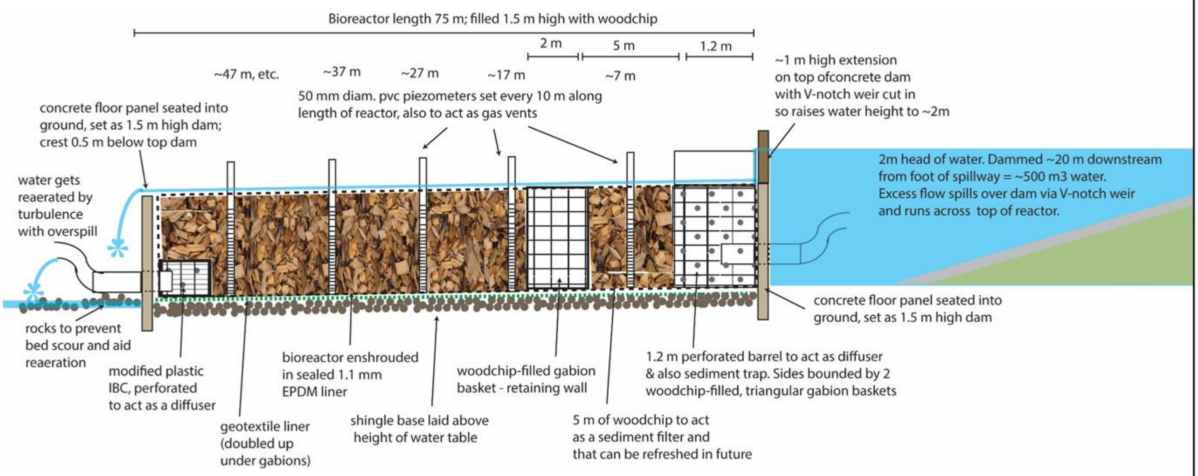

Figure 1: Schematic showing longitudinal profile of the in-stream woodchip denitrifying bioreactor at Woodbury, South Canterbury.

Robertson and Merkley (2009), and later Christianson et al. (2017), cautioned about the issue of sediment clogging in in-stream WDBs, which can greatly reduce their performance over time. Accordingly, some steps were taken to incorporate sediment control concepts in the WDB design. Firstly, it was presumed that with a volume of approximately 500 m^3, the reservoir at the head of the bioreactor would allow for some settlement of particulate matter from the drain water. Secondly, the WDB is of modular design. Within the WDB, positioned 5 m from the inlet, are gabion baskets filled with woodchip (see Figure 1). These provide a baffle/retaining structure, separating woodchip near the inlet from the bulk of the reactor. It is envisaged that should the bioreactor suffer severe clogging, it might be opened up and woodchip/sediment at the head of the bioreactor removed using a vacuum-tanker and replenished with fresh woodchip. All without disturbing woodchip in the bulk of the bioreactor. Thirdly, as a final precaution, the inlet pipe was instrumented with an actuated knife-gate valve, which can be closed automatically, if needs be.

2.3 Operation and environmental monitoring

For the purpose of this pilot study and to avoid the regulatory requirement of obtaining a discharge resource consent for operation of the woodchip bioreactor, we contained effluent from the bioreactor for the period it presented a chemical hazard to the drain (as required under rules in Schedule 5 of the CLWRP). This was possible at our field site, owing to the proximity of the bioreactor to the farm irrigation pond and accessibility to a mains power supply. Discharge from the WDB was captured in an industrial bulk container, from which it was pumped to the nearby irrigation pond to supplement the farms irrigation water. A slight disadvantage of this set-up was that it precluded us from making a direct assessment of the environmental impacts an in-stream WDB has on a watercourse. An evaluation of the WDB effluent characteristics was nonetheless possible.

As with previous woodchip bioreactor field trials, the example at Woodbury has not been without complications caused by extreme climatological events that we had not forecast. Operation of the bioreactor started in March 2021 under an unusually low flow condition – maximum achievable flows into the bioreactor at the time were less than 2 L/s (see Figure 2). At the end of March 2021, ground maintenance works undertaken on the farm during a drought condition inadvertently reduced water in the target drain to a level that effectively could not supply the WDB and the treatment system was temporarily shut down. After surviving the floods of a one in 200-year rainfall event in May 2021 (which broke the drought), operation of the WDB resumed in August 2021. Water levels in the drain however were still below what was anticipated, sufficient only to supply the bioreactor with an average flow of 3 L/s (i.e., 50% of the flow rate for which it was optimally designed to treat). Remedial works made on the farm drainage network in November 2021 restored water levels in the target drain and a flow condition for which the WDB was originally intended to treat, as can be seen in the flow data plot in Figure 2.

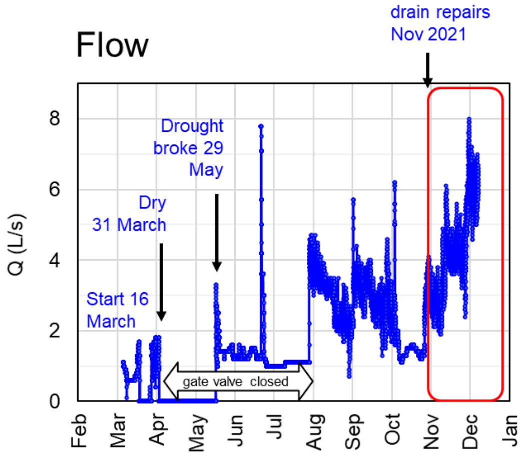

Figure 2: Flows conditions for the in-stream WDB at Woodbury, from the first start-up time (16th March 2021). The red box marks the period for which flows have been at a rate consistent with what the bioreactor was designed for and were anticipated from past records (described in Sarris and Burbery, 2018).

The WDB installation is instrumented with an OPUS optical nitrate sensor and an Aquatroll 600 multiparameter water quality sonde that are operated through a Neon Remote Terminal Unit (RTU). Via a bank of centrifugal pumps and a manifold system, the RTU controls water sampling from seven locations across the study site (including samples of the influent and effluent water of the WDB), eight-times/day. Automated measurements are made of nitrate, nitrite, dissolved organic carbon (equivalent), total suspended solids, temperature, pH, electrical conductivity, oxidation reduction potential, dissolved oxygen and ammonium. A Unidata starflow QSD continuously records flows into the WDB and any overflows are determined from the water level in the reservoir, which is monitored by a Unidata 6541 encoder.

Automated monitoring is supplemented with manual grab sampling of influent and effluent water. For the two WDB start-up events (when it was anticipated export of wood leachate would be at its peak), over the first week of operation, manual water sampling was conducted at between 2 and 3-day intervals. Manual sampling frequency was gradually reduced to a monthly sampling regime. Samples were collected and processed following standard practices (NEMS, 2019), and submitted to an IANZ accredited lab for analysis of nitrogen species (nitrate; nitrite; total Kjeldahl nitrogen (TKN); ammonium), dissolved reactive phosphorus (DRP), total phosphorus (TP), dissolved organic carbon (DOC), pH, alkalinity, sulphate, in addition to other parameters. We limit our presentation of results to water chemistry determined from the manual sampling events.

3. *Results and Discussion*

3.1 Pollution swapping and implications for resource management

Select water quality standards that apply to discharge activity rules for artificial watercourses, as specified in the CLWRP, are shown in Table 1. Relevant values measured for properties of discharges monitored from the WDB are presented for comparison. From the results in Table 1, temperature change is the only standard that we can be confident the WDB would have met, had we allowed the effluent to discharge to the drain (being mindful that Schedule 5 in the CLWRP provides for a 200 m mixing zone for dispersion and dilution of point discharges).

Despite efforts to wash the woodchip beforehand to reduce the amount of labile DOC the woodchip bioreactor could export to the farm drain where it could present an environmental hazard, DOC concentrations measuring as high as 62 mg/L were measured in the effluent leaving the bioreactor on first start-up (Figure 3). Flow through the WDB at the time was 0.11 L/s, which is significantly less than the 6 L/s for which the bioreactor was designed to treat. A second peak DOC concentration of 84 mg/L was measured in November 2021 and once again when flows were sub-optimal (0.3 L/s). We suspect the secondary release of DOC was caused by the rewetting of woodchip, caused by fluctuating water levels, such as has been reported in other WDB trails (e.g., Maxwell et al., 2018). These DOC maxima are far above the 2 mg/L DOC increase in receiving waterway permitted under Schedule 5 of the CLWRP and would have required a dilution-factor in excess of 40 to have met the water quality standard (Table 1). Conceivably, had we been able to operate the WDB at the flow for which it was designed for at the outset then DOC concentrations in the effluent would have been lower, owing to shorter hydraulic retention times. This is reflected in the late time data plot in Figure 3 when flows through the WDB were increased to rates that had been anticipated at the design stage.

Table 1: Select water quality standards applicable to discharges to an artificial waterway as prescribed in Schedule 5 of the CLWRP, versus 'worst' values measured in effluent form the in-stream WDB at Woodbury. Note: in the CLWRP, water quality standards are assessed 200 m downstream of the discharge point, whereas our measurement were made for raw effluent from the WDB.

	Dissolved organic carbon (mg/L)	**Temperature (°C)**	**pH**	**Dissolved inorganic nitrogen (mg/L)**	**Dissolved reactive phosphorus (mg/L)**
Standard/attribute for receiving water, for discharge activity to be ruled a permitted activity.	Change shall be less than 2.0	Average change shall not exceed 2°C	Shall be between 6.5-8.5	Shall be less than 1.5	0.016
Attribute measured for WDB	81	1.1	5.3-6.7*†	5.7$	0.144¥

* pH values <6.0 all coincided when flows were <0.3 L/s (i.e., very high hydraulic retention times).
† baseline pH for untreated drain water at the site was 6.1 < pH < 7.0.
¥ maximum DRP measured for untreated drain water at the site was 0.252 mg/L
$ maximum DIN in the untreated drain water was 16.1 mg/L

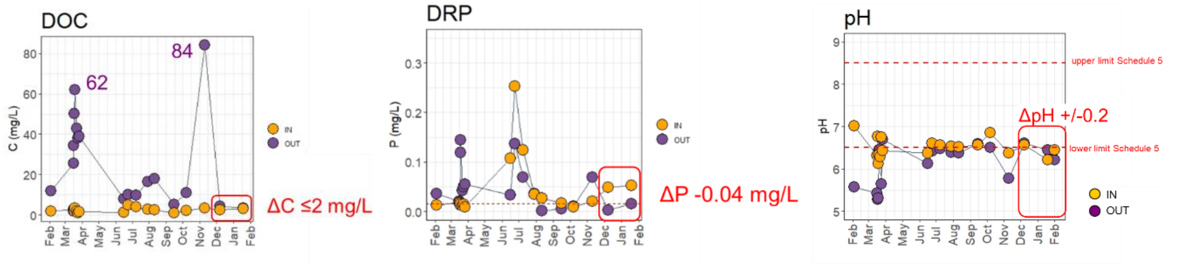

Figure 3: [left:] Dissolved organic carbon (DOC); [centre:] dissolved reactive phosphorus (DRP); [right:] pH, in influent (IN) and effluent (OUT) water of the in-stream WDB at Woodbury. The red box highlights the period for when flows for which the bioreactor was designed were eventually met. Plots cover period February 2021 – February 2022.

Similar to what was observed for DOC, the WDB initially acted as a net exporter of dissolved reactive phosphorus. The maximum concentration of 0.144 mg/L measured in effluent was 10-times the discharge quality standard prescribed in the CLWRP (Table 1). Nonetheless, 0.144 mg/L is below the maximum background DRP concentration measured for the untreated drain water (of 0.252 mg/L), which was recorded in the winter month of June, coinciding with high flow condition, following storm conditions. Following the initial export of phosphorus (presumably leached from the fresh woodchip), the WDB has for the most part demonstrated DRP attenuation, which is similar to what Rivas et al. (2020) found for the second year of operation of their experimental WDB at Tatanui, Waikato region. Operating under the flow conditions it was designed for, the latest results from the WDB at Woodbury show it to be reducing DRP concentrations by 0.04 mg P, equivalent to a daily mass removal rate in excess of 15 g P/day. Whether the WDB continues to offer long-term P-removal properties remains to be seen.

Early on, the pH of discharge from the WDB ranged between pH 5 and 6, which is more acidic than the standard for permitted discharges to drainage water in the CLWRP (Figure 3). We assume the low flow rate/high retention time (which forced redox potentials below what was necessary for nitrate reduction) strongly influenced the outcome and enhanced acidogenic conditions. As with the DOC and DRP result, we believe that had operation of the bioreactor commenced under more optimal (higher) flow conditions then this would have mitigated some of the effect. Indeed, we have seen no mention in the scientific literature reporting WDB field case-studies, of pH ever being a water quality issue of concern in, in practice. It is helpful to note that freshwaters in the Canterbury region naturally tend to exhibit very mildly acid properties, because of the low carbonate content/buffering capacity of the local terrain, which is dominated by quartzo-feldspathic mineralogy, derived form the greywacke geology. This is reflected in the drain water at the field site, which on occasion had background pH values under the water quality standard set for discharge rules. This limits their capacity to receive any acidic discharge, the implications for WDB operation in the future are not clear.

3.2 Nitrate removal and nitrogen-dynamics

The in-stream WDB has proven effective at reducing nitrate. Nitrate concentrations in the effluent have always been less than influent concentrations (Figure 4). At the first start-up in March 2021 (when very low flow rates were possible and there was plenty of labile DOC (e.g., Figure 2, Figure 3)), the treatment system was limited with respect to reactive nitrogen, as can be seen in the time-series plots of Figure 4. We note that the original intention had been to start operation of the bioreactor at high flow rates, to capitalise on the bioavailable carbon potential, but this practice was foiled by the drought conditions. The 'over-treated' effluent from the bioreactor was nitrate-free yet it contained some ammonium (<0.3 mg NH_4-N/L) for the first month. Coincidentally, the maximum ammonium concentration that was briefly measured in the WDB effluent was on par with the background level of ammonium that was on occasion detected in the drain water.

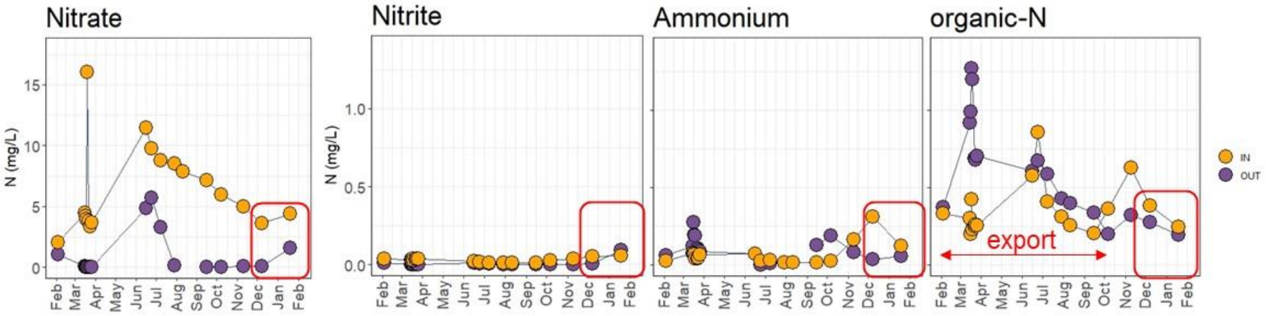

Figure 4: Speciated nitrogen results for the in-stream WDB at Woodbury between February 2021 and February 2022. Note: the difference in y-axis scale between nitrate and other species. The red box highlights the period for when flows for which the bioreactor was designed were eventually met.

As can be seen in Figure 4, at the outset there was a net export of organic nitrogen from the WDB, sourced from the fresh woodchip. On the basis that there has been no evidence of nitrite production and only minor quantities of ammonium produced, which can be attributed to the initial stages of operation, we assume denitrification is the dominant reaction pathway by which nitrate is being removed in the WDB. Following the leaching of the most reactive DOC, organic-N and phosphorus from the woodchip media, and late establishment of a flow rate for which the WDB was designed to treat, results since December 2021 reveal the in-stream WDB to have reduced nitrate concentrations by between 2.8 and 3.5 mg N/L. This equates to an N-removal rate of between 1.2 and 1.7 kg N/day. Whilst in absolute terms, this mass removal rate is significantly higher than rates reported from other WDBs demonstrated on farm drainage systems in New Zealand (e.g., Hudson et al., 2109; Rivas et al., 2020) it remains almost 50% of the rate Sarris and Burbery (2018) predicted the WDB would treat, for the same flow rate. Sarris and Burbery (2018) based their predictions on the best available knowledge of WDB functionality available at the time and within a stochastic framework. The disparity we have found between predicted and observed N-removal rates, serves to highlight a need for more practical field trials of WDBs to reliably assess their performance under New Zealand conditions and parameterise predictive models.

3.3 Scope for future research

Tasks for the future include integrating the high-resolution automated water quality and flow data record with the manual water quality data that were presented here. From that exercise, mass fluxes for carbon, phosphorus and nitrogen will be calculated and evaluated against other WDB studies. An objective is to be able to predict with confidence how long WDBs function as net exporters of reactive compounds, to improve risk assessment of them for regulatory and planning purposes.

Greenhouse gases (GHGs) dissolved in the WDB effluent have been monitored and the data remain to be processed. Early indications however are that the WDB originally produced methane, but more recently has been exporting the more noxious greenhouse gas, nitrous oxide. Quantification of GHG emissions from the WDB and elucidation of the factors regulating will provide for a more robust pollution-swapping assessment.

In-stream WDBs are inherently susceptible to clogging effects, as Robertson and Merkley (2009) demonstrated. Hydraulic gradients are regularly monitored in the WDB at Woodbury and those data remain to be correlated against flow rates recorded for the bioreactor, to evaluate changes in the hydraulic function of the bioreactor and predict the bioreactors longevity. Tracer tests to characterise solute transport pathways through the bioreactor and evaluate the retention times are seen as valuable activities to constrain reaction rate interpretations.

4. Summary and conclusions

An in-stream WDB trial has commenced on an open artificial drain of a dairy farm near Woodbury, South Canterbury. Drought conditions and unforeseen complications with the farm’s drainage network hindered the ability to operate the 430 m^3 bioreactor under optimal conditions to which it had been designed. The bioreactor was started up when both flow and nitrate conditions were far below average, leading to excessive ‘over-treatment’ of the drainage water and causing high concentrations of DOC, DRP, organic-N and ammonium (and low pH values) in the bioreactor leachate. Whilst this ‘pollution-swapping’ phenomenon was acute and our WDB trail benefitted from the ability to contain effluent from the treatment system, had this not been possible then under the rules of the CLWRP, due to the chemistry of the nitrate-treated water, then operation of the bioreactor would have required a discharge consent. The findings demonstrate considerate planning is required to manage pollution-swapping phenomenon inherently linked to woodchip bioreactors.

Nitrate removal so far offered by the WDB is almost half the rate predicted during the bioreactor design stage. This disparity reveals a weakness in the predictive models for WDBs. Moreover, it highlights a need for more practical WDB field trials to be carried out to reliably parameterise mathematical models of WDBs and strengthen the assessment of their viability, to which data from the Woodbury trial is contributing to. Despite the lower-than-expected nitrate-removal performance, the most recent monitoring results (obtained when the bioreactor was functioning at flow rates for which it was designed for) show the in-stream WDB at Woodbury to be removing in excess of 1 kg N/day. How long this treatment continues and evaluation of greenhouse gas emissions from the WDB, as an undesirable pollution-swapping phenomenon, are on-going lines of investigation.

5. Acknowledgements

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