A preliminary cost-effectiveness analysis of denitrifying bioreactors in the Lower Burdekin

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Background

A cost-effectiveness (CE) analysis was undertaken to assess the cost per kilogram of nitrate-nitrogen ($/kg N) removed by denitrifying bioreactor beds in a sugarcane production system in Queensland. The preliminary analysis evaluates the CE of a 34m^3 bioreactor bed trialled on a sugarcane farm in the lower Burdekin delta district, conducted as part of the Bioreactors for GBR Project, funded through the Queensland Reef Water Quality Program. The aim of the project was to investigate the nitrate removal performance of bioreactor beds receiving run-off from sugarcane farms in the lower Burdekin. In addition, the CE of a hypothetical 100m^3 bioreactor scenario is also explored.

The project trialled and monitored three bioreactor beds in the lower Burdekin. Of the three trials, one produced a more comprehensive dataset compared to the others that had experienced significant blockages during the trial period. Data from this trial was therefore utilised in the CE analysis. High-frequency water quality monitoring was undertaken over 12 months (May 2019 - April 2020) with nitrate concentration, woodchip saturation and water flow analysed to enable calculation of the nitrogen removal rate[1] (NRR).

Denitrifying bioreactors, and other treatment systems, can potentially complement agronomic best management practices, such as precision fertiliser application, as part of a whole of catchment approach to improving water quality. The first denitrifying bioreactors were installed in Queensland during 2015. The first bioreactors in the GBR catchment were installed in 2018 on sugarcane farms (as part of the Bioreactors for GBR project and other projects in the Wet Tropics region), to assess their nitrogen removal performance in the tropical Queensland climate.

While there have been some bioreactor CE analyses published (e.g. Schipper et al. 2010; Christianson et al. 2013; Lepine et al. 2018), there are none available on bioreactors in Australia or tropical agricultural systems. Estimates of bioreactor CE based on predicted NRR were used in reports to inform investment into water quality programs, e.g. Alluvium 2019. This CE analysis aims to update existing CE information on bioreactors in the GBR using actual NRR calculated through intensive field-based monitoring. This CE analysis, combined with NRR results from other trials (Manca et al. 2020) and NRR published in the literature (Robertson , 2010; Schipper, Robertson, Gold, Jaynes, & Cameron, 2010), will enhance the information available to government and non-government organisations on the CE of bioreactors in reducing nitrate loads from agricultural land. The results of this CE analysis will also contribute to the development of bioreactor guidelines on the use of bioreactors on farms in Queensland.

Methodology

The following section includes the methodology used in the CE analysis. It describes how the total present value costs (TPVC) for both the 34m^3 and the 100m^3 bioreactor were determined, followed by calculations used in determination of the NRR level and bioreactor CE.

The two bioreactor sizes selected for the CE analysis were 34m^3 (the size of the bioreactor bed trial) and 100m^3 (a larger bioreactor bed sized to intercept more paddock run-off). Inclusion of a hypothetical larger bed size was based on preliminary trial results that demonstrated a need for larger bioreactors in the lower Burdekin to treat a greater proportion of the run-off (Manca, Grace, Robinson, & Wegscheidl, 2020b). A 100m^3 bioreactor was chosen as a practical size for a sugarcane farm, i.e. for intercepting and treating a proportion of irrigation tailwater within the constraints of land availability on a farm. In practice, the actual size of a bioreactor bed would be site specific.

[1] Nitrate removal rate (NRR, g N m^{-3} d^{-1}) is a preferred metric for reporting bioreactor performance as it normalises the performance of a bioreactor as mass of nitrate removed per unit volume of bioreactor substrate (woodchip) per unit of time and enables comparison between bioreactors in different contexts.

Costs

The initial analysis is based on results from the 34m^3 bioreactor trial, with the actual costs incurred presented in Table 1. Costs used in the analysis were derived from actual construction costs for a bioreactor field trial in the lower Burdekin. Costs were separated into both fixed and variable, with variable costs dependent on the bioreactor size (cubic meters). In addition, discounted maintenance costs were also included.

Due to only one year of field trial data, assumptions were made, and partly informed by other studies (Alluvium, 2019), on design, planning and on-going maintenance costs for the larger bioreactor (100m^3) over an estimated lifespan of 10 years. Table 1 also presents estimated costs of the envisaged 100m^3 bioreactor.

Table 1 Upfront fixed and variable costs associated with the 34m^3 and the 100m^3 bioreactor bed construction in the Lower Burdekin.

Item	Variable costs ($/m^3)	Variable costs (34m^3) ($)	Variable costs* (100m^3) ($)	Fixed costs/ bioreactor ($)
Woodchip (inc. delivery)	$56.60	$1,924	$5,660	
Gravel	$4.80	$163	$480	
Gabion gravel	$6.64	$226	$664	
Excavator contractor and oversight	$207.00	$7,038	$20,700	
Gabion baskets and sleepers				$1,700
Liner, sealant, PPE, laser level hire, disposables				$550
Pipes				$150
Star pickets				$200
Site selection (1 Week)				$4,500
Design and on-site installation oversight (1 week)				$4,500
Total	$275.04 (per m ^{3})	$9,351	$27,504	$11,600

**Estimated variable costs.*

Discounting costs

Maintenance costs, including regular inspections, gravel replacement and topping up of woodchips, were assumed to be $1000/yr irrespective of bioreactor size due to a large part of the cost being the cost to visit the site, conduct inspections and clean out inlet or outlet rather than actual replacement of woodchips[2].

Future maintenance costs were discounted with a 7% discount rate (Alluvium, 2019) to determine the present value. This follows the approach by Rust and Star (2018), and Hassan and Smart (2020) represented by:

$$PVC_i = \frac{FVC}{(1+r)^t}$$

where PVC = present value cost
FVC = future value cost (not inflation corrected)
r = real discount rate
t = number of time periods (usually years) in the future

[2] Note the amount of gravel in the inlet does not vary substantially between different size bioreactors.

The sum of discounted future maintenance costs was added to the upfront establishment costs for the bioreactor to give the total present value cost (TPVC). TPVC was annualised to give an annualised present value (APVC) to allow costs to be expressed in $/year, by dividing the TPVC with the annuity factor (Hasan & Smart, 2020). This allows for comparing projects of different investment horizons or time frames. The annuity factor is calculated as:

$$Annuity\ factor = \frac{1-(1+r)^{-T}}{r}$$

where: r = real discount rate
T= assumed lifespan

Pollutant removal

The nitrogen removal rates (NRR) used in the CE analysis were calculated using the inlet and outlet nitrate concentrations, saturated volume of woodchip and water flow monitored at the field trial. The lowest, average and highest NRR (g N/m^3/day) calculated during each irrigation event over the trial period were used in the analysis to compare the effect of different NRR levels:

1. Average NRR being 3.4g N m^{-3} d^{-1}
2. Highest (i.e. max) NRR being 9.3gN m^{-3} d^{-1}
3. Lowest (i.e. min) NRR being 0.7gN m^{-3} d^{-1}

Nitrate concentrations, woodchip saturation and water flow varied during each irrigation event, leading to different NRRs. These NRRs are within the range (0.07 to 44 g N m^{-3} d^{-1}) for bioreactor beds in published literature (Schipper et al., 2010) and were used in the CE analysis to provide high, low and average CE scenarios for bioreactor beds in the lower Burdekin.

Different scenarios of performance decline (decreased NRR) over the lifespan of the bioreactor were assessed. Queensland bioreactor trials have not been monitored for long enough to provide accurate performance data over the 10-year lifespan, so assumptions were made based on literature (Addy, et al., 2016; Schipper, Robertson, Gold, Jaynes, & Cameron, 2010) and expert opinion.

The total nitrate load reduction (kg N removed per year) is strongly influenced by the annual number of treatment days (i.e. days of water flowing through the bioreactor/year). In the field trial we used 90 days as the estimated number of treatment days (i.e. based on the average number and duration of irrigation events and number of days of rainfall in the lower Burdekin likely to lead to run-off). It is recommended that in future, sites with more regular water flow be selected to ensure a sufficient flow of nitrates through the bioreactor. A 250-treatment day period was also used in the analysis for the envisaged 100m^3 bioreactor as this is expected to be larger and located in place to receive regular water flow from several blocks irrigated at different times.

Cost-effectiveness

Cost-effectiveness was calculated by dividing annualised present value cost with total load reduction (TLR) in kg nitrate-N per year using:

$$Cost\ effectiveness\ (in\ \$\ per\ kgN) = \frac{APVC\ (in\ \$\ per\ year)}{AALR\ (in\ kgN\ per\ year)}$$

where: APVC = Annualised equivalent present value cost
AALR = Average annual load reduction (Total load reduction/ no. years)

While some studies suggest using annualised total load reduction due to a higher value placed on earlier benefits (Hasan and Smart 2020), load reductions were not discounted for purposes of this report. This was to ensure consistency with other P2R Projects (Van Grieken, et al., 2015), as well as to comply with Queensland Government Treasury's recommendation that only costs be discounted in a CE analysis (Queensland Government, 2015).

Results

Size of bioreactor

The bioreactor trial installed in the delta district of the lower Burdekin contained 34m^3 of woodchip and was estimated to be treating water (i.e. number of days per year with irrigation or rainfall runoff flowing through the bioreactor) for 90 days a year. The CE of the 34m^3 bioreactor was calculated using field trial data collected reflecting the average NRR of 3.4 g N m^{-1} d^{-1}. Table 2 shows the difference in CE with the number of treatment days, showing CE to improve significantly with more treatment days.

Table 2 Cost-effectiveness comparison of 34m^3 bioreactor with different treatment days

Volume of woodchip (m^3)	Bioreactor cost (TPVC)	Average NRR (g N/m^3/d)	Annual treatment days (days of runoff)	Lifespan (yrs)	Assumed performance reduction after year 1	Cost-effectiveness ($/kg nitrate N)
34	$27,467	3.4	90	10	33%	$536.97
34	$27,467	3.4	250	10	33%	$193.31

The field trial results suggest that if larger bioreactors are installed in the lower Burdekin, and are well located to increase water interception, catching a larger proportion of the runoff for a greater part of the year, that CE would improve significantly. The potential CE of a hypothetical 100m^3 bioreactor was calculated assuming both 90 and 250 treatment days per year (Table 3).

Table 3 Cost-effectiveness comparison of hypothetical 100m^3 bioreactor with different treatment days

Volume of woodchip (m3)	Bioreactor cost (TPVC)	Average NRR (g N/m3/d)	Annual treatment days (days of runoff)	Lifespan (yrs)	Assumed performance reduction after year 1	Cost-effectiveness ($/kg nitrate N)
100	$45,619	3.4	90	10	33%	$301.93
100	$45,619	3.4	250	10	33%	$108.70

The cost of treating nitrate run-off with a 100m^3 bioreactor would be almost half that of a 34m^3 bioreactor, through assumed efficiencies of scale with a larger bioreactor. Well-positioned bioreactors, intercepting and treating water for more days of the year, appear to be considerably more cost-effective. The following analyses are therefore limited to CE estimates based on the hypothetical 100 m^3 bioreactor.

Bioreactor treatment performance

The maximum, minimum and average NRR, as recorded in the field trial, are presented in Table 4. The NRR ranges recorded in the field trial are comparable to those reported in literature (Schipper et al 2010, Addy et al 2016) and in trials held in the wet tropics (unpublished reports). The observations are therefore considered a realistic representation of the range of nitrate removal levels likely to be experienced in the field. Lower rates of NRR are associated with nitrate limited conditions, as has been experienced in many of the Queensland bioreactor trials. Table 4 shows the difference in CE based on the three different NRRs for a 100m^3 bioreactor, over 10 years with 250 treatment days per year.

This table presents the benchmark NRR, without performance decline (i.e. a constant removal rate through the life of the bioreactor). Literature (Addy, et al., 2016; Robertson , 2010; Schipper, Robertson, Gold, Jaynes, & Cameron, 2010) suggests that performance decline in bioreactors is likely determined by the original NRR. Low NRR is usually associated with nitrate limited conditions and this is also expected to be associated with a lower rate of performance decline (Manca, et al., 2020a).

While it is likely that some performance decline will be experienced during the life of the bioreactor, the lack of long term trial data on which to develop a reliable set of assumptions for different NRRs in the lower Burdekin led us to use the benchmark scenario (shown in Table 4) and hence these CE figures should be interpreted with caution. This analysis highlights that bioreactors are most cost-effective when receiving consistent nitrate concentrations to avoid nitrate limitation.

Table 4 Effect of different NRR on cost-effectiveness of bioreactors with no performance decline over 10 years

Average NRR ($g N/m^3/d$)	Size of bioreactor (m^3)	No. of treatments (days/ year)	Total N removed over life of bioreactor (kg)	Cost-effectiveness ($/kg nitrate N)
Maximum 9.3	100	250	2,325	$27.94
Average 3.4	100	250	850	$76.41
Minimum 0.7	100	250	175	$371.15

Performance decline over time and cost-effectiveness

The bioreactor field trials were only monitored for 12 months and therefore performance decline over longer-term periods are based on assumptions from literature. Robertson (2010) and Addy et al. (2016) suggest that bioreactor nitrate removal is highest in the first year and declines in the second year while remaining constant for the balance of its life. Manca et al. (2020a) on the other hand, suggest that in nitrate limited conditions in South-east Queensland, nitrate removal efficiency would not decline after year 1. Table 5 presents the level of nitrates removed annually under various scenarios included in the CE analysis. Over the 10-year life span of the bioreactor, the figures illustrate the differences in total load removal over the period at an average NRR of 3.4 g N m^{-3} d^{-1}.

Table 5 Amount of nitrates removed annually for different scenarios over 10-year period

Year	Amount of Nitrate Removed Annually (kg N/Year)		
	Scenario 1	Scenario 2	Scenario 3
1	85.0	85.0	85.0
2	57.0	56.7	42.5
3	57.0	56.7	42.5
4	57.0	37.8	42.5
5	57.0	37.8	42.5
6	57.0	25.2	85.0
7	57.0	25.2	42.5
8	57.0	16.8	42.5
9	57.0	16.8	42.5
10	57.0	11.2	42.5
Total	597.6	369.0	510.0
Annual Average	59.8	36.9	51.0

The three scenarios were compared for the average NRR to determine how differences in bioreactor performance decline would affect CE. Results for a $100m^3$ bioreactor with 250 treatment days per year, over a 10-year lifespan are shown in Table 6.

Table 6 Cost-effectiveness under different performance decline scenarios for a 100m³ bioreactor over a 10-year lifespan

Scenario	Performance decline during lifespan	Initial NRR (Year 1) (g N/m^3/d)	Cost-effectiveness ($/kg N)
1	33% decline after Year 1, then constant	3.4	$108.70
2	33% decline after Year1, then 33% every 2 years	3.4	$176.00
3	50% decline in year 2, then constant until woodchip replaced at the end of Year 5 and repeat cycle (with 25% lower maintenance costs every year except Year 1 and Year 6)	3.4	$135.25

This assessment demonstrates that assumptions on performance over time can have a significant impact on the CE of bioreactors. For example, replacing woodchips in year 5, with slightly lower maintenance costs in all other years would be more cost-effective (Scenario 3) than when the performance of the bioreactor is left to decline continually over the life span.

Conclusion

This analysis is the first detailed CE assessment of bioreactors in Queensland. It is based on observed field trial data over 12 months that were then used to extrapolate NRR over the 10-year lifespan of the bioreactor. It enables assessment of the CE under different scenarios of size, NRR, treatment days/year and performance decline. It demonstrates significant variability in the CE of denitrifying bioreactors depending on site, size and performance decline. This highlights the need for meticulous site selection and design to maximise the CE of bioreactors as a nitrogen mitigation tool. In the right location i.e. regular water flow with moderate nitrate concentration, bioreactors could prove a cost-effective option for reducing nitrate from agricultural run-off and therefore complement other water quality initiatives. This analysis provides preliminary insight into the CE of a 34m^3 bioreactor trial in the Burdekin region and explores various hypothetical 100m^3 bioreactor scenarios. To improve confidence in the CE results and to be able to apply them more generally, NRR data would need to be collected from longer-term trials and across multiple sites.

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