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A COMPARISON OF THREE DIFFERENT EDGE-OF-FIELD NITRATE MITIGATION PRACTICES, AS REALISED FROM FIELD TRIALS

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Introduction

Constructed wetlands and woodchip denitrifying bioreactors are developing edge-of-field mitigation practices, for reducing contaminant loads from pastoral land in New Zealand (NZ) (e.g., Schipper et al., 2010a; Praat et al., 2015). There is, however, little information available on the cost of such practices, which is needed for assessing their viability. In this paper we make a cost comparison of three edge-of-field technologies for the removal of nitrate that we have trialled over the past seven years. These being:

i. a constructed wetland;
ii. a woodchip denitrification bed;
iii. a woodchip denitrification wall in a shallow gravel aquifer.

Methods

Technical design aspects

Constructed wetland

Kaiwaiwai constructed wetland in the Wairarapa region is an example of an off-line, multi-celled, surface flow wetland with a serpentine design. Design details are documented in Praat et al. (2015) and summarised in Table 1. The wetland was installed on a working dairy farm for intercepting and removing nitrate in surface drainage water. In terms of NZ wetland case studies, the off-line design feature is relatively uncommon, as is the serpentine design, which gave a high length/width aspect ratio. The constant hydraulic loading rate and uniform mixing provided by these two respective design aspects are known to enhance nitrate removal in constructed wetlands (Tanner and Kadlec, 2013). The treatment (i.e., wetted) area of the wetland was 5,000 m^2, and the total area occupied was 7,500 m^2, which was retired from pasture. The wetland was constructed in September 2014 and Praat et al. (2015) reported on its design and treatment performance after 6 months when wetland plants were still establishing. The nitrate removal efficacy at that early stage was 48%. The wetland has been monitored monthly for seven years, from which long-term treatment performance statistics were derived.

Denitrification bed

A full description of the woodchip denitrification bed can be found in Burbery and Abraham (2022). The woodchip bed is an example of an 'in-stream' bioreactor placed in the bottom of adrain that flows year-round. This is in contrast to more conventional woodchip bioreactors where the bed is installed close to the outlet of a tile drain (e.g., Hudson et al., 2018; Rivas et al., 2020). The instream bioreactor comprised 430 m^3 of radiata pine woodchip (fuel for denitrification) and represents one of the largest ever trialled in NZ. It is sited on a dairy farm in the Barkers Creek catchment near Geraldine, South Canterbury. Nitrate is a priority water quality contaminant within the catchment (Kelly, 2015; Graham, 2019). The bioreactor was designed to treat 6 L/s of the drain water; assuming an average nitrate concentration of 6 mg N/L (Sarris and Burbery, 2018) this corresponded to a daily nitrate load of 3.1 kg. The bioreactor was completed in March 2021, but due to issues with reduced flow, it was not operationalised until December 2021, by which time the woodchip was two years old. Additional costs were incurred because of construction delays that under normal circumstances would not be incurred. This artefact has been taken into account in the cost comparison exercise. Operation of a woodchip bioreactor (or a constructed wetland) in Canterbury region requires a discharge consent which requires compulsory monitoring of water quality. We purposefully captured effluent from the bioreactor and disposed of it to land through the farm irrigation system to circumvent the need to obtain resource consent, and hence costings for this device do not include any consent monitoring requirements. Water quality was continuously monitored using automated water quality sensors that measured nitrate, dissolved oxygen, pH, dissolved organic carbon, electrical conductivity and temperature. Monthly grab samples of water up-stream and down-stream of the bioreactor were also taken and were analysed in the laboratory for speciated nitrogen and phosphorus, also dissolved organic carbon.

Denitrification wall

Details of the woodchip denitrification wall can be found in Burbery et al. (2020; 2022). The woodchip wall was built in November 2018, as part of a research project aimed to examine the functionality of woodchip denitrification walls applied to fast-flowing gravel aquifer settings. In contrast to the constructed wetland and woodchip bed examples, which target treatment of surface water, the denitrification wall removes nitrate from shallow groundwater. The experimental wall was sited in a public recreational reserve near Kaiapoi, North Canterbury. The wall was 25 m long x 5 m wide x 3 m deep and comprised a 50/50 mix of coarse gravel and radiata pine woodchip. Groundwater at the site is usually around 0.5 m and contains 6.2 – 8.6 mg NO_3-N/L (average 7.1 mg NO_3-N/L). Prior to 1868 the site was an active part of the Waimakariri River, and because of the unconsolidated nature of the sand and gravel alluvium that made up the ground, sheet-piling was required to stabilise the trench walls during construction. This preventative measure added greatly to the cost of construction, yet we know from irrigation galleries dug across Canterbury that this would not be required under all circumstances. Under the rules of the Canterbury Regional Plan, an excavation permit was required to trench into the aquifer (consent #CRC182663) and a discharge consent was required for deposition of organic material (woodchip) below the water table (consent #CRC182664). Conditions of the discharge consent required regular monitoring of groundwater quality both up-gradient and down-gradient of the woodchip wall. This was achieved using five monitoring wells that were positioned along the centreline of the anoxic plume of treated water that emanated from the woodchip wall. After two years of monthly monitoring, sufficient evidence had been collected to demonstrate the groundwater quality changes induced by the woodchip wall had attained a state of equilibrium and were benign. At the cost of an application to change the conditions of the resource consent, the monitoring requirement was removed (consent #CRC221001).

Table 1: Technical specifications of the three case-studies.

	Wetland[1]	**Bed**[2]	**Wall**[3]
Location	Kaiwaiwai, Wairarapa	Woodbury, Sth Canterbury	Silverstream, Nth Canterbury
Design	off-line, serpentine	in-stream	gravel aquifer
Dimensions	0.5 ha x 0.3 m deep; high L/W aspect ratio = 145	75 m long x 1.5 m high	25 m long x 5 m wide x 3 m deep
Reactive media†	raupō; kapungawha; rautahi	430 m^3 woodchip	375 m^3 woodchip/gravel
Flow rate	~11 L/s; loading rate 0.2 m/d	1 – 10 L/s; average 6 L/s	~1.6 L/s; specific discharge 2.6 m/d
Nitrate-N: range; average	1 – 5 mg/L 3 mg/L	4 – 9 mg/L 6 mg/L	6 – 9 mg/L 7 mg/L
Build date	Sept 2014	2017 - 2020	Nov 2018
Average nitrate mass removal rate, MRR	452 kg N/yr	504 kg N/yr	214 kg N/yr

1. Praat et al (2015); 2. Burbery and Abraham (2022); 3. Burbery et al. (2020)

† in the case of Kaiwaiwai, these are the wetland plants.

Treatment performance

The average annual nitrogen removal rates determined for the three mitigation case studies are listed in Table 1. Nitrate removal rates in the constructed wetland demonstrated seasonal variation, but on an annual basis were the most consistent and the removal rate value in Table 1 represents the annual average removal rate from 7 years of monitoring. The dynamics of nitrate removal by woodchip bioreactors is very different from that of wetlands. The treatment efficiency of woodchip bioreactors tends to follow a two-stage pattern. Initially, woodchip bioreactors have a heightened potential for nitrate removal due to the labile organic carbon in the fresh woodchip media. Following the flush of this highly labile carbon fraction, the ability to reduce nitrate drops down. Schipper at al. (2010b) suggest that after 2-years operation it is normal for the denitrification capacity of woodchip bioreactors to drop to 50% of the initial capacity, which represents a pseudo-steady state long-term condition.

We noted a similar 'drop-off' pattern of behaviour in both the in-stream woodchip denitrification bed and woodchip denitrification wall case studies. In the case of the woodchip bed, nitrate removal efficiencies started at 100% then appear to have stabilised around 40%. For the woodchip wall, nitrate removal efficacy rates for the groundwater were >90% for the first 17 months, reducing to around 60% since. We assume these latter rates reflect the long-term behaviour. The mass removal rates (MRRs) listed in Table 1 are time-weighted averages that compensate for the dynamic behaviour.

A technical limitation of in-stream woodchip bioreactors are their susceptibility to clog, which is detrimental to treatment performance (e.g., Robertson and Merkeley, 1998). The instream woodchip bed we are trialling has been designed to be serviceable for clogging impacts. The idea is that woodchip over the first 10 m of the bioreactor serves also as a filter of suspended solids entering the system. When required, this 57 m^3 of woodchip can be accessed and refreshed. Although there has been no commensurate reduction in nitrate removal performance, we have noticed a reduction in the hydraulic performance of the woodchip bed over the first 12 months of monitoring. We predict that the bulk hydraulic conductivity of the bioreactor will likely reduce to 10% of its initial condition within three years and we estimate this would be the likely service interval for this system.

Costing model

The cost-effectiveness of N removal was analysed following standard methods described by Christianson et al. (2013) and Kavehei et al. (2021), assuming a 25-year project life and a discount rate of 8% (NZ Treasury, 2022) that are consistent with other cost analyses for edge of field mitigation devices (e.g., Daigneault and Elliot, 2017; Weeber et al., 2022). Costs were calculated in New Zealand dollars for the second quarter of 2022 value and adjusted for inflation using the consumer price index (Reserve Bank of NZ, 2022).

A total present value cost (TPVC) [NZ$] was calculated from:

$$\text{TPVC} = C_{upfront} + \sum_{t=1}^{P} \frac{C_{ongoing}(t)}{(1+r)^t} \tag{1}$$

$$C_{upfront} = C_{establishment} + C_{construction} + C_{plants/wood} + C_{land} \tag{2}$$

Where $C_{upfront}$ reflects up-front costs associated with planning, design and construction, incurred in year $t = 0$, and $C_{ongoing}$ reflects on-going costs incurred by operation, maintenance, and repairs of the mitigation practices. In the case of the constructed wetland for which 0.75 ha of productive land was retired, $C_{ongoing}$ included the annual loss of forage crop foregone. P [T] denotes the evaluation period (25 years) and r is the discount rate (8%). Details of activities that contributed to the individual cost components in Equation 1 are presented in Table 2.

TPVC was converted to an annualised equivalent present value cost (APVC) with units of NZ$/ yr:

$$\text{APVC} = \text{TPVC}\left[\frac{1}{1-(1+r)^{-P}}\right] \tag{3}$$

Division by the average annual nitrate mass removal rate (MRR; Table 1) yielded the cost-effectiveness of N removal (CE) with units NZ$/ kg N:

$$CE = \frac{APVC}{MRR} \tag{4}$$

Table 2: Description of the various upfront and ongoing costs associated with the three mitigation devices, as applied to the realised projects (these are represented by scenarios 1.0, 2.0, 3.0 in Table 3).

		Constructed wetland	**Denitrification bed**	**Denitrification wall**
$C_{upfront}$	$C_{establishment}$	Design. Consultation.	Design. Consultation. Baseline flow and nitrate monitoring (1 year).	Design. Consultation. Site investigation to determine baseline hydrogeological conditions; involved installation of 5 monitoring wells. Resource consent applications (2 of).
	$C_{construction}$	Excavator. Pipework. Telemetered flow recorder.	Excavator. Dams and pipework. Rubber liner. Geotextile. Dewatering. Flow and water quality monitoring equipment + telemetry.	Excavator. Front loader. Tipper truck. Sheet-piling. Dewatering. General project management by civil engineering firm.
	$C_{wood/plants}$	Wetland plants.	430 m^3 woodchip.	188 m^3 woodchip. 188 m^3 processed gravel.
	C_{land}	0.75 ha pasture retired.	n/a	n/a
$C_{ongoing}$	$C_{maintenance}$	Routine checks on flow and clogging; minor weeding (6h/month). Major plant harvest/weeding every 5 years. Flow meter replaced every 10 years. Telemetry charges.	Routine checks on flow and clogging (8 h/month, which includes water sampling).	n/a
	$C_{monitoring}$	n/a for wetland in Wellington region.	Monthly water quality monitoring and analysis (2 samples). Telemetry charges. Refreshment of 57m^3 woodchip every 3 years to control clogging.	Groundwater quality monitoring and analysis across 5 wells: weekly over 1st 3 months; monthly thereafter. Consent conditions changed to no monitoring requirement after year 2.
	$C_{lostproductivity}$	6,750 kg dry matter/year foregone.	n/a	n/a

Costing scenarios

Whereas Kaiwaiwai constructed wetland was more of an applied project, the woodchip bioreactor case studies were scientific research projects. Being proof of concept trials, more time and resources were invested in the bioreactor case studies than had they been ‘applied’ projects. To correct for the ‘science premium’ that significantly increased the cost of the bioreactor projects we ran some alternative costing scenarios in which we removed the ‘science premium’ components to provide an estimate of real-world costs for an ‘applied’ scenario.- For the instream denitrification bed we compared the cost of automated monitoring versus conventional manual grab sampling (in the realised project we did both). We assumed electronic monitoring equipment had a 10-year operational life, after which it would require replacement.

Regional plan rules are more permissive for constructed wetlands in Wellington region than they are in Canterbury region, which will influence the cost-effectiveness between regions. To account for such geographical bias and normalise costs across the three case studies, we modelled the hypothetical case of Kaiwaiwai wetland being located in Canterbury region and subject to compliance (resource consent and monitoring) costs that apply there. The cost of obtaining resource consent was included in establishment costs and water quality monitoring for compliance was added as an on-going maintenance cost. We assumed similar water quality monitoring required as applied to the operation of Te Ahuriri constructed wetland (resource consent #CRC191841). Those being: during the first year of operation: fortnightly monitoring of eight water quality parameters, reducing to monthly monitoring thereafter and for a period of nine years. Our understanding is that woodchip bioreactors likely require a resource consent in many regions, hence we did not apply any regional correction to those cases.

For wetlands, we also included a scenario where the constructed wetland was located on marginal land of little commercial/productive value, which tends to be the preferred practice when siting wetland. The various scenarios we costed are described in Table 3.

Table 3: Description of scenarios modelled to correct for project bias.

Scenario	Constructed wetland	Scenario	Denitrification bed	Scenario	Denitrification wall
1.0	Realised project - see Table 2	2.0	Realised project – see Table 2 (n.b. realised costs included costs of postponements and delays during the build process, and sophisticated, automated, continuous water quality monitoring apparatus = 'science premium').	3.0	Realised project – see Table 2
1.1	Assume built on worthless, marginal land = no loss in land value or productivity.	2.1	2.0 less the science premium, albeit maintain fully automated flow and water quality monitoring and assume apparatus require renewal every 10 years. Include costs of obtaining resource consents to divert and discharge water.	3.1	3.0 less the science premium (i.e., assume time/charges associated with processing resource consents is 50% and forego project management/consultancy costs associated with contracting a civil engineering company – comparable to omitting sheet piling costs).
1.2	As per 1.1 + assume requires resource consent & compliance water quality monitoring such as required in Canterbury region.	2.2	As per 2.1 but replace automated water quality monitoring with monthly manual sampling and lab analyses of influent and effluent: weekly sampling for 6 months, reducing to indefinite monthly sampling thereafter.		
1.3	As per 1.0 + assume requires resource consent & compliance water quality monitoring such as required in Canterbury region.				

Results and Discussion

Total and Annualised value costs for three different edge-of-field mitigation practices are presented in Figures 1 and 2, respectively. The cost-effectiveness of nitrate removal for the different scenarios are presented in Figure 3. For all bar one scenario, the constructed wetland out performed the woodchip bioreactors for cost-effectiveness of nitrate removal. We calculate the realised cost-effectiveness of Kaiwaiwai constructed wetland to be $33 /kg N removed and a range of $21 - 40 /kg N for the alternative scenarios we examined.

For the wetland, we estimated that the APVC of siting of the wetland on 0.75 ha of productive land in the Wairarapa region equates to $5,100 /year and contributed 34% to the cost of nitrate removal. If the wetland were subject to the policies and rules of the Canterbury Land and Water Regional Plan then the predicted compliance costs for construction and operation of the wetland increased the APVC by $3,485 /year. This translates to a relative increase in nitrate removal cost of between 19 and 24% (depending on what assumptions are made regarding the foregone productivity of the land).

When science premium costs were removed for the instream woodchip bed the estimated cost-effectiveness of nitrate removal was around $37/kg N (scenario 2.2). Note that this scenario still retained resource consent and compliance water quality monitoring costs. It is close to what we expect the cost-effectiveness of Kaiwaiwai wetland to be, if it were subject to compliance costs, as apply in Canterbury region. An important assumption here is that the instream woodchip bed has a 25 year operational life. Whereas wetlands and woodchip denitrification walls have a proven longevity, woodchip beds have yet to be examined over such a long timeline. We assumed woodchip at the head of the in-stream bioreactor will be replaced every three years as an ongoing maintenance cost and to maintain hydraulic conductivity. In doing this we expect the periodic replenishment of reactive organic carbon (13% of the initial mass) will extend the denitrifying capacity of the bioreactor over 25 years. We calculated the cost of automated water quality monitoring added approximately $84,000 to the TPVC of the woodchip denitrification bed case study (compare scenarios 2.1 vs 2.2 in Figure 1). This was largely attributed to the high capital expenditure of the equipment (remote terminal unit + nitrate sensor + multiparameter water quality sensor + pumps) plus maintenance costs that assumed instrument replacement every ten years.

Despite not incurring any maintenance or land-loss opportunity costs that applied to the other devices, the groundwater woodchip wall was the most expensive nitrate mitigation option evaluated. This reflects the much higher establishment and construction costs. It is helpful to note that the field site at Silverstream Reserve represented a very challenging environment in which to build a woodchip and the need to employ sheet-piling for trench stabilisation purposes added greatly to the construction cost. This cost burden however is largely discounted in scenario 3.1, for which N-removal costs were still twice those evaluated for any of the other devices. Woodchip walls and irrigation galleries have been built successfully elsewhere in NZ without the need for shoring and alternative trench stabilisation methods are available to sheet-piling, from which we anticipate some marginal cost-efficiencies might be made. The need for installing wells from which to characterise hydrogeological conditions and conduct water quality monitoring from also burdened the cost of the denitrification wall option.

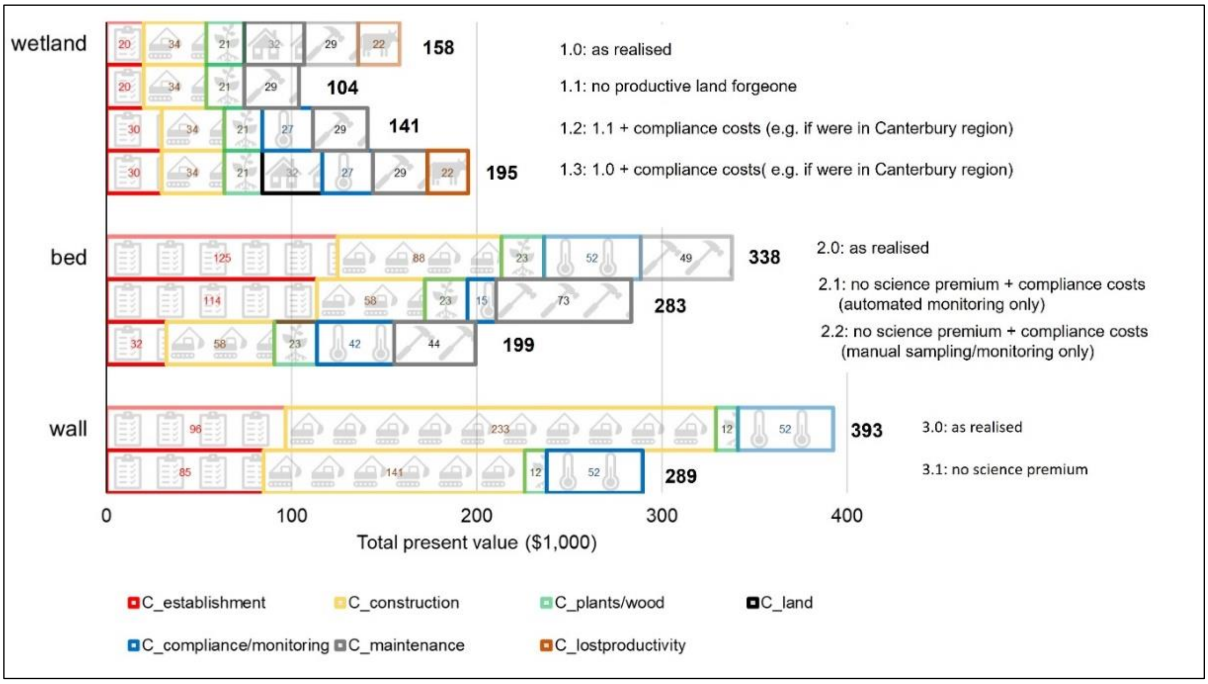

Figure 1: Total present value costs, evaluated for the three different edge-of-field mitigation practices for the realised projects together with alternative, hypothetical scenarios. All scenarios assume a 25-year project life.

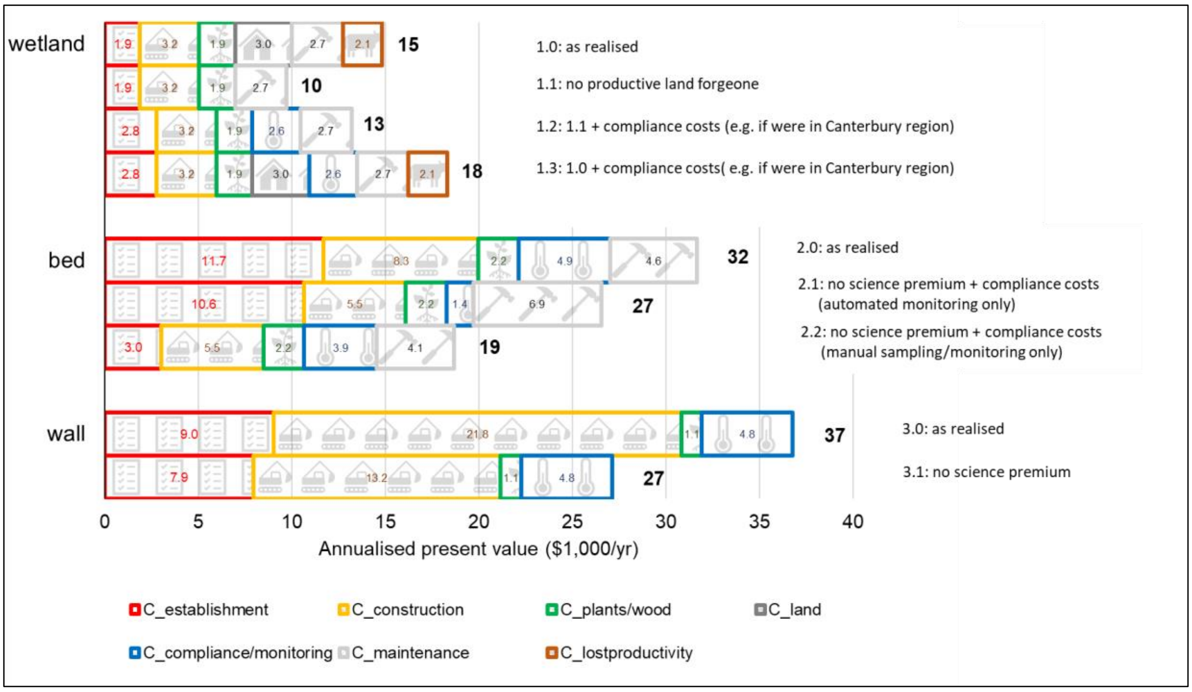

Figure 2: Annualised present value costs, evaluated for the three different edge-of-field mitigation practices for the realised projects together with alternative, hypothetical scenarios. All scenarios assume a 25-year project life.

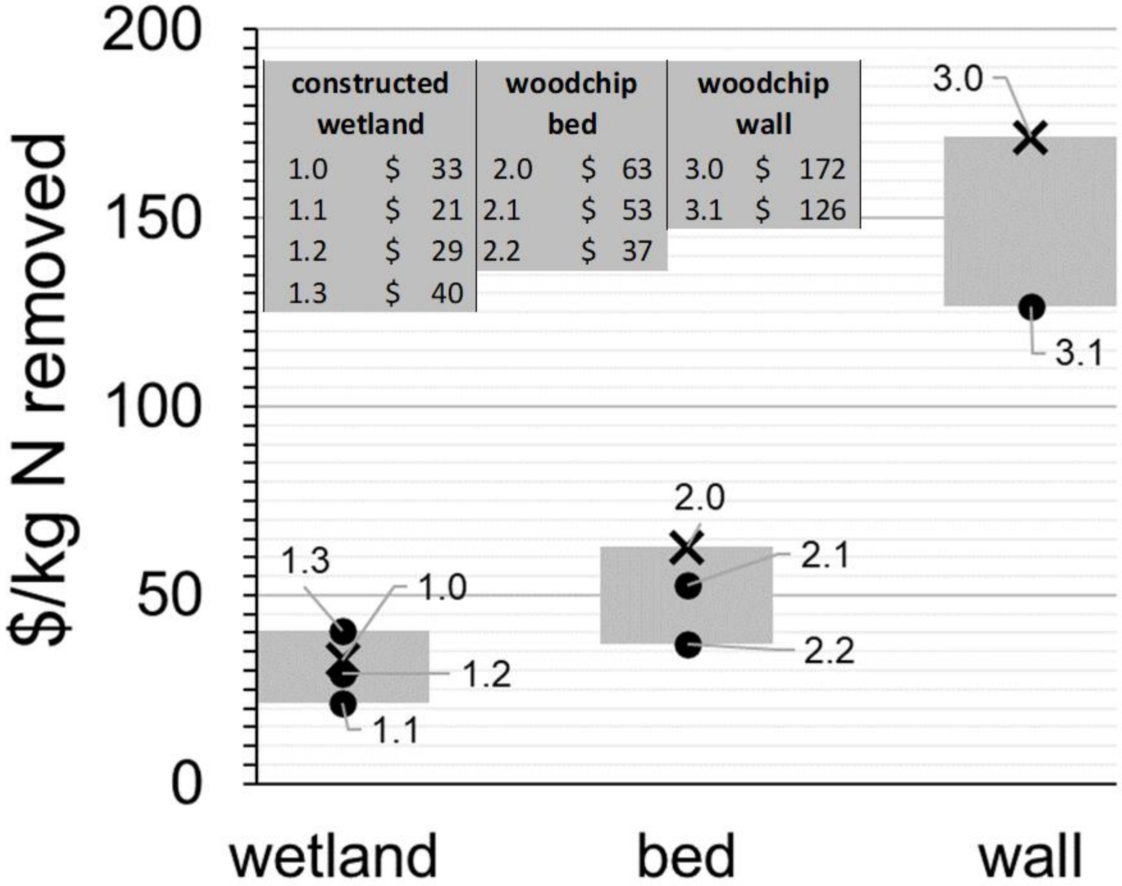

Figure 3: Cost-effectiveness of nitrate removal for the three different edge-of-field nitrate mitigation practices evaluated. Crosses mark the realised projects; dots mark the hypothetical alternative scenarios, as described in Table 3.

Conclusion

The cost effectiveness of nitrate removal evaluated for three different edge-of-field N-mitigation practices ranged from $21 – $172 / kg N removed. The order of cost-effectiveness followed: constructed wetland < woodchip denitrification bed < woodchip denitrification wall. Whereas the costs associated with the woodchip denitrification bed bordered those of the constructed wetland, the woodchip denitrification wall that targeted treatment of shallow groundwater proved to be over twice as expensive. Our findings show that for the Canterbury region, compliance costs in the form of resource consents and mandatory monitoring add substantially (13-26%) to the cost of implementing edge-of-field N-mitigation practices.

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