



“The CarP-N neutral Project”: Removal, processing and reuse of invasive fish in local terrestrial conservation projects

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1 | INTRODUCTION

Invasive species have caused substantial ecological and economic problems globally (Lowe, Browne, Boudjelas, & De Poorter, 2000). In the United States, the economic cost of non-indigenous species invasions is estimated to be between US\$128 and US\$147 billion annually (Pimentel, Zuniga, & Morrison, 2005), but the total cost is likely to be greater if ecosystem damage is also considered (Lovell, Stone, & Fernandez, 2006). Of this, economic losses from the effects of invasive fish in aquatic systems are believed to comprise US\$1–5.7 billion annually (Pimentel et al., 2005).

In New Zealand, a number of invasive fish species occur and are, in some places, particularly abundant. The acknowledged epicentre and only formally defined containment area for invasive koi carp (an ornamental strain of *Cyprinus carpio*) in New Zealand is located in the North Island in the Lower Waikato River Basin (LWRB; Grainger, 2015). Eutrophic conditions combined with a temperate climate and connected shallow riverine lakes and wetlands provide ideal conditions for the proliferation of this (Bajer et al., 2015; Vilizzi, Tarkan, & Copp, 2015) and other invasive fish such as the brown bullhead catfish *Ameiurus nebulosus* and goldfish *Carassius auratus*.

In this paper, we describe an invasive fish management programme where unwanted organisms are removed from the aquatic habitat and converted into beneficial products to address

or support environmental issues and initiatives related to conservation and/or restoration. The underlying closed loop philosophy of the programme is also to demonstrate core values of traceability and sustainability in the development, deployment and performance of these products. In particular, we discuss the importance of nutrient transfer between ecosystems, from aquatic organism capture through to uptake in terrestrial and coastal environments to illustrate the integrated framework within two case studies.

The first study describes the use of processed invasive fish as a replacement for imported synthetic fertiliser tablets typically used in small-to-medium scale replanting programmes by restoration managers and community groups. For this case, we describe an experiment conducted across a regional dune restoration planting programme. The second is the use of invasive fish material as a lure in trapping programmes to control other introduced pests (e.g. introduced rats and mustelids) which have undesirable impacts on native terrestrial plant and animal taxa in New Zealand.

Invasive fish for both these case studies were harvested at our invasive fish “demonstration site” using a fixed semi-automated fish cage (Figure 1). The fish cage is fitted with a customised mesh shape and size to minimise native fish by-catch while retaining the smallest invasive fish possible (David, 2015). Following euthanasia, fish are processed on site in a bacterial digester.

Catching and processing invasive fish for environmental gain

One method for generating a low energy recycled N,P,K fertiliser is to process/digest invasive fish in an aerobic bacterial digester where thermophilic protein consuming bacteria (*Bacillus subtilis*) rapidly converts them into a nutrient rich fish meal within 48–72 h. The temperature produced by the thermophiles assists in drying the resultant fish meal without the need for an externally derived heat energy source. Untreated sawdust adds carbon and the lignin enables the fish meal to be pelletized locally without requiring artificial binders. The dry pelletized material remains stable and is stored in 25 kg paper sacks.



FIGURE 1 Fish cage and digester (left top), raw (screened) digested product (right), fish fertiliser following direct compression (bottom left), bagged and ready for transport (bottom right). Pelletising doubles the density of pellets but halves the storage volume. When used in planting initiatives, a pelletised format is logistically easier to manage, transport and dispense than the dry powdery raw product produced following digestion (Bergin & Bergin, 2016) [Colour figure can be viewed at wileyonlinelibrary.com]

2 | CASE STUDY 1: PROCESSED INVASIVE FISH AS A NUTRIENT SUPPLEMENT FOR DUNE PLANT ECOSYSTEM RESTORATION

Historically marine seabird nesting sites were abundant throughout coastal New Zealand dunes and the marine-derived nutrients that birds brought back to nesting sites were important for fuelling growth of native sand-binding dune plants (Hawke & Newman, 2007). These plant species have undergone substantial population declines, however, due to a range of human-induced stressors (Hawke & Newman, 2007). Nitrogen is now recognised to be the limiting nutrient for plants in these dune systems (Bergin & Kimberley, 1999) and planting programmes aimed at restoring dune plants generally use artificial fertiliser tablets to replace depleted nutrients and improve long-term plant survival and growth.

A wide range of fertiliser tablets are available to consumers varying in nutrient and trace element composition, and different tablets are often used interchangeably by community groups in restoration planting programmes. However, tracing the source(s) of components used in artificial fertiliser manufacture, the majority of which are imported from overseas, can be a formidable challenge (Wood & Cowie, 2004). The production and distribution of artificial fertilisers, particularly

those containing nitrogen (N), phosphorus (P) and potassium (K), are energy intensive (Bindraben, Dimpka, Nagarajan, Roy, & Rabbinge, 2015). Atmospheric N is typically synthesised into a useable form via the Haber–Bosch process, and the energy source used to drive the process (typically natural gas or gassified coal) results in emissions which purportedly vary considerably from 3.42 (EU) to 11.06 (China) kg CO₂/kg N produced (Fertilisers Europe 2016, <http://www.yara.dk/godning/miljo/reducing-carbon-footprint/fertilizer-life-cycle-perspective/life-cycle-analysis-of-ammonium-nitrate/>). Phosphate on the other hand is typically mined from finite resources. Both processes generate considerable greenhouse gas emissions and other waste products (Wood & Cowie, 2004). Therefore, understanding the life cycle of components (footprint) used to assemble and produce an artificial tablet (that may subsequently be used in a restoration project) is in our view an important consideration. Recently proposed regulations for fertilisers by the European Commission to encourage use of recycled materials (e.g. biowaste) and to reduce, for example, soil accumulation of cadmium (an element commonly found in artificial fertiliser; Fertiliser Matters 2016) supports this perspective.

Our proposed approach is a low footprint, locally produced recycling process where the infeed materials comprise predominantly unwanted organism protein (invasive fish) and other local recycled



FIGURE 2 Equivalent quantities by weight and N of 1, 2 or 3 fertiliser tablets vs. invasive fish pellets [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

by-products (e.g. untreated sawdust, Figure 1). In terms of ecosystem energetics, fish provide a valuable nutrient recycling service in freshwater because these fish convert ingested material into biomass as they grow (Andersson, Granéli, & Stenson, 1988; Drenner, Day, Basham, Durward Smith, & Jensen, 1997). For instance, a study by Kitchell, Foonce, and Tennis (1975) calculated that up to 70% of phosphorus in the pelagic zone of Lake Wingra, USA, was embodied in fish biomass and that decomposition of dead post-spawned fish was likely to contribute substantially to the supply of phosphorus in lakes. Although carp also liberate nutrients during defecation and suctional feeding (Morgan & Hicks, 2013), comparative phosphorus contributions from excretion of live fish are likely to be much lower (Andersson et al., 1988). The ability to remove this nutrient-rich biomass and reuse it elsewhere may be particularly beneficial to systems like the LWRB where substantial nutrient losses from intensive agriculture into water bodies have resulted in water quality declines driven predominantly by increases in total phosphorus and nitrate (Vant, 2008).

In this case study, we compared the performance of recycled invasive fish fertiliser against artificial tablets for fuelling two species of dune plants—the New Zealand endemic sand-binding pingao *Ficinia spiralis* and native spinifex *Spinifex sericeus*. These species were planted in three coastal New Zealand dune systems to compare growth (plant spread and vigour) in response to nutrient additions at the time of planting (i.e. invasive fish and commercial fertiliser tablets vs. no fertiliser controls). The pelletised invasive fish had a lower nitrogen content than the tablets (Table S4), so to ensure comparability in trials, 72 g of fish pellets was equivalent to a 10 g commercial fertiliser tablet. Three dose rates were tested (1, 2 or 3 tablets, 72, 144 or 216 g pellets, Figure 2). More specific methodological and result details for this case study including experimental design, planting plot layouts and replication can be found in the supplementary information provided (Supplementary information 1, Figures S1 and S2).

In summary, in most cases, invasive fish pellets produced a similar boost in plant growth and vigour to that achieved using commercial fertiliser pellets at all three sites and all fertilised plants



FIGURE 3 Example trial plot image at Port Waikato dune restoration site. Pingao and spinifex native sand binders planted with synthetic tablets (red circle) v invasive fish pellets (green) v control (blue—no fertiliser) trials. See also Figure S3 [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

grew significantly greater with respect to vigour and spread than no fertiliser controls (ANOVA, 0.05, Figures 3 and 4, Tables S1–S3, Figure S3). There was little additional growth at the medium- and high-dose rates for either fertiliser type suggesting that a single dose of either tablets or pellets is sufficient for growth performance while maintaining manageable field deployment logistics (material transport and application, Bergin & Bergin, 2016). Furthermore, stable isotope analysis of the nitrogen in dried dune plant material indicated clear uptake of nutrients into plant tissues from both pellets and tablets. Plants supplied with either fertiliser type (pellets or tablets) exhibited consistent but significantly different $\delta^{15}\text{N}$ signatures, reflective of the origin and composition of the added nutrient source (Table 1).

In effect, locally produced invasive fish pellets appear to be a viable and comparably performing alternative to imported artificial fertiliser tablets for dune restoration planting initiatives. In contrast to artificial tablets, information regarding the origin, composition and life cycle process to manufacture the fish pellets is transparent and traceable for consumers. We have also demonstrated that it is possible to regionally reposition nutrients embodied in invasive fish obtained from an ecosystem in which they are in excess and undesirable, into one in which they are presently depleted but were historically more naturally abundant.

3 | CASE STUDY 2: LURE FOR CONTROLLING TERRESTRIAL INVASIVE ORGANISMS

Flora and fauna in New Zealand exhibit high levels of endemism and organisms evolved in an environment that was historically free of terrestrial mammalian predators (Bull & Whitaker, 1975). Following relatively recent human occupation and the coincident introduction of numerous mammalian pests, catastrophic and widespread declines in biodiversity occurred (Atkinson, 1989), and continue today. Unsurprisingly, a wide range of governmental and community-based mammalian pest control and eradication programmes are in place

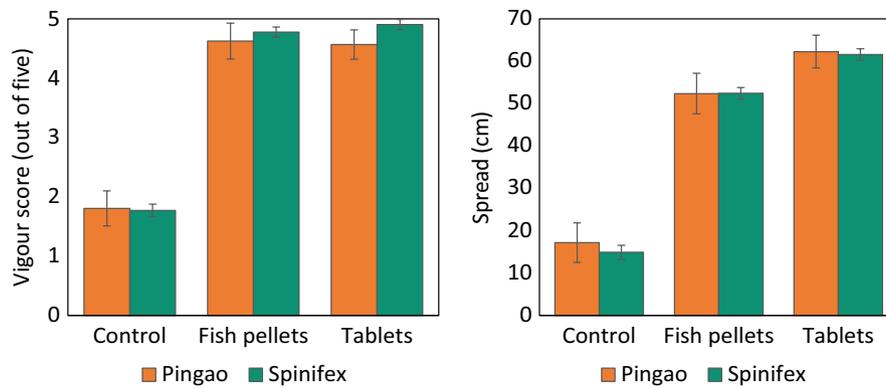


FIGURE 4 “Vigour” score (left) and “spread” (right) of pingao and spinifex in response to fertiliser and no fertiliser treatments in a dune restoration planting trial at Port Waikato, New Zealand. Error bars show standard errors. Tukey’s test indicated that compared with unfertilised controls, invasive fish pellets produced a highly significant increase in plant vigour (Pingao: $t_{17} = 8.11, p < .0001$; Spinifex: $t_{29} = 22.6, p < .0001$) and plant spread (Pingao: $t_{17} = 6.15, p < .0001$; Spinifex: $t_{29} = 16.9, p < .0001$). There was no significant difference between invasive fish pellets and commercial fertiliser tablets in plant vigour (Pingao: $t_{17} = 0.27, p = .96$; Spinifex: $t_{29} = 1.12, p = .51$) and plant spread in Pingao ($t_{17} = 2.21, p = .098$), but the pellets performed slightly poorer for plant spread in Spinifex ($t_{29} = 4.97, p < .0001$). More detailed analysis of this trial and a similar trial at Nukuhakari can be found in Tables S1–S3 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Mean (± 1 SD) nitrogen stable isotope signatures ($\delta^{15}\text{N}$ parts per mille) and percent nitrogen for pellets and plants in dune trial plots. Three subsamples were chosen at random from a homogenised sample of each of the nutrient sources. For plant material, three leaf samples were analysed from each of three planting plots collected from plots treated with fertiliser and invasive fish nutrient sources. For control plants, six samples were collected from a single plot. Analyses were performed at the Waikato Stable Isotope Unit, the University of Waikato, Hamilton, New Zealand. Kruskal–Wallis rank sum test indicate that $\delta^{15}\text{N}$, and percent N were significantly different amongst different sources, for both plant material and nutrient sources at a $p \leq .05$ significance level, except for $\delta^{15}\text{N}$ in plant material where the significance level was $< .01$. NA, Not applicable

Comparison	Measure	Sample type						χ^2	p
		Commercial tablet		Invasive fish pellets		Control			
		Mean (SD)	N	Mean (SD)	N	Mean (SD)	N		
Fertiliser type	$\delta^{15}\text{N}$ (O)	0.1 (0.05)	3	20.6 (0.31)	3	NA	NA	3.86	.05
	Percent N	22.6 (1.08)	3	4.2 (0.14)	3	NA	NA	3.86	.05
Plant material	$\delta^{15}\text{N}$ (O)	0.2 (1.03)	9	24.1 (3.84)	9	-0.9 (1.17)	6	17	<.01
	Percent N	0.8 (0.11)	9	0.5 (0.17)	9	0.5 (0.17)	6	7.43	<.05

throughout New Zealand and play an important role in biodiversity conservation (Ewen, Adams, & Renwick, 2013). Protein-based baits are typically used as lures for terrestrial pest control programmes. In particular, introduced mustelids (stoat *Mustela erminea*, weasel *Mustela nivalis*, ferret *Mustela furo*), feral cat *Felis catus*, rat species (Norway rat *Rattus norvegicus*, ship rat *R. rattus*), house mouse *Mus musculus* and European hedgehog *Erinaceus europaeus* are the primary targets for protein lures. Currently, the most effective lure is considered to be a commercially available rabbit-based product (“Erayz,” Connovations, NZ, C. Gillies, pers. comm.) that is typically deployed by conservation groups in kill traps. Chicken eggs are often used in tandem with rabbit jerky as an additional visual lure for mustelids.

In this case study, a new line of 50 kill traps (DOC 250’s, Curtis Metal Products, NZ—double-ended spring-loaded, <http://www.predatortraps.com/>) were established around the perimeter of the National Wetlands Centre, North Island, New Zealand. A

combination of egg and rabbit or invasive fish pellet baits was placed in alternating kill traps by a local conservation community group with bait type (rabbit/egg or fish) in the first trap determined randomly. Traps were checked approximately monthly by volunteers (Figure 5) and results of any kills documented and reported. Preliminary results after 9 months of trapping suggest that invasive fish baits are attractive to some terrestrial pests, in particular hedgehogs and rats (Table 2). Currently, traps with fish bait have a greater number of confirmed kills for hedgehogs (Friedman rank sum test, $p = .014$), and a comparable number for rats ($p = .479$), compared to traps with rabbit/egg baits. Thus far, only stoats ($p = .025$) and mice ($p = .045$) have been preferentially lured by traps with rabbit/egg baits. Based on these results, invasive fish baits appear to be a durable, promising and complementary lure for controlling rats and hedgehogs in particular. Further ongoing testing is expected to provide more robust conclusions on the long-term effectiveness of fish-based bait for this purpose.



FIGURE 5 Volunteers at the National wetlands centre ready to deploy invasive fish and rabbit-based baits to terrestrial DOC 250 kill traps. Photo courtesy of Nardene Berry (New Zealand Landcare Trust) [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

Internationally many examples exist where invasive animals are commercially harvested from non-native habitats and various components reused. In most cases, the end products tend to support other human needs and wants with the majority of invasive product outputs related either directly or indirectly to food consumption (e.g. Nuñez, Kuebbing, Dimarco, & Simberloff, 2012) and or clothing production (e.g. <http://thefishleather.co/>). For example, there are cookbooks dedicated to the consumption of invasive species (e.g. Franke, 2007).

As exemplified in the two trial case studies presented, the general philosophy of the “CarpN-neutral project” has been to use invasive species products for addressing other conservation problems rather than more typically creating products that directly benefit human consumption or use. Whether used as an alternative fertiliser or as a complementary lure in terrestrial pest control, the material has a low footprint and the products are likely to be organically certifiable. In New Zealand, organic certification can be obtained from two primary service providers: BioGrow NZ and AssureQuality. Each have minimum requirements to meet the standard for “compost”

which predominantly relates to heavy metal concentrations and the presence of pesticides in the final invasive fish pellet product, both which have been extensively tested for with results suggesting that requirements could be met (Tables S5 and S6).

An operational model whereby the running costs of this regional programme (currently paid for by regional ratepayers) could be recovered is possible with an increase in scale of our existing demonstration site (Figure 1). At present, managers and community groups pay an average of NZD 15 cents/artificial imported fertiliser tablet. Thus, to fertilise c. 350 dune plants with artificial fertilisers would cost around NZD \$50 (c. 3.5 kg tablets)—for invasive fish pellets, NZD \$50 equates to a 25 kg bag to deliver the same dose of nutrients to the same number of plants. The actual cost to produce 1 tonne (including pelletising and bagging but excluding harvest labour) is c. NZD \$400. For pest lures or baits, rabbit jerky currently costs NZD 45c/piece/trap while the fish lure costs NZD 14c/trap (c. 70 g pellets/trap). However, it is acknowledged that commercialisation of such organisms can result in incentivising or facilitating further spread (Nuñez et al., 2012) which could result in a potential net environmental loss rather than gain (e.g. Barbier & Knowler, 2006). Consequently, our proposed regional government concept adopts a non-profit philosophy to remain cost neutral in this regard to discourage potential for profiteering through invasive species spread.

A common argument regarding security of supply in such cases concerns the sustainability of the programme if harvest volumes decline due to intensive harvest pressure. Evidence from elsewhere in the Southern Hemisphere where invasive fish harvest has been commercialised suggests that, while temporary reductions in catch may occur within a given waterbody subject to intensive harvest, the wider population recovers rapidly once harvest pressure is reduced with little evidence of reductions in either distribution or biomass being sustained by harvest at larger scales (Koehn, Brumley, & Gehrke, 2000).

Information relating to harvest impact is valuable for river managers as it clearly indicates that harvest pressure can reduce local biomass, and therefore, conservation priority catchments can be targeted for ongoing harvest pressure to achieve localised conservation outcomes (assuming other contributing anthropogenic pressures are also addressed). Meanwhile, a wider strategy which allows

TABLE 2 Documented kills from the predator trapping programme. Data are from a 9 month trapping period (12 May 2016 to 23 January 2017) comprising records from 50 DOC-250 traps (25 alternating sets with rabbit/egg baits and 25 with fish pellets, $n = 12$ occasions). * denotes statistical significance for $p < .05$ using Friedman rank sum test (the test statistic for the Friedman's test is a chi-squared)

Pest	Fish bait		Rabbit/egg		χ^2	df	p-value
	Total	Mean (SD)	Total	Mean (SD)			
Weasel	1	0.08 (± 0.29)	3	0.25 (± 0.45)	2	1	.157
Rat	15	1.25 (± 1.22)	10	0.83 (± 0.83)	0.5	1	.479
Hedgehog	27	2.25 (± 2.73)	11	0.92 (± 1.56)	6	1	.014*
Stoat	0	0 (0)	6	0.5 (± 0.67)	5	1	.025*
Mouse	0	0 (0)	7	0.58 (± 1.00)	4	1	.045*
Cat	0	0 (0)	2	0.17 (± 0.39)	2	1	.157
Ferret	1	0.08 (± 0.29)	2	0.17 (± 0.39)	1	1	.317
Total	44		41				

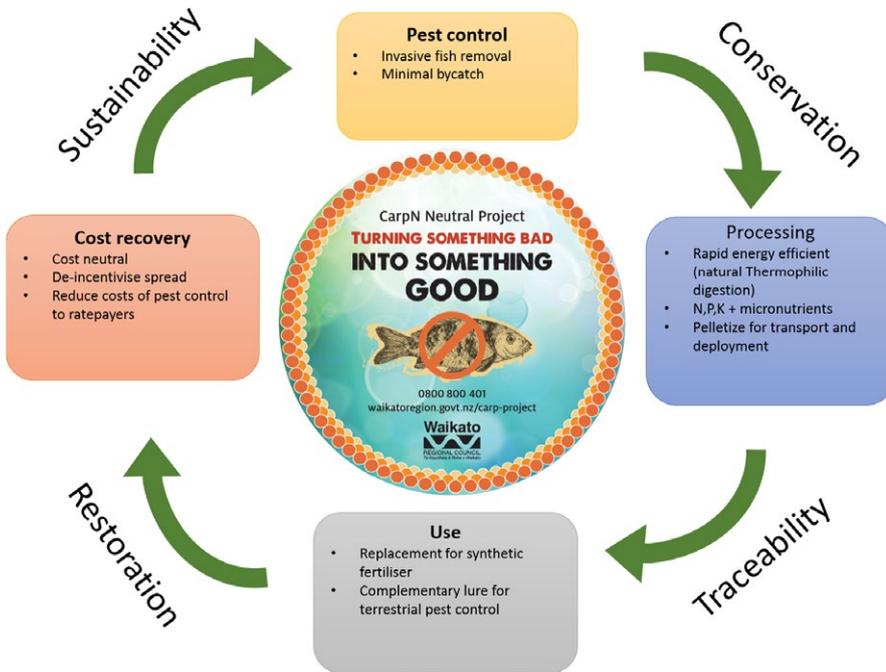


FIGURE 6 Concept diagram [Colour figure can be viewed at wileyonlinelibrary.com]

for a centralised processing facility and safe disposal point for harvest occurring in other areas, or by other entities (e.g. commercial operators, recreational anglers) could ensure security of supply of material. For instance during 2016, the CarpN Neutral programme provided a fish disposal service for the New Zealand Bowhunters Society at the annual “Koi Carp Classic” (<http://www.nzbowhunters.nz/events/koi-carp-classic/>) where c. 5 tonnes of invasive fish were harvested from the river by members during the event. These fish were then processed into pellets and later used in regional dune restoration planting.

Although the scale of our dune planting trials was relatively small (2,400 plants in total), annual nursery propagation of sand-binding dune plants in New Zealand is estimated to be around 250,000 plants. If each of these plants was provided with 72 g fish pellets, c. 18 tonnes of invasive fish fertiliser (equivalent to c. 40 tonnes of processed wet weight fish) could be repositioned into dunes annually potentially replacing c. 2.5 tonnes of artificial fertiliser tablets.

An important consideration of our concept is traceability and sustainability through various parts of the programme including: minimising by-catch of native fish species (David, 2015), using an energy efficient method to process invasive fish onsite (thermophilic bacteria), minimising carbon use in both production and distribution by using the material locally (Figures 1 and 6) and incorporating carbon into the product in the form of sawdust. As part of the dune planting experiment, we undertook chemical analyses of two other commercial fertiliser tablets commonly used in New Zealand. We noted that there was high variability in different trace and heavy metal elements between these two tablets (Tables S4 and S5). Although quality manufacturing standards for commercial artificial fertiliser production exist, disclosing all components within them (e.g. compounds for binding) appears to be voluntary.

5 | FUTURE OPPORTUNITIES

Taking our concept one step further, we are currently trialling the incorporation of biochar, a by-product of pyrolysis from corn production, into digested invasive fish. Biochar has been shown to increase nitrogen retention and lower greenhouse gas emissions when added to animal compost (Agyarco-Mintah et al., 2016). With respect to the use of biochar in fish pellets, the objective is to test its performance as a slow release fertiliser and also as a means of long-term carbon replacement and storage in sand and soil.

Significant potential to further develop raw invasive fish flesh and liquid for use in other conservation projects also exists. For instance, foliar application of digested invasive fish “juice” as a potential liquid fertiliser and anti-lagomorph (e.g. rabbit) browse/repellent in native planting programmes is currently underway. New dune plantings can be heavily browsed by introduced herbivores during early growth. It is proposed that the oily content and strong “sulphurous” smell of this liquid may possess useful compounds as suggested by Trent, Nolte, and Wagner (2001), to reduce herbivorous browsing during early plant growth. At present, a U.S. produced bovine blood-based product is commonly applied in New Zealand for this purpose; <http://www.plantskydd.com/rabbit-repellent.html>. Other alternatives such as installing plant guards and fences to deter browsing in dunes are logistically challenging and costly to implement.

6 | CONCLUSIONS

Irrespective of the application, we posit that the simple approach of turning such outputs back into restoration programmes (and using products from one invasive animal to control another)

creates potential to reduce overall costs for biodiversity enhancement and biosecurity while simultaneously dealing with unwanted organisms in areas where they are problematic. This project demonstrates a practical method of processing pest fish for use in restoration of other degraded ecosystems or put simply it is about “turning something bad into something good.” We consider this concept to be an alternative approach to restoration whereby an aquatic biosecurity problem is specifically being used to improve indigenous biodiversity outcomes across a range of other ecosystem types. We propose that this project is a useful vehicle to demonstrate genuine sustainability and promote awareness of the origin and fate of nutrients within and between ecosystems. It also illustrates alternate ways in which invasive products can be applied to these systems for positive environmental outcomes. A similar philosophy should be applicable to problematic and abundant invasive species elsewhere, particularly where those organisms are susceptible to either point source control or efficient mass harvest.

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AUTHORS' CONTRIBUTIONS

B.O.D. conceived the project; D.O. and M.A.P. assisted in manuscript preparation and some analyses; D.B. and M.B. carried out dune planting trial design, plant responses and data collation. All authors critically reviewed drafts and have approved the final version.

DATA ACCESSIBILITY

Data available from the Dryad Digital Repository <https://doi.org/10.5061/dryad.50jf82v> (David, Özkundakci, Pingram, Bergin, & Bergin, 2018).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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