A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

NeoBiota 94: 101–125 (2024)
DOI: 10.3897/neobiota.94.122939

Review Article

Strangers in a strange land; freshwater fish introductions, impacts, management and socio-ecological feedbacks in a small island nation – the case of Aotearoa New Zealand

Calum MacNeil[1], Robin Holmes[1], Edward Challies[2], Kiely McFarlane[1], Jason Arnold[3]

1 *The Cawthron Institute, 98 Halifax Street East, Nelson 7010, Private Bag 2, Nelson 7042, New Zealand*
2 *Waterways Centre for Freshwater Management, School of Earth and Environment, Faculty of Science, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*
3 *Kauati Limited, The Forge Level 1/20 Athol Street, Queenstown 9300, New Zealand*
Corresponding author: Calum MacNeil (calum.macneil@cawthron.org.nz)

Abstract

Invasive non-native species (INNS) are key drivers of global biodiversity loss. This is particularly evident in freshwater ecosystems, where the rates of both vertebrate biodiversity loss and biological invasion exceed those of marine and terrestrial systems. Aotearoa New Zealand (henceforth Aotearoa) like many other island nations, has a troubled history with NNS. However, it is also unique, as the main islands were the last major landmasses on Earth to remain uninhabited by humans. The endemic fauna had evolved in isolation from any anthropogenic influence or introduced NNS, until the mid-thirteenth century with the arrival of Māori, the first people to inhabit Aotearoa. Centuries later, following European colonisation, many non-native freshwater fish were deliberately introduced by acclimatisation societies. Currently, most of the native freshwater fish species of Aotearoa are at risk of extinction, despite almost 90% of these being found nowhere else on earth. Many of these species are highly valued by the indigenous people of Aotearoa, who have repeatedly highlighted biases towards NNS in freshwater fish management. With the rate of biological invasions increasing, it is timely to address interconnected issues concerning the history, impacts, management and current / future policy directions, including those involving biosecurity, for non-native freshwater fish in Aotearoa. We do this by applying a social-ecological systems (SES) lens, with a focus on causal-loop relationships and feedbacks to improve understanding of the dynamics of drivers, mechanisms and impacts of such invasions. We highlight the tensions that have resulted from managing some NNS as 'pests' threatening native biodiversity, while simultaneously promoting a tourism and recreational fishery resource for specific NNS. This has generated extremely polarized views on the 'status' of non-native freshwater fish species and given rise to contradictory and divergent goals for their management. We show how a disjointed and often incoherent policy landscape has contributed to legal 'anomalies' for NNS, including policy misalignments and gaps, hampering effective use of resources, while also entrenching contradictory management programmes for different stakeholders. Our study shows how these interconnected issues have been manifested in social-ecological feedback loops on core aspects of NNS policy and management, past and present. Consequently, there is a need for increased comprehension of the diverse array of potential impacts of NNS for different environments, stakeholders and Māori while developing coherent and practical management methods to reduce such impacts and improve social-ecological resilience. We conclude that adopting a SES approach will aid this endeavour.

Key words: Biosecurity, causal-loops, fish introductions, freshwater fish policy, non-native species, social-ecological system

OPEN ACCESS

Academic editor: Shana McDermott
Received: 13 March 2024
Accepted: 14 June 2024
Published: 26 July 2024

Citation: MacNeil C, Holmes R, Challies E, McFarlane K, Arnold J (2024) Strangers in a strange land; freshwater fish introductions, impacts, management and socio-ecological feedbacks in a small island nation – the case of Aotearoa New Zealand. NeoBiota 94: 101–125. https://doi.org/10.3897/neobiota.94.122939

Introduction

Invasive non-native species (INNS) are intrinsically linked with many stakeholder actions (governments and public) throughout the world, to affect human well-being via negative or positive social-economic and social-ecological impacts. An INNS is a non-native species (NNS) which has expanded its range beyond its point of introduction and has had a measurable impact on factors such as ecology, ecosystem services, economics and human health (Sinclair et al. 2020). They can be key drivers of social-ecological regime shifts, which are large-scale, potentially irreversible changes in social-ecological systems (SES) (Shackleton et al. 2018) and are either solely or partially responsible for 60% of recorded global animal and plant extinctions (IPBES 2023). Such biodiversity loss is particularly pronounced in freshwater ecosystems, where the rate of decline in vertebrate biodiversity is higher than in either marine or terrestrial systems (Grooten and Almond 2018; Tickner et al. 2020). This is partially a result of freshwater systems experiencing a higher rate of biological invasions than other ecosystems (Gallardo et al. 2016; Tickner et al. 2020; McFadden et al. 2023). Understanding the impacts of INNS on different recipient environments, ecosystem services and stakeholder values, and focussing on those INNS capable of causing social-ecological regime shifts, are increasing priorities for governments and the research community (Shackleton et al. 2018; MPI 2023).

Aotearoa New Zealand (henceforth Aotearoa) like many other island nations, has had a troubled history with NNS, stretching back several centuries (King 2019). Accidental introductions such as the Norwegian rat (*Rattus norvegicus*) and domestic cat (*Felis catus*) have had devastating impacts on naïve native species (King 2019), while in 2023 the freshwater Gold-Asian clam (*Corbicula fluminea*) was first detected, which could completely 're-engineer' the country's river and lake ecosystems (MPI 2023). Many freshwater fish such as trout and salmon species, were deliberately introduced for aquaculture, sport and tourism (McDowall 1990). Such deliberate fish introductions, like accidental introductions, have had profound impacts on ecology, stakeholders and Māori (McDowall 1990, 2011; Collier and Granger 2015).

The historical context of biological invasions and introductions in Aotearoa is globally unique (Champion 2018). The main islands were the last major landmasses on Earth to remain uninhabited by humans and until the mid-thirteenth century, the endemic fauna had evolved in isolation from any introduced NNS (King 2019). Despite 88% of freshwater fish species in Aotearoa being found nowhere else on earth (Department of Conservation (DOC) 2020), almost the same percentage (76%) are currently either facing extinction or at risk of being threatened with extinction (StatsNZ 2023). The country's freshwater ecosystems are also increasingly prone to invasion, due to global trade and climate change (Champion 2018). Many of these threatened native fish are also taonga (treasured) species for Māori and central to mahinga kai (the traditional value of food resources and their ecosystems, as well as the practices involved in their production, harvesting and protection) (Harmsworth et al. 2016; Rainforth and Harmsworth 2019).

Although there is a complex interplay among drivers of freshwater fish invasions (Milardi et al. 2022), humans can, to a degree, influence invasion processes and outcomes by planning for and responding to the detection, transport, introduction and spread of NNS (Sinclair et al. 2020; Milardi et al. 2022). It has been shown that a SES approach which focusses on causal-loop relationships and feedbacks can provide a valuable insights on how INNS management strategies work in practice (Shackleton et al. 2018). Feedbacks occur when the initial interaction between two or more elements 'feed-back' to the initiating process with positive (reinforcing) or negative (dampening) effects (see Figs 1, 2 for fish examples and definition of terms; Sinclair et al. 2020).

These feedbacks provide a useful starting point from which to build a SES approach to understand interdependent systems, such as governance institutions and goals for development, biodiversity and ecosystem services (Reyers and Selig 2020). For example, Aotearoa has adopted increasingly stringent biosecurity measures within the country and at the border, including measures applicable to freshwater fish (Champion 2018). When effective, these measures generate negative feedback loops that work to stabilise or reduce invasions through detection, prevention, elimination or management of specific INNS designated as 'unwanted organisms' by the government (Champion 2018; Shackleton et al. 2018; Sinclair et al. 2020).

The identification and strengthening of negative feedback loops associated with biosecurity, is also increasingly important in an era where climate change is accelerating the rate of biological invasion (Tickner et al. 2020). Research shows that the range expansion of many physiochemically tolerant aquatic NNS is favoured by higher temperatures and changing precipitation regimes (Rowe and Wilding 2012; Copp et al. 2021). There is also the potential for non-native 'sleeper' species, whose population size and range in a country such as Aotearoa is currently limited by climate, to become more widespread and problematic as climate change progresses (Hulme 2017). Despite these growing concerns, Aotearoa remains relatively free from freshwater NNS compared to Europe and North America (Champion 2018). This means NNS still remain a significant unrealised threat to freshwater ecosystems in Aotearoa, with a high degree of latent impact that may manifest in the future (Gluckman 2017). Given the increasing threats of invasion and climate change, we feel it is it is very timely to address several interconnected core issues concerning the history, impacts, management and current policy directions for non-native freshwater fish in Aotearoa, and to identify the social-ecological feedback loops underlying these.

Over recent decades, concerns about the ecological impacts of freshwater NNS have existed alongside a drive for economic expansion of aquaculture and sports-fishing / angling tourism, shaping government policies. The tensions that have resulted from managing some NNS as 'pests' threatening native biodiversity, while simultaneously promoting a tourism / fishery resource for other NNS, have unsurprisingly generated highly polarized views on the 'status' of introduced freshwater fish species (Chadderton 2003; Jellyman et al. 2018; Tadaki et al. 2022). This promotion of contradictory and divergent goals for introduced fish species has resulted in fisheries policies, legal status and terminology that function differently for different species or even the same species in different regions of the country (Chadderton 2003). Our study will show how this has been associated with 'branding' of NNS with more loaded terms, including negatively as 'pest', 'noxious' and 'unwanted', or positively as 'sports fish' (Dean 2003).

It is increasingly argued that there is a need to 'strike the right balance' between native and non-native species in fisheries management in Aotearoa (Chadderton 2003).

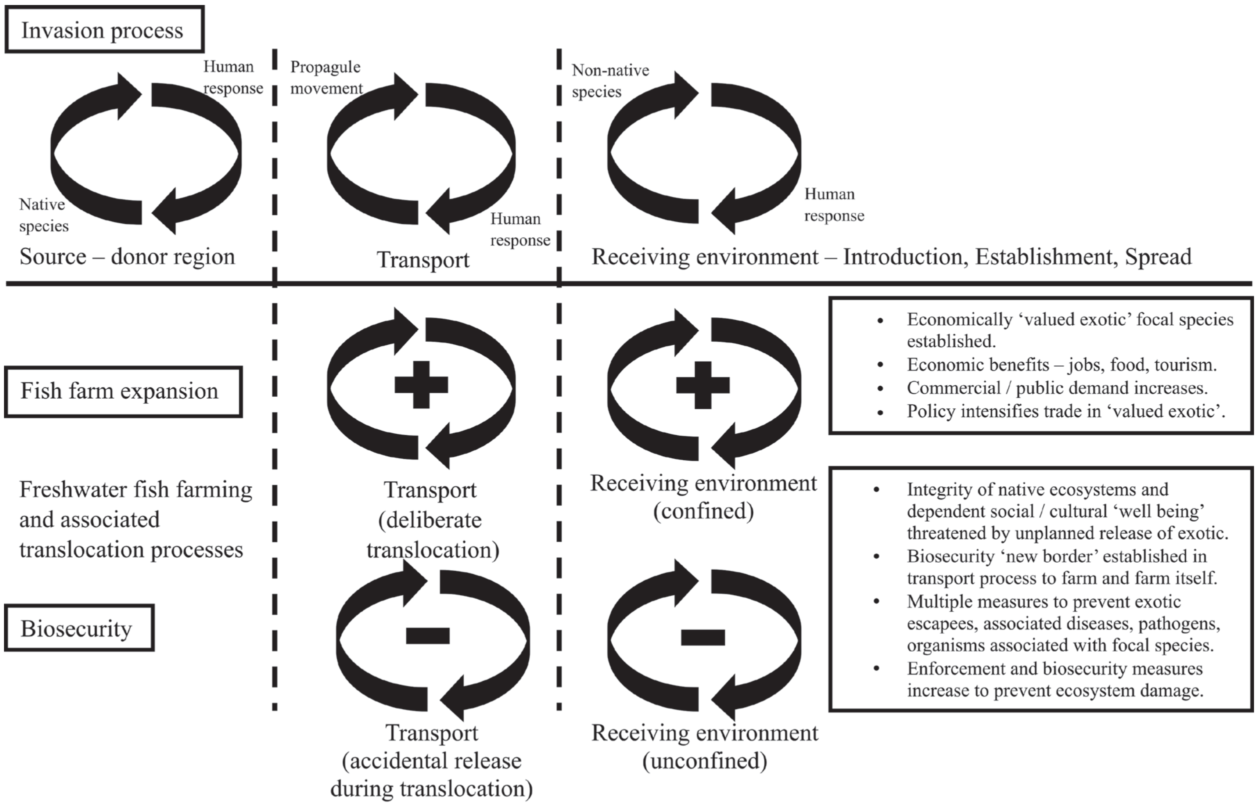


Figure 1. Different stages of biological invasion (adapted from Colautti et al. 2006 and Sinclair et al. 2020), focussed through human-natural systems and positive/negative feedback loops associated with fish farming, translocation and biosecurity. A social-ecological system can be defined as a complex, interconnected network of people and the environment, highlighting the interactions between human society and the ecosystems that support it. In a social-ecological system, both social and ecological factors influence and are influenced by one another, and changes in one element of the system can have cascading effects on other parts of the system (Shackleton et al. 2018). A feedback loop can be defined as a self-regulating system in which the output of the system has an impact on the input of the system, which then modifies the output. Feedback loops can be positive or negative, depending on whether the output of the system reinforces or counteracts the input.

This means managing NNS in a context dependent way, based on the interacting needs of stakeholder groups and Māori at a 'local' or regional scale. This balancing act has not always been achieved and arguably is still not being achieved in many cases. This has contributed to current legal 'anomalies' in the governance of NNS, including policy misalignments, gaps and duplications, which hamper effective management and efficient use of resources. This has also entrenched divergent management programmes and stakeholder and Māori interests. Our study will document these interconnected issues and show how these have been manifested in social-ecological feedback loops, past and present, involving introductions, biosecurity, aquaculture, possession, translocation and fish passage. By clearly identifying both loops and drivers, we aim to show how an SES approach to non-native freshwater fish management can inform more coherent, effective policies in the future, despite the legacies of a confused legislative landscape still manifest in present-day Aotearoa.

A social ecological systems approach to examining NNS management

A social-ecological systems (SES) approach can provide insights into the drivers, mechanisms and impacts of biological invasions (Shackleton et al. 2018). It is crucial to recognise the multiple socioecological feedback loops within the invasion process

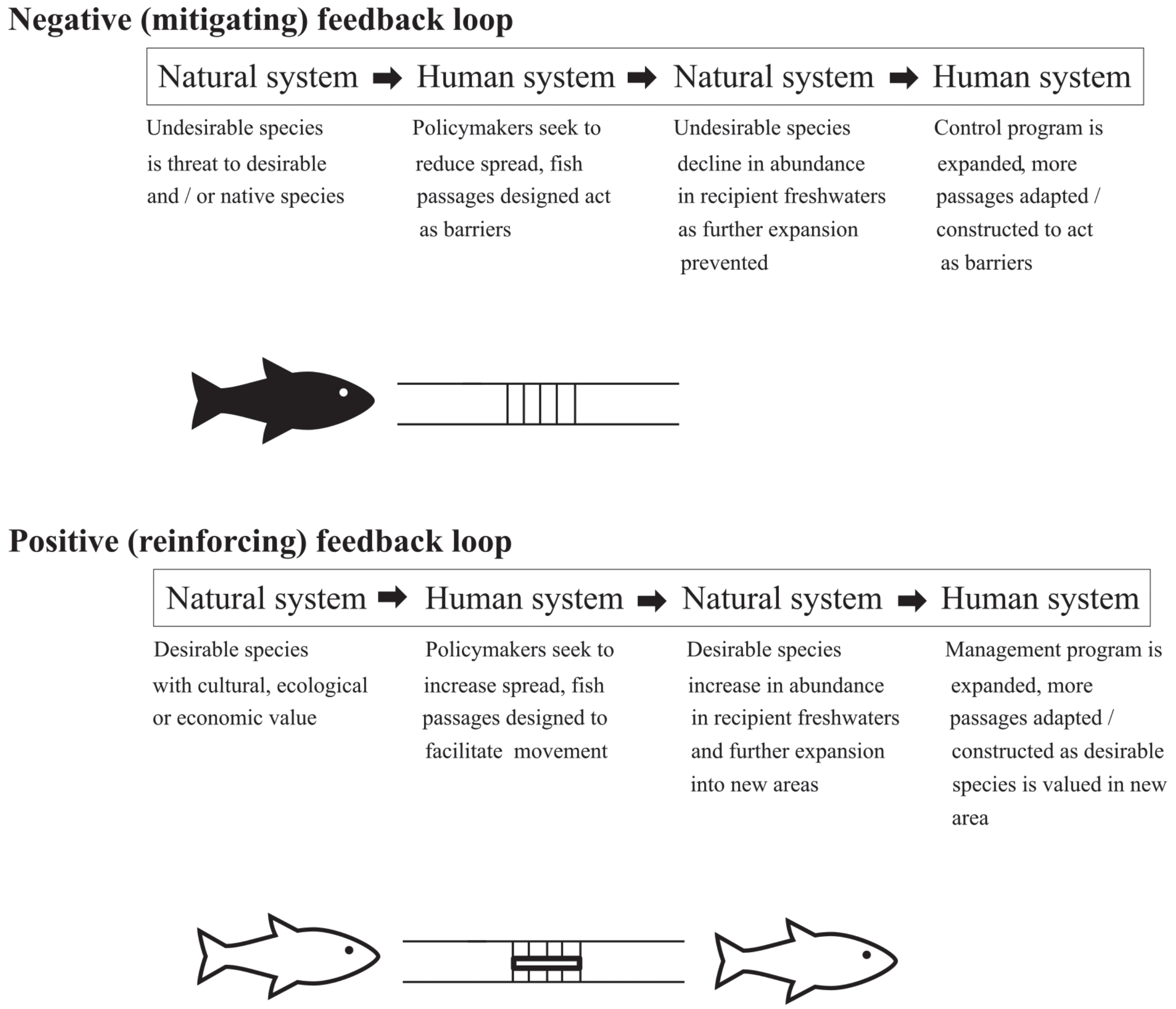


Figure 2. Current Aotearoa policy for in-stream structures such as fish passages to simultaneously act as barriers to 'undesirable' species spread and facilitators of 'desirable' species spread focussed through human-natural systems and simultaneous negative (mitigating) and positive (reinforcing) feedback loops for 'undesirable' and 'desirable' species respectively.

that highlight the role that humans can play, be it by deliberate introductions, management actions and biosecurity measures, or other interventions (Fig. 1). For instance, while the invasion process can be positively driven by economic interests such as non-native fish farming, biosecurity measures work negatively on any undesirable species spread. The source loop encompasses the human response in the NNS source (donor) region. Here, collection of desired freshwater fish is approved of, then the transport loop associates people with the introduction / translocation process where desired species are in established ongoing and future transport mechanisms (i.e. air, ocean and land freight) from the donor to recipient regions (Figs 1, 2). Concurrent with the transport loop, the risks associated with non-focal species which may be inadvertently caught up in the transport mechanism have to be managed and minimised. The recipient loop encompasses the way humans and ecosystems interact with the arrival, establishment and spread of non-native fish, for example via aquaculture). Subsequent sections of this paper apply this SES lens to identify and reflect upon the feedback loops resulting from non-native fish management in Aotearoa.

Realised and potential ecological impacts of non-native freshwater fish species in Aotearoa

To understand why freshwater fish legislation has evolved as it has, it is first important to appreciate the impacts of past and current invasions documented in Aotearoa, and second, to consider the risk profile of future potential invaders, which have had impacts in similar bioclimatic regions, albeit with different faunal assemblages (Kumschick et al. 2015; Torres et al. 2018). From the mid-19th century onwards, a range of freshwater fish were deliberately introduced to the new British colony of New Zealand via Victorian 'acclimatization societies'. These fish were part of a diverse array of what was then presumed 'innoxious' animal and plant introductions, for commercial and recreational benefit (McDowall 1990, 2006). This included species such as the brown trout (*Salmo trutta*), which from the 1860s onwards were repeatedly introduced from Britain for over a century (McDowall 2006; Jones and Closs 2018).

Such fish introductions can drive positive socioeconomic feedback loops that increase donor fish transfer out of source regions over time. This is because the perceived success and value of previous fish introductions in recipient areas increases demand, 'trade volume' and the number of potential species within these trades (Sinclair et al. 2020). Sinclair et al. (2020) has pointed out that the purely ecological 'invasional meltdown' hypothesis, where one INNS and the disturbance it causes in the recipient environment can facilitate further invasions (Simberloff and Von Holle 1999), can be mirrored by a socio-economic invasion meltdown, whereby economic and social benefits drive further introductions (Fig. 3). Such a feedback loop is evident in Aotearoa, whereby the perceived economic success of early brown trout introductions led to further introductions of not only brown trout but other salmonids including the Chinook salmon (*Oncorhynchus tshawytscha*) and rainbow trout (*Oncorhynchus mykiss*), with the aim of creating similarly successful fisheries (McDowall 1990,1994). Several coarse fish were also introduced to freshwaters deemed unsuitable for salmonids (de Winton et al. 2003) and other species were introduced as ornamental garden pond or aquarium specimens (NIWA 2020).

The active 'acclimatisation' movement continued up until as recently as the late 1960s in Aotearoa (Champion 2018). At the time of the original introductions, little thought was given by acclimatisation societies to the impact on native ecosystems or the people dependent upon them (McDowall 2006). For instance, writing in an 1880 newspaper, an anonymous commentator welcomed Societies' plans to continue repeated stocking of rivers with salmonids, noting that once established, native fish would provide an 'inexhaustible' food supply for the introduced fish (Anonymous 1880).

However, even in Victorian times there was some questioning of the general lack of appreciation of the impacts of introduced species on the receiving environment. The author of a letter to *The Colonist* newspaper in 1873 calling themselves a 'Disbeliever in Too Much Acclimatisation', jokingly suggested that if leopards were introduced, they could be sustained on local school children (Anonymous 1873). Another author, writing from the viewpoint of a native bird, the shag, complained about the replacement of native fish with introduced trout, which were too big for it to eat (Alic 1890). During all of this, the views of Māori, whose culture had been intimately connected with native freshwater fish, were marginalised or absent. It was not until the end of the 1960s that the ecological and economic risks of such introductions were highlighted by the scientific community (Champion 2018). Recognition of

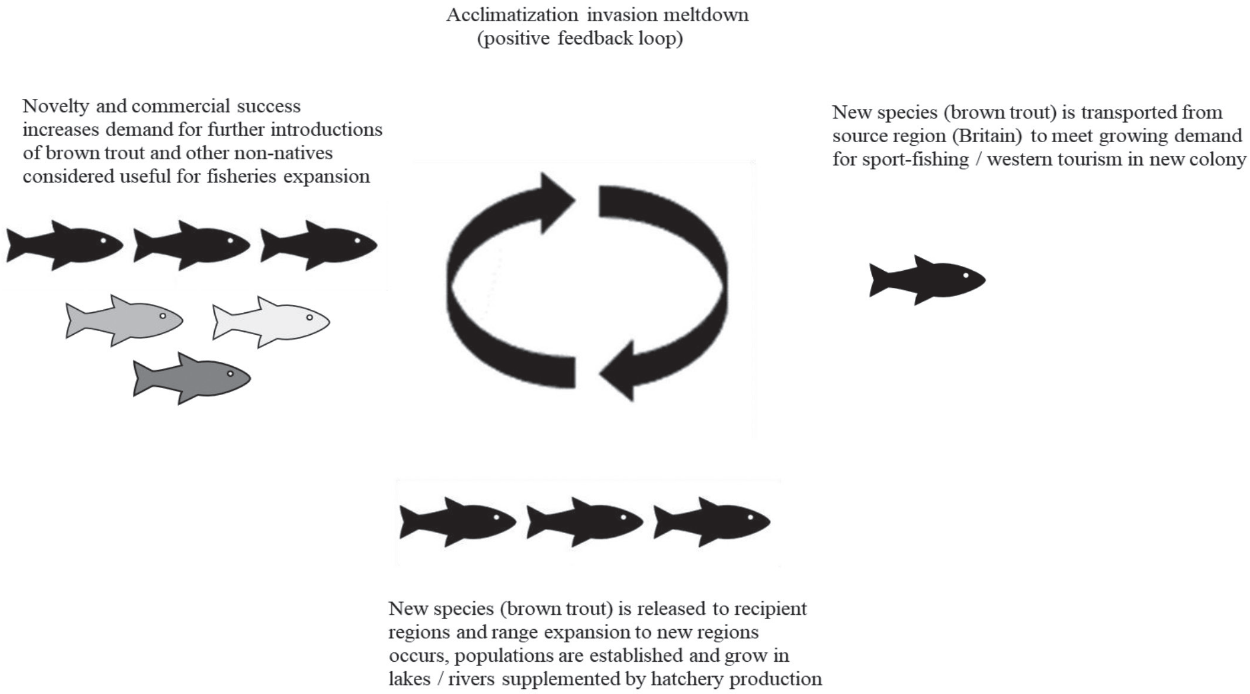


Figure 3. Socio-ecological invasion meltdown (positive, reinforcing feedback loop) for brown trout introductions into the British colony of New Zealand by Victorian acclimatisation societies. Intentional introduction and establishment in recipient regions is done without consideration of any potential negative impacts on native fish species and the cultural / resource values that the indigenous human population attribute to these.

the cultural impacts and the need to involve Māori in decision-making and management of freshwater fish is only now gradually being reflected in policy.

Introduced freshwater fish can have a wide variety of direct and indirect ecological impacts on native fish and ecosystems (for examples of major reviews see Gozlan et al. 2010; Cucherousset and Olden 2011; Bernery et al. 2022; Britton 2022). Direct impacts include competition with native fish for resources, such as food and habitat, predation on native species and alteration of ecosystem dynamics, including the structure and function of food-webs with cascading effects on ecosystem processes (Gozlan et al. 2010; Cucherousset and Olden 2011; Bernery et al. 2022; Britton 2022). Indirect impacts include alteration of physical and chemical water quality through bioturbation, changes in nutrient cycling and the introduction of novel diseases and parasites (Collier and Granger 2015; Bernery et al. 2022; Britton 2022). In the case of Aotearoa, many native freshwater fish species are small, benthic and cryptic and have evolved without large pelagic predatory species, while the majority of freshwater fish introduced for aquaculture, such as salmonids, are much larger (McDowall 2006; Joy and Death 2013). Consequently, introduced fish are at or near the top of food chains in many of the country's rivers and lakes and negatively impact on smaller native fish via predation and / or competition (McDowall 1990, 1995, 2006). Indeed, in the early years of the 'acclimatisation' of brown trout to Aotearoa, Spackman (1892) noted that a diet of small native fish accounted for the trout's high growth rates. Since then, the wide-ranging predatory impacts of brown trout on freshwater fish and food webs in Aotearoa have been well documented (McIntosh and Townsend 1996; McDowall 2006; McIntosh et al. 2010; Jellyman et al. 2018).

Although the brown trout is by far the best studied non-native fish in terms of ecological impacts, it is just one of many freshwater fish introductions that have impacted waterways in Aotearoa. Previous global reviews of the ecological impacts of freshwater non-native fish species have found it helpful to consider impacts at different levels or scales of biological organization, ranging from genetic to individual to population to community and finally ecosystem level (Cucherousset and Olden 2011; Britton 2022; Bernery et al. 2022). In Table 1 we adopt this useful organisational framework to consider ecological impacts of a selection of INNS in the freshwaters of Aotearoa. Our review identified that many of the potential ecological impacts of freshwater INNS already present in Aotearoa are assumed from documented impacts of the same INNS overseas. This is despite the uniqueness of Aotearoa's freshwater ecosystems and fish assemblages. We have therefore attempted to summarise the ongoing ecological impacts of INNS using only Aotearoa-based studies where possible. We would argue this is the optimum approach to ensure future policies and management are based on accurate and robust data from Aotearoa. It must also be appreciated that Table 1 is not exhaustive, in terms of fish species now present in Aotearoa and not all introduced NNS became invasive, for instance Mackinaw trout (*Salvelinus namaycush*) was introduced from North America for sport fishing in the early 1900s but never expanded beyond its introduction lakes or significantly increased in abundance over time (McDowall 1990).

It must also be appreciated that any consideration of ecological impacts needs to acknowledge the complicated and multifaceted mechanisms at play across different spatial and temporal scales. Thus, the various impacts on native species and ecosystems described in Table 1, such as food-web modification and alteration of physical habitat, seldom happen in isolation from one another and can be both additive and synergistic (Rowe 2007; Kumschick et al. 2015). In addition, the impacts of a single introduced fish species can span multiple scales of organization, ranging from impacts on individual animal behaviour, to population dynamics, to the structure and function of communities and ecosystems (Townsend 2003, Table 1). This can be readily witnessed for introduced cyprinids (carp) and Ictaluridae (catfish), which are archetypal 'ecosystem engineers', radically transforming their invaded physical environment with ramifications for multiple trophic levels (Field-Dodgson 1987; Jellyman et al. 2018; Britton 2022, Table 1). For instance, they disturb sediments, increasing turbidity and reducing light availability to aquatic plants that stabilise lakebeds (de Winton et al. 2003). At sufficiently high densities they can even actively uproot plants further destabilising lakebeds and increasing turbidity due to wave action on newly exposed sediments, which can in turn further increase nutrient availability (de Winton et al. 2003).

Nine non-native freshwater fish species have been identified as the most serious 'pests' for natural heritage managers in Aotearoa in terms of their ecological impact and spread (NIWA 2020). These are the brown bullhead catfish, goldfish, koi carp, mosquito fish, gudgeon, orfe, perch, rudd, and tench (NIWA 2020). This list purposely does not include the commercially important salmonids, which government agencies do not label as pests (see 'gaps and labels' section), despite their well-documented negative impacts on ecosystems (Table 1). All nine NNS seldom occur in isolation from one another (Collier et al. 2015), which in many invasion scenarios further complicates attempts to ascribe impacts to any one NNS in particular. For instance, an investigation on the impact of fish introductions on water clarity in 49 lakes in Aotearoa found 83% contained two or more NNS, with some containing as many as six NNS, including rudd, tench, perch, catfish, koi and goldfish (Rowe 2007). This meant the specific role of each individual NNS in causing identified ecological impacts could not be distinguished (Rowe 2007).

Table 1. Examples of ecological impacts of non-native freshwater fish species in Aotearoa. (Note only Aotearoa based studies are included and potential effects ascribed to overseas studies are purposely excluded).

Scale of biological organization	Impact and examples of mechanisms	Description
Genetic	Altering genetic resources via hybridization.	Tench may have the potential to hybridize with other introduced cyprinid fish such as goldfish, rudd and orfe (Rowe 2004). This is relevant if this increases the resilience, physiological tolerance and spread of hybrids.
Individual	Animal health and growth via altered behaviour, disease and parasite transmission.	Diel rhythm of habitat (water column and stream substratum) use by mayfly nymphs was affected by presence of brown trout, which exerted a different selection pressure on invertebrate drift behaviour than native galaxiids (McIntosh and Townsend 1996; Townsend 2003).
		Tench have a potentially high infestation rate with the gut parasite *Ligula intestinalis*, which is already present in North Island lakes. Tench populations could act as a reservoir for this parasite which also infects native fish such as common bullies (Rowe 2004).
		Interactions between mosquitofish and native mudfish (Galaxiidae) can negatively impact mudfish foraging behaviour and prey capture rates (Barrier and Hicks 1994)
Population	Population size decline via predation, competition, disease and parasite transmission.	Brown trout have replaced nonmigratory galaxiid fish in some streams and diminished population sizes in others and have altered the distribution / range of large invertebrates such as crayfish (Townsend 2003; Townsend and Simon 2006; McIntosh et al. 2010; Jellyman et al. 2018). Predation of native mudfish (*Neochanna* Galaxiidae) has potential to eliminate populations of this threatened 'nationally critical' species (Eldon 1979).
		Brown trout and rainbow trout feed on a range of macroinvertebrate species in a South Island lake (McCarter 1986).
		Predation by rainbow trout has caused significant declines in koaro (a native galaxiid fish) in North Island lakes (McDowall 1990).
		Small brown bullhead catfish feed on chironomids, Cladocera, gastropods, caddisfly larvae, plant material and detritus. and large catfish prey on native crayfish, fish and terrestrial invertebrates in Lake Taupo (Barnes and Hicks 2003). Catfish can also feed on other NNS including goldfish and brown trout (Dedual 2019).
		Perch include smelt, common bullies and macroinvertebrates such as mysids and damselflies in their diets in a South Island river (Griffiths 1976), while Ludgate and Closs (2003) found perch suppressed populations of common bullies in experimental ponds through a combination of predation and competition.
		Mosquitofish predate fry of native black mudfish and may exclude them from some habitats (Ling and Willis 2005).
		In lake field trials and tank experiments rudd selectively eat different macrophytes, potentially influencing composition of macrophyte communities and this selective feeding may prevent re-establishment of these species in restoration programmes (Lake et al. 2002).
		An intensive removal of koi carp from a North Island lake led to significant reductions in the koi carp population, which coincided with an increase in native eel abundance, suggesting dietary overlap and competition for food between carp and eels may have been suppressing eel population size (Tempero et al. 2019).
		Tench populations could act as a reservoir for a gut parasite and widespread transmission could reduce populations of native fish hosts such as common bullies (Rowe 2004).
Community	Species extinction and reduction in native biodiversity	Presence of brown trout is a driver for elimination of non-migratory galaxiids from some streams (Townsend 2003; Townsend and Simon 2006; McIntosh et al. 2010; Jellyman et al. 2018).
	Changes in composition of native species assemblages.	Brown trout have suppressed grazing pressure from macroinvertebrates on algae biomass and thus can enhance algal biomass and alter algal species composition and potentially macroinvertebrate community (Townsend 2003; Jellyman et al. 2018).
	Alteration / modification of food webs.	Annual production of macroinvertebrates is consumed by brown trout and not galaxiids where the native fish have been replaced and algal primary productivity can be six times higher in a 'brown trout stream' than a 'galaxiid stream' (Townsend 2003; Jellyman et al. 2018).
		Mosquito fish (*Gambusia affinis*) can induce changes in zooplankton community which diminish diets of native mudfish (Barrier and Hicks 1994).

Scale of biological organization	Impact and examples of mechanisms	Description
Ecosystem	Modification of nutrient cycles.	Greater algal primary productivity in streams where brown trout have replaced galaxiids leads to an increased nutrient flux from the water to benthic community (Townsend 2003; Jellyman et al. 2018).
		A range of NNS (rudd, tench, perch, brown bullhead catfish, goldfish, and koi carp) alters nutrient levels, affecting lake trophic processes, with excretion and bioturbation increasing nutrient levels (Hanchet 1990; Rowe 2007).
	Loss / modification of habitat, native species refuges.	Salmon redd construction by Chinook salmon in two salmon spawning streams decreased the abundance of mosses, algae, macrophytes and sediment and detritus, causing a geomorphic modification of pool-riffle sequences and this was associated with a decrease in the abundance of benthic macroinvertebrates (Field-Dodgson 1987).

Collier et al. (2015) summarised the main impacts of such multiple species assemblages acting in unison in Aotearoa lakes. These are: feeding, which influences bioturbation and water clarity; excretion, which influences nutrient levels; and predation or grazing which impact native food-webs, biodiversity and habitats. At a global scale, multiple NNS presence and their impacts are also a world-wide driver of increasing biotic homogenization of species, with more countries having an increasing number of species in common (Rahel 2000; Dudgeon et al. 2006; Joy and Death 2013; Bernery et al. 2022).

Table 1 purposely does not cover economic or cultural / social impacts of NNS introductions but as these are invariably interrelated with ecological impacts, they should also be acknowledged. Economic impacts can include negative impacts on local commercial and native fisheries (through competition / predation with focal species) and the local economy (i.e. adverse effects on tourism). Conversely, positive impacts can include new export opportunities, new fisheries / tourist opportunities (for a valued sports fish), increased employment and food resources (Dedual 2019). Economic damage and management costs of all biological invasions in Aotearoa have been estimated as US$120 million per year, and freshwater NNS would represent a significant proportion of this (Bodey et al. 2022). The cultural and social impacts of NNS tend to be largely negative for Indigenous people both globally and in Aotearoa (Rypel et al. 2021). Impacts include decline of native fish species relied on for food, with an associated loss of cultural practices and knowledge surrounding their use, and secondly the decline of aesthetics and 'contamination' by NNS of culturally important lake and river habitats (Dedual 2019). Approximately 83% of freshwater and marine taonga (treasured by Māori) native fish are classified as at risk of extinction (StatsNZ 2023) and there remains a lack of recognition of the cultural significance of native fish for Māori in policy and management. This 'blind-spot' is not unique to Aotearoa and arguably is still evident in the majority of European and North American fisheries management contexts (Rypel et al. 2021). Given that Indigenous communities have inter-generational experience in confronting NNS introductions, their knowledge and expertise would likely enhance NNS policy and management significantly (Harmsworth et al. 2016; Wheeler and Root-Bernstein 2020).

Dealing with risk – biosecurity policy and public messaging

At its simplest level, biosecurity consists of a number of feedback loops (positive and negative) aiming to influence different aspects of the biological invasion process (Fig. 1). Some governments and regions define biosecurity in purely scientific terms, such as in European Union (EU) guidelines (zu Ermgassen et al. 2020), whereas risks to cultural and social values are at the forefront of biosecurity policy in Aotearoa (MPI 2016a).

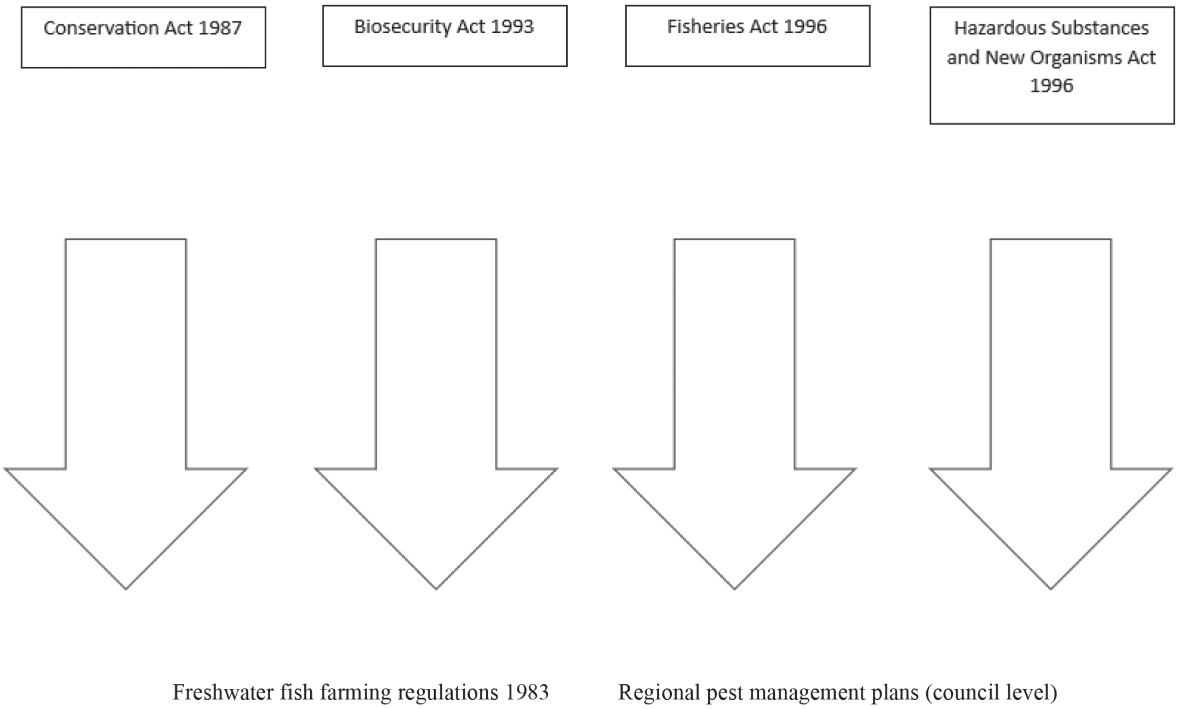
If we focus on fisheries management in countries such as Aotearoa, government resources and legislation are invariably applied to a limited suite of species deemed 'important', whether these are 'desirable' natives or non-natives which policies favour, or 'undesirable' non-natives which policies work against (see Davis et al. 2011). A complex and arguably fragmented governance and legal framework for biosecurity is currently driving very different socio-ecological feedbacks for 'important' freshwater fish species in Aotearoa.

Biosecurity, specifically as it relates to non-native freshwater fish in Aotearoa, is regulated in the context of four principal pieces of legislation: the Conservation Act 1987, the Biosecurity Act 1993, the Fisheries Act 1996 and the Hazardous Substances and New Organisms Act 1996, working alongside the Freshwater fish farming regulations 1983 and council administered regional pest management plans (see Fig. 4). These legislative components often operate in parallel but are not fully integrated, resulting in duplications and inconsistencies in both terminology and application of existing legislation. For example, under the Freshwater Fisheries Regulations 1983, it is illegal to have 'Noxious Fish' 'under control, or rear, catch, hatch or consign', whereas under the Biosecurity Act 1993, 'Unwanted Organisms' can have 'restricted sale, distribution and propagation' (Fisheries New Zealand 2021).

Prevention is always better than cure when it comes to biological invasion and the Hazardous Substances and New Organisms Act 1996 (Ministry for the Environment 1996) is another legislative tool that aims to regulate species introductions at the border (Fig. 4). This requires a rapid risk assessment and only permits entry if the species is unlikely to form a self-sustaining population, displace a valued or native species and / or affect native genetic diversity, cause habitat deterioration or a disease problem, or adversely affect human health and safety (Rowe and Wilding 2012). Despite this, a major flaw in the system is that there is no specific guidance on how the risk of these impacts should be assessed for taxa such as freshwater fish (Rowe and Wilding 2012). It has been suggested that non-native fish risk assessment models for Aotearoa, could be based on species traits associated with 'invasiveness', such as r-selected traits including rapid growth, early maturity and high fecundity, as well as tolerance of a wide range of physicochemical conditions, a large native range or a documented history of invasion success in other countries or regions (Ricciardi and Rasmussen 1998; Rowe and Wilding 2012).

Gaps and labels – how some species don't legally exist, and some can simultaneously be a 'problem species' and the 'right species' depending on where they are

A core aspect of any biosecurity programme requiring public support is the language used to describe species and biosecurity objectives. 'Branding' certain species as 'invasive aliens' or as 'pests', sends out an unambiguous message, that such species are undesirable (Nesbit 2020; NIWA 2020; Tadaki et al. 2023). The Department of Conservation (DOC) defines aquatic pests as 'aquatic organisms that may be problematic to aquaculture and ecosystems' (https://www.doc.govt.nz/nature/pests-and-threats/freshwater-pests/), but this general definition has no legal basis.



Sports Fish	Noxious Fish	Unwanted Organism	Prohibited Organism	Restricted Species
Brown trout	Walking catfish	Koi carp	Venomous fish	Grass carp
Rainbow trout	Rudd	Mosquitofish	Stickleback	Silver carp
Chinook salmon	Koi carp			
Tench				
Perch				
Rudd (Auckland -Waikato only)				

Figure 4. Main government legislation in Aotearoa dealing with the biosecurity, presence / possession and culture of non-native freshwater fish species and the classifications of selected fish species that have resulted from application of such legislation (table adapted from Dean 2003).

It could be argued that certain species emerge as 'pests' in the policymaker's mind due to ecological, economic and cultural damage associated with this species or its analogues, witnessed in other regions or countries. However, it has also been increasingly argued that deliberately prejudiced language has confounded reasoned, evidence-based ecological decision-making on NNS, and that these negative labels are being applied to animals which are just highly adaptable and successful generalists (Nesbit 2020).

Pest, alien, invasive, unwanted, undesirable and noxious are all terms that government agencies have purposely used to prompt the public to actively discriminate against non-native species labelled as such (Inglis 2020). Prevention, detection and elimination are all components of a negative feedback loop that seek to manage such 'problem species', because they are not the 'right species' such as a salmonid 'sports fish' (Abbate and Fischer 2019; Fig. 1). Fig. 4 shows non-native freshwater fish species classifications within the current legislative and regulatory framework (adapted from Dean 2001). These classifications represent the culmination of government risk assessments and management recommendations and are part of an ever-evolving legislative landscape. The resulting legislative landscape is so contradictory, that the 'right species' can be a 'valued introduced species' in one region of the country, while being a 'problem species' in another region. For instance, tench, perch and rudd are termed 'pest fish' in most regional council pest management plans but are also defined as 'sports fish' in the Auckland / Waikato Fish & Game region of the country (Freshwater Fisheries Regulations 1983 – Fish & Game being a non-government public entity representing a large hunting and fishing fraternity). Rudd, in fact, has three labels as it also bears the additional label of a 'noxious' fish, except where it is regarded as a 'sports fish'.

While this multiple labelling could be regarded as a pragmatic fisheries management approach, we suggest that it also reflects problems with policy (such as duplication), which are exacerbated by a current lack of 'joined up' centralised and holistic management of freshwater fisheries. Currently, different sectors of government, as well as public entities, have different responsibilities and accountabilities for different freshwater fisheries. To complicate matters further, a core piece of freshwater environmental legislation, the National Policy Statement for Freshwater Management (NPSFM-2020) only explicitly protects the habitats of two freshwater fish species and these are both NNS, namely trout and salmon. Perversely, only one native freshwater fish has full legal protection in Aotearoa legislation (the Freshwater Fisheries Regulations 1983), and that is the grayling (genus *Prototroctes*), a fish extinct since the 1930s (Mitchell 2018).

Members of the Carp family (Cyprinidae) are also subject to multiple labels in Aotearoa, depending on the species involved and their perceived 'usefulness' or threat. The koi carp is classified as both a noxious fish and an unwanted organism, depending on the legislation applied (Freshwater Fisheries Regulations 1983 for the former and the Biosecurity Act 1993 for the latter). McDowell (1990) also highlighted problems with the management of another NNS, that of rudd (*Scardinius erythophthalmus*), and pointed out that if an angler catches rudd, it is then illegal to keep it but also to release it, so an offence cannot be avoided. Despite this, Hicks (2001) also noted that the noxious status of rudd has failed to prevent its spread. Conversely, grass carp (*Ctenopharyngodon Idella*) and silver carp (*Hypophythalmichthys molitrix*) share a unique status in Aotearoa law as 'Restricted Fish' (section 26ZQA of the Conservation Act 1987), permitting both species to be farmed and released as biocontrol agents for aquatic weeds (http://legislation.govt.nz/act/public/1987/0065/latest/DLM106031.html).

While legal approval must be sought to possess a range of named freshwater animal and plant pests, including non-native *Gambusia* mosquito fish, no approvals at all are needed for a species such as the goldfish (*Carassius auratus*). Indeed, there are currently many freshwater NNS that are not covered by existing legislation and therefore effectively have no legal status in the context of current legislation. Apart from goldfish, these NNS 'gaps' with no legal status, include other aquarium / ornamental fish, brown bullhead catfish (*Ameiurus nebulosus*) and invertebrates. Although catfish and goldfish have no strict legal status, fishing regulations for recreational and commercial fishers require all captured catfish to be killed, and eradication of goldfish may be covered under regional council pest management plans such as in the Waikato Region of Aotearoa. Despite these latter attempts to 'cover these gaps', such omissions are worrying, especially given that the freshwater ornamental aquarium trade is arguably the greatest current biosecurity threat to freshwater ecosystems in Australasia (Ebner et al. 2020). This threat may only be exacerbated by climate change, with gradual increases in median water temperature favouring physiologically tolerant freshwater fish species (Dedual 2019).

The continuing tension between different legislation, governing organisations, and management objectives has been at least partially acknowledged. A recent proposal sought to create a new special permit to enable all species that can be defined as pest fish in areas where a specific problem has been identified, to be managed or eradicated under a single purpose, regardless of any other legislation (Fisheries New Zealand 2021).

Freshwater fish aquaculture – confused and confusing legislation

The sustainability of the freshwater aquaculture sector depends on minimising the environmental impact generated by freshwater farms (Mavraginis et al. 2017), and anything which inadvertently complicates this process or fails to engage the farmer in their statutory duties is problematic. Commercial farming of introduced fish is an inherently risky business in respect of the recipient ecosystem, as it introduces the threat of the possibility of escape or accidental release of NNS to a naïve ecosystem. To some extent a rudimentary negative feedback loop incorporating preventative biosecurity at the individual fish farm level, is the optimum approach to prevent ecosystem impact, with early detection and reporting the next 'best' approaches to minimise ecosystem impacts. Despite biosecurity regimes at fish farms, it should be acknowledged that fish farm escapes are relatively common and attempts to eradicate freshwater NNS have rarely been successful globally, so robust prevention in Aotearoa, as in other countries, remains as the critical safeguard against ecosystem impacts (MPI 2016b, c, d).

Fish farmer education and biosecurity initiatives do in their own way constitute negative socio-ecological feedback loops with respect to non-native fish (see Figs 1, 2 and associated definitions). These loops are working in the context of a species that policymakers have already decided is commercially valuable to the country and therefore 'worth the risk', as regards any potential negative impacts on native ecosystems from fish farm escapees, diseases and pathogens. Indeed, the New Zealand Government's Biosecurity 2025 Direction Statement refers to the protection of the environment, including 'valued exotic species' not just indigenous biodiversity (MPI 2016a). Only a limited number of selected non-native fish are legally licensable for aquaculture purposes (Freshwater Fish Farming Regulations 1983; MPI 2020). Despite the ecological impacts of fish introduction documented in Table 1, there have been notable 'near-misses' in terms of government-sanctioned species introductions for aquaculture purposes. We refer to these as 'near-misses' because if such species had escaped from farms or been deliberately released, they could have had far-reaching consequences on ecosystems in Aotearoa. Two such 'near-misses' occurred in the late 1980s.

In 1987, a proposal was made to introduce channel catfish (*Ictalurus punctatus*) from North America for aquaculture (Townsend and Winterbourn 1992). Despite information on the impacts of introducing this species in other countries being inadequate for a realistic assessment of potential effects in Aotearoa (Townsend and Winterbourn 1992), a government permit was granted to import fertilized catfish eggs. Eggs were hatched in quarantine, the need for environmental trials was dropped and the species was poised to be released for aquaculture, subject only to an independent two-person review team assessing whether the environmental risk was acceptable (Townsend and Winterbourn 1992). Because the available evidence from North America, albeit very limited, indicated that the catfish would probably eventually escape from an aquaculture facility and pose a major threat to one or more valued fish or invertebrate species, the review team recommended that the risk was unacceptable. This recommendation was accepted by the Fisheries Minister, and all catfish held in quarantine were subsequently destroyed.

In 1989, a fish farm in the Auckland region was initially granted permission to farm the Australian Marron Crayfish *Cherax tenuimanus* at one location (Rowe 1992). Shortly after this, approval to transfer the crayfish to other farm sites (new locations) was refused due to concerns over the potential impacts on native ecosystems, including displacement of native crayfish. This led to the 500,000 farmed Marron Crayfish already in Aotearoa being destroyed (Rowe 1992). A confused legal situation had been created in which introduced crayfish were being legally farmed and could be sold live throughout the country but could not be legally transferred to other farms (Rowe 1992). In 2005, two ponds in Auckland were subsequently found to contain 300 Marron crayfish, which then had to be destroyed by government agencies (Beston 2005; Champion 2018).

These cases demonstrate how the misalignment of legislation at the time allowed the legal importation of two INNS into Aotearoa despite their known histories of ecological damage in other jurisdictions, before subsequently legally preventing their release within the country. Both cases also demonstrate the continuing tension between economic interests and ecological protection as drivers in decision-making over the management of non-native fish (see Townsend and Winterbourn 1992; Gozlan et al. 2010).

Moving and stopping – translocation and fish barriers

Although many translocations of freshwater non-native fish in Aotearoa happened in the past, due to the activities of acclimatisation societies, legislation now restricts translocations to native fish only (section 26ZM 'Transfer or release of live aquatic life' of the 1987 Conservation Act (2019 amendment). The current government approval process has two broad pathways: First, releasing species where they don't already occur, which includes stocking a freshwater species at a fish farm for the first time, and second, releasing a species where it already occurs. Because only indigenous species are legally allowed to be translocated, a positive (reinforcing) feedback loop can be established, where native freshwater species, valued for conservation purposes and native fish farm expansion to supplement native populations under pressure or decline, drive more translocations of selected native species (Fig. 1). If the public in the recipient environment value the translocated native species, this again reinforces the loop by driving increasing demand for further translocations (Raine et al. 2020).

As discussed earlier, there are two notable NNS exceptions to the 'native only' translocation policy and these are the grass and silver carp which are legally termed 'restricted species', as opposed to 'pests'. Their translocation and release are allowed under licence provided they are 'under control'. However, this system is not foolproof and there have been instances of previously legally released carp escaping to water bodies, other than the ones allowed in the licence (Otago Daily Times 2024). In terms of unwanted NNS, the freshwater translocation of native species also carries risks, as NNS 'hitchhikers' can be inadvertently introduced as either parasites of translocated hosts or can exist free living in the water and/or on material used in the transport process (Duggan and Pullan 2017). This is currently a serious problem in parts of Aotearoa where the Gold-Asian clam has recently (2023) been detected and where fish translocations have been an established integral part of fisheries management (MPI 2023).

Fish passage in Aotearoa is managed to prevent the passage of 'undesirable' fish species in order to protect 'desirable' fish species, their life stages, or their habitats' (Ministry for the Environment 2024). Every regional council has to make or change its policies to identify 'desired fish species' for which instream structures must provide passage, while simultaneously identifying 'undesirable fish species' for which passage should be prevented. In effect, such management of fish passages in the recipient environment presents two basic simultaneous feedback loops, a negative (mitigating) feedback loop associated with the 'undesirable', usually non-native species, and a positive (reinforcing) feedback loop, associated with the 'desirable' native species (Fig. 2). The use of fish passages as a tool to both prevent non-native fish and enhance native fish movements is arguably creating tension in management strategies, especially where agencies are charged to deliver one without considering the other.

Past and present troubles with brown trout, as an exemplar of the persistent tensions surrounding deliberate introductions

As discussed previously, the acclimatization societies were dynamic drivers of fish introductions to bolster tourism and sport in the fledgling British colony of New Zealand (McDowall 1990). In these narrow aims, such introductions were largely successful. Nearly a century ago, Zane Grey, the famous American writer, declared 1920s New Zealand to be the 'angler's Eldorado' (Grey 1926), and a century later, in 2020, the New Zealand Federation of Freshwater Anglers (NZFFA) claimed to a government select committee, that the country's sports trout (brown and rainbow) fishery was worth over a billion New Zealand dollars annually (c. 700 million U.S.). Despite speculation on the economic benefits, the introduction, spread, management and continued presence of brown trout are becoming increasingly controversial issues. The current conservation status of brown trout in Aotearoa is 'introduced and naturalized'. These three words hide a myriad of complex, confusing, often contradictory and sometimes highly polarized views on the current 'status' of this iconic species. While brown trout is regarded as a 'pest' species by some as it out-competes and predates native species, to others it is the centre of their recreational lifestyle or culture (Tadaki et al. 2022). The management of such a fish remains an ongoing challenge for government agencies in Aotearoa (Chadderton 2001; Tadaki et al. 2022).

Being the only country in the world where trout farming and commercial sale of trout is banned, government documents with any reference to trout culture use the term 'trout production' to distinguish it from all other freshwater 'finfish aquaculture'. This is because although commercial farming is prohibited, hatcheries continue to produce trout for re-stocking purposes for recreational angling. The situation is culturally and politically complicated, with some iwi (Māori extended kinship group(s)) in some regions wanting the law changed to allow farming of trout (Kupenga 2019). This law change continues to be resisted by angling organisations, who see trout farming as a threat to the recreational fishery.

Non-native fish introductions can drive policy-based socioeconomic positive feedback loops that increase fish transport out of source regions over time, as the perceived success and value of the introduced fish in recipient areas induces a 'socio-economic invasion meltdown', whereby economics drive further introductions as part of a positive feedback loop (Fig. 3). Such a loop has been witnessed in the initial introductions of fish such as chinook salmon and brown trout by acclimatisation societies and although this historic feedback loop may no longer exist, its ramifications have arguably driven a host of more recent socio-ecological (negative mitigating) loops, as opposed to socio-economic (positive reinforcing) feedback loops. These more recent mitigating loops seek to manage the presence of introduced fish and their ecological or cultural impacts. Taking brown trout as an example, components of such loops include banning of trout fish farming, more restrictions on trout hatcheries, banning of trout translocation and establishment of instream structures to act as barriers to trout movement in and between watercourses. More controversially, such loops would also include elimination / removal of trout from water bodies, where native species are threatened and / or river restoration projects are underway. It could also be argued in general terms, that the extremely detailed and tightly policed biosecurity regulations at the borders of both Aotearoa New Zealand and Australia are strong negative feedback loops, which are just as much a response to a past history of ecological and economic damage involving INNS, as they are a current response to new INNS threats.

Conclusions

The debate over non-native freshwater fish management continues, and that is the 'new reality in New Zealand' (Jellyman et al. 2018). Legislation, policy, language and the social-ecological feedbacks generated, are a result of a series of value judgements on native and non-native fish. These value judgements have themselves evolved over time and will continue to change. Such change is inevitable, as the spread and impacts of INNS continues to accelerate, presenting policymakers and public with an issue that threatens to get worse and become more confrontational in the decades to come.

Currently, the prevailing legislation, despite its shortcomings, seeks to promote negative feedbacks mitigating against the establishment and spread of INNS, and positive feedbacks that reinforce the recovery, persistence and growth of culturally important native species and fisheries. Continued use of language and selective 'labelling' of some INNS as 'pests', 'noxious' and 'undesirable' is a powerful tool in policy terms to promote negative feedbacks seeking to detect, manage and eliminate INNS. However, it should be acknowledged that some non-native fish such as brown trout are now so widespread in Aotearoa and have already drastically changed the trophic ecology of freshwater systems, that it is probably impossible to eradicate them, even if they are increasingly regarded as pests that need to be removed so native biodiversity can be restored (Chadderton 2001; Jellyman et al. 2018). In contrast, it should also be acknowledged that there is increasing debate in the global scientific community, about all NNS being vilified as 'evil aliens' and natives being 'beloved', and it has been argued that conservationists should assess species on their impacts, rather than whether they are native or non-native (Davis et al. 2011). In the context of Aotearoa, where non-native fish introductions have largely reflected colonial values and interests, there is increasing recognition that the priorities and expectations of Māori communities need to be provided for, in weighing these questions.

In Aotearoa, arguments over ecosystem restoration from a western fisheries perspective, with a *status quo* of established non-native sport or aquaculture species desirable to some stakeholders, as opposed to 'reimagining' fishery management with indigenous knowledge and values as a focal point, continue. Māori values and perspectives concerning freshwaters, which were all too often ignored in the past (Stewart-Harawira 2020) are now increasingly informing freshwater management (Harmsworth et al. 2016), highlighting opportunities to incorporate more diverse values and impacts into legislation concerning NNS. While Aotearoa policy still has a long way to go in this regard, in recent years *mana whenua* [customary authority exercised by iwi or hapū (Māori descent groups) in an identified area] rights and obligations are increasingly manifest in legislative fisheries management frameworks, as well as in core freshwater environmental protection legislation (Ministry for the Environment 2024). In contrast, Fish and Game New Zealand in a 2023 manifesto document, have raised concerns among its angling members that recent legislative proposals focussing solely on protection of native fish biodiversity, are inevitably to the detriment of non-native sports fish valued by its members (Fish and Game New Zealand 2023). The debate over where non-native freshwater fish into future legislative and actual landscapes in Aotearoa continues (Jellyman et al. 2018). From a global perspective, some fish introductions judged beneficial for biodiversity and/or economy, may still be promoted in the future, alongside increasingly stringent measures against those species which have caused ecological damage in other jurisdictions (Gozlan 2008; Gozlan and Newton 2009). Biosecurity, fisheries and aquaculture policies in Aotearoa, as in other countries, will have no choice but to acknowledge and deal with this apparent paradox (Gozlan 2008; Gozlan et al. 2010).

We would argue the current legislative landscape in Aotearoa is a patchwork, 'make-do-and-mend' approach to freshwater fish management, rather than a coordinated, coherent pragmatic approach. We would advocate the latter, until a much wider national debate has taken place on what people need and want from their freshwater fisheries in Aotearoa and how this could be achieved. A coordinated approach would require government organisations, iwi entities, and different stakeholder groups working together in a more equitable, unified way than previously witnessed. Only by doing this, can modernised, coherent policies and legislation be produced, whereby gaps, inconsistencies, anomalies and duplication can be minimised and when identified, resolved quickly. Using a SES approach with a focus on causal-loop relationships and feedbacks will be extremely valuable to improve understanding of the dynamics of drivers and outcomes underlying current non-native freshwater fish polices and how these can be manipulated to achieve agreed outcomes.

Acknowledgements

This research was conducted through the Fish Futures MBIE Endeavour programme, contract CAWX2101. Thanks to Joanne Clapcott for reviewing this manuscript. We thank both the editor and reviewer for their very constructive comments.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Funding

This study was funded by the Ministry of Buiness, Innovation and Employment, through the Fish Futures MBIE Endeavour programme.

Author contributions

Conceptualization: CM. Methodology: CM. Writing – original draft: CM. Writing – review and editing: JA, RH, EC, KM.

Author ORCIDs

Calum MacNeil https://orcid.org/0000-0003-0402-9292
Robin Holmes https://orcid.org/0000-0002-8737-2717
Edward Challies https://orcid.org/0000-0003-0689-858X
Kiely McFarlane https://orcid.org/0000-0003-0321-2028

Data availability

All of the data that support the findings of this study are available in the main text.

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